EXPERIMENTAL STUDIES ON EFFECT OF COLOR TEMPERATURE ON DRIVER'S PERFORMANCE TOWARDS OBJECT DETECTION : A HUMAN CENTRIC APPROACH

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CERTIFICATE OF RECOMMENDATION

This is to certify that the thesis entitled "***EXPERIMENTAL STUDIES ON EFFECT OF COLOR TEMPERATURE ON DRIVER'S PERFORMANCE TOWARDS OBJECT DETECTION : A HUMAN CENTRIC APPROACH*** " is a bonafide work carried out by **Jyotipriya Roy** under my supervision and guidance for partial fulfilment of the requirement of ***MASTER OF ENGINEERING IN ILLUMINATION ENGINEERING***, during the academic session 2021 - 2022.

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Abstract

Illumination has been considered as a very important part of human lifestyle since a very long time. It goes with the conjunction of human wellbeing, mood, and motivation. On the other hand, roads and streets have been contributing as an important segment in the history of development of a society and its people. Under these circumstances, street lighting is a broad domain which incorporates various aspects of illumination. As, light and the way of lighting have direct and indirect effects on human perspective, various aspects of human centric parameters revolve around this domain. Because of this reason, lighting has been an area of research interest to the scientists for decades. Studies have found that light has immense effect on the behaviour and visual and non-visual task performances of human being.

With the increasing number of road accidents since several decades, the safety of a human individual has been a major concern for the researchers throughout the globe. It is found from field surveys that one major reason behind road accidents is the poor conditions of the road lighting schemes. Under these inadequate circumstances of road lighting, recognition and identification of objects on the streets cannot happen properly which further lead to severe road accidents. studies have found that lighting parameters like CCT, Illuminance, Luminance etc. are directly correlated with the human parameters like brain functioning, reaction time (RT), visibility level (VL), efficiency in task performance etc. So, optimization in those lighting parameters can lead to a broader effect on the human health as well as on the society with positive outcomes.

This study analyses the variations of the reaction time (RT) with the changes in the correlated colour temperatures (CCT) of light sources in a laboratory based controlled environment at the Illumination Engineering Laboratory of the Electrical Engineering Department of Jadavpur University to better understand how drivers react towards the changing CCTs (Correlated Color Temperature) of light sources. By using two of the same LEDs as auxiliary sources, one LED as the main source and with some special arrangements, a replica of real road lighting scenario is being developed inside the laboratory. Impacts of this study also assess the effects of peripheral sources on reaction time (RT) of the driver. It is found that, average reaction time (ART) decreases as ambient illumination level increases by the peripheral sources. Most importantly, it is clear from the study that there is some degree of correlation between reaction time (RT) and CCT. Under various lighting circumstances, the effects of peripheral source on on-axis visual task performance by human observers are robustly analysed. It is found from this this study that, the performance of the driver on a real road is also influenced by the Color Temperature of the primary and auxiliary light sources.

Overview of the thesis

Chapter 1 Provides the general introduction of the street lighting, overview of the experiment and some terminologies used in this thesis.

Chapter 2 Discusses about the background of this work and provides number of literature reviews on previously performed research regarding human performance under various street lighting conditions. This chapter also discusses how this research problem is formulated.

Chapter 3 Describes the evolution of street lighting throughout centuries.

Chapter 4 Provides the knowledge about the concept "human centric lighting".

Chapter 5 Provides the description of the overall experiment through a work flow diagram.

Chapter 6 Provides the details regarding the experimentation and data analysis. The process of the overall experiment, data analysis technique, and the results that have been achieved are described in this chapter.

Chapter 7 Deals with the conclusion and the future scope of the thesis.

References

Appendix 1 Contains the list of various abbreviations used in this thesis.

Appendix 2 Contains the brief discussion of the instruments used in this project.

Appendix 3 Contains the details of various circuitry components used in this project.

Appendix 4 contains the Arduino programme used in this project.

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Chapter - 1

Introduction

1.1. History of Street Lighting :

Vision is one of the most important and essential objectives for any living being. In case of human-vision perspective, our visual system does not provide us with the ability of seeing any object in total darkness. Sun being the natural source of light, in absence of daylight, proper vision for human being is achieved only through artificial lighting. But in the ancient times the scenario was far more different than the current era. The first artificial source of light for the primeval human being was the use of fire itself. Centuries have passed since then and humans have invented, adapted, and constantly modified the way of lighting on the path of evolution accordingly. In the night-time, to satisfy the need of performing any physical task outside of the residence, using streetlights was the new adaptation. The journey from the use of oil-lit lantern, through the arc lamps (after invention of electricity), incandescent bulbs, metal halide (MH) bulbs, to the sodium vapour lamps (SVL), high intensity discharge lamps (HID), compact fluorescent lamps (CFL) and in the modern era the use of light emitting diode (LED) in the street lighting aspect has followed a very long path. The basic requirement in earlier days was just to provide basic visuals in the streets. But this scenario has changed with the course of time tremendously. Following the path of modernisation and performing extensive research in the domain of lighting has unfolded broader objectives and perspectives of light and lighting schemes in human life. Studies have proven that light does not only stimulate the visual system, rather it significantly influences the non-visual aspects of human being such as mood and motivation, alertness and circadian rhythm i.e., sleep-wake cycle [1]. Light influences the overall task performances of an individual. Proper illumination can increase the quality of human task performance, the aesthetics of an area and psychological well-being of its occupant's [2].

The Honourable Prime Minister, India announced the Street Lighting National Program (SLNP) on January 5, 2015, with the goal of replacing outdated street lights throughout India with modern, energy-efficient LED street lights [3]. According to the PM Gati Shakti National Master Plan, the Indian government has set a goal to construct 25000 km of national highways in the fiscal year 2022–2023. Government planning can be more effective if a suitable design plan is upheld. A competent road lighting system is crucial for creating a safe route.

1.2. Relevance :

The effects of lighting on human perspective can be seen broadly in the streets when the street lighting domain is analysed. Driver's performance, alertness and visual comfort relies on the quality of lighting design for the streets. But in Indian context proper street lighting schemes and standards are not followed on the roads or streets or pathways. Even in the National Highways in India, lighting is not applied keeping in mind the relationship between light and human perspective. As per latest data available on an average 17 people die every hour in India due to road accidents and this rate is increasing at the rate of 13.5% per year. Also 70% of accident-prone areas are the highways which incidentally amount to only 2% of Indian roads. It has also been seen that the most common reason behind road accidents (78%) is driver's fault and such faults can be mitigated by proper road lighting installations. Proper street lighting can reduce

21% of all road accidents, 29% of all casualty events [4]. Fatal road accident rates during darkness, however, are approximately three times greater than those during daylight, mainly due to reduced level of visibility during this period. Proper visibility of on road objects is the main area of focus for the driver's performance on driving. From the driver's perspective the main area of concern while driving on the road, is proper realization of the vehicular and non-vehicular traffic movements, pedestrian movements which are approaching towards the road. Under this circumstances, proper visibility of the frontal vicinity of driver's eye is very much important for safer movement of traffic. It is also very common in streets that disturbance or instability of any individual effects the overall traffic on that region. So, for every individual who is driving on road, the visibility and activeness of mind are the most fundamental requirements while moving.

The purpose of street lighting is to provide proper visibility and reveal if there are any obstacles present or not so that to ensure safer vehicular and non-vehicular movements. In Case of night-time scenario when the level of visibility of the road users are comparatively lower than from the daytime, streetlights ensure the proper visibility for better traffic movements. A proper road lighting reduces the no of accidents in the night-time when the mesopic visibility of human eyes work actively. According to the Commission Internationale de I'Eclairage (CIE), the primary goals of street lighting are:

(i) to ensure the safety of all road users, including drivers of motor vehicles, bicycles, and animal-drawn vehicles

(ii) to help pedestrians see hazards, get their bearings, identify other pedestrians, and feel secure and the last one is

(iii) to enhance the day and at night time visibility of streets.

CIE 115:2010 [5], EN 13201-1 [6], EN 132021-2 [7], IESNA/ANSI RP-8 [8], and BIS 5489-2013 [9] are a few examples of international guidelines that offer quantitative recommendations for street lighting. Two different types of lighting guidelines are covered by the European standard and CIE, one for motor vehicles and the other for pedestrians. Based on traffic movements, the roads of any country is categorized in some groups. Similarly in Indian scenario, the roads have been classified in 4 Groups according to IS:1944 part I & part II. The descriptions are given below in a tabular form :

Classification of Lighting Installation	Type of Road	Average Level of Illumination on Road Surface (lux)	Ratio Minimum/Average Illumination	Transverse Variation of Illumination	Type of Luminaire	
					Preferred	Permitted
Group A1	Important traffic routes carrying fast traffic	30	0.4	33	cut-off	semi-cut-off
Group A2	Other main roads carrying mixed traffic, like main city streets, arterial roads, through ways, etc.	15	0.4	33	cut-off	semi-cut-off
Group B1	Secondary roads with considerable traffic like principal local traffic routes, shopping streets, etc.	8	0.3	20	cut-off or semi-cut-off	non-cut-off
Group B2	Secondary roads with light traffic	4	0.3	20	cut-off or semi-cut-off	non-cut-off

Table 1.1 : Classification of lighting installation and levels of illumination in IS:1944(Part I and II)

1.3. Overview :

In today's road lighting design, the roadways are illuminated with standard illuminance levels in the method used for modern road lighting. However, illumination has little to do with human response or comfort. The lighting should be adapted to match human comfort. Studies have shown that, the color temperature plays a significant impact in increasing visibility and lowering the risk of an accident.

A new direction in street lighting was made possible by the invention of Light Emitting Diodes (LED). Compared to previously used High Intensity Discharge Lamps, LEDs are more efficient (HID). Additionally, LEDs come in a variety of color temperatures. Thus, LED is the ideal option when designing a human-friendly road lighting system.

Through different literature surveys, it is also found that, the peripheral light sources play significant role on the on-axis target detection. This experimental study incorporates peripheral light sources along with main light source to find the effect of different CCT level only driver’s response time in task performance. A laboratory based experimental setup has been developed and components to collect the reaction time data of human observer has been prepared. Further, replica of real road lighting scenario has been created within the laboratory. By varying the

CCTs of main source and peripheral sources it is found that the reaction time of individuals is highly correlated with the amount of CCTs. It is also evident from this study that higher levels of CCTs of peripheral sources obtain better visibility of target objects and further reduces the response time of the observer in object detection, identification and other visual and non-visual task performances.

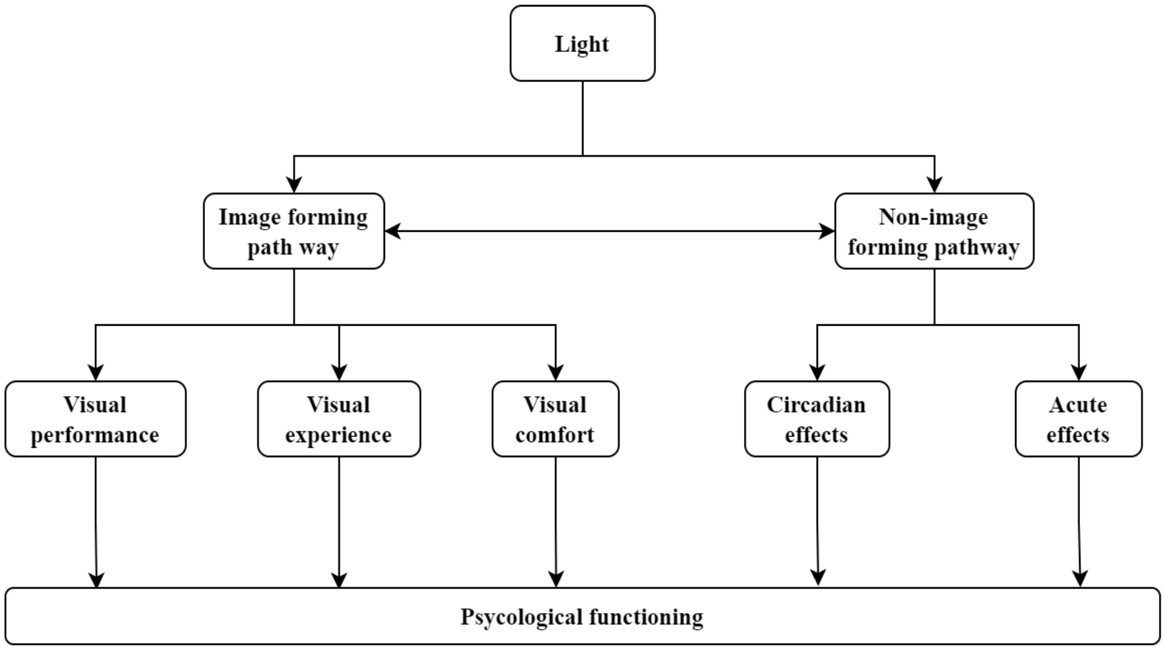


Fig 1.1 : Pathways of light relevant to psychological functioning.

1.4. Objective :

A road serves as more than just a link between two locations; in a larger sense, it serves as a site where transactions can take place. It carries out the exchange between a person and their surroundings, culture, and environment. Quality road lighting ensures highest level of safety and comfort for the drivers during night-time when the level of traffic on roads remains at the peak. The fundamental objective of this thesis is asserted below:

a) **Visibility level improvement –** To improve the level of visibility of existing road lighting. A good quality road lighting must ensure the successful detection of visual information for the other moving traffic, pedestrians, non-motorized vehicle such as cyclists etc [10][11].

b) **Accidents reduction –** The on-road risks become very high at the night-time. A failure of good quality road lighting affects the performance of driver which can lead to life casualties. So, it is essential to design the road lighting in such a way that can reduce the number of accidents in night-time.

c) **Safer road design –** Along with the lighting schemes the design of road should be incorporated in such a way that will always consider the safety of drivers and other road users along with the pedestrians as well.

d) **Energy Consumption optimization –** Since road lighting consumes 20-40% of the total generated energy (in India) [12], the design should be energy efficient and the consumptions can be optimized.

e) **Suitable color temperature detection –** The dependency of human task performance on the color temperature is already established by research in this domain. This thesis has the objective to detect a color temperature level suitable for driver's comfort, focus and performance and further to incorporate this in road lighting designs.

f) **Improvement of existing road lighting standards –** Age old road lighting schemes and standards need to be corrected and improvised so that performance outcomes of lighting become more efficient and convenient.

1.5. Terminology :

There are several photometric and radiometric terminologies which have been incorporated in this thesis. Eventually, they need further explanations. This section provides a description of those terminologies used in this literature.

1. **Radiometry :** The science of measuring radiant quantities is known as radiometry, which measures optical radiation.

2. **Photometry :** The measurement of radiation that incorporates human visual response into account is a particular subfield of radiometry.

3. **Human Vision :** It is possible to divide the human visual system into two components. The eyes serve as image sensors, capturing light and turning it into signals that are then sent to regions of the brain responsible for processing images. The signals or impulses from the eyes are processed by these centres, which then create an internal "picture" of the scene being observed. Because the human eye has two different types of photoreceptors - cones and rods; this sensitivity relies on whether the eye is adapted for bright light or darkness.

   Cones are responsible for light adaptive vision. They are highly resolution and colour responsive. The spectral luminous efficiency function for Photopic Vision ($V\lambda$) is the term used to describe the relative spectral response of the eye. Peak sensitivity is at 555 nm.

   Dark adaptive vision, which lacks colour information and has poor resolution, is caused by rods. The spectral luminous efficiency function for Scotopic Vision ($V'\lambda$) measures how well the eye adapts to spectral changes in the dark. Maximum sensitivity is at 507 nm.

a. **Photopic vision :** In case of photopic vision, the cone photoreceptors of the retina predominate in the viewing process when the luminance level sustains higher than 3 cd/m^2. Photopic vision provides the human eye with high resolution and good quality vision of the elements of the scene.

b. **Scotopic vision :** Under scotopic vision, the rod photoreceptors predominate in the seeing process when the luminance level falls less than 0.001 cd/m^2. Scotopic vision provides the human eye with colorless images and very dull visibility.

c. **Mesopic vision :** When mesopic vision sustains, the cone cells gradually lose absolute sensitivity and rod cells take over. As a result, the resolution and colour perception of the scene suffer. This vision has luminance values that range between the photopic luminance of 3 cd/m^2 and scotopic luminance of 0.001 cd/m^2.

4. **Luminous Flux (Φ_L) :** It is the time rate of flow of total luminous energy responsible for visual sensation as weighted by V(λ). Unit is Lumen (lm).

5. **Luminous Intensity (I) :** The luminous flux emitted by the source per unit solid angle in any direction is what is meant by the term "luminous intensity" in that direction. It indicates the ability of a light source to produce illumination in a given direction. Luminous intensity is used to quantify the distribution of light from a luminaire. Unit is lumen/steradian or candela (cd).

6. **Luminous Efficacy (η_L) :** It is the ratio of the total luminous flux emitted by a source to the total lamp power input to the source. Unit is lm/watt.

7. **Illuminance (E) :** Incident luminous flux per unit area of a surface is known as illuminance. Unit is Lumen/m^2 or lux.

8. **Luminance (L) :** Luminous intensity in any particular direction is defined as the luminous flux emitted by the source per unit solid angle in that direction. It tells us about how much the appearance of one object is brighter than another. Unit is candela/meter^2 or cd/m^2.

9. **Spectral Composition :** Radiated power is distributed differently throughout the electromagnetic spectrum depending on the source. The combination of all those radiated power across the electromagnetic spectrum is called the spectral composition of the visible spectrum. This spectral power data is commonly presented in two ways:

a. **One-dimensional chromatic presentation :** The brightness of the line and colour at a particular wavelength serve as representations which range a wide spectrum of wavelengths. The lines can be continuous or separated.

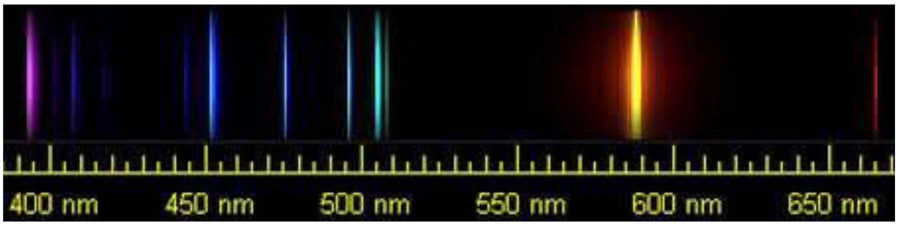


Fig 1.2 : One dimensional chromatic presentation of spectral composition.

b. **Two-dimensional presentation or Spectral Power Distribution (SPD) Curve :** These plots are represented by a wavelength's radiant power and colour which frequently used to represent spectral composition. The graph shows wavelength on the x-axis and spectral power magnitude in the y-axis. The SPD Curve displays the type of emitted energy from the radiator body shown over a variety of wavelengths. While gas discharge lamps display a line spectrum with a discontinuous spectrum and thermal radiators provide a continuous SPD curve. It gives details on the total amount of radiation and how much of it is visible.

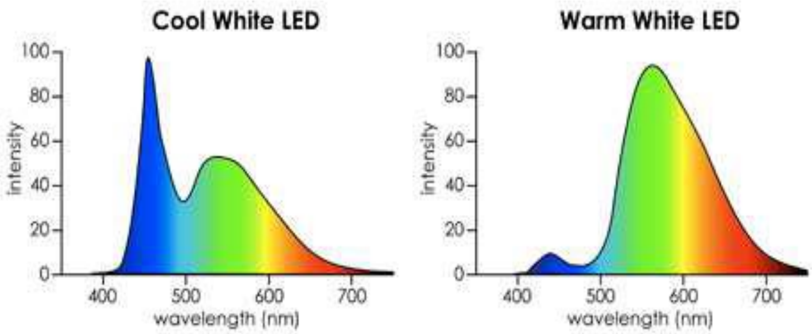


Fig 1.3 : Spectral Power Distribution (SPD) curve of Cool White & Warm White LED.

10. **CRI or Color Rendering Index :** Colored objects may appear differently colored depending on the spectral power composition of the lamp used to illuminate them. CRI is the measure of the degree of color shift objects undergo when illuminated by the light source as compared with the color of those same objects when illuminated by a reference source, of comparable color temperature. CRI of natural Daylight is 100.

11. **CCT or Correlated Color Temperature :** It is the absolute temperature of a blackbody whose color appearance most nearly resembles that of the light source. Unit is Kelvin (K).

    The color temperature is typically used to describe the color of a light source by a single distinct value. "The temperature of a Planckian radiator whose emission has the same chromaticity as that of a particular stimulus," is how the CIE [13] defines color temperature. This means that to a human observer, the black body's appearance should be the same hue as the test source. However, the CIE did not specify the level at which chromaticity should be "identical," thus colour temperature evolved into a broader perspective on the idea. Because of this, Correlated Color Temperature (CCT) is employed to introduce a relative assessment of the color of light sources in the majority of photometric measurement instances (where light sources have significantly different spectral power distribution from the Planckian radiator) [14]. CIE 1960 (u,v) diagram is used to determine CCT of a specific light source by determining the chromaticity co-ordinate of the closest black-body radiation. CIE 1960 (u,v) diagram defines CCT as "the temperature of the Planckian radiator whose perceived colour most closely resembles that of a given stimulus at the same brightness and under specified viewing conditions" [15].

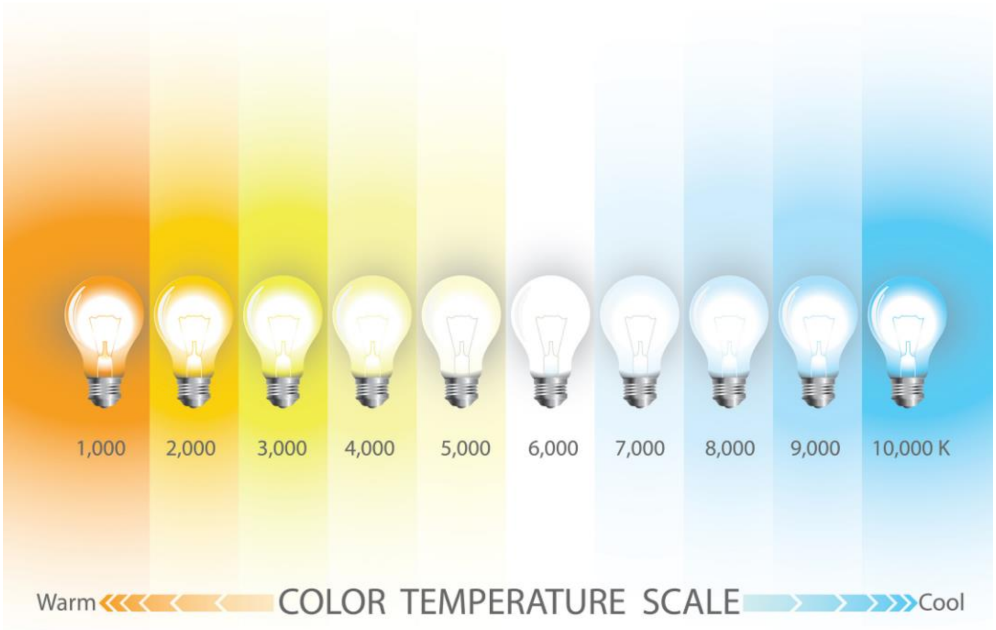


Fig 1.4 : Different levels of CCT and their color appearances.

12. **Reaction Time (RT) :** between the presentation of visual or aural stimuli and a specific response that is triggered by the stimuli and supplied via a response key [16]. The time required to recognise the inputs, decide on a specific action, and begin the action by employing a specific set of muscles, is indicated by this [17]. The ability of a subject to make quick decisions is related to RT [18]. Driving at night requires a driver to have a low reaction time (RT), which requires them to recognise obstacles fast and react appropriately when necessary. A study found that ambient lighting and contrast significantly affect reaction speed [17]. Additionally, it depends on the age, mental health, neurological health, visual health, and muscle performance of the driver.

13. **Visibility Level (VL) :** The visibility level (VL), a standard measure for designing road lighting, is used to assess the effectiveness of vehicular lights. In contrast to illuminance levels, the VL provides a link between lighting design and driving performance. The

benchmark performance of the VL is the identification of a small uniform object standing on a uniform background (the road surface) [19]. The Small Target Visibility (STV) technique was created to take into account the effects of reaction time, glare, age, and the type of contrast (positive or negative) with the effect of contrast. The formulas for calculating VL as well as an explanation of the STV method or VL calculation method and the effects of the aforementioned parameters were supplied by Dr. Ing. W. Adrian in his article.

Chapter - 2

Background of The Work

2.1. Detailed History Through Literature Review :

The correlation between lighting and human work performance has been studied since a very long time. From the very beginning of the 20th century, lot of field studies have been performed in this context. Many claims have been made about the effect of lighting conditions on human work performance and productivity that are a little more than assertions. However, there are few field studies that are significant and deserve attention. Among the earliest times of research there were studies of such visual tasks as silk weaving (Elton, 1920), Linen weaving (Weston,1922), and typesetting by hand (Weston and Taylor, 1926), although these tasks have now almost disappeared. It is not unexpected that since all of these tasks rely on the detection of small, low-contrast details, they tend to support the notion that when lighting conditions are insufficient for a task to be viewed clearly, so performance is improved by increasing the illuminance level. The illuminance at which this improvement ceases will depend on the nature of the task [20][21][22].

In the early 20th century few international studies, particularly in the US and Europe, have begun to focus on people's satisfaction with acceptance of the lighting conditions. Actually, since the development of the Photopic Luminous Efficiency Function V(λ) by renowned scientists Tyndell and Gibson in 1924, human interference in lighting design has been formally acknowledged [23].

Since that time, a number of scientists, including Dr. Weston, Dr. Beutell, Dr. Peter Boyce, Dr. Marc Rea, Dr. Blackwell and many other researchers have worked rigorously to find the human factors in lighting. Today's human-centric lighting approach is the result of scientists' ongoing attempts to incorporate human acceptance as a crucial design element for lighting design. With the highest level of human performance, this human-centric approach to lighting encompasses a wider range of energy-efficient lighting [24].

Beutell (1934) made the initial effort to develop a generic model of how lighting affects work. His approach was to first describe a typical task on which the impact of lighting was examined and the illuminance for any performance level was calculated [25].

Weston (1935, 1945) adopted Beutell's concept as inspiration for a system he created to examine how lighting affects productivity. He conducted a simple task that involved measurement and identification. It was a chart of Landolt rings. He instructed the participants to read the diagram and indicate all the rings with gaps pointing in a particular direction. Under various lighting conditions, the amount of time required, and the number of mistakes committed were counted. To provide metrics of work speed and precision, the measurements were then merged [26]. Several different visual tasks were used to verify Weston's (1945) findings several times (Khek and Krivohlavy, 1967; Boyce, 1973; Smith and Rea, 1978, 1982, 1987; Rea, 1981).

While the human-centric approach is being carefully examined, the area of street lighting seemed to be an essential component of lighting design. When it comes to road illumination, the major goal is to give the driver adequate vision, object perception, and identification. Because of that concept, investigations based on visibility needed attention. L.L. Holladay (1926) performed studies into many ways in which glare of a light source affects the visibility. The investigation's findings indicate that the least perceptible brightness difference between an object and its background rises directly with the amount of illumination received by the eye from the glare source alters approximately inversely with the square of the angle the glare source makes with the line of vision, and is essentially unaffected by the brightness, size, type, distance, etc. of the glare source [27].

Further investigations were done onto the connection between the visual threshold and the size of the surrounding field (Dr-Ing. W. Adrian et al. 1969). The visual threshold of a test field has been established as a function of the surrounding field's size using various surround luminances as a parameter. The luminance difference threshold curves derived by plotting them against the angle occupied by the surrounding field are demonstrated to have a flat minimum in the size range of 3 to 10°. Light scattered in the eye's media increases the threshold for larger surrounding fields, but the rise in smaller fields is still not understood in terms of pupil effects and will be the focus of further research [28].

After this finding, A measure is required to enable the quantification of the visibility level (VL), which is introduced as a criterion for the available visual information. Based on data from Adrian, Aulhorn, and Blackwell; W. Adrian (1989) has developed a method for calculating the luminance difference thresholds (ΔL) of visual targets of varying size and positive and negative contrast. Another parameter relevant to the ΔL is the observation time to deal with practical viewing circumstances, in which fixation was discovered to be constrained to 0.1 to 0.2s. Age-related variations in threshold contrast as well as glare from disabilities have been incorporated. The quantitative description enables the determination of the visibility level (VL) of objects in the visual field [29].

Furthermore, in the year 2002, Turkish scientists Önder Güler and Sermin Onaygil performed photometric measurements using observers as part of this study on the actual road on the Ayazaa Campus of Istanbul Technical University to evaluate the authenticity of visibility level (VL) formula proposed by W. Adrian for road lighting calculations in view of real road lighting scenario. They found a correlation of roughly 0.75 between the calculated and evaluated visibility levels and justified the validity of the formula [30].

While driving on a road, not only the recognition of the objects on the frontal vicinity of the driver is important but also the objects on the sideways need attention for consideration. Therefore, both the on-axis and the off-axis or peripheral visions are equally important from a driver’s perspective. Several studies have been done to understand the influence of the off-axis visions on driver’s visual and non-visual performances. Along with vision, the color perception for an object, present on both on and off-road also influences the driver’s performance. From the monochromatic yellow of low-pressure sodium, through the orange of high-pressure sodium, to the white of metal halide light sources, the perceived color of road lighting differs significantly. Numerous experiments have been conducted to determine how well these light sources perform at illuminating mostly achromatic items on the highway, but none have yielded conclusive results, suggesting that any effects are negligible. (Eastman and McNeils 1963; de Boer 1974; Buck et al. 1975). One common characteristic of these evolutions is that all measurements were obtained by fixating the object, or simply with the retinal picture falling on the fovea [31].

More recent measurements of the effect of light spectrum on the detection of off-axis targets suggest that there may be a significant effect of light color relevant to road lighting. specifically, He, Rea et al. (1997) carried out a laboratory experiment in which high-pressure sodium and metal halide light sources were compared for their effects on the reaction time to the onset of a 2-degree-diameter disc with the centre either aligned in on-axis or 15 degree off-axis, for a range of photopic luminances from 0.003 cd/m^2 to 10 cd/m^2. The luminance contrast of the disc against the background was constant at 0.7. There was no color difference between the stimulus and its background because the same light source was employed to produce both the background luminance and the stimulus. This study clearly demonstrated that for both on-axis and off-axis object detection, reaction time increases when photopic luminance decreases from the photopic to the mesopic state. While at the same time, they examined how observers reacted when a high-contrast character was made to change on a changeable message sign that was 15 degrees off-axis to the observer. The environment consisted of a road illuminated by either metal halide or high-pressure sodium light sources, resulting in an average road surface luminance of 0.2 cd/m^2. The observers were instructed to wear glasses with a transmittance of 0.1 that further resulted in achieving an effective average road surface luminance of 0.02 cd/m^2 [32].

Lewis (1999) also obtained similar results, which show the mean reaction time to correctly identify the vertical or horizontal orientation of the grating (a large, achromatic, high contrast, 14 degree by 10 degree grating was lit by one of five different light sources: low-pressure sodium, high-pressure sodium, mercury vapour, incandescent, and metal halide) plotted against the photopic luminance. The visual system does not distinguish between the various light sources as long as they provide the same photopic luminance, which is between 3 and 10 cd/m^2. However, the different light sources resulted in different reaction times while the visual system was in the mesopic state, which was at 1 cd/m^2 and 0.1 cd/m^2. It was found that the light sources (incandescent, mercury vapour and metal halide) that better stimulate the rod photoreceptors giving shorter reaction times than the light sources (low- and high-pressure sodium) that comparatively less stimulate the rod photoreceptors. By repeating the experiment described above but using a disclosure of a female pedestrian having to stand at the right side of a roadway in the presence of trees and a wooden fence in place of the gratings, Lewis further demonstrated that the spectral Power Distribution of a light source does have an influence on the time taken to extract relevant information to driving. The woman was facing towards the road in one disclosure, and she was facing away from the road in the other. The subject had to determine the direction that the woman was facing. The outcomes of the experiment showed that there is no distinction between the light sources when the visual system is in the photopic state, but once it switches to the mesopic state, the light sources that more powerfully excite the rod photoreceptors exhibit quicker reaction time. [33].

Another method of assessing the impact of the light spectrum under mesopic conditions investigated the likelihood of spotting a target off-axis. Bullough and Rea (2000) used a basic driving simulator that was operated by computer software and was primarily focused on a projector based image of a road. Through the steering wheel and accelerators, the subject could control the vehicle's speed and direction as it travelled down the road. The computer kept track of how long it took to finish the course and how many crashes there were. In order to stimulate the spectrum of both high-pressure sodium and metal halide light sources as well as more intense red and blue light for a variety of luminances, filters were added to the projected image of the course. There was a significant distinction between the ability to recognize the presence of a target close to the edge of the roadway but interestingly, there was no effect of light spectrum on the time taken for completion of the course (i.e., driving speed). A higher possibility of direction was produced by light spectra (blue and metal halide) that more efficiently stimulated rod photoreceptors than by light spectra that did not (red and high-pressure sodium) [34].

Naturally, driving a simulator has quite different potential consequences from operating a real vehicle on the road, and this may make participants less focused on what they are doing. Thankfully, Akashi and Rea (2002) extended this investigation into the real world by having individuals drive cars over a brief road while they monitored their reactions to objects that were 15 and 23 degrees off-axis. Either high-pressure sodium (HPS) or metal halide (MH) road lighting was installed on the road in the same quantity and distribution, and was visible both with and without a vehicle's halogen headlamps. Particularly, for both angular eccentricities, the mean reaction time to the commencement of the targets was faster for the metal halide road lighting than it was for the high-pressure sodium road lighting. By adding halogen headlamps from a parked car to the side lane and instructing a static driver to detect off-axis targets at 15 degrees and 23 degrees while the street lighting was provided by metal halide and high-pressure sodium lighting, the researchers also investigated the effects of disability glare. Once more, compared to metal halide road lighting, high pressure-sodium road lighting exhibited longer mean reaction times to the commencement of the targets. As expected, when the headlights in the opposing vehicle were turned on, the average reaction times were similarly longer [35].

It is undeniable that light sources that more effectively excite the rod photoreceptors boost performance on off-axis detection tasks when the visual system is functioning in the mesopic state. However, it is arguable at what brightness the mesopic condition actually commences. Bullough and Rea et al. (2004) developed a unified model of photopic, mesopic, and scotopic photometry based on reaction times that shows the mesopic vision begins at 0.6 cd/m^2 [36].
Based on performance of tasks allegedly important to driving, another model of mesopic effects known as the MOVE model of Elhoma and Halonen (2006) and literature of Goodman et al. (2007), show mesopic vision can have an impact up to 10 cd/m^2 in the driving environment. Majority of traffic-related road illumination is made to provide the typical road surface luminances as in the range between these two limitations [37][38].
Rea and Bullough (2007) further performed assessment of the predictions from the two models i.e., the unified system of photometry of Rea et al. (2004) and The MOVE model of Elhoma and

Halonen (2006). The mesopic luminances were plotted against the photopic luminances and S/P raitos were calculated. The result indicates that there are only minor differences between these two models. This further suggests that either model might be used to determine the importance of spectral power distribution in road lighting [39].

Researchers Dr. Suddhaswata Chakraborty, Rakesh Bishwas, and Pratik Nath tested the temporal processes in the brain for object detection and which type of light is preferred by a straightforward match-mismatch task in the paper "Laboratory Based EEG Study to Investigate the Influence of Light Source of Brain Processing for Detection of Object Designed with Metal Halide and High Pressure Sodium Vapour Lamp". The outcome demonstrated that MH lamps detect objects more quickly than HPS lamps. This study also proved that Electroencephalography (EEG) is a reliable and cutting-edge method for visual acceptance designing since it is not subject-biased [40].

Further study by Dr. Suddhaswata Chakraborty, Debtanu Roy, and Ishan Palit titled "An EEG based Comparative Study on Drivers Performance Under the Influence of Metal Halide and High Pressure Sodium Vapour Light" showed us about drivers performance in an actual road condition illuminated by MH and HPS lamps. The test involves a behavioural analysis and an EEG analysis of driver's reaction times. According to the findings, metal halide lamps improve human cognitive function [41].

2.2. Research Problem Formulation :

After doing all the literature surveys, it is clear that the cycle of development of the society is very much dependant on the aspects of lighting. The effects of lighting on human wellbeing are broadly seen in the area of street lighting. But any failure in the design and proper functioning of road lighting can lead to severe accidents. When safety is the main concern in streets or roads, lighting designs or lighting schemes must not be compromised. Till date, much research works, and experiments have been carried out since the nineteenth century to understand the correlation between various lighting parameters and human centric parameters. It can be found that there are numerous numbers of luminance-based research works regarding the human mesopic vision and off-axis target detection have been performed throughout a very long period of time. These studies are very much significant keeping in mind that in the night-time on the roads and streets, human mesopic vision dominates over the photopic and scotopic vision in order to identify and recognise any moving or static object present on both on-road and off-roads. The response time or reaction time (RT) regarding the task performance of a driver while driving on the roads is also an area of interest for the researchers since a very long time. Literature surveys have shown that, while driving on the road, the driver's reaction time (RT) is undoubtedly dependant on various lighting parameters and lighting conditions for that particular environment. For an example, the illuminance levels of a road under a particular lighting condition have a huge impact on the reaction time for visual and non-visual task performance of a driver [41]. The correlated color temperature (CCT) being another fundamental lighting parameter is found to have greater impacts on the human task performance as well. In case of indoor lighting designs, it is already seen that tunable CCTs have significance influence on the human reaction time (RT). But, in case of road lighting scenario, the correlation between CCT of a light source and the driver's reaction time (RT) for any visual and non-visual task performance is not established clearly. There is a huge research gap found that is significant in establishing the aspects of lighting parameter like CCT on the human centric parameter like reaction time (RT). This thesis is all about to bridge that gap in between the correlations off lighting parameter and human centric parameter. The goal is to design a lighting scheme in such a way that it can improve the human task performance which incorporates object identification, object recognition and motor action or simply muscle movements and to optimise the energy consumption for the system to reduce the cost function in the development of a society.

2.3. Peripheral Sources :

Based on the area of coverage, the human vision can be divided into two segments, i.e., on-axis vision and off-axis vision. The on-axis vision incorporates the light sources that are present in the frontal vicinity of the eye of a human observer whereas the light sources that are present on the peripheral vicinity of the eye is accountable for the off-axis vision for that same observer. The light sources that can provide a human individual with the vision of objects that are not present on the line of sight without turning the head or moving the eye, is simply referred as the peripheral sources. In case of outdoor lighting designs, especially in the field of street lighting circumstances, the peripheral sources play a significant role in the visibility of objects. Additionally, it provides the observer with the small movements that happen on the sideways of a road or simply on the footpaths or pathways other than the fixation targets on road. If we consider a real driving scenario on the roadway, it can be seen that the relative position of the road light pole is always changing with respect to the driver's position inside a vehicle. This simply means that from the perspective of a driver, if there is a light source positioned on a road light pole that first appears along the on-axis field of view, it eventually shifts towards the peripheral vicinity of that same observer with the changing position of the vehicle. So, every time when the position of the vehicle changes, the position of the light sources or light poles also shifts from main source to peripheral sources. Hence, in the context of road illumination, the notion of the main source and peripheral source is not actually absolute but rather relative. Therefore, whether it is a real road experiment or a laboratory-based simulated experiment, it is absolutely crucial to include the peripheral sources in addition to main source in case of performing road lighting experimentations.

2.4. Glare :

A visual symptom of excessive and uncontrolled brightness is glare. It may be disabling or just uncomfortable. It is subjective, and glare sensitivity can vary greatly. Because of how the eye ages, older people are typically more sensitive to glare [42]. Disability glare and discomfort glare are two different types of glares. Disability glare is the type of glare that has a detrimental effect on visual performance. The light scatter occurring in the observer's eye provides the best explanation for the mechanism by which the loss of visual performance caused by glare occurs.

In case of driving on the road, the headlights from the vehicles that are coming from the opposite side often create glare on the driver's eye. Also, the peripheral sources often create glare on the driver's eye which create disturbances in visibility further causing severe accidents. So, in case of street lighting design, the effects of glare must be taken into account. The cause of glare should be optimised according to the nature of the street and the surrounding area.

2.5. Effect Of Contrast :

The distinction between an object and its representation in an image or display is made possible by contrast, which is a difference in luminance or colour. Contrast in visual perception of the real world is determined by the difference between the colour and brightness of an object and the background in the same field of vision in terms of colour and brightness. The target can have a higher luminance than the background which is reffered to as positive contrast and in case of darker luminance of the target from the back ground it is reffered to as negetive contrast [29]. The performance of the driver depends on the effects of contrast as it a key feature in the object visibility. So, in case of road lighting design, the lighting schemes should be incorporated with the effects of luminance of the light source. The surface of the roads must be designed in such a way that it can provide the optimum level of contrast for better visibility towards driver's eye.

Chapter - 3

Evolution of Street Lighting

What we see in street lighting today, is the result of rigorous study and development in the domain of road illumination for centuries. The scenario of lighting scheme today is reaching towards a magnificent level of smartness while in the past centuries it was far more different. In the earliest days of civilization, for thousands of years, humans have used fire to illuminate their ways in addition to the natural light provided by sun and moon. The 500 B.C. Chinese invention of fixed position lighting is the oldest example that has been found. People in Peking made flaming torches for streetlamps out of bamboo piping and naturally occurring gas vents [43].

Ancient lamps were first utilised by the Greek and Roman cultures, where light was largely used for security, both to prevent wanderers from stumbling over obstacles and to prevent potential robbers. Wealthy citizens of ancient Rome used oil lamps made of vegetable oil in front of their homes, and they employed specific slaves whose sole responsibility it was to tend to those lamps by lighting them, putting them out, and making sure they always had oil [44].

In 1417, Sir Henry Barton, the mayor of London, established an ordinance requiring all homes to hang lanterns outside at dusk during the winter. This marked the first organized method of public street lighting [45].

Paris streets were first illuminated by candles or lanterns during night-time hours in the year 1524 by law and order which mandated that all homes with street-facing windows have light in the windows at night [44].

In the United Kingdom, the first streets were lit by antique oil lanterns in 1684 when Lord Provost brought 24 lanterns from London and installed them in the High Street and Cowgate street. Following that, the Edinburgh Town Council appointed an oil lantern where it felt it was appropriate and erected it in 1701. After installing the first street lights, for fifty years, the Edinburgh Town Council was in charge of maintaining 307 lamps in 1786.

Era of more efficient street lighting starts with Scottish inventor William Murdoch who ignited the Soho Foundry's outside with a gas light powered by coal gas for the first time in 1802. Following that, London received its first gas-lit street in 1807. In the United States, Baltimore was the first city to use gas for streetlights in 1816, while Paris began utilising gas for streetlights in 1820. The gas lamps that were mounted on poles were supplied with gas by pipe installations. Every night the lanterns were lit and every morning they were extinguished by the lamplighters, individuals whose job it was to maintain the gas streetlights [44]. This practise continued up to the development of the mechanism that lighted the lamps when the gas inside the bulb was released. After that, electricity arrived and increased the effectiveness of street lighting.
Paris once again raised the standard for innovation in street lighting in 1878 when the “Electric Candle” or "Yablochkov candle" (developed by a Russian, Pavel Yablochkov, in 1875 [46]) was installed in a lamp post. This revolutionary invention used an electric arc as its light source [43]. By the year 1881, some 4000 arc lamps were incorporated in street lighting scheme, taking the place of gas lamps on the poles. By 1890, more than 130,000 arc lamps had been placed as streetlights in the United States following the arc lamp's widespread use there. The majority of them were mounted atop so-called "moonlight towers," tall metal structures that simultaneously lit up whole city blocks [44].

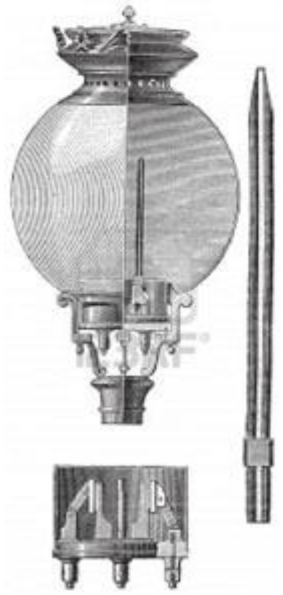


Fig 3.1 : "Yablochkov candle".

Between two carbon rods inside an arc lamp, an electric arc or spark that travels through the air forms the light. The distance between the rods needs to be the proper size. The arc will flicker more or may even burn out if the gap is too large, and it will generate less light if it is too small [47]. Arc light fixtures, however, had a few serious drawbacks. They weren't particularly durable, and the light they produced was very harsh and uncomfortable to the human eye.

Fig 3.2 : A lit arc lamp from the 1880s as was used in urban lighting and factories.

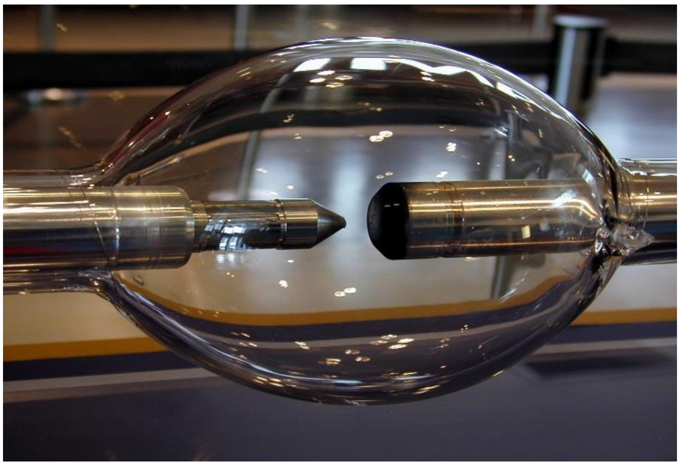


Fig 3.3 : Old Xenon Arc Lamp.

After the carbon arc lamps, incandescent lamp was the second form of electric light to be developed for commercial use in street lighting. The first incandescent light was produced by Sir Humphry Davy in 1802 (England) by passing current through a platinum strip [47]. A wire "filament" is heated to a glowing state inside an incandescent lamp, which is an electric light. To prevent oxidation, the filament is housed inside of a bulb. Terminals or wires buried in the glass provide current to the filament. Electrical connections and mechanical support are provided by a bulb socket. It is produced in a variety of sizes, shapes, voltage ranges, and light outputs. It can run on both alternating current and direct current, has cheap production costs, and doesn't need any regulating apparatus.

When Thomas Edison figured out how to make a perfect vacuum in his lightbulbs, he revolutionised the world. The introduction of the carbon-thread incandescent lamp by Edison in 1879 sparked the creation of light bulbs for streetlights. Within a very short duration, Thomas Edison's invention then substituted the arc lamps on lamp posts around the country with incandescent bulbs. The carbon-thread incandescent lamp, which was introduced in 1879, eventually replaced other lighting options for electric street-lamps [43] as more preferred way of street illumination.

Despite the fact that Edison is credited with developing the first incandescent light that was commercially viable. He wasn't the only person attempting to create an incandescent light bulb; neither was he. In reality, according to some historians, more than 20 people invented incandescent lamps before Thomas Alva Edison created his. The fact that Edison's version outperformed prior versions due to a combination of three factors - an efficient incandescent substance, a greater vacuum than other inventors were able to generate, and a high resistance - means that he is frequently given credit for the invention [47][48].

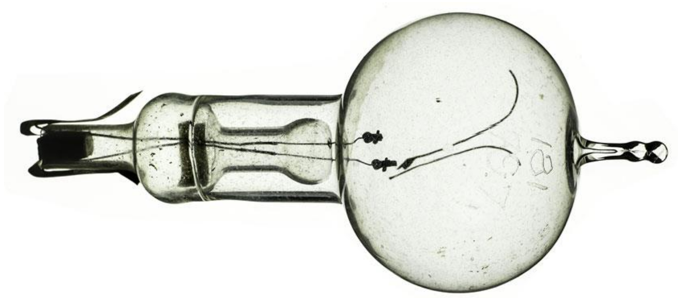


Fig 3.4 : Edison's Incandescent Lamp.

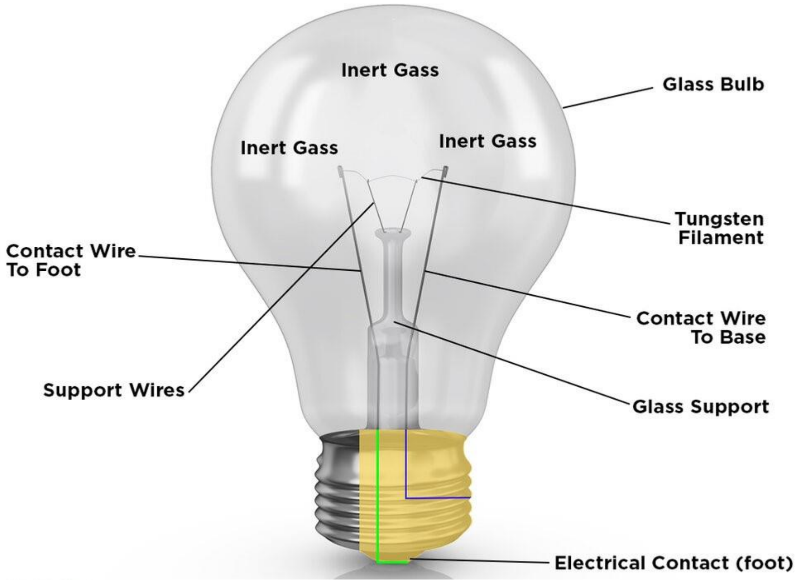


Fig 3.5 : Commercial Incandescent Lamp.

Further in the process of modernization, gas-discharged lamps have been invented and it occupied the place of incandescent lamps in the schemes of road illumination. Gas discharge lamps can be categorized into two types i.e.,

a. **Low Pressure Sodium (LPS) lamps, and**
b. **High Pressure Sodium (HPS) lamps.**

Arthur H. Compton at Westinghouse originally developed low pressure sodium (LPS) lights in 1920 [5]. The original lamp had two electrodes on each side of a circular bulb. On the bottom centre of the lightbulb, the solid sodium metal was still present. The metal would evaporate when heated, and the lamp would glow yellow. The metal had to cool when the lamp was switched off, and the sodium tends to migrate to the coolest portion of the bulb where it hardens, therefore the lamp had to be made in the shape of a spherical. These lamps maintained a high temperature to keep the sodium in vapour form and included a detachable outer jacket and vacuum layer for insulation. The LPS lamp is also called a SOX lamp (SO for sodium).

Philips produced the first sodium lamps available for purchase commercially in 1932 [47]. In order to keep the bulb hot enough to maintain the sodium in vapour form, the first lamps had a removable outer jacket with a vacuum between the glass.
The first sodium lamp to be created was the LPS lamp. It is recognised by the distinctive monotone yellow color. Due to its weak CRI or colour rendering, it is mostly used in Europe. As a result, other markets did not find it appealing. It is one of the world's most effective lights because it makes use of all available current to produce light at the color (frequency) that the human eye is most sensitive to.

Fig 3.6 : LPS lamp luminaire mounted on street light pole.

Early sodium lamp creators were aware that greater pressure in the arc tube would improve efficiency. The issue was that no material could withstand sodium's high pressure, high temperature, and corrosive characteristics.

An appropriate material for creating an HPS lamp was finally found 35 years after Compton created the sodium lamp. A substance called Lucalox was created by a scientist by the name of Robert L. Coble while he was employed at the General Electric Research Lab close to Schenectady, New York. The brand name for aluminium oxide ceramic was lucalox. His work paved the path for the creation of the HPS lamp by William Louden, Kurt Schmidt, and Elmer Homonnay in the year 1955 [47].

The high pressure sodium (HPS) lamp is the most ubiquitous lamp for street lighting on the planet The lamp is superior to the LPS lamp because it has a more tolerable hue and the superior sodium lamp efficiency. A small trade-off is made for the improved colour rendering; it is less efficient than the LPS. The lamp was initially created by General Electric in Schenectady, New York, and Nela Park, Ohio. In 1964, the first lamp entered the market [47].

The HPS lamp comprises of a frame in a bulb supporting a small arc tube. In order to increase efficiency, the arc tube has a high internal pressure. Inside the arc tube, sodium, mercury, and xenon are typically employed. Aluminum oxide ceramic, which is used to make the arc tube, is resistant to the corrosive effects of alkalis like sodium.

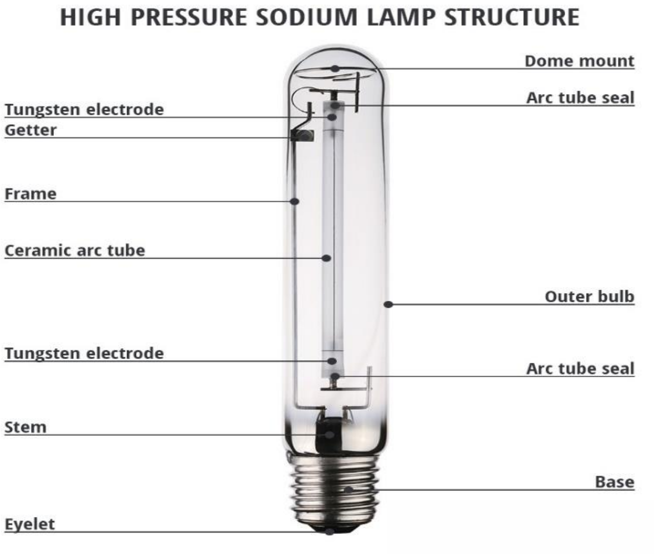


Fig 3.7 : High Pressure Sodium (HPS) Lamp structure.

Fig 3.8 : HPS lamp luminaire mounted on street light pole.

In the meantime, another type of lamp was invented for street lighting purposes. It was the metal-halide (MH) lamps that incorporates high intensity discharge (HID) of halide compound to provide illumination. Charles P. Steinmetz was the first to use halide salts in a mercury vapour lamp in 1912. Using the halides, he was able to adjust colour, but he was unable in obtaining a continuous arc. In the year 1962, The first reliable MH lamp was developed by Robert Reiling using recent advancements in the high-pressure mercury vapour lamp [47].

It gets most of its light from an electric arc that exists inside a tiny discharge tube. It is becoming more and more well-liked because of its excellent white light and high effectiveness. The lamp employs high pressure mercury vapour to produce the bright light, but it also contains additional metals (halide salts) to enhance the colour. A halogen paired with an electropositive element, or in the case of lamps, a metal, forms a chemical combination known as a Halide.

Halogens are monovalent elements that effortlessly produce negative ions. Fluorine, chlorine, bromine, iodine, and astatine are the five halogens. Sodium iodide is the substance most frequently employed as a metal halide. When the arc tube achieves operating temperature, the sodium separates from the iodine, enhancing the spectrum of the light with orange and red. Metal-halide lamps emit an intense white light and have a high luminous effectiveness of roughly 75-100 lumens per watt, which is about double that of mercury vapour lights and 3 to 5 times that of incandescent lights.

Fig 3.9 : Metal Halide (MH) lamps.

Fig 3.10 : Metal Halide street light luminaire.

After HID lamps, the fluorescent light is the next product in the commercial sector. In the year 1865, Daniel McFarlan Moore gave the first ever demonstration of it [46]. The vital parts of fluorescent lamps were the result of decades of invention and development of cheaply produced glass tubing, inert gases for the tubes' filling, electrical ballasts, durable electrodes, mercury vapour as a source of luminescence, efficient ways to create a dependable electrical discharge, and fluorescent coatings that could be activated by ultraviolet light. Daniel McFarlan Moore was successful in creating the Moore Tube, the first ancestor to the fluorescent light, in 1895. Apart from being longer and producing pink and white light using CO2 and nitrogen, the tube resembled modern lighting extremely closely. He supplied regional retail establishments in New York City with his dependable lighting. The lamp had a brief lifespan due to its high replacement cost and it had the Mercury Vapor lamps as the competitor in the commercial market.

The first true fluorescent light is created in 1934 by George Inman, Richard Thayer, Eugene Lemmers, and Willard A. Roberts. Its lamp is solid, dependable, and their design hasn't changed much in 78 years. It also features actual white phosphors [47].

Fluorescent lamps, often known as fluorescent tubes, are low-pressure mercury vapour gas discharge lamps that emit visible light by fluorescence. Mercury vapour is excited by an electric current in the gas, producing short-wave ultraviolet light that illuminates a phosphor coating inside the lamp. Compared to incandescent lights, fluorescent lamps convert electrical energy into useable light far more efficiently. Fluorescent lighting systems typically have a luminous efficacy of 50 to 100 lumens per watt, which is significantly higher than the efficacy of incandescent bulbs with a similar light output. It is widely used as street lights in our country.

Fig 3.11 : Fluorescent lamp luminaire mounted on street light pole.

A compact fluorescent lamp (CFL) is a fluorescent lamp designed to replace an incandescent light bulb. Some can be used in lighting fixtures made to accommodate incandescent bulbs. A small electronic ballast is housed in the lamp's base and a tube that is bent or folded to fit within an incandescent bulb is used in the lights. CFLs use one-fifth to one-third less electricity and last eight to fifteen times longer than general-purpose incandescent lights while producing the same amount of visible light. Because of this, it is a common option for street lighting.

Fig 3.12 : Different types of CFL Lamp.

The concept of lighting has been changed totally when the ground-breaking invention of LED, light emitting diode took place in the history of illumination. The development of the LED began in the early stages of wireless technology, when little was known about semiconductors in general and even less about the potential for using them to produce light. Although LEDs have been commercially available since the 1960s, their history stretches considerably further; the invention of the LED has its origins in much older research. The earliest findings were far ahead of their time, and other discoveries were lost as a result of war, which contributed to the lengthy development process for the LED. The LED couldn't be fully developed and released onto the market until the allied technologies had reached a sufficient maturity point.

Beginning around the start of the twentieth century, the light emitting diode effect was first seen. In 1907, H J Round, a British radio engineer who worked with Marconi, conducted some tests using crystal detectors. He used silicon carbide and a cat's whisker to discover electroluminescence. Years later, At Texas Instruments, James R. Biard and Gary Pittman developed the infrared LED in 1961 which was recognized as the first modern LED [47][49].

LEDs emit light by the electroluminescence of semiconductors. When an electric current or electric field is transmitted through a material, the phenomenon known as electroluminescence occurs. This happens when electrons are sent through the material and fill electron holes, causing the substance to emit light. Where an atom has a positive charge due to the absence of electrons (negative charge), this is known as an electron hole. To manufacture and regulate the quantity of electron holes, semiconductor materials such as germanium or silicon can be "doped." Doping is the process of adding more components to a semiconductor material to modify certain aspects of it. Two different types of semiconductors can be created in the same crystal by doping one semiconductor. A p-n junction is the distinction between the two types of boundaries. Because of the junction's one-way current restriction, they are used as diodes. P-n junctions are used to create LEDs. Electron holes are filled as electrons move from one crystal to the next. They produce photons (light).

Due to its effectiveness, LED lamps are very popular right now, and many people think they represent "new" technology. The LED has been around for more than 50 years in its current form. It has gained popularity as an alternative for other white light sources due to the recent development of white LEDs. The longer lifespan of LED lighting fixtures is one of its main benefits. The most durable LED light fixtures have been evaluated to survive as long as 100,000 hours, whereas incandescent light bulbs were designed to last roughly 1,000 hours. The typical lifespan of LED light bulbs is at least 20 years [50]. The most advanced, commercially available, and energy-efficient LED bulbs have efficiency of 200 lumens per watt (Lumen/W).

Fig 3.13 : Flexible LED strip & Fig 3.14 : LED street light luminaire.

Even though individual red, green, and blue LEDs can be used to produce white light, the colour rendering is poor because just three concentrated wavelength bands of light are being produced. The first white LED was developed not long after high efficiency blue LEDs were achieved. A Y3Al5O12:Ce coating, often known as "YAG" or Ce : YAG phosphor, is cerium-doped to create yellow light in this device. That yellow light combined with the remaining blue light appears white to the eye. Through fluorescence, green and red light are produced by using various phosphors. When compared to wavelengths from the blue LED/YAG phosphor combination, the resulting blend of red, green, and blue is seen as white light and has better colour rendering. In 2014, it was shown that experimental white LEDs can last up to 100,000 hours and emit 303 lumens per watt of power (lm/W). As of 2020, however, commercially available LEDs will be capable of up to 223 lm/W of effectiveness.

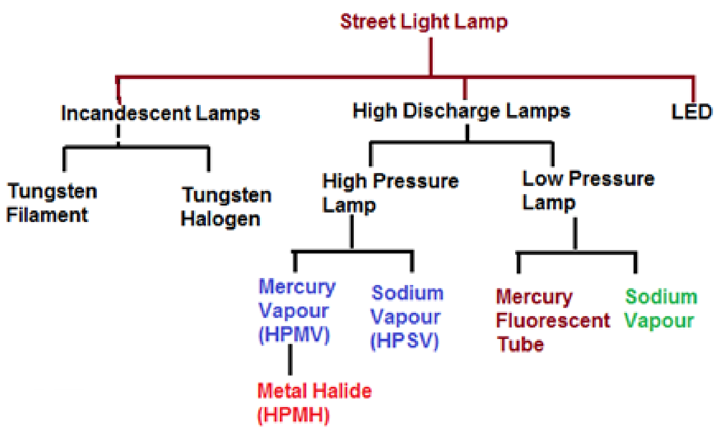


Fig 3.15 : Various Types of lamps used for street lighting.

Chapter - 4

Human Centric Lighting (HCL)

4.1. What is Human Centric Lighting (HCL) ?

Compared to the late 90s, the concept of lighting has advanced significantly in the present. A lot more research have been done and developments are made. In the process a very new term surfaced in the research domain i.e., “Human Centric Lighting” (HCL). Previous research works have made it obvious that light and lighting have immense effect on human vision, perception, mood, sleep cycle (i.e., circadian rhythm). Along with that, light also has significant role in the visual and non-visual task performance of human being. There is a photopigment in human eyes called Melanopsin which is found in Intrinsically Photosensitive Retinal Ganglion Cells (ipRGCs). This photoreceptor cells have a particular sensitivity towards the absorption of short-wavelength (blue light: wavelength approximately between 380 nm and 500 nm) and communicate through exchange of information to the Suprachiasmatic Nucleus (SCN) area of the brain. The SCN is also known as the “body clock” in mammals [51]. The concept of HCL is integrated around the idea that light has direct and indirect effect on visual and non-visual responses and behavioural responses in humans. With this idea the essence of lighting has been changed completely. The way of lighting revolves around the connections towards human health, mood, biological responses and moreover well-being. Human Centric Lighting (HCL) is defined as lighting designed to benefit human health, biological and psychological wellbeing in addition to providing the fundamental functional requirements in building or streets [52]. An individual’s perception, satisfaction, behaviour, and attitude are highly influenced by the luminous environment around them. Studies have proved that in working environments people prefer daylighting over electrical lighting. For driver’s perspective this goes similar for street lighting. So, incorporating daylighting with HCL and application on LED in future will open several doors towards the broader aspects of lighting [53].

There are some human centric parameters that are very much dependent on the lighting parameters, given in the Fig-4.1 below :

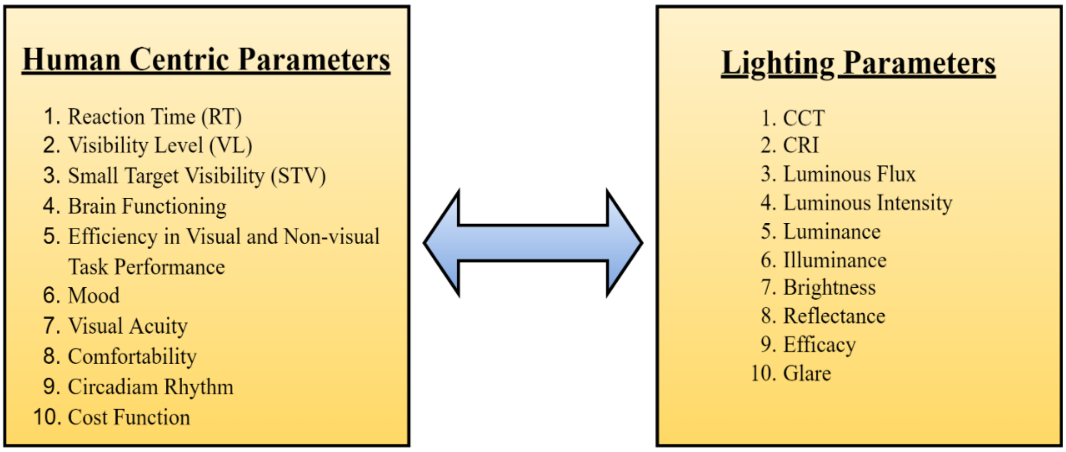


Fig 4.1 : Interconnectivity between various human centric parameters and lighting parameters.

4.2. The Contributing Factors to HCl :

In order to comprehend the relationship between lighting and work, it is necessary to first determine the pathways by which lighting might influence human performance. There are three such pathways such as the visual system, circadian timing system, and mood and motivation through which lighting can affect human performance [54]. The most visible impact of light on humans is its impact on vision. The vision incorporates the way in which an image of the external world is formed on the retina by the optics of the eye. some proportion of image processing takes place at the retina. Up to the visual cortex of the brain, different parts of the retinal image are interpreted through several channels. The spatial structure of the visual system consists of two parts, i.e., the fovea of the retina, which can perceive small details, and the periphery, which essentially functions as a detecting system indicating where in the field of view, the fovea should be directed. In addition to that, the entire retina is active when there is a plenty of light present, such as during the day. The fovea is blind in low light conditions, such as on a moonless night, and only the peripheral retina functions.

A theoretical framework outlining the three ways that lighting conditions might influence the human task performance is given in the Fig 4.2. It demonstrates a conceptual framework for the variables that affect the development along each route and how those variables interact. The five dimensions of visual size, luminance contrast, colour difference, retinal image quality, and retinal illuminance can be used to describe any stimulus to the visual system. These factors play a crucial role in determining how well the visual system can recognise and detect the stimuli.

i. **Visual Size:** The solid angle that the stimulus subtends at the eye, often provides the visual size for detection. The larger is the solid angle, the easier it is to recognise the stimulus. The circumstances of lighting have little effects on the visual size of 2D objects whereas shadows can be employed to enhance some 3D item's effective visual size.

ii. **Luminance contrast:** An object's luminance in relation to its immediate background is expressed by the luminance contrast of the stimulus. The higher is the luminance contrast, the simpler it is to notice the stimulus. The luminance contrast of a stimulus can be altered by lighting parameters such as by changing the luminances of its constituent parts and by inducing disability glare in the eye.

iii. **Color difference:** The color appearance of a stimulus is very much influenced by the wavelengths emitted by the stimulus itself. It is conceivable for a stimulus with zero luminance contrast to still be recognised because of how distinctively coloured it is from the background. When multiple light sources with different spectra are employed, lighting can change the color difference between an object and its background.

iv. **Retinal image quality:** For all image processing systems, the visual system functions best when it is given a sharp image. The spatial frequency distribution of the stimulus can be used to measure how sharp the stimulus is. For instance, an image that is sharp will have high spatial frequency components present, but an image that is blurry won't.

v. **Retinal illuminance:** The degree of adaptation of the visual system is influenced by the illuminance on the retina, which significantly affects the visual system's capabilities.

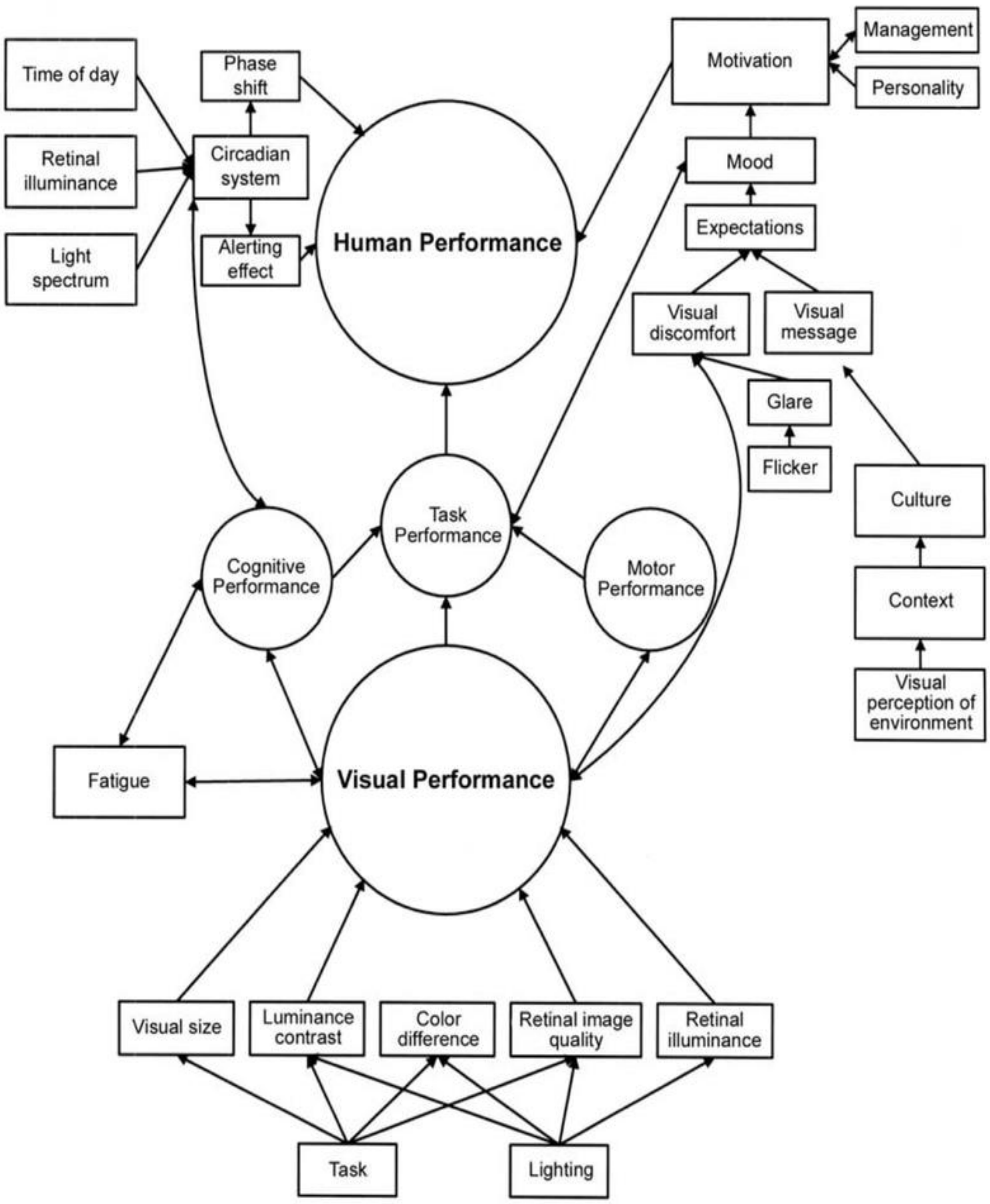


Fig 4.2 : A theoretical framework outlining the three ways that lighting conditions might influence the human task performance. (Source: Peter Boyce - Human factors in lighting).

The level of visual performance that is achievable, depends on the stimulus and the present state of operation of the visual system. However, this is not the end of the story. Most apparently the three components of visual tasks are visual, cognitive, and motor. The process of gathering information relevant to completing the task using the visual sense is referred to as the visual component. The method by which sensory stimuli are evaluated and the best course of action chosen belongs to the cognitive component. The method by which information is derived from inputs and chosen actions are carried out is known as the motor component. These three elements collaboratively produce a complicated pattern between stimulus and reaction that, in turn, affects the task is performed. The balance between the visual, cognitive, and motor components of each task is also distinct, as is the impact that lighting conditions have on task performance. As a result of this individuality, it is impossible to generalise about how lighting affects the performance of one task to that of another.

The non-image-forming system is another way that lighting conditions might impact work. The circadian timing system is the only component of the nonimage-forming system that is unquestionably known to have an impact on human performance. The occurrence of the sleep-wake cycle is the most evident external proof that humans have a circadian timing system. Light, functioning through the circadian timing system, can be employed in two different ways to enhance task performance. One being the phase-shifting mechanism in which exposure to intense light at particular periods can accelerate or delay the phase of the circadian rhythm (Dijk et al., 1995) [55] and the another is the acute consequence of the hormone melatonin being suppressed during night that heightens alertness (Campbell et al., 1995) [56].

There has also been interest in determining whether daytime exposure to light can improve task performance by influencing the hormone cortisol. The effects on what happens the rest of the day are not entirely obvious, but there is evidence that exposure to high light levels shortly after waking up raises cortisol concentration (Scheer and Buijs, 1999) [57]. Ruger et al. (2006) exposed volunteers to 5000 lx between noon and 16.00 h and found that alertness was positively affected but that cortisol concentration was unaffected [58]. Similar findings were made by Kaida et al. (2007), who discovered that exposure to over 2000 lx during the early afternoon boosted alertness [59].

The third way that lighting can influence productivity is through mood and motivation. An emotional reaction may result from the visual system's creation of a model of the visual environment. Among many other factors, this emotional reaction has the potential to affect someone's mood and motivation for work. Further, lighting can affect mood and motivation in the simplest ways possible when it causes visual pain.

4.3. Advantages of Human Centric Lighting :

HCL combines the visual and non-visual impact on human being to provide improved visual comfort, mood and human health. There are apparently six key ways through that Human Centric Lighting can benefit both people and society.

The first approach is to enhance **Circadian Rhythm**, the 24-hour body clock. This controls the human sleep cycle using information from the appearance of colour temperature of the surround light sources. However, since electrical lighting was developed, humans are constantly exposed to lighting both during the day and at night. The human body is not built up like that. So, this phenomenon has a significant impact on our sleep cycle. Not only this, but the biological clock also significantly affects several other hormones, including dopamine (controls the feeling of pleasure, Alertness in day time), cortisol (stress response), and serotonin (controls impulse control and carbohydrate craving). Malfunctioning of these hormone productions negatively impact the body harmony. These issues can be resolved by setting ambient lighting controls based on our circadian rhythm.

The second approach is through enhancing the **Mood**. According to the research by Gilles Vandewalle et al., specific hues or types of light can influence cognition, mood, and emotions of human being [60]. Human emotional responses to light vary depending on its spectral quality. A person's mood and satisfaction can be boosted if they have control over the task lighting (i.e., they can turn the light on and off and change the CCT). Human emotions like anger, sadness, happiness can be characterized by human centric lighting.

Third advantage is through enhancement of **Visual Acuity**. Human activity is mostly performed under the controls of the visual organs. 80-90 % of the information is received through them [61]. The eye is designed to function in such a way that turns light into visual sensation. Retina is the place where the transformation of light energy into nervous response occurs spontaneously. The realization of any object depends on the quality of visual information received. Visual Acuity (VA) is the measure of the clearness or sharpness of the vision. Precisely it is the measure of the eye to distinguish between different shaped objects and their detailing when kept in a certain distance from the observer. It examines how well the observer can describe about the object under consideration from a certain distance.

The fourth benefit is through enhanced **Perception**. A specific CCT of light or a particular hue of a light can immensely be influential to the perception of the appearance of any object which has further impacts on human psychology. As for application, this concept is used by several brand showrooms to promote their products effectively. Lighting can influence how goods are seen.

The fifth benefit is through **Productivity**. Human alertness, mental satisfaction, and clear vision can all be impacted by lighting. These result in an increment in productivity of any task performance. If human centric lighting is incorporated for various task lighting, the overall performance can be improved. One example is the illumination found in streets. The likelihood of an accident on the road decreases if the CCTs of the street lights are maintained at its optimal level. Similarly, employing descent lighting in a classroom might help students to pay more attention.

Last but not the least, the benefit through **Energy Sustainability**. In earlier days, lighting energy savings used to imply lowering the intensity of light or shutting off the light. However, recent advancements in LED lighting have altered this perception. Nowadays, various lighting parameters play a major role. For an example, more energy is saved by CCT with 5000K lights than by CCT with 3500K LEDs. Therefore, energy can be conserved by utilising the appropriate CCT for each task.

Whether it is public places like office, school, hospital, manufacturing sites or private places like residential areas, requirement of a proper and efficient lighting is very much essential. These are advantages for those who use light, such as patients, residents, and staff in medical facilities and nursing homes; students and teachers in classrooms; workers in offices and manufacturing facilities; and residents in private residences who can benefit from adequate lighting in their home environment.

The benefits of HCL differ according to the application area [62].

1) Visual Benefits: clear and comfortable visibility, safety.
2) Biological Benefits: improved alertness, focus, sleep-wake cycle stability, and cognitive performance.
3) Emotional Benefits: improved mood, impulsive control, and relaxation.

The goal of human-centric lighting is to mitigate the physiological and psychological effects of the differences between artificial and natural light while also enhancing visual environments and enhancing people's task performance. It is believed that the HCL principle should be incorporated into all lighting designs for environments where people live, work, and study.

Human Centric Lighting is making a difference in the applications where individuals want to treat illnesses and conditions brought on by circadian disruptions, as well as in situations where a better learning or working experience may be achieved using circadian lighting. It is obvious that healthcare facilities need to apply HCL in order to improve patient satisfaction, encourage patient recovery, address patients' sleep problems, and treat and/or prevent depressed symptoms. Education facilities are well suited to use HCL systems that encourage learning environments customised to diverse activities since light with varying spectrums and intensities is found to support concentration, minimise weariness, and improve cognitive performance. Conference rooms, offices, and manufacturing facilities are additional environments where circadian lighting can be used. Although these locations are flooded with blue-rich light to boost staff or workers' dedication, motivation, and productivity, flexible modulation of the light's spectral makeup and intensity throughout the workday can improve worker happiness and performance.

It is important to note that a significant portion of the global population has been exposed to high CCT artificial light (6000 K and higher) throughout the day and night. Their circadian cycles are disrupted and exposed to excessively blue-rich light for an extended period exposes them to photobiological dangers (blue light hazard). These at-risk individuals urgently require circadian illumination.

4.4. Experimental Approach to Study Human Centric Lighting :

The study of human centric lighting has three fundamental approaches. The approaches can be assessed with two quality parameters i.e., face validity and generality. The approaches alone with their quality parameters are describes in Table-4.1 :

Type of Approaches	Face Validity	Generality
Real Task Studies	High	Very Low
Laboratory Simulation based studies	Moderate	Low
Analytical approach towards developments of a model	Low	Very High

Table 4.1 : Human Factors in Lighting.

Three different approaches can be used to determine whether people accept a particular road lighting installation :

(1) Subjective Judgment using some questionnaires and statistical analysis of the data,

(2) Behavioural Study and statistical analysis of the data, and

(3) A new methodology using an Electroencephalography (EEG)-based method in conjunction with the behavioural study.

This study is based on the second approach, which combines behavioural study with statistical data analysis. The participant's perception of the specific installation was recorded along with their individual reaction time for particular trials under this experimentation. The results are then statistically analysed and correlated with various lighting parameters. Determining the ideal lighting scenario for an individual is crucial in the context of road lighting.

Chapter - 5

Work Flow Diagram

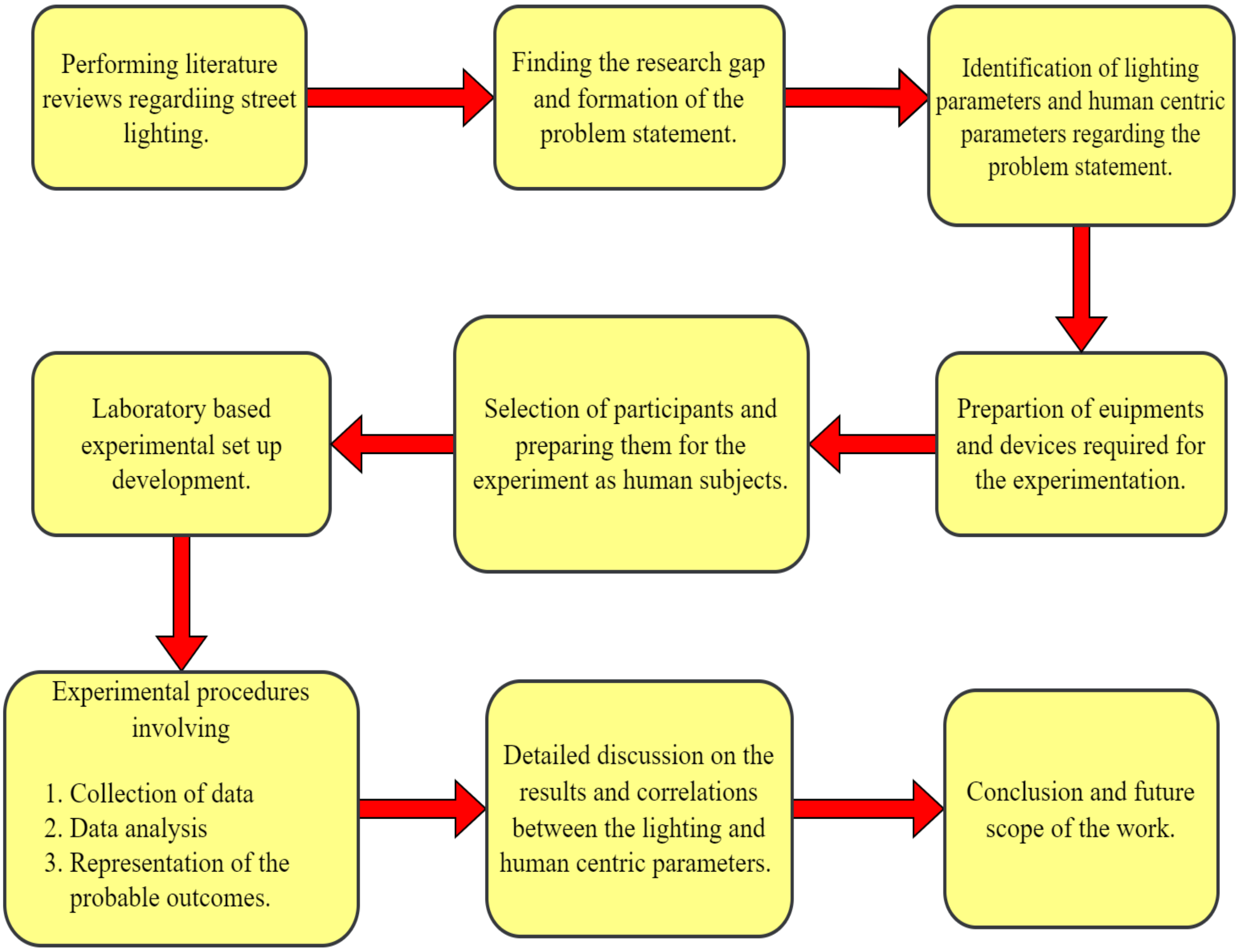


Fig 5.1 : Work flow diagram for the overall experiment.

From performing previous literature surveys to performing experiments through problem formulation, the overall pathways of this project are given in a flow chart diagram above in Fig-5.1.

The researchers have performed the total experimental procedures step by step in accordance with the previously mentioned workflow diagram. At the very beginning, a number of previously performed experiments on human performance under various street lighting conditions have been thoroughly studied.

These led the researchers find the research gap in this field and helped to formulate the problem statement of this project. Further, identification of various lighting parameters which has direct and indirect effects on human body is done. According to that, the equipments that are necessary in this experiment have been prepared.

After that, human subjects have been selected and explanation of this study is provided thoroughly to the subjects. Further, the subjects are prepared for the experiments with their consent.

On the other hand, the laboratory set up is prepared for the experiment following the road light standards properly.

Then experimentation is done, and data has been collected and rigorously analysed and further conclusion is made on the basis of the outcomes daddy experimentation provided the researchers.

Chapter - 6

Experimentation and Data Analysis

6.1. Laboratory based experimental setup development :

This study is a part of a broader experiment on street lighting and its direct and indirect effects on human visual and non-visual responses. To find and establish the correlation between street lighting conditions and a person's focus, comfort and task performance, this kind of experimental research work is very much necessary. But like any other field studies, before experimenting in practical scenarios in a large scale, it is preferred to first understand the outcomes from a laboratory-based experiments comparatively in a smaller scale. So, with this approach, this study is completely performed in controlled environment. A replica of road lighting scenario has been set up in the laboratory of Illumination Engineering in Electrical Engineering Department of Jadavpur University, Kolkata to understand the observer's behaviour and performance for recognition of an object under varying CCTs and different lighting combinations. The laboratory is totally concealed from natural light, the walls are covered with dark black paint and other instruments are covered with dark black cloaks to prevent light reflection and to safeguard the instruments from external stray lights so that experimental errors can be minimized.

Fig 6.1 : Performing measurements and drawing the grid points for the experiment.

For the human centric behavioural parameters, the Reaction Time (RT) has been measured and analysed and checked whether there is a correlation between RT and changing CCTs of smart LED lights present or not. As luminaire, three smart tunable LED bulbs are used. One bulb is used as the Source light and the rest two are used as the Peripheral Sources. The RT measurement is performed for two different conditions:

(i) When only Source (S) is ON.

This approach actually replicates the real road lighting scenario in which light source from street light poles are falling upon directly to the driver's eyes. That means only the on-axis vision of the driver is active and analysed.

(ii) When Source (S) along with two Peripheral sources (P) are ON.

This condition replicates the real road lighting scenario in which light source from street light poles as well as lights from surrounding vehicles falling upon the driver's eyes. That means lights coming from street light poles are providing the on-axis vision and lights from other vehicles are providing the peripheral vision to the driver.

The smart LED lights are mounted on street light poles inside the dark room laboratory. The Source light is kept at a pole height of 2m whereas the Peripheral lights are kept at a pole height of 1.5m. The reason behind keeping the pole heights as such level is that it can replicate the relative height between the light source that is mounted on a street light pole and driver's sitting position inside the car seat in real road scenario. The experiments are performed while the subjects are positioned on 0.45m chair. The source light (S) and the peripheral lights (P) are respectively measured to be present within 2° and 15° field of view to the observer's eye which is naturally seen in the real road scenarios. All the light sources are covered with conical shaped dark black paper so that light flux cannot enter the observer's eye directly. So, here the black paper acts as baffle to the luminaire. At the very beginning the source is kept on at 5000 K CCT and intensity of 100%. Under this condition the nadir point (E1) is identified by following the standards of CIE 140-2000 [63]. Keeping the nadir point E1 as the reference 40 grid points are drawn having 0.5 m of distance between each other. The grids are drawn containing 8 rows and 5 columns (8x5 grid). The observer is placed 4.5 m away from the point E1. The grid points are placed on the frontal vicinity of the subject's eyes (when the experiment will be performed).

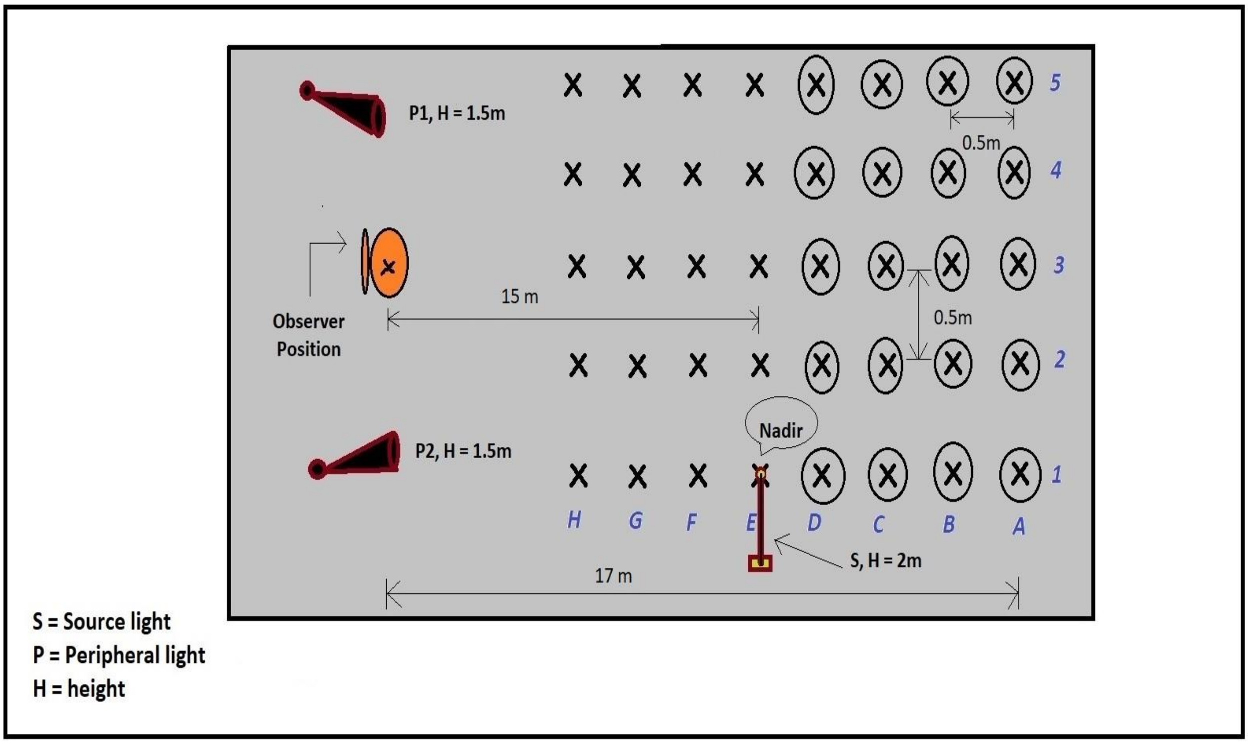


Fig 6.2 : Schematic diagram of top view of the experimental setup. Objects are positioned only on the circled grid points.

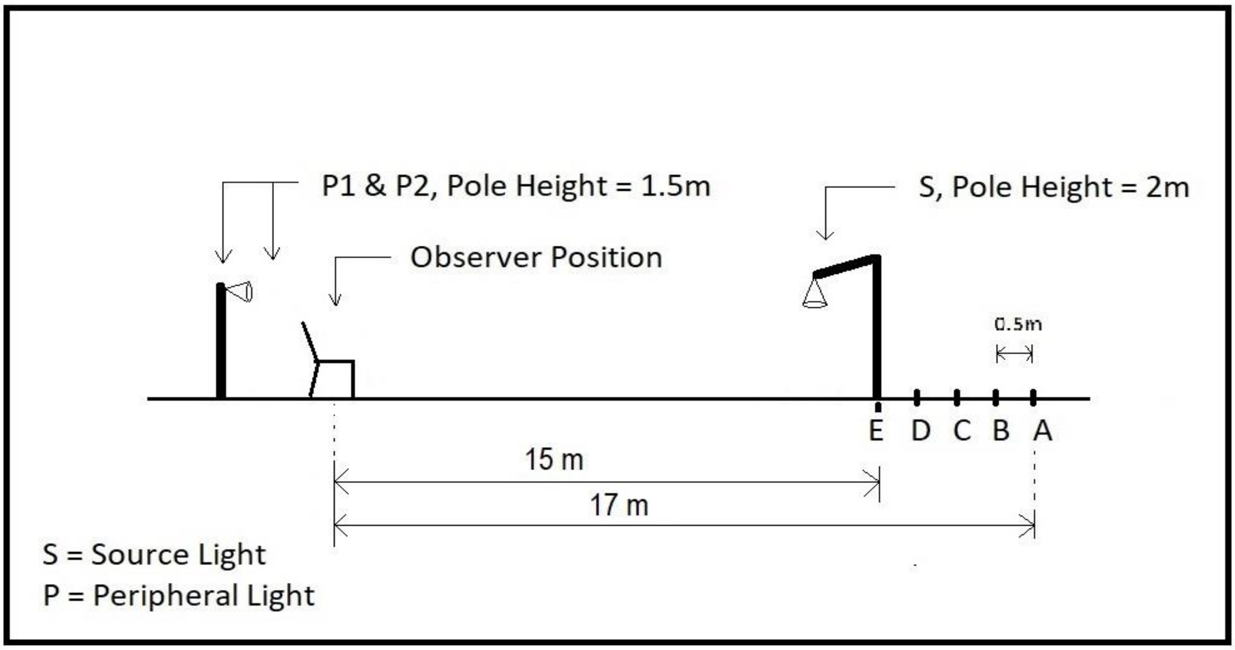


Fig 6.3 : Schematic diagram of side view of the experimental setup.

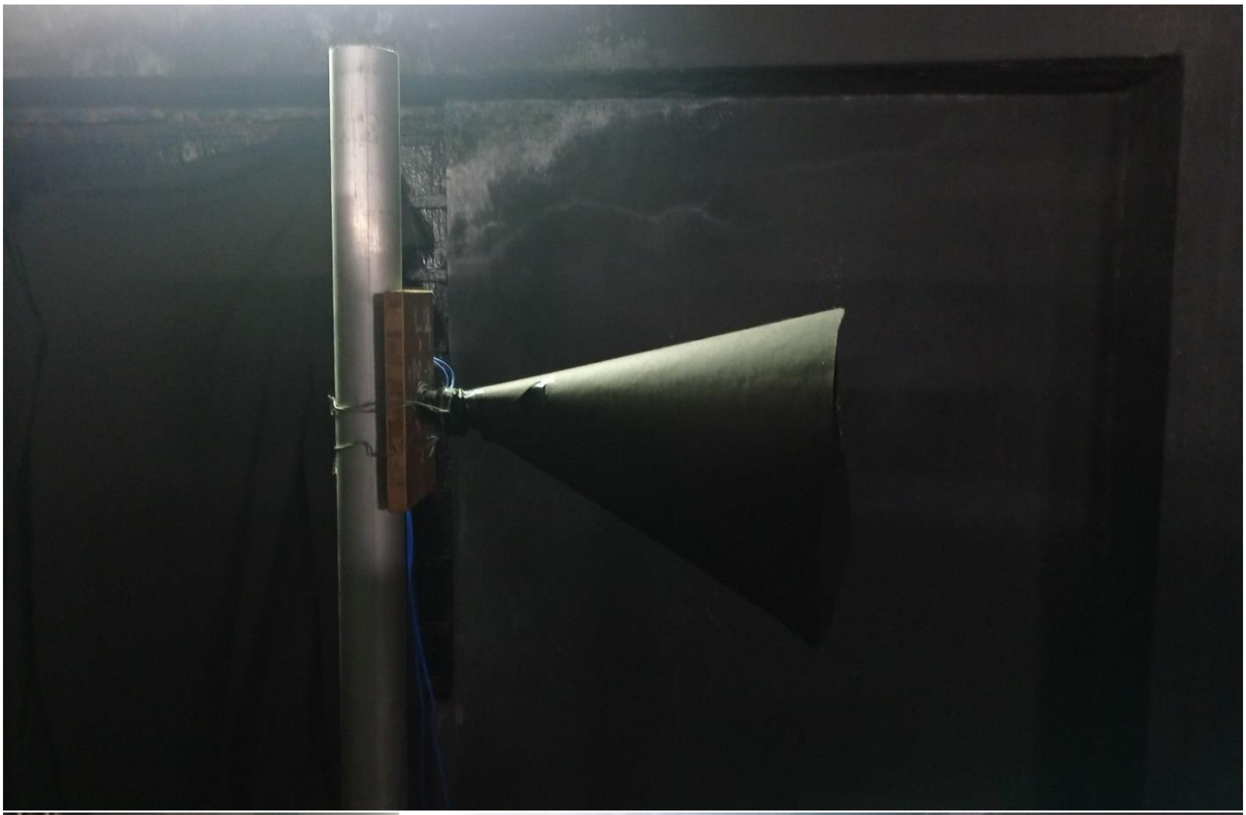
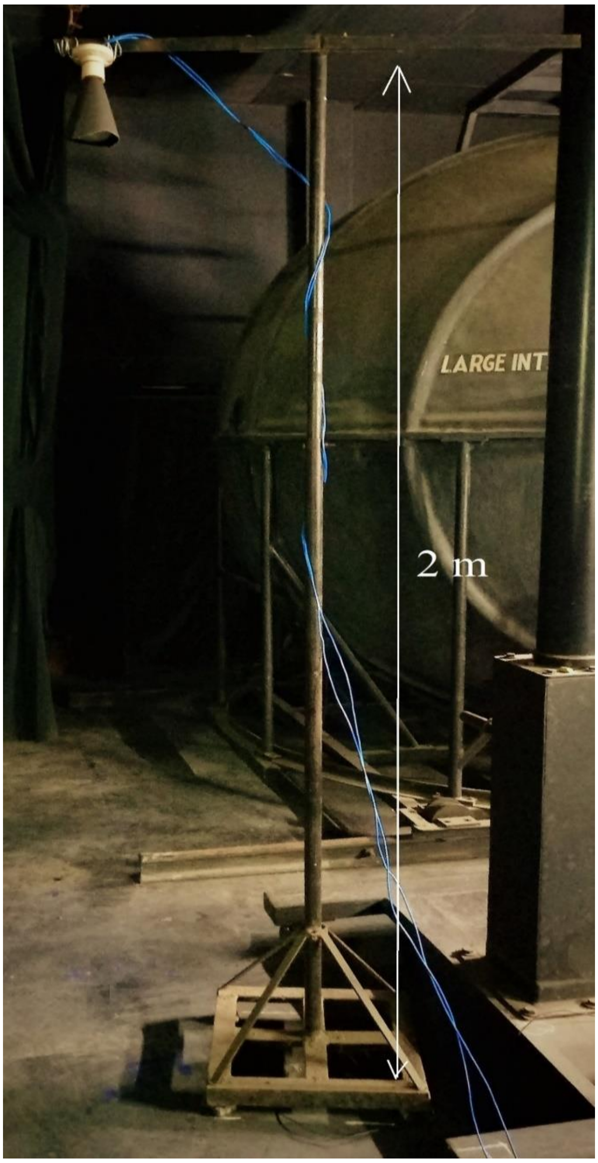


Fig 6.4 & Fig 6.5 : Baffle incorporated to the light sources.

This experiment is consisting of five key components i.e., light source, coloured objects, reaction time measuring compact device, special active shutter glass, and human participants.

Light Source : Three smart LED lights from Halonix have been incorporated in this experimental procedure. Those three LED light sources have the electrical ratings of 12 watts, input voltage AC 220~240V, 50Hz, Base-B22 and the photometric ratings as luminous flux of 820 Lumen. These RGBW LED lights are featured with dimmable intensity control (0 to 100 %), CCT control (2500 K to 6500 K), color changing capability and can be controlled with a 2.4 Hz advanced WIFI-based android app and operates at -10°C to +50°C. One LED is used as the main light source (S) and rest two LEDs are used as the peripheral light sources (P). These light sources are mounted on street light poles keeping the main source (S) and the peripheral sources (P) at a mounting height of 2m and 1.5m respectively.

Fig 6.6 : LED light source used as main source (S) and peripheral sources (P).



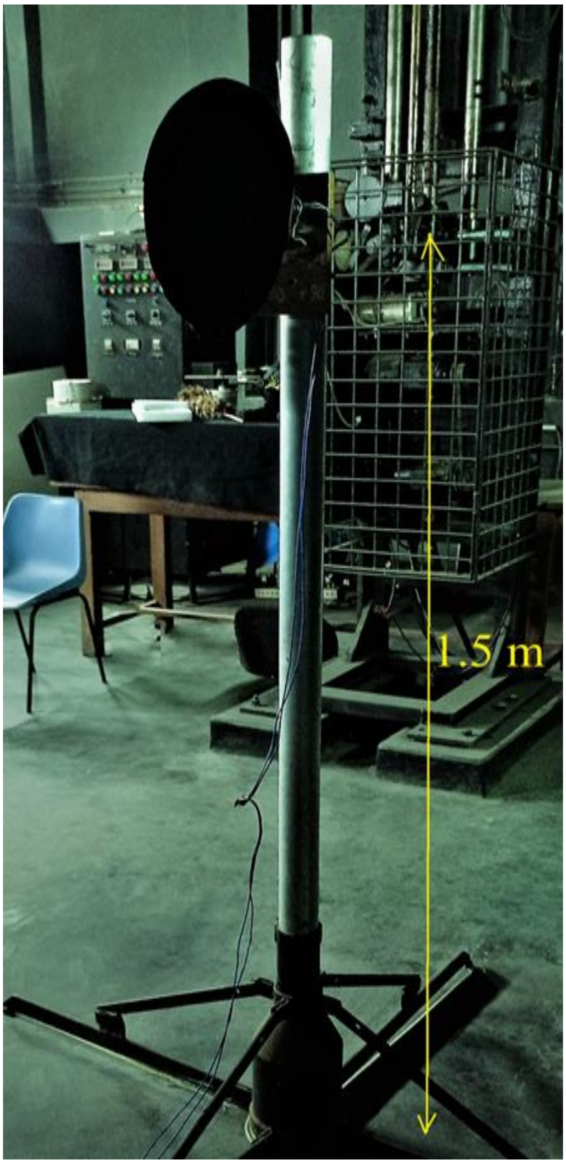


Fig 6.7 & Fig 6.8 : Main source (S) and Peripheral source (P) are mounted on 2m and 1.5m street light pole respectively.

The spectral compositions of the light source measured by Konica Minolta CL-70F colorimeter, under four different CCT levels (i.e., 3000 K, 4000 K, 5000 K, 6000 K) of main source (S) is given below in Fig-6.9, Fig-6.10, Fig-6.11, Fig-6.12 respectively.

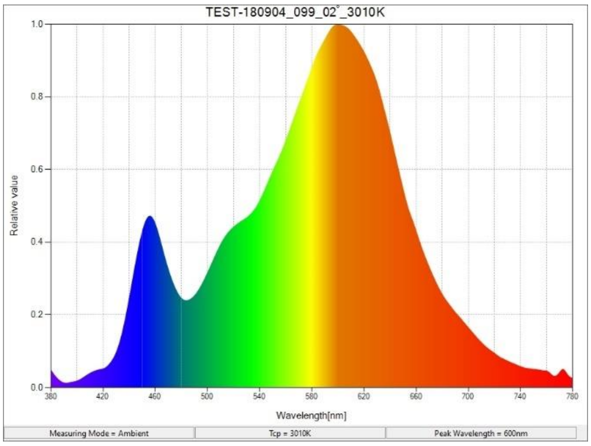


Fig 6.9 : SPD of main source (3000 K).

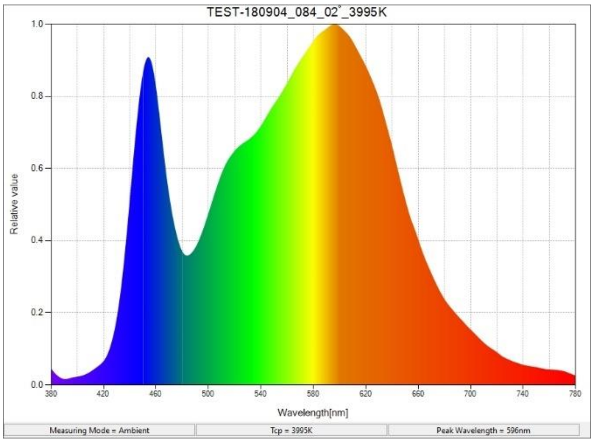


Fig 6.10 : SPD of main source (4000 K).

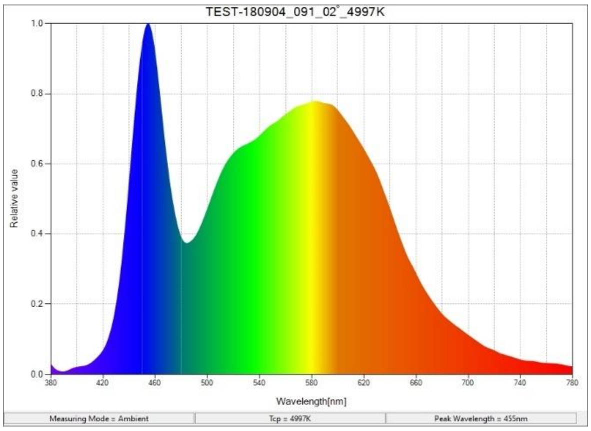


Fig 6.11 : SPD of main source (5000 K).

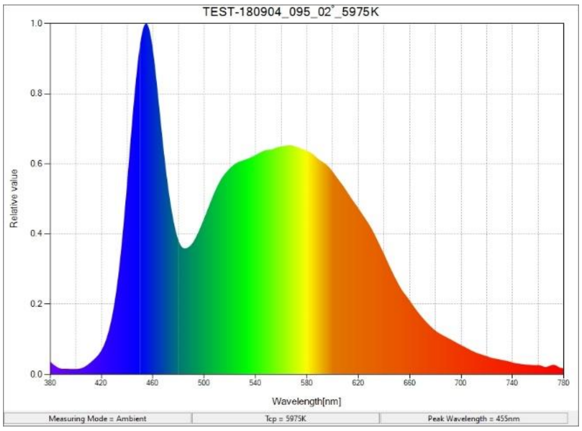


Fig 6.12 : SPD of main source (6000 K).

Coloured Objects : For the measurement of Reaction Time (RT) for any object recognition, twelve standard objects of specific shape and colour are made accordingly. Firstly, the objects are made of card boards shaped in three forms i.e., Cuboid, Cylindrical and Prismatic respectively. Following this, the objects are covered with colored papers. Four standard colors have been chosen for the objects i.e., Yellow, Green, Violet, and Black. All the objects have specific dimensions. The individual reflectance has been calculated and found to be according to the standards [64]. The detailed specifications of the objects are given in table 6.1 and, along with that, one example photo of an object is given in fig 6.13 below :

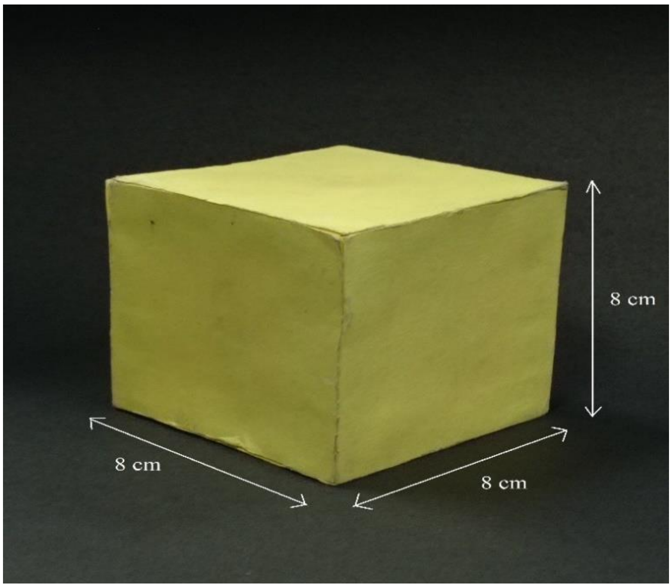


Fig 6.13 : Standard Object (Yellow Cuboid) used for used in the experiment.

Sl No.	Object Shape	Object Colour	Object Reflectance (%)	Object Dimension		Picture of Object
1	Cuboid	Yellow	19.2	length (cm)	8	
2		Green	16.6	Width (cm)	8	
3		Violet	17			
4		Black	15.6	Height (cm)	8	
5	Cylindrical	Yellow	19.1	Diameter (cm)	8	
6		Green	24			
7		Violet	18.6	Height (cm)	9	
8		Black	19.5			
9	Prismatic	Yellow	13.9	length of the Base (cm)	10	
10		Green	15	Width of the Base (cm)	10	
11		Violet	13.2			
12		Black	14.8	Height cm)	8	

Table 6.1 : Details of the objects used under experimentation.

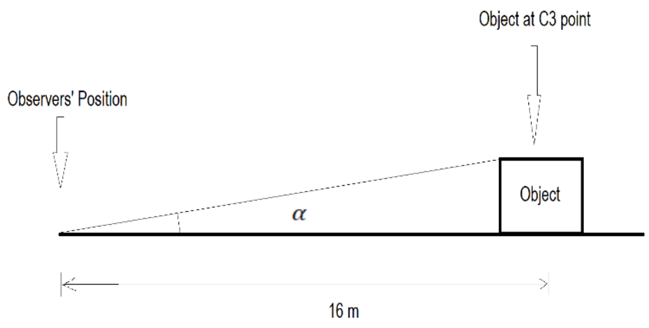


Fig 6.14 : Depiction of angular size of the object.

Reaction Time Measuring Compact Device (RTMCD) : A microcontroller-based Arduino controlled compact timer circuit device is prepared for measuring the Reaction Time (RT) of the human subjects under experimentation. The recorded timing can be shown on a 16x4 LCD display attached within the device. all the combination of the active shutter glass circuit, the Arduino controlled circuit, the LCD display and the wirings are put in a portable box. Further this compact device is called the reaction time measuring device. The overall circuit combination is operated by a 9V battery. The device can measure the time stamping in millisecond range. The start stamping is initiated by one of the researchers and the stop stamping is solely performed upon the observer or the subject of this experiment. All the switching performances are done by push buttons. The functioning of the circuit is discussed further under experimental procedures. Detailed picture of light sources (S&P), subject position and object positions are given in Fig-6.2 and Fig-6.3 above.

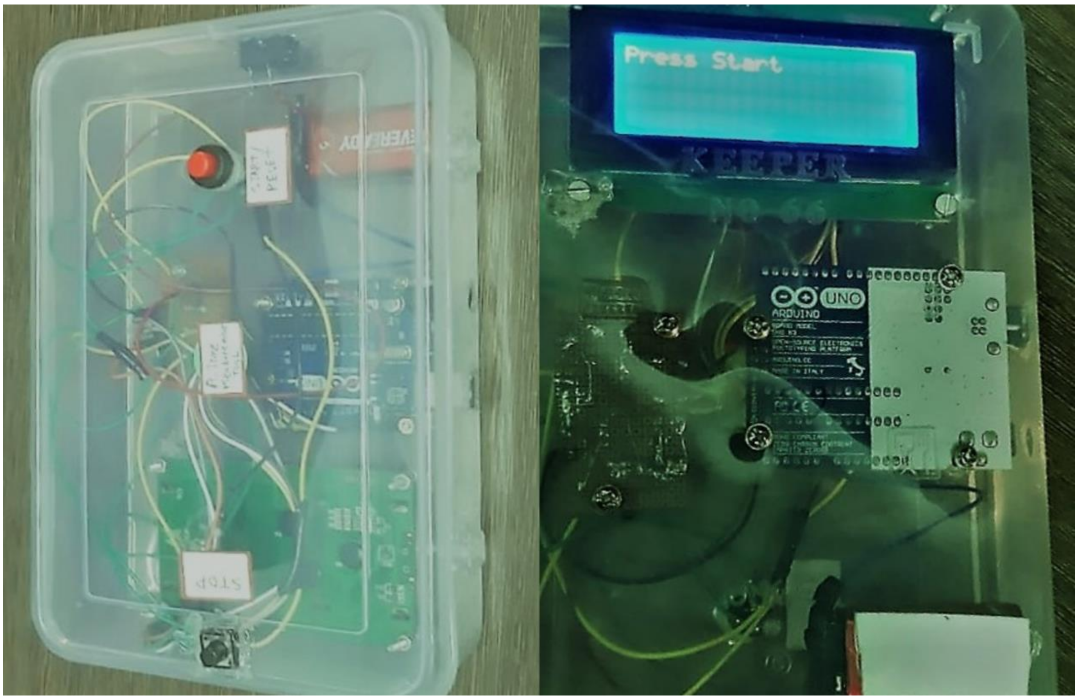


Fig 6.15 : Reaction Time Measuring Compact Device (RTMCD).

Special Active Shutter Glass : This is special type of spectacle made of Electro Luminescence Glass normally used in 3D cinemas, Virtual Reality (VR) glasses etc. The spectacle has a specific function that allows its glasses remain in OPAQUE form with explicitly dark lenses in normal condition, which prevents any visual sensation. There is an electronic circuit inside the frame which has been modified such a way that a 9V battery operated push button switching can change the status of the glass from opaque to transparent state. The main objective of this active shutter glass is to control the exposure time of the human subjects. It is already known from literature surveys that the exposure time of 100 ms is minimum requirement for any average human being in object recognition. On the other hand, the active shutter glass is designed such a way that it provides 700 milliseconds of exposure time which is more than enough for an average human being in object recognition and identification. The shutter glass circuit is connected with the microcontroller-based Arduino module. Manually controlled push button enabled activation is provided to the spectacle which makes the shutter glass goes from opaque condition to transparent state and return to opaque state automatically again after 700 ms. That makes the frontal vicinity where the grid points are drawn clearly visible to the observer eye at an eccentricity angle of about 2° for 700 ms.

Fig 6.16 : Special active shutter glass.

Participants : Six physically and neurologically healthy subjects (three males and three females) with a mean age of 22.5 years and a standard deviation of 1.5 were selected for this study. All of the individuals reported vision that was normal or corrected to be normal. Before taking part in the trial, they received a thorough explanation of the entire process and signed an informed consent form. The institutional Ethics Committee gave the procedure the green light.

6.2. Experimental Procedure :

6.2.1. Data and Calculation :

It is found from previous literature surveys that human behavioural responses are directly intertwined with the lighting conditions. For an example, human response time for performing any task is explicitly dependant on the lighting scenarios under that area of consideration. As for this study, object recognition ability of human subjects is measured with respect to different CCT (Correlated Color Temperature) levels of the LEDs [main source (S) & peripheral sources(P)]. To be specific, subject's Reaction Time (RT) to recognize different shaped and coloured objects is being chosen as the parameter for consideration. At the very beginning only the source LED is switched ON and kept at CCT levels of 3000 K, 4000 K, 5000 K, and 6000 K respectively with the luminous intensity of 100%. The level of CCT is controlled by an wi-fi based android app called "Halonix Smart" and measured by Konica Minolta CL-70 F colorimeter. Under this condition, the illuminances of all grid points are measured by Metravi 1310 Digital Lux Meter. Further, the average illuminance (E_{avg}) and uniformity (U_0) of the complete grid is calculated for all the previously mentioned CCT levels.

The overall experiment is divided into two stages:

where in the **Stage I,** only source light is kept ON and the experiment is performed for four different CCT levels of 3000 K, 4000 K, 5000 K, and 6000 K with 95% accuracy. The intensity of the source is kept at 100%. CCT levels are controlled and measured by an android app (Halonix Smart) and Konica Minolta CL-70 F colorimeter respectively. In Indian context, generally Sodium Vapour lamps, Compact Fluorescent lamps and largely LEDs are used as street light sources. Usually, the lighting levels are found to be having the CCT range from near about 3000 K (warm white) to 6000 K (cool white). That was the major reason behind the experiment being performed under the above-mentioned CCT levels. So that having the CCT ranging from 3000 K to 6000 K, it could provide the researchers with the similar exposure like Sodium Vapour lighting, warm white LED lighting and cool white LED lighting. Thus, the experimentation was carried out having a wide range of variable CCT levels to study the outcomes.

Whereas in the **Stage II,** combination of four levels of main source CCT i.e., 3000 K, 4000 K, 5000 K, and 6000 K and three levels of peripheral source CCT, respectively 3000 K, 4500 K and 6000 K with 95% accuracy, are maintained under this experimentation. Throughout the experiment the Luminous Intensity (*I*) of the main source (S) is kept at 100 % and for peripheral sources (P) it is 70%. When driving on streets, it is usually seen that the lights coming into the driver's eye from the periphery have CCT levels that are similar to warm white or cool white in nature. To account for this, in this experiment, peripheral LED sources have been assigned with the CCT values as specified above.

First of all, the illuminance values for each grid point are measured under the four levels of CCT of source (S) LED. So, a table of forty lux [Illuminance (E)] levels are measured for each level of CCT. Further, the uniformity of the overall grid is determined. The aim was to maintain the average illuminance of the grid at a level that it can incorporate the mesopic vision of the human observer alike the on-road driving scenarios according to IESNA 2006 [65]. The measured illuminances, average illuminances, uniformities of the grid under different CCT levels of main source (S) and peripheral sources (P) are given on Table-6.2, Table-6.3, Table-6.4, Table-6.5, and Table-6.6 respectively.

(S) 3000 K	**1**	**2**	**3**	**4**	**5**	**E_{avg}**	**U_0**
A	6.1	5.9	5.1	3.8	2.8	15.89	0.176211
B	11.9	11.2	8.8	6.3	4.5		
C	21.6	19.6	14.8	9.9	5.9		
D	34	30.8	21.5	13.6	7.8		
E	39.6	36.8	26.1	15.5	8.4		
F	37.5	34.1	24.4	14.3	8		
G	28.2	25.5	18.2	11	6.5		
H	16.8	14.9	11.5	7.6	4.8		

Table 6.2 : Illuminance, Average illuminance, and Uniformity values of the grid under CCT of 3000 K.

(S) 4000 K	**1**	**2**	**3**	**4**	**5**	**E_{avg}**	**U_0**
A	6.5	6.4	5.1	4.1	3.1	16.7775	0.184771
B	12.5	11.7	9.3	6.5	4.6		
C	22.6	20.8	15.7	10.4	6.2		
D	36.2	32.1	22.6	14.5	8.3		
E	43	38.7	26.9	16.3	9.1		
F	39.5	36	25.6	15.2	8.5		
G	29.8	26.9	19.2	12.1	6.9		
H	17.6	15.6	12.1	7.9	5		

Table 6.3 : Illuminance, Average illuminance, and Uniformity values of the grid under CCT of 4000 K.

(S) 5000 K	1	2	3	4	5	E_{avg}	U_0
A	6.5	6.4	5.2	4.1	2.9	16.73	0.173341
B	12.5	11.8	9.3	6.6	4.4		
C	22.9	20.8	15.6	10.3	6.2		
D	36.2	31.8	22.6	14.5	8		
E	43.2	38.7	27	16.1	8.7		
F	39.9	36	25.6	15	8.3		
G	29.4	26.9	19.1	11.6	6.8		
H	17.6	15.8	12.1	7.9	4.9		

Table 6.4 : Illuminance, Average illuminance, and Uniformity values of the grid under CCT of 5000 K.

(S) 6000 K	1	2	3	4	5	E_{avg}	U_0
A	6.6	6.5	5.3	4.2	2.9	16.825	0.172363
B	12.8	12.1	9.5	6.7	4.5		
C	23	21.1	15.8	10.3	6.1		
D	36.5	32.2	22.7	14.5	8.2		
E	42.7	38.9	27.2	16.5	8.9		
F	39.9	35.9	25.9	15.1	8.4		
G	29.3	27	19.1	11.8	6.8		
H	17.5	15.7	12.1	7.9	4.9		

Table 6.5 : Illuminance, Average illuminance, and Uniformity values of the grid under CCT of 6000 K.

(S) Source CCT	(P) Peripheral CCT	B2	B3	B4	C2	C3	C4	E_{avg}	U_0
3000 K	3000 K	10	7	5	19	14	8	10.5	0.476
	4500 K	10	7	6	19	14	9	10.83	0.554
	6000 K	10	7	6	19	14	9	10.83	0.554
4000 K	3000 K	11	8	5	20	15	10	11.5	0.435
	4500 K	11	9	6	21	15	10	12	0.5
	6000 K	11	8	6	21	15	10	11.83	0.51
5000 K	3000 K	11	8	5	21	16	10	11.83	0.422
	4500 K	12	8	6	21	15	10	12	0.5
	6000 K	11	9	6	22	16	10	12.33	0.486
6000 K	3000 K	12	9	6	22	16	10	12.5	0.48
	4500 K	12	9	6	22	16	10	12.5	0.48
	6000 K	12	9	6	22	16	10	12.5	0.48

Table 6.6 : Illuminance, Average illuminance, and Uniformity values of the grid under various CCTs of the Main and Peripheral sources.

Considering the different CCT levels of main source (S) and peripheral sources (P), there is a combination of total sixteen (4+12) different lighting conditions which are maintained throughout the experiment. The human subject or observer is asked to sit on a chair which has its position predefined and provided with the special active shutter glass to wear simply as a spectacle. The push button enabled reaction time measuring compact device (RTMCD) is also provided to the observer sitting on the chair. When the special glass is given 9V DC power supply, it switches to opaque condition making the subject under the experiment unable to see through the glass. So, the frontal vicinity where the grid points are placed is not visible for that time being. Meanwhile, one of the particular size and shaped standard objects (described earlier) is placed on one of the grid points (within the previously selected twenty grid points) by one of the researchers. Another researcher is positioned behind the observer while holding another push button that initiates the reaction time (RT) stamping. After positioning the object on a particular grid point, the individual subject is asked whether or not they are ready for the experiment. When they are ready and deliver the green signal by saying "YES", the researcher standing behind the observer presses the switch which initiates the time stamping as well as turns the active shatter glass into transparent condition. Now, the frontal vicinity becomes clearly visible to the observer's eye. Soon after realising the object placed on a particular grid point, the observer presses the push button which stops the timer of the RTMCD. The millisecond level measured time is displayed on the LCD which is attached to the RTMCD. As previously discussed, the exposure time on the special active shutter glass is already set to 700 ms. That means after 700 ms, the special glass again turns into opaque condition indicating the end of the exposure time for the observer for that particular trial. The time is being noted down by the researchers. After the trial is completed, the observer is asked to give answer for particular multiple-choice questions regarding the experimentation. the questionnaire is prepared consisting of four questions in such a way that it delivers the feedback of that trial. There are two subjective questions, and two objective questions were prepared regarding the details of the standard object, lighting condition, quality of vision and level of comfort for the task performance for the individual observer under each trial. In the fig 6.15, an example photo of one questionnaire is given. Under one lighting condition i.e., one particular level of set CCT, total twenty experimental trials are performed positioning the objects randomly on the twenty previously chosen grid points and the observer is asked twenty exact set of questions regarding the experiment. The answers are marked and noted down for further analysis. The researchers have marked every twenty runs under any particular CCT level as a 'Set'. So, for every individual subject, total sixteen set of data have been collected. Furthermore, in between two consecutive sets, all the observers are provided with 15-20 minutes of normal light exposure to help them recollecting the focus of mind from previous lighting condition of the trial and to be ready for the next. Some images regarding the experiment are given below:

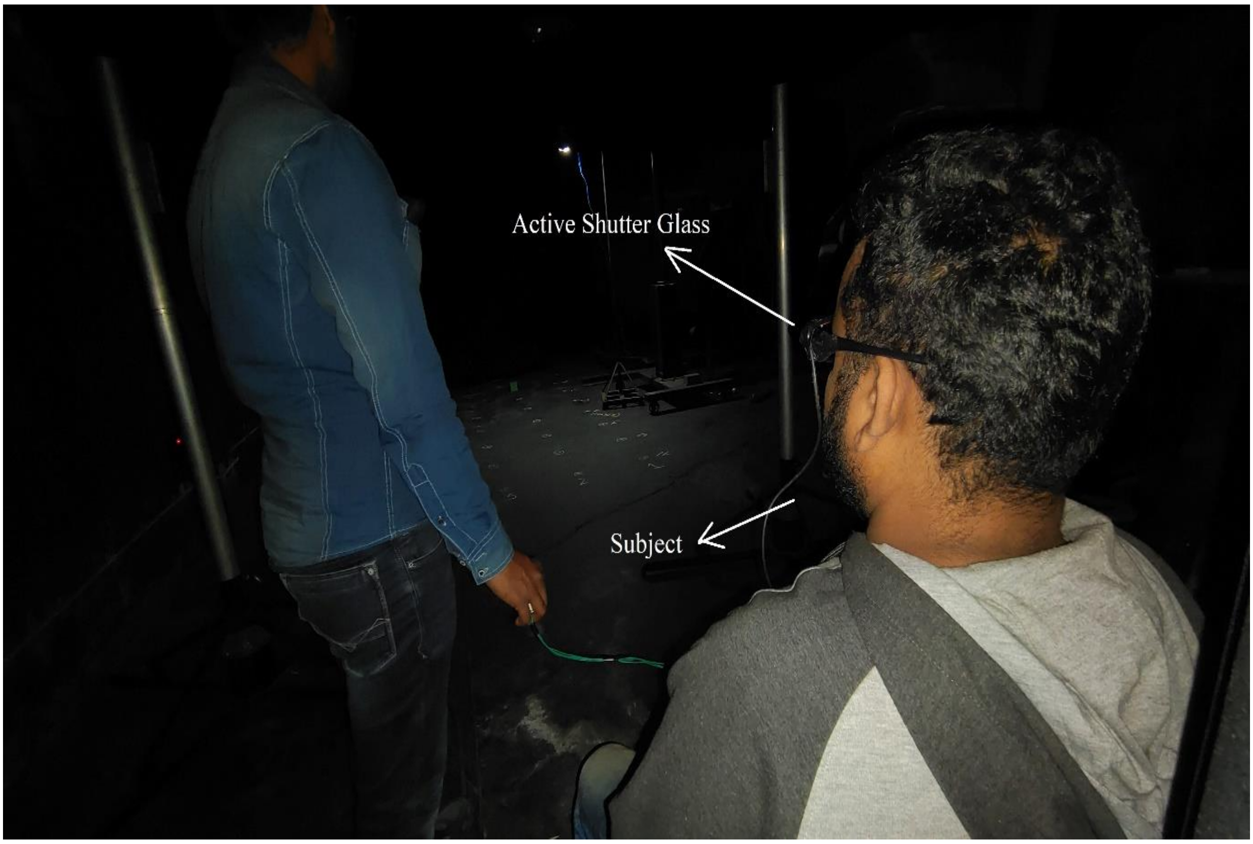


Fig 6.17 : Experiments and measurements are going on.

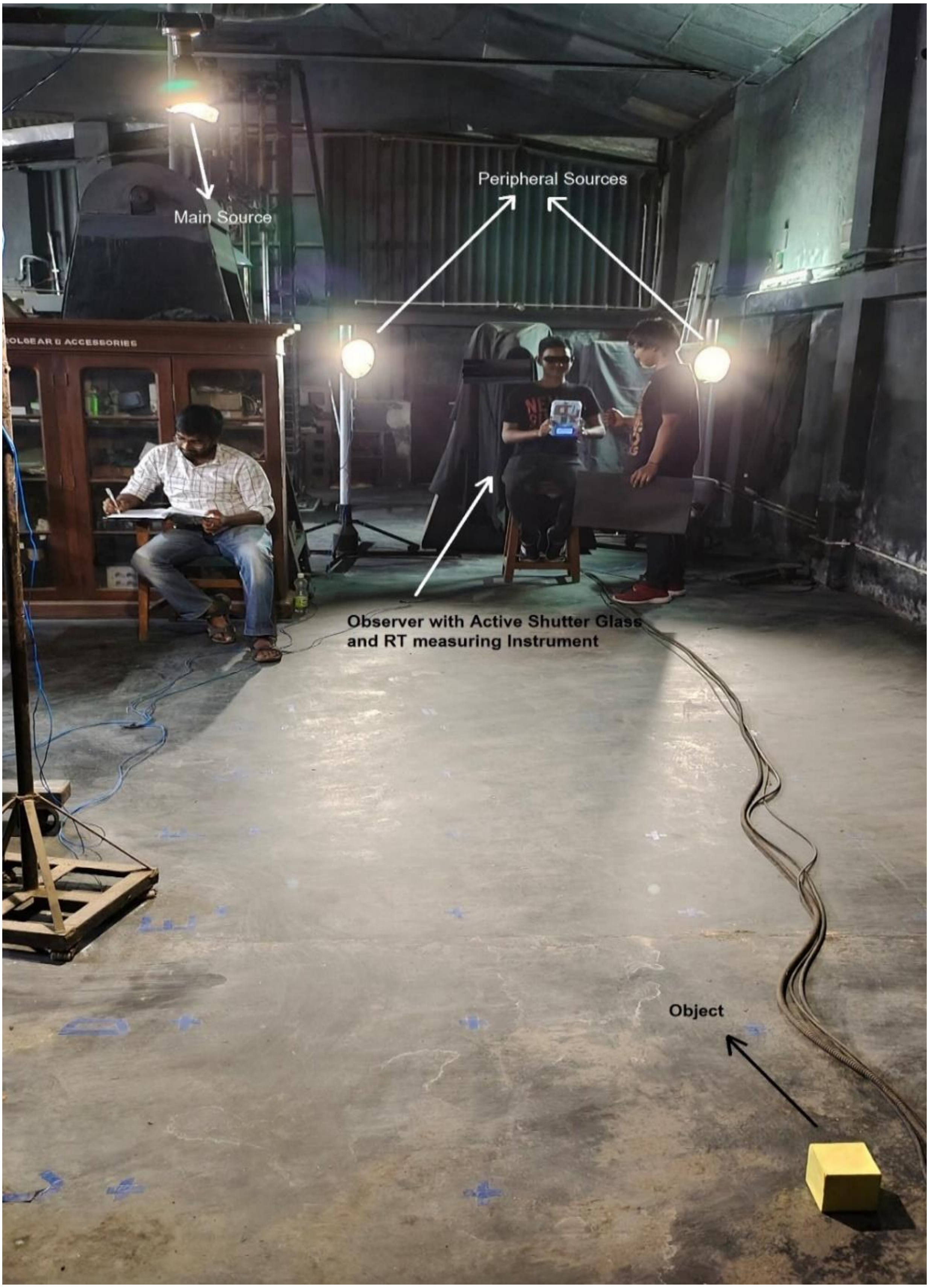


Fig 6.18 : Overall field of experiment with the researchers and object.

Experiment on Object recognition under variable CCT

Illumination Engineering Laboratory

Electrical Engineering Department

Jadavpur University

❖ **Please Tick (✓), where you want...**

1) What was the status of the Object?

a) Fully Visible	☐	RT –
b) Moderately Visible	☐	Pos –
c) Poorly Visible	☐	OD –
d) Not Visible	☐	

2) If the Object is Visible, then what was the shape of the Object?

a) Cuboid ☐
b) Spherical ☐
c) Cylindrical ☐
d) Prismatic ☐

3) If the Object is Visible, then what was the color of the Object?

a) Yellow ☐
b) Green ☐
c) Violet ☐
d) Black ☐

4) How can you rate the lighting?

a) Excellent ☐
b) Good ☐
c) Moderate ☐
d) Poor ☐

Fig 6.19 : Questionnaire set asked to the observer as feedback about individual experimental run.

The average reaction times of the subjects for the trials under four different levels of CCTs when only source (S) light being ON are given in the Table-6.7 below :

CCT	Overall Uniformity (U0)	Average RT (Seconds)
3000 K	0.17621	0.4567
4000 K	0.18477	0.4328
5000 K	0.17334	0.4298
6000 K	0.17236	0.469

Table 6.7 : Overall Uniformity and subject's Average Reaction Time under different levels of Source CCTs.

The average reaction times of the subjects for the trials under four different levels of CCTs of main source (S) and three different levels of CCTs of peripheral sources (P) are given in the Table-6.8 below :

CCT (Source)	CCT (Peripheral)	Overall Uniformity (U0)	Average RT (Seconds)
3000 K	3000 K	0.476	0.3433
	4500 K	0.554	0.24
	6000 K	0.554	0.2616
4000 K	3000 K	0.453	0.266666667
	4500 K	0.5	0.29
	6000 K	0.51	0.225
5000 K	3000 K	0.422	0.2216
	4500 K	0.5	0.2466
	6000 K	0.486	0.2
6000 K	3000 K	0.48	0.2116
	4500 K	0.48	0.1883
	6000 K	0.48	0.1833

Table 6.8 : Overall Uniformity and subject's Average Reaction Time under different levels of Source and peripheral source CCTs.

For the four different levels of the CCTs, the total average marks and the object average marks based on the answers given by the subjects for the questionnaires under the condition when only source light (S) was ON is given in the Table-6.9 below :

CCT	Total Avg.	Obj. Avg.
3000 K	7.783	3.05
4000 K	7.983	3.233
5000 K	7.967	3.15
6000 K	7.65	3

Table 6.9 : CCT of Source (S) and Total Average and Objective Average.

Similarly, for the four different levels of the CCTs of the main source (S) and three different levels of the CCTs of the peripheral sources (P), the total average marks and the object average marks based on the answers given by the subjects for the questionnaires is given in the Table-6.10 below :

CCT (Source)	CCT (Peripheral)	Total Avg.	Objective Avg.
3000 K	3000 K	8.417	3.633
	4500 K	8.633	3.667
	6000 K	8.55	3.7
4000 K	3000 K	8.8	3.8
	4500 K	8.675	3.8
	6000 K	8.575	3.7
5000 K	3000 K	8.8125	3.75
	4500 K	9.0125	3.95
	6000 K	8.625	3.65
6000 K	3000 K	8.325	3.5
	4500 K	8.525	3.5
	6000 K	9.15	4

Table 6.10 : CCT of Main source (S) and Peripheral sources (P) and Total Average and Objective Average.

6.2.2. Results :

First of all, the reaction time of individual subject's is measured using the measuring instrument (RTMCD) for each trial of the experiment under a certain level of CCT. As mentioned earlier the total experimentation is divided into two stages, when only the source (S) is ON and source (S) along with peripheral sources (P) are ON respectively. Further, the recorded Reaction Times (RT) are correlated with the CCT levels. This study clearly shows that presence of peripheral sources does influence the observer's reaction time (RT) for object recognition. When in the first phase of the experiment, where only the source light was ON, the average of the recorded reaction time (ART) is found to be higher compared to the recorded average reaction time (ART) in the second stage, where two peripheral light sources (P) were turned ON along with the main light source (S). In the first stage of the experiment, at 3000 K CCT of main source, the ART is 0.4567 s, and it gradually decreases up to the CCT of 5000 K but again increases towards the CCT of 6000 K, providing the ART of 0.469 s. While at the same time, the CCT levels of 4000 K and 5000 K yield lesser reaction times i.e., 0.4328 s and 0.4298 s respectively.

Fig-6.20 shows the variation between the average reaction time (ART) and the CCT levels of main source (S).

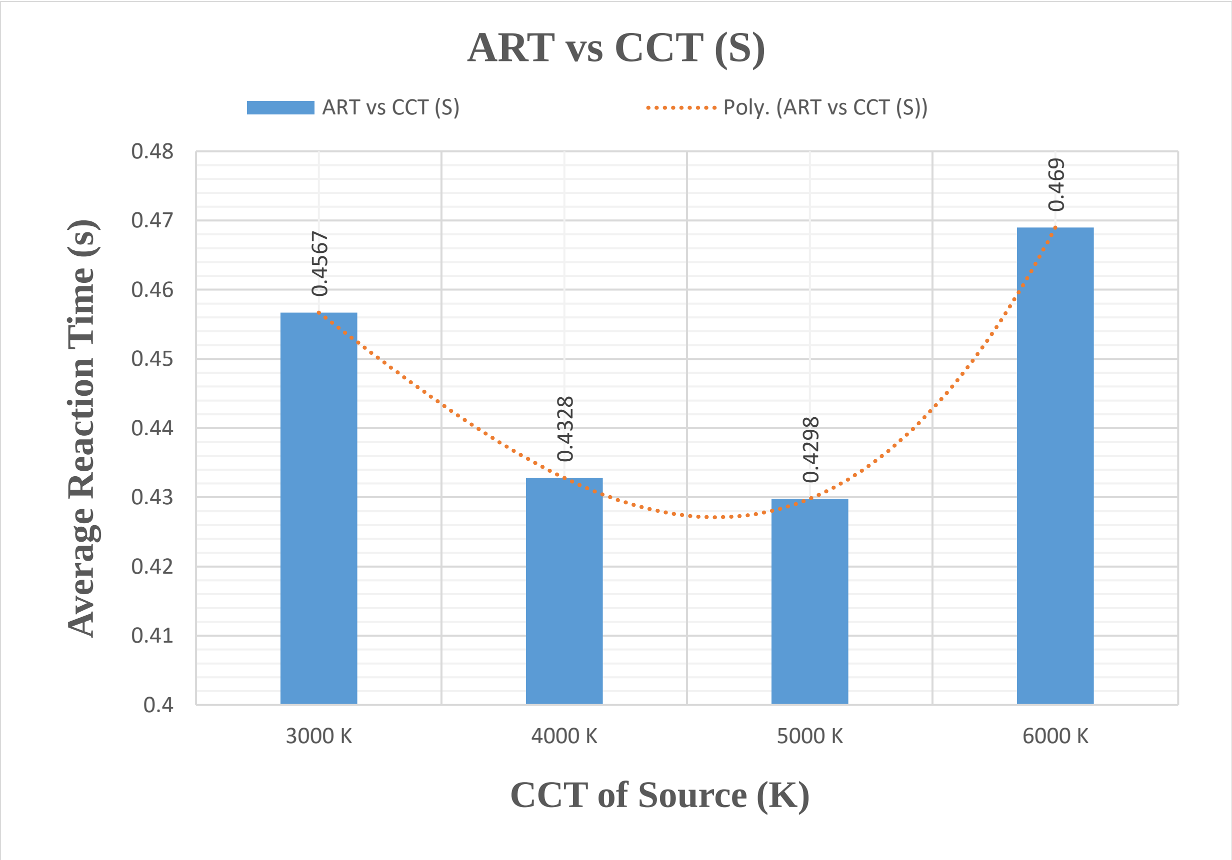


Fig 6.20 : Average Reaction Time vs. CCT of Main source (S).

In the second stage of the experiment, the reaction time is found to be less, when CCTs of main source and peripheral sources are high. Firstly, under CCT of 3000 K of main source (S) and CCT of 4500 K of the peripheral sources (P), the recorded ART is 0.24 s which is comparatively less than that of the ART under peripheral source's CCT of 3000 K and 6000 K which are found to be 0.3433 s and 0.2616 s respectively. Under 6000 K CCT of the peripheral sources (P), and four different levels of the main source's (S) CCT i.e., 3000 K, 4000 K, 5000 K, and 6000 K, the average reaction times (ART) are respectively 0.2616 s, 0.225 s, 0.2 s, and 0.1833 s which are gradually decreasing. Further calculation shows that in case of higher levels of the main source's (S) CCT like 6000 K, the average reaction time (ART) is 0.1944 s (average of the three ARTs), where CCTs of peripheral sources are varied from 3000 K to 6000 K. It is also evident from the study, that at a CCT of 3000 K of main source, the average reaction time (ART) is 0.2816 s (average of the three ARTs) with same variation of CCT of peripheral sources. So, it is evident from the results that, irrespective of the main source's (S) CCTs, higher levels of the CCTs of the peripheral sources (P) yield lesser average reaction times (ART).

Fig-6.21 shows the variation between the average reaction time (ART) and the different CCT levels of the main source (S) and the peripheral sources (P).

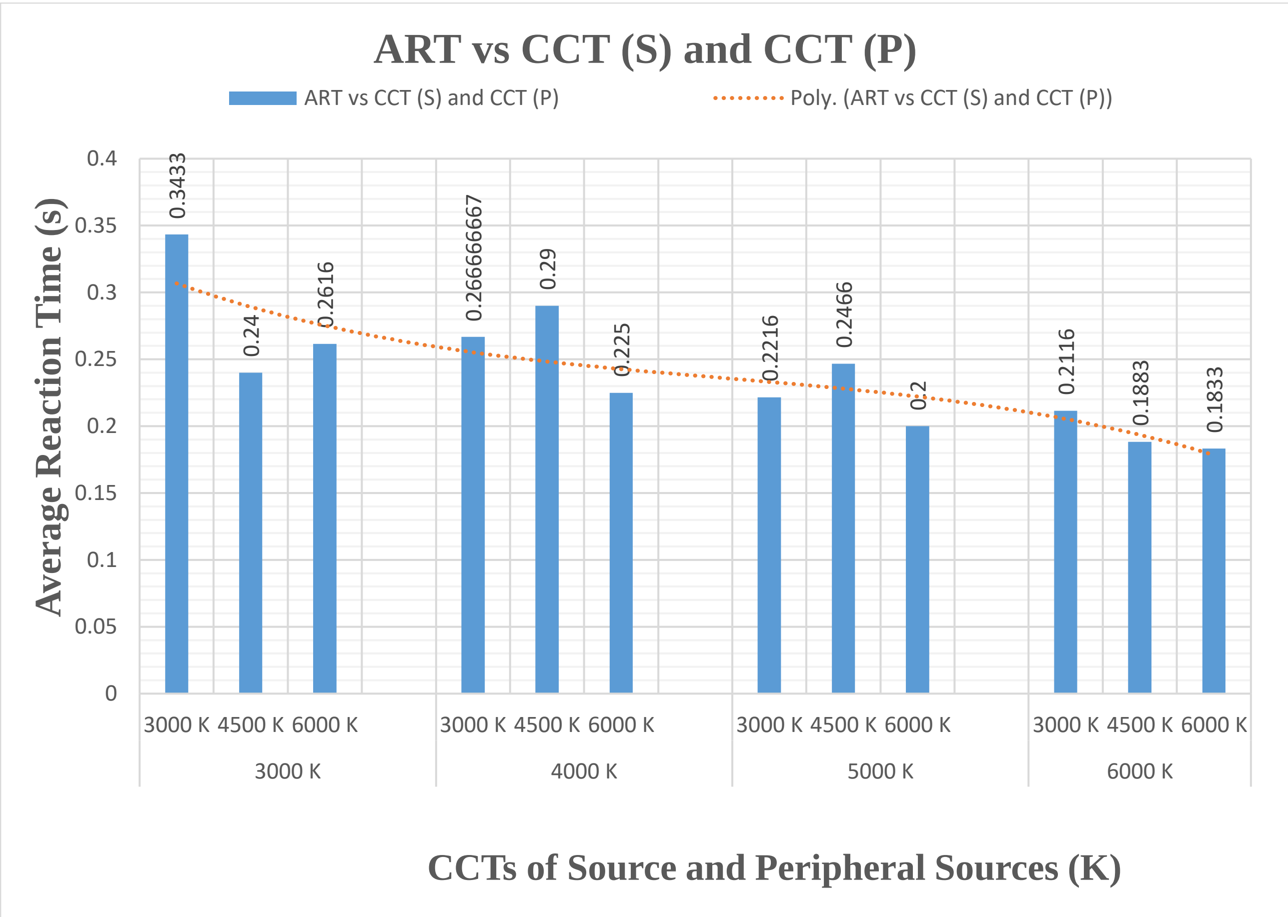


Fig 6.21 : Average Reaction Time vs CCT of Main source (S) and Peripheral sources (P).

In each of the above-mentioned lighting scenes, participants are asked four specific questions assembled in a questionnaire for one object position. Marks are assigned to each question based on whether or not the answers matched the actual size or shape of the objects and other subjective information. After total marks for one object position are determined, total marks for the other nineteen object positions are averaged to grade the lighting scenes. Comparative studies are performed after grading to determine the best and worst lighting conditions. Additionally, the questionnaire's four questions are separated into two groups. One category, called the "subjective category," contains the first and last questions of the questionnaire; the other, called the "objective category," contains the second and third questions of the questionnaire. The answers to these questions depend on the subject's perception of the objects as well as the shape and colour of the objects. The cumulative effect of the subjective and objective categories is given to us in the first segment of each lighting scenario, while the only effect of the objective category is given to us in the second segment. According to these calculations, the best lighting scenario for object recognition and observer comfort is one with a main source CCT of 4000K, while one with a CCT of 6000K is the worst. Additionally, when peripheral sources are present, the main source's 5000K CCT produces the ideal lighting conditions, whereas 3000K produces the poorest conditions when the effects of the peripheral sources are averaged. Furthermore, where the influence of the main source is averaged, 6000K CCT of peripheral sources produces the best lighting scenario, whereas 3000K produces the poorest. Additionally, the best lighting situation results from having both the main source and peripheral sources with a CCT of 6000K, whereas the worst lighting scene results from having a main source with a 6000K CCT and peripheral sources with a 3000K CCT. Variations of sectional scores are portrayed in the graphs given below in Fig-6.22 and Fig-6.23. Another two graphs consisting of the variation of sectional scores with variation of main and peripheral source’s CCT are also given below in Fig-6.24 and Fig-6.25.

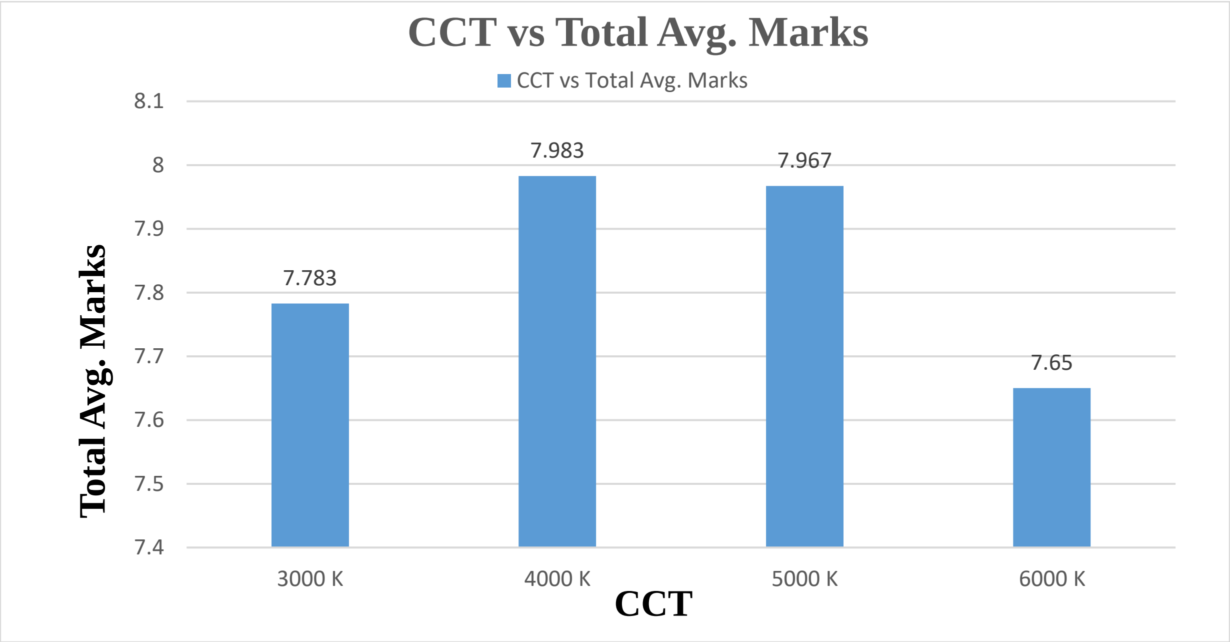


Fig 6.22 : Graph between CCT and Total Average Marks when peripheral sources are off.

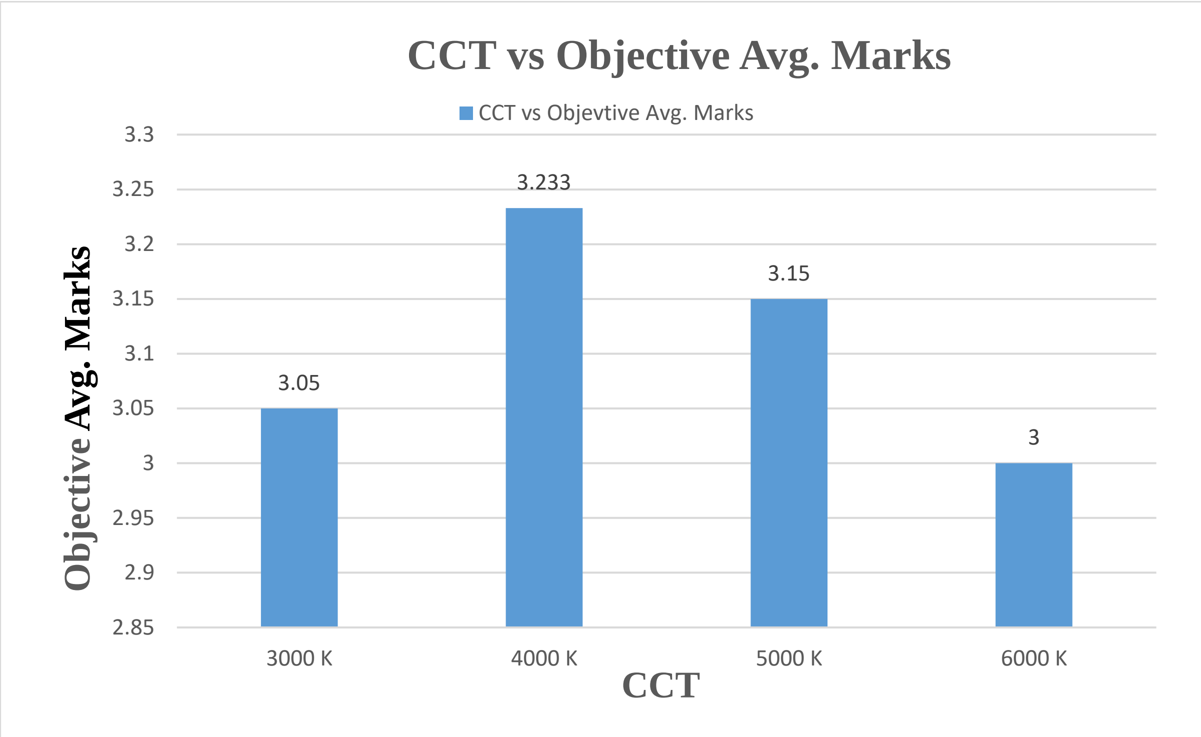


Fig 6.23 : Graph between CCT and Objective Average Marks when peripheral sources are off.

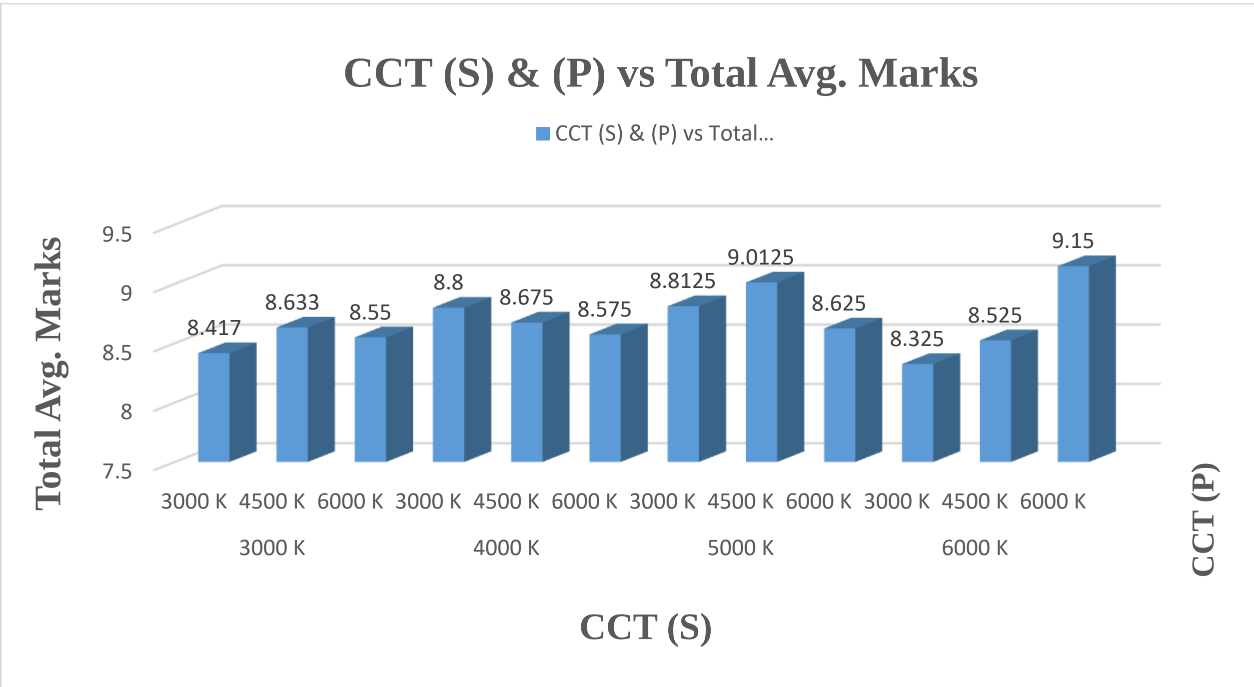


Fig 6.24 : Graph between CCT & Total Average Marks with combination of Main & Peripheral source.

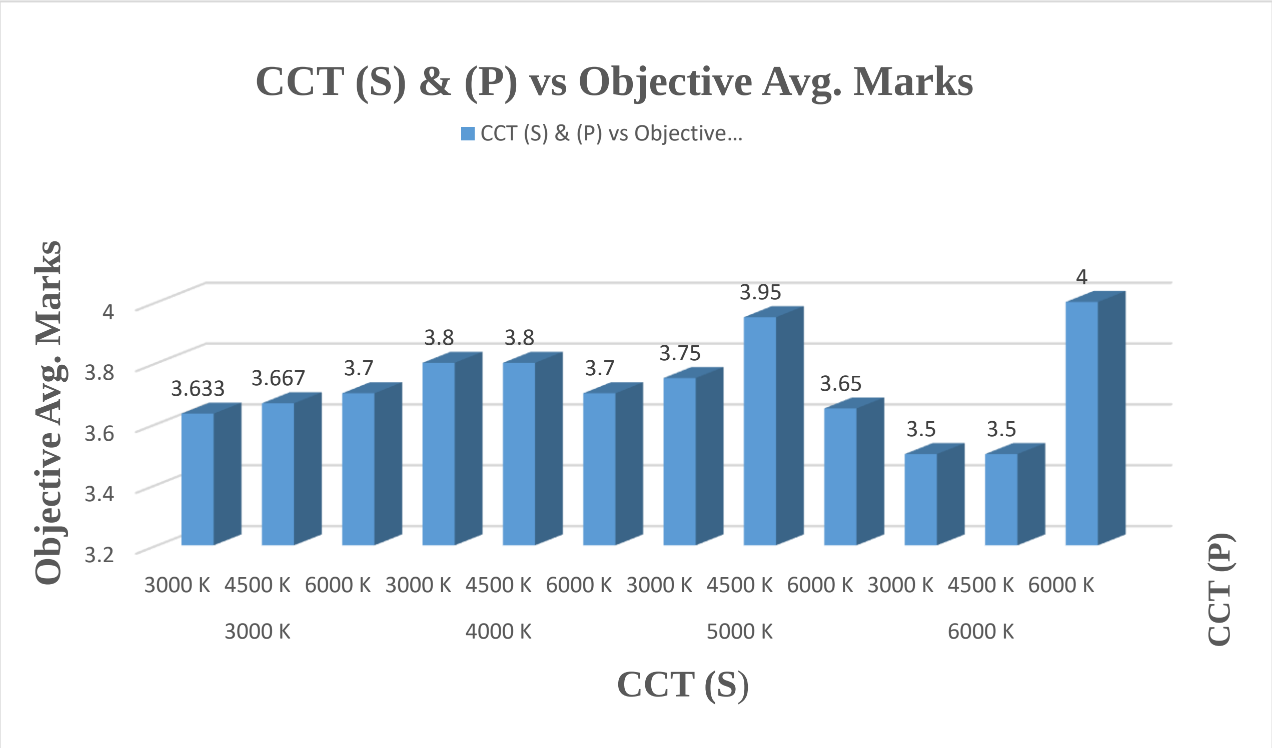


Fig 6.25 : Graph between CCT & Objective Avg. Marks with combination of Main & Peripheral source.

Chapter - 7

Conclusion and Future Scope

The study conclusively demonstrates that the amount of eye adaptation and eye sensitivity both increase with higher CCT levels of main and peripheral light sources. It is shown that average reaction times (ART) for drivers significantly reduce at higher CCT levels of both sources. Further, the reduction in reaction time (RT) of any human individual means the reduction in the timing of the overall sequence of processes consisting of object identification, object recognition, decision making and task performance (i.e., motor action and muscle movements). This simply means, the users of the road, especially the drivers will be having more time to take decisions and perform their task according to that. Along with the on-road safety, the safety of the pedestrians is also an important concern. So, reduction in average reaction times (ART) of the road users as well as the pedestrians will undoubtedly result in providing more safety towards the vehicular and non-vehicular movements on the road. This study strongly suggests that while designing any type of road illumination in Indian context, higher CCT values for streetlights should be taken into consideration.

Furthermore, an optimized road lighting design should be incorporated in Indian streets and roads so that it can be energy efficient along with having a better longevity and requiring very less concerns for maintenances. Additionally, the Indian Government will benefit economically from this lighting design approach.

As this study is conducted inside a laboratory-based controlled environment, a thorough investigation on real roads is required before it can be asserted that streetlights with higher CCT improve driver's mental cognitions and make it simpler to spot obstacles. Visibility Level (VL) being another important human centric parameter like reaction time (RT), studies on the correlation between lighting design and VL should be conducted in future research works.

Besides that, Flickering is an important issue for LEDs. It can have effects on the visibility and both the cognitive and task performance of human individuals. So, it is obvious that same previously described study should be performed with flickering effects on the peripheral sources and the possible outcomes should be thoroughly examined.

Along with that, EEG based experiments should be performed in future to better understand the behavioural responses of human being which are correlated with various lighting parameters.

It is also found that the age-old road lighting schemes in India incorporate the Illuminance-based model which has become inappropriate in today's context. However, the Luminance-based models have more accuracy as compared to Illuminance-based models. So, it is suggested that in Indian road lighting design and standard, the Luminance-based models should be considered for better outcomes in the field of illumination.

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Appendix - 1

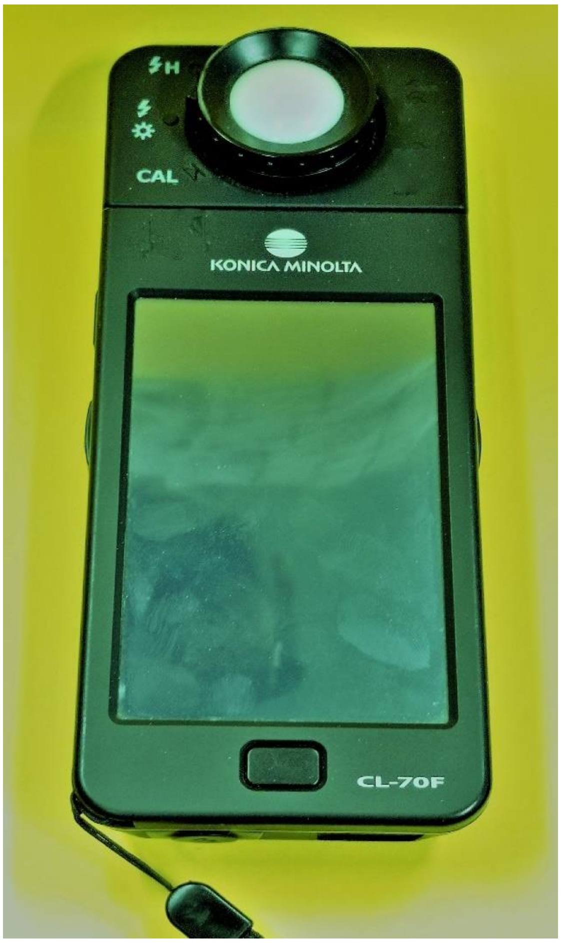
LIST OF ABBREVIATIONS

Sl No.	ABBREVIATION	Full Form
1	E	Illuminance (Lumen/m^2 or lux)
2	L	Luminance (candela/m^2/steradian)
3	I_L	Luminous Intensity (candela or cd)
4	Φ_L	Luminous Flux (Lumen or lm)
5	η_L	Luminous Efficacy
6	E_{avg}	Average Illuminance (lux)
7	U_0	Uniformity
8	H	Pole Height (m)
9	S	Main Source
10	P	Peripheral Source
11	CCT	Correlated Color Temperature (K)
12	CRI	Color Rendering Index
13	RT	Reaction Time (s)
14	ART	Average Reaction Time (s)
15	VL	Visibility Level
16	STV	Small Target Visibility
17	RTMCD	Reaction Time Measuring Compact Device
18	HCL	Human Centric Lighting
19	SCN	Suprachiasmatic Nucleus
20	VA	Visual Acuity

Appendix – 2

Different Instruments Used in This Experiment

- **Konica Minolta CL70-F CRI Illuminance Meter :** This is a multifunctional device for assessing the illuminance, color temperature, and color rendering index of different light sources, including LEDs and fluorescent lights. This instrument was primarily used to measure the color temperature and spectral power density. Here, a CMOS linear image sensor is being employed as the sensor of the device. Its spectral wavelength ranges from 380 to 780 nm. The device is facilitated with a utility software for communicating with PCs. This software extracts the data that the instrument recorded.



Main Specifications of CL-70F

Model	CRI Illuminance Meter CL-70F
Illuminance meter class	Conforms to requirements for Class A of JIS C1609-1 : 2006 "Illuminance meters Part1:General measuring instruments; Conforms to DIN 5032 Part 7 Class C
Sensor	CMOS linear image sensor
Spectral wavelength range	380 nm to 780 nm
Output wavelength pitch	1 nm
Measuring range	Constant light: 1 to 200,000 lx; 1,563 to 100,000 K (Chromaticity display requires 5 lx or more) Flash light: 20 to 20,500 lx·s; 2,500 to 100,000 K
Accuracy (Standard Illuminant A) (*1, 2)	E_V: ±5%±1digit of displayed value
	xy: ±0.003 (at 800 lx)
Repeatability (Standard Illuminant A) (*1)	E_V: 30 to 200,000 lx: 1%+1digit; 1 to 30 lx: 5%+1digit (*3)
	xy: 500 to 200,000 lx: 0.001 (*4) xy: 100 to 500 lx: 0.002 (*4) xy: 30 to 100 lx: 0.004 (*4) xy: 5 to 30 lx: 0.008 (*4)
Visible-region relative spectral response characteristics (f1')	Within 9%
Cosine correction characteristics (f2)	Within 6%
Temperature drift (f_T)	E_V: ±5% xy: ±0.006
Humidity drift (f_H)	E_V: ±3% xy: ±0.006
Power	2 AA-size batteries (Alkaline batteries or manganese dry cells); USB bus power
Response time	Constant light (Maximum): 15 sec Constant light (Minimum): 0.5 sec Flash light: 1 to 1/500 sec (in 1-step intervals) (*5)
Color indication modes	Correlated color temperature T_{cp}, Difference from blackbody Δuv, XYZ, xy, u'v', Dominant wavelength λ_d, Excitation purity P_e, Spectral irradiance, E_V, CRI (Ra, Ri), Peak wavelength λ_p, exposure value
Other functions	Data memory: 999 data; Preset function; Auto power off function
Display languages	English, Japanese, Chinese (Simplified)
Interface	USB 2.0 Mini B
Operation temperature/ humidity range	-10 to 40℃ , relative humidity of 85% or less (at 35℃) with no condensation
Storage temperature/ humidity range	-10 to 45℃ , relative humidity of 85% or less (at 35℃) with no condensation
Size	73 (W)× 183 (H) × 27 (D) mm (Not including projecting buttons) D (max): 40 mm
Weight (without battery)	230 g

- **Metravi 1310 Digital Lux Meter :** This device is used to measure the illuminance level of light sources. It has a 4 digits backlit LCD display which shows the measured illuminance value in either LUX or in FC (foot-candle) unit with the accuracy of ±5%. The device is equipped with Split Probe Type Sensor which can measure the illuminance ranging from 0 to 199,900 lux of illuminance. 3 AAA alkaline batteries are used to power this device.

- Split Probe type separate sensor
- Sampling Rate 0.5S
- Auto Range
- Lux / Fc Selectable
- Max / Min Record
- Hi/Lo Overload Indication
- Data Hold
- Backlit LCD Display
- Auto Power Off
- Low Battery Indication
- Range: 0 – 199,900 Lux / Fc
- Accuracy:- ±5%
- AAA Battery Operated

- **Halonix Wi-Fi Enabled Smart LED Bulb :** It is a 12 watt smart LED bulb with Wi-Fi capabilities. It's pluggable into a B-22 holder. A smartphone application can be used to control the lightbulb. It may be lit up in more than a million different colours. Additionally, it can convert warm white to cold white. The range of the CCT is 2500 K to 6000 K. Using the smartphone application, user may also regulate the brightness or intensity.

About this item

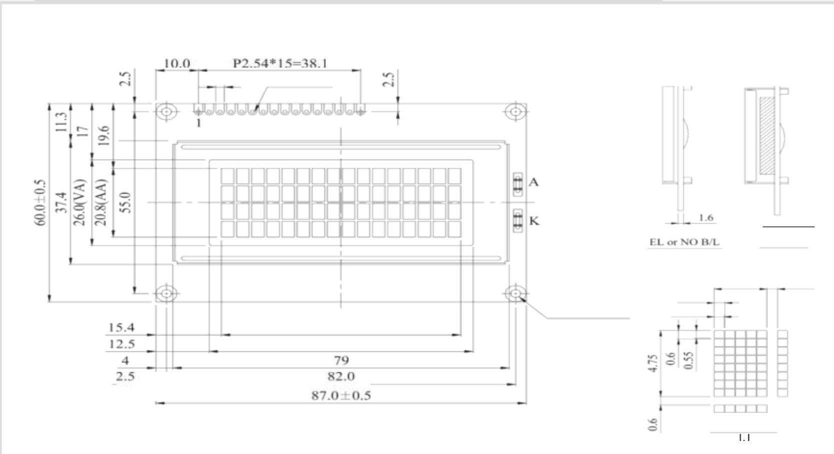
- Wattage: 12 watts smart led bulb, Base-B22, Input Voltage : AC220~240V, 50Hz
- Wifi Requirement: Requires a secured 2.4 GHz Wi-Fi network connection.
- Shades of light-With this Smart RGB wifi Led bulb, you can light up any room with millions of shades to choose from the colour palette. Choose the brightest colour while studying or a soft warm shade when you enjoy a cup of coffee. You can choose a random colour while you party at your home.
- Virtual assistant-Control this smart LED bulb by voice with a virtual assistant such as Alexa or Google assistant.
- Dim or Brighten-Control the brightness of the LED from one to hundred percent that too of any colour.
- Timing function-With the inbuilt timing function, you can easily automate the LED to turn on and off at any given time. It is a perfect smart wifi light for home
- Control the lighting at your fingertips; just download the Halonix Wi-Fi app from play store or apple store
- Warranty- 12 Months
- Country of Origin: India

Appendix - 3

Different Components Used in This Experiment

❖ 16x4 LCD Image and Data Sheet :

WH1604A Character 16x4



Feature

1.5x8 dots includes cursor
2 Bulit-in controller (ST7066 or Equivalent)
3.5V power supply (Also available for 3V)
4.N.V, optional for 3V power supply
5.1/16 duty cycle
6.LED can be driven by PIN1, PIN2, PIN15, PIN16 or A and K
7.Interface : 6800, option SPI/I2C (RW1063 IC)

Pin No.	Symbol	Description
1	V_{SS}	Ground
2	V_{DO}	Power supply for logic
3	V_I	Contrast Adjustment
4	RS	Data/ Instruction select signal
5	R/W	Read/Write select signal
6	E	Enable signal
7	DB0	Data bus line
8	DB1	Data bus line
9	DB2	Data bus line
10	DB3	Data bus line
11	DB4	Data bus line
12	DB5	Data bus line
13	DB6	Data bus line
14	DB7	Data bus line
15	A	Power supply for B/L +
16	K	Power supply for B/L -

Mechanical Data

Item	Standard Value	Unit
Module Dimension	87.0 x 60.0	mm
Viewing Area	62.0 x 26.0	mm
Mounting Hole	82.0 x 55.0	mm
Character Size	2.95 x 4.75	mm

Electrical Characteristics

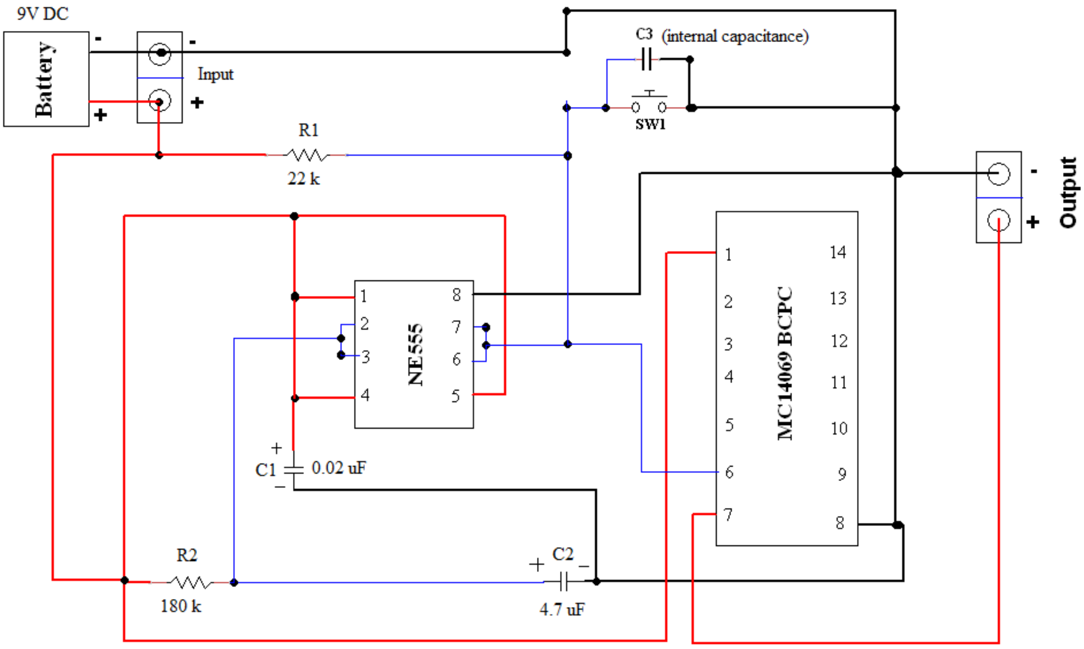
Item	Symbol	Standard Value typ.	Unit
Input Voltage	VDD	3/5	V
Recommended LCD Driving Voltage for Normal Temp. Version module @25°C	VDD-VO	4.35	V

Display Character Address Code

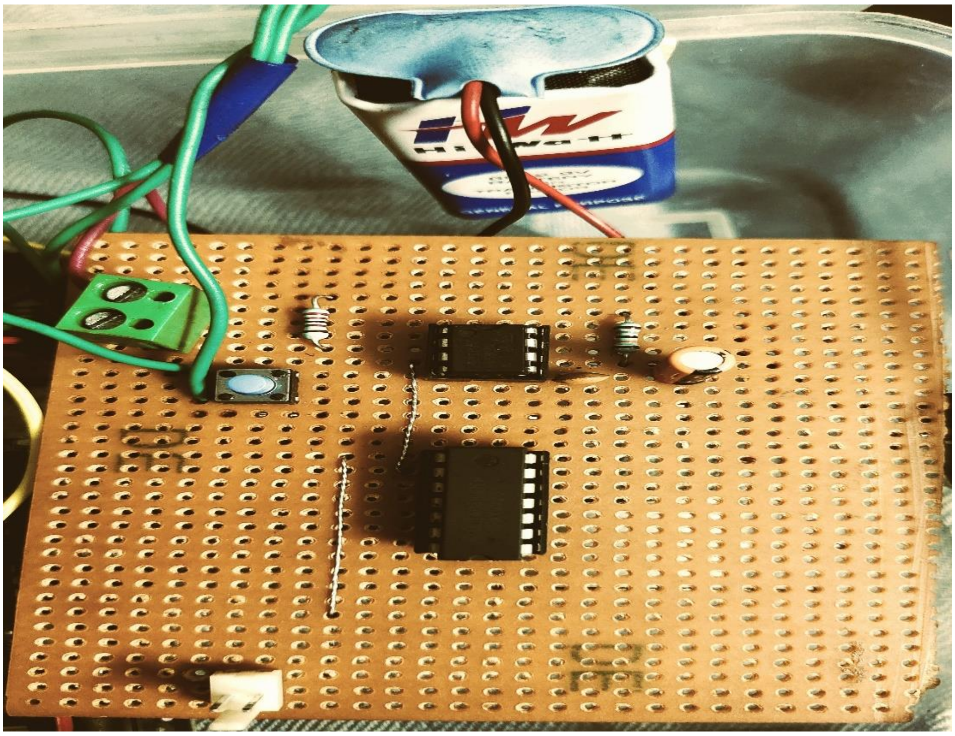
D ÌS {DIâ 0 E ti0 W 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
D D RAM Ad d re s s 00 01
D D RAM Ad d re s s 40 41
D D R A M Ad d re s s 10 11 1F
D D RAM Ad d re s s 50 51 SF

42

❖ Circuit Diagram of the Reaction Time Measuring Circuit :



❖ Reaction Time Measuring Circuit :



❖ Image and Data Sheet of 9 V Battery (With Connector) :

Brand	Generic
Battery Cell Composition	Manganese
Net Quantity	5 count
Voltage	9 Volts
Item Dimensions LxWxH	10 x 8 x 4 Centimeters
Item Weight	0.4 Pounds

About this item

- Compatible with all development board
- Reuse of specially designed cells
- Primary battery

Specifications for this item

Brand Name	Generic
Item Weight	181 grams
Manufacturer Series Number	robokart_176
Model Number	robokart_176
Number of Items	5
Part Number	robokart_176
Specification Met	
Voltage	9 volts

❖ IC - MC14069 Hex Inverter Datasheet :

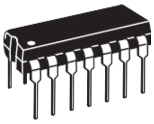
ON Semiconductor

http://onsemi.com

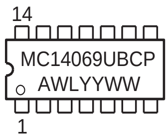
The MC14069UB hex inverter is constructed with MOS P–channel and N–channel enhancement mode devices in a single monolithic structure. These inverters find primary use where low power dissipation and/or high noise immunity is desired. Each of the six inverters is a single stage to minimize propagation delays.

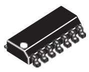
- Supply Voltage Range = 3.0 Vdc to 18 Vdc
- Capable of Driving Two Low–Power TTL Loads or One Low–Power Schottky TTL Load Over the Rated Temperature Range
- Triple Diode Protection on All Inputs
- Pin–for–Pin Replacement for CD4069UB
- Meets JEDEC UB Specifications

MARKING DIAGRAMS

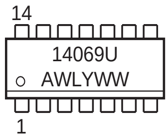


PDIP–14
P SUFFIX
CASE 646

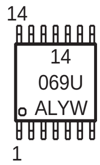


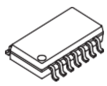


SOIC–14
D SUFFIX
CASE 751A

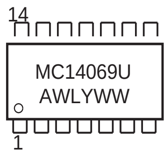


TSSOP–14
DT SUFFIX
CASE 948G





SOEIAJ–14
F SUFFIX
CASE 965



MAXIMUM RATINGS (Voltages Referenced to V_{SS}) (Note 2.)

Symbol	Parameter	Value	Unit
V_{DD}	DC Supply Voltage Range	–0.5 to +18.0	V
V_{in}, V_{out}	Input or Output Voltage Range (DC or Transient)	–0.5 to V_{DD} + 0.5	V
I_{in}, I_{out}	Input or Output Current (DC or Transient) per Pin	±10	mA
P_D	Power Dissipation, per Package (Note 3.)	500	mW
T_A	Ambient Temperature Range	–55 to +125	°C
T_{stg}	Storage Temperature Range	–65 to +150	°C
T_L	Lead Temperature (8–Second Soldering)	260	°C

❖ IC - NE555 Precision Timers Datasheet :

TEXAS INSTRUMENTS

xx555 Precision Timers

1 Features

- Timing From Microseconds to Hours
- Astable or Monostable Operation
- Adjustable Duty Cycle
- TTL-Compatible Output Can Sink or Source Up to 200 mA
- On Products Compliant to MIL-PRF-38535, All Parameters Are Tested Unless Otherwise Noted. On All Other Products, Production Processing Does Not Necessarily Include Testing of All Parameters.

2 Applications

- Fingerprint Biometrics
- Iris Biometrics
- RFID Reader

3 Description

These devices are precision timing circuits capable of producing accurate time delays or oscillation. In the time-delay or mono-stable mode of operation, the timed interval is controlled by a single external resistor and capacitor network. In the a-stable mode of operation, the frequency and duty cycle can be controlled independently with two external resistors and a single external capacitor.

The threshold and trigger levels normally are two-thirds and one-third, respectively, of V_{CC}. These levels can be altered by use of the control-voltage terminal. When the trigger input falls below the trigger level, the flip-flop is set, and the output goes high. If the trigger input is above the trigger level and the threshold input is above the threshold level, the flip-flop is reset and the output is low. The reset (RESET) input can override all other inputs and can be used to initiate a new timing cycle. When RESET goes low, the flip-flop is reset, and the output goes low. When the output is low, a low-impedance path is provided between discharge (DISCH) and ground.

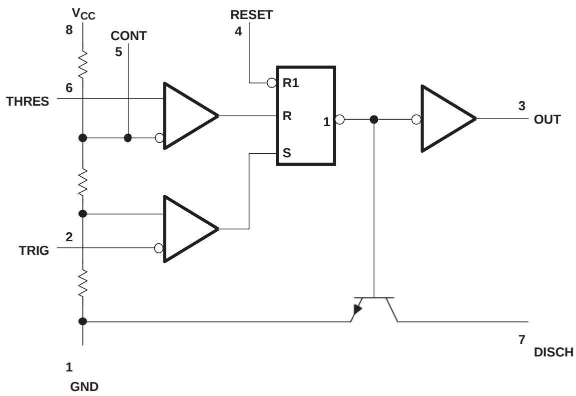
The output circuit is capable of sinking or sourcing current up to 200 mA. Operation is specified for supplies of 5 V to 15 V. With a 5-V supply, output levels are compatible with TTL inputs.

Device Information(1)

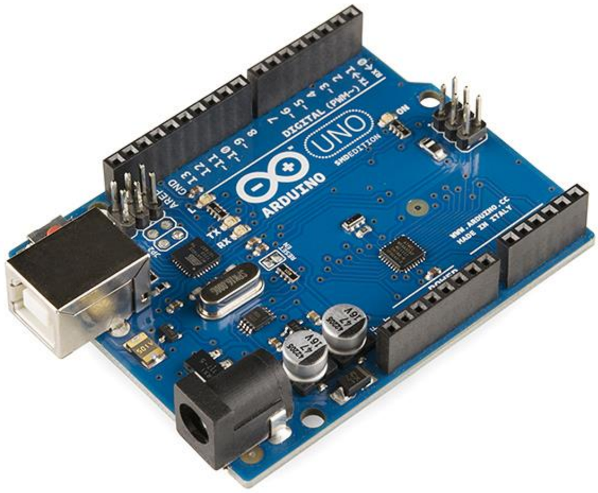
PART NUMBER	PACKAGE	BODY SIZE (NOM)
xx555	PDIP (8)	9.81 mm × 6.35 mm
	SOP (8)	6.20 mm × 5.30 mm
	TSSOP (8)	3.00 mm × 4.40 mm
	SOIC (8)	4.90 mm × 3.91 mm

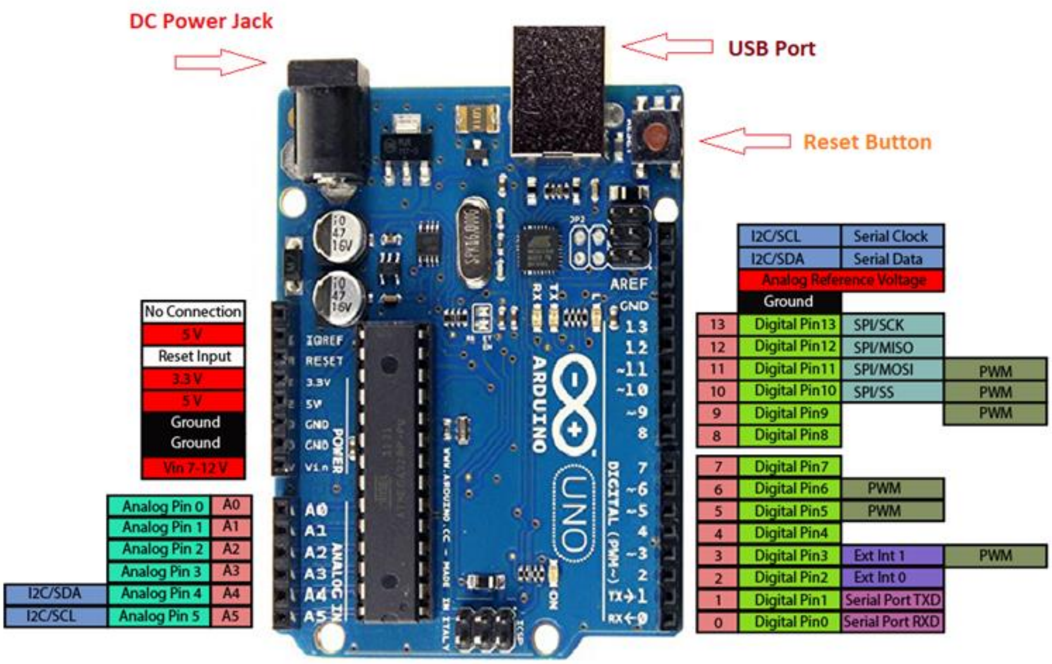
(1) For all available packages, see the orderable addendum at the end of the datasheet.

4 Simplified Schematic



❖ Arduino UNO Module with Pin-out Diagram and Datasheet :





Arduino Uno Pinout

1 The Board

1.1 Application Examples

The UNO board is the flagship product of Arduino. Regardless if you are new to the world of electronics or will use the UNO as a tool for education purposes or industry-related tasks.

First entry to electronics: If this is your first project within coding and electronics, get started with our most used and documented board; Arduino UNO. It is equipped with the well-known ATmega328P processor, 14 digital input/output pins, 6 analog inputs, USB connections, ICSP header and reset button. This board includes everything you will need for a great first experience with Arduino.

Industry-standard development board: Using the Arduino UNO board in industries, there are a range of companies using the UNO board as the brain for their PLC's.

Education purposes: Although the UNO board has been with us for about ten years, it is still widely used for various education purposes and scientific projects. The board's high standard and top quality performance makes it a great resource to capture real time from sensors and to trigger complex laboratory equipment to mention a few examples.

1.2 Related Products

- Starter Kit
- Tinkerkit Braccio Robot
- Example

2 Ratings

2.1 Recommended Operating Conditions

Symbol	Description	Min	Max
	Conservative thermal limits for the whole board:	-40 °C (-40°F)	85 °C (185°F)

NOTE: In extreme temperatures, EEPROM, voltage regulator, and the crystal oscillator, might not work as expected due to the extreme temperature conditions

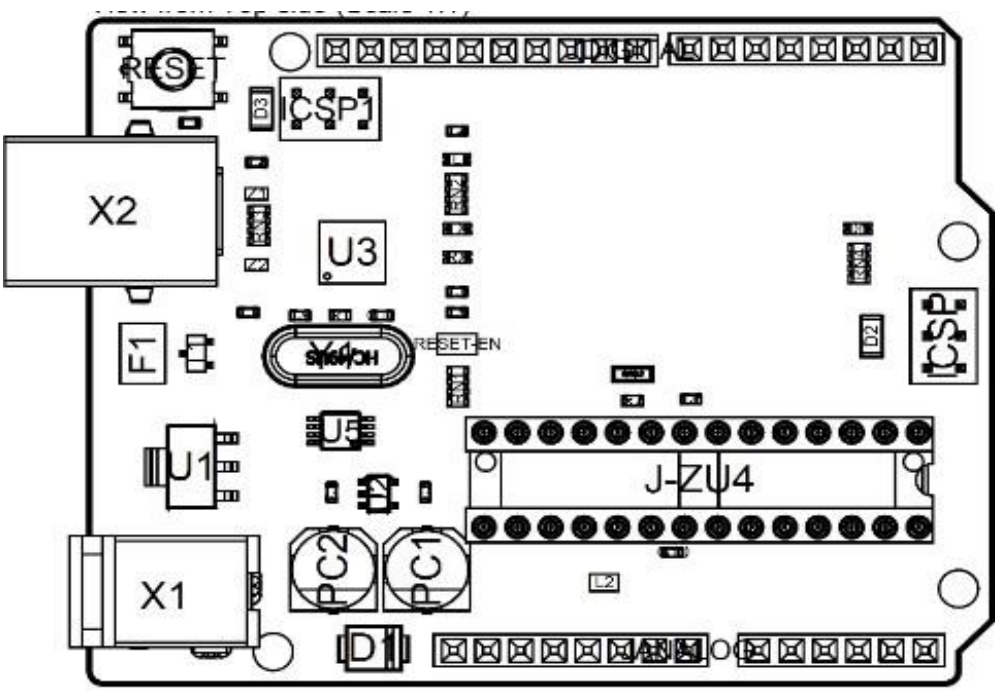
1.1 Power Consumption

Symbol	Description	Min	Typ	Max
VINMax	Maximum input voltage from VIN pad	6	-	20
VUSBMax	Maximum input voltage from USB connector		-	5.5
PMax	Maximum Power Consumption	-	-	xx

2 Functional Overview

2.1 Board Topology

Top view



Board topology

Ref.	Description	Ref.	Description
X1	Power jack 2.1x5.5mm	U1	SPX1117M3-L-5 Regulator
X2	USB B Connector	U3	ATMEGA16U2 Module
PC1	EEE-1EA470WP 25V SMD Capacitor	U5	LMV358LIST-A.9 IC
PC2	EEE-1EA470WP 25V SMD Capacitor	F1	Chip Capacitor, High Density
D1	CGRA4007-G Rectifier	ICSP	Pin header connector (through hole 6)
J-ZU4	ATMEGA328P Module	ICSP1	Pin header connector (through hole 6)
Y1	ECS-160-20-4X-DU Oscillator		

Features

- **ATMega328P** Processor
  - **Memory**
    - AVR CPU at up to 16 MHz
    - 32KB Flash
    - 2KB SRAM
    - 1KB EEPROM
  - **Security**
    - Power On Reset (POR)
    - Brown Out Detection (BOD)
  - **Peripherals**
    - 2x 8-bit Timer/Counter with a dedicated period register and compare channels
    - 1x 16-bit Timer/Counter with a dedicated period register, input capture and compare channels
    - 1x USART with fractional baud rate generator and start-of-frame detection
    - 1x controller/peripheral Serial Peripheral Interface (SPI)
    - 1x Dual mode controller/peripheral I2C
    - 1x Analog Comparator (AC) with a scalable reference input
    - Watchdog Timer with separate on-chip oscillator
    - Six PWM channels
    - Interrupt and wake-up on pin change
  - **ATMega16U2 Processor**
    - 8-bit AVR® RISC-based microcontroller
  - **Memory**
    - 16 KB ISP Flash
    - 512B EEPROM
    - 512B SRAM
    - debugWIRE interface for on-chip debugging and programming
  - **Power**
    - 2.7-5.5 volts

Appendix - 4

❖ **Arduino UNO code for Time Stamping :**

```
#include <LiquidCrystal.h>
LiquidCrystal lcd(12, 11, 5, 4, 3, 2);

double i = 0;
double a = millis();
double c ;
int d = 0;

void stpwatch();
void pause();

void setup()
{
  lcd.begin(16, 4);
  lcd.clear();

  Serial.begin(9600);

  pinMode(8, INPUT);
  digitalWrite(8, LOW);
  pinMode(7, INPUT);
  digitalWrite(7, LOW);
}

void(*resetFunc)(void)= 0;

void loop()
{
  lcd.clear();
  lcd.print("Press Start");
  delay(100);
  Serial.println("press start");

  if (digitalRead(8) == HIGH)
  {
    if (digitalRead(8) == HIGH && d == 1)
    {
      resetFunc();
      }
    stpwatch();
    pause();
```

```
  }
}

void stpwatch()
{
  Serial.println("8 = high");
  lcd.clear();
  a = millis();
  Serial.println(a);
  while (digitalRead(7) == LOW)
  {
    Serial.println(" d ");
    c = millis();
    i = (c - a)  / 1000;
    lcd.print(i);
    lcd.setCursor(7, 0);
    lcd.print("Sec");
    lcd.setCursor(0, 0);
    Serial.println(c);
    Serial.println(a);
    Serial.println(i);
    Serial.println("......");
    delay(10);
  }
}

  void pause()
  {
    if (digitalRead(7) == LOW)
    Serial.println("7 = high");
    while (digitalRead(8) == LOW)
    {
      Serial.println(" e ");
      lcd.setCursor(4, 2);
      lcd.print(i);
      lcd.setCursor(10,2);
      lcd.print(" Sec");
      lcd.setCursor(11, 0);
      lcd.print("");
      lcd.setCursor(0, 0);
      delay(10);
      d = 1;
    }
  }
```