Exploring the Effects of In-Car Lighting on Driver Comfort and Alertness During Night-Time Driving

By

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The candidate confirms that this submitted work is their own and that appropriate credit has been given where reference has been made to the work of others.

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Abstract

Driving at night presents unique challenges, such as reduced visibility and increased mental fatigue. This research investigates how interior car lighting can help drivers feel more comfortable and stay alert. To achieve this, a mix of qualitative and quantitative research methods was used, including data-driven analysis and psychological experimental evaluations conducted through virtual reality (VR) driving scenarios. The study began by examining 174 images of car interiors to identify key colour patterns using K-means clustering, which informed subsequent experiments. In the VR simulations, participants experienced night-time driving with various lighting setups and shared their impressions of visual comfort and alertness levels. At the same time, their brain activity was monitored to gather objective data. The results revealed that blue lighting enhanced alertness during demanding tasks, but it lacked emotional comfort. In contrast, pink and green lighting created a more relaxing atmosphere and improved the aesthetic appeal of the car interior, although they were less effective at maintaining focus. Brainwave data supported these observations, showing distinct neural responses to different lighting colours. Interestingly, stable beta and delta activity suggested that lighting alone might not fully address driver needs, underscoring the importance of integrating additional design features. Overall, the findings suggest that adaptive lighting systems could enhance safety and comfort during night-time driving.

Chapter 1 Introduction

Night-time driving presents distinct visual and cognitive challenges, which can significantly impact driver safety and comfort (Evans et al., 2020). Due to the human eye's adaptation to daylight, low-light conditions at night require a heightened level of visual effort, often leading to increased strain and fatigue. As a result, both visual comfort and sustained alertness are essential for drivers to maintain focus and respond effectively to road conditions and unexpected events. However, traditional in-car lighting systems have primarily aimed at functionality—illuminating controls and displays—without fully considering the broader psychological and physiological effects on drivers, especially under night-time conditions. Addressing this research gap, the aim of this thesis is to investigate how optimised in-car lighting designs can improve visual comfort and cognitive alertness during night-time driving, with the goal of enhancing driver safety, comfort, and well-being.

Emerging research suggests that interior lighting has a notable effect on human perception and cognitive states, with implications for the driver's experience in vehicles. In a recent study, a comprehensive methodological framework was adopted that combined virtual simulation, multimodal sensing, and user-centred evaluation to investigate how intelligent in-vehicle interaction technologies influence driver behaviour and comfort (Ackaah et al., 2020; Murali et al., 2022). Previous studies have shown that lighting can influence mood, alertness, and even cognitive performance, suggesting that lighting configurations might be designed to support specific psychological states (Jiang et al., 2022; Xia et al., 2023). For drivers operating vehicles at night, a lighting design that supports alertness and visual comfort could mitigate the cognitive burden associated with low-light driving conditions, potentially reducing the risk of accidents associated with fatigue and decreased attention. Recent studies have demonstrated the value of combining intelligent in-vehicle systems and psychophysiological validation to understand driver comfort and safety. For example, research into intelligent in-vehicle interaction technologies integrates multimodal sensing—such as visual, haptic, and auditory feedback—to assess user states and adapt interior environments dynamically, including lighting, in response to driver fatigue or emotional cues (Weirich et al., 2022a). In parallel, quantitative methodologies employ real-world and virtual reality driving experiments to establish relationships between objective physiological indicators (e.g., pupil dilation, saccadic velocity) and subjective visual comfort under varying luminance conditions. These methods use both statistical modelling and participant-based questionnaires to determine optimal illumination parameters that enhance comfort while maintaining visual acuity and energy efficiency (Caberletti et al., 2010). Together, these approaches validate the importance of integrating intelligent sensing and perceptual evaluation frameworks into vehicle interior design. Applying such methodologies to the study of in-car lighting extends their principles to night-time driving contexts, providing an empirical basis for quantifying how lighting characteristics influence driver alertness and perceived comfort (Kimlin et al., 2020; Liang et al., 2024). Nevertheless, while insights from other controlled environments - such as office spaces, hospitals, and industrial settings - underscore lighting's role in enhancing comfort and cognitive performance (Allen and Macomber, 2020), these findings have yet to be systematically applied to the automotive context. Given the unique demands of night-time driving, it is essential to investigate how these principles can be adapted to create supportive and effective in-car lighting systems.

Among the various factors influencing driver perception and performance, the colour of lighting are recognised as critical determinants of alertness and visual comfort. Specific hues have been shown to evoke emotional and cognitive responses that are beneficial to the driving task. For instance, cooler hues such as blue and green are associated with relaxation and sustained focus, whereas warmer hues, including red and yellow, may enhance alertness but risk inducing fatigue with prolonged exposure (van Bommel, 2023; Fan et al., 2024). To systematically examine colour preferences and trends within automotive interior design, this study adopts a data-driven approach grounded in machine learning analysis. The K-means clustering algorithm is employed to categorise the dominant hues from a dataset of 174 interior lighting images (Chapter 4), as it offers an objective, replicable means of identifying underlying colour groupings within large visual datasets.

VR technology provides an immersive, controllable platform for simulating night-time driving conditions, enabling the safe and rigorous examination of various in-car lighting configurations. Unlike real-world testing, which is subject to environmental and safety constraints, VR allows for the replication of low-light scenarios under controlled conditions, facilitating the exploration of a wide range of lighting effects. In contrast, real-world studies of in-car lighting are often constrained by external variables such as fluctuating traffic density, weather conditions, and ambient light interference, all of which can compromise experimental consistency and data reliability. Moreover, ethical and safety considerations limit the extent to which potentially distracting or unconventional lighting designs can be tested with drivers in motion. Real vehicle experiments also demand considerable logistical and financial resources, making repeated or parametric testing impractical. Consequently, VR-based experimentation offers a methodologically robust alternative that allows for precise manipulation of lighting parameters while ensuring participant safety and experimental reproducibility. Prior research has validated VR's ability to replicate real-world driving experiences, making it a valuable tool for studying human responses to simulated environments (Zou et al., 2021; Newman et al., 2022). By combining subjective assessments, such as self-reported comfort and alertness levels, with objective physiological measures, including brain activity monitored via electroencephalography (EEG), this research captures a comprehensive picture of how lighting schemes affect drivers' perceptual comfort and cognitive alertness. The originality of this study lies in its integrative methodological framework, which unites data-driven colour analysis, immersive VR simulation, and neurophysiological evaluation to explore in-car lighting effects in a unified experimental design. Unlike previous research that has typically examined lighting influences in isolation—focusing either on perceptual preferences, physiological responses, or system design—this study bridges these domains to provide a holistic understanding of driver experience under controlled, yet ecologically realistic, night-time conditions. By validating lighting realism through participant-based evaluation and correlating subjective comfort with objective neural indicators, the research advances both methodological innovation and theoretical insight into how intelligent interior lighting can enhance safety and wellbeing in modern vehicles. The findings of this thesis aim to address critical gaps in existing automotive lighting standards, providing evidence-based recommendations for the design of user-centred lighting systems that enhance night-time visual comfort and alertness. By integrating K-means clustering and VR simulation, this research offers a novel methodological framework that bridges controlled experimental research with real-world applications. The results are expected to inform the development of adaptive lighting systems that dynamically respond to drivers’ visual and cognitive needs in low-light conditions, aligning with the growing trend towards adaptive and intelligent vehicle technologies.

Ultimately, this thesis seeks to advance the field of automotive ergonomics and lighting design by providing an in-depth exploration of how in-car lighting affects driver perception and alertness during night-time driving. Current vehicle interior lighting systems are often static and fail to adapt to drivers’ changing visual and cognitive needs, limiting their ability to support comfort and alertness during night-time driving. By addressing the limitations of current lighting systems and proposing data-informed, user-centred design solutions, this study contributes to the development of safer, more comfortable in-car environments. The findings will set a foundation for further research in adaptive and responsive lighting technologies in the automotive industry, aligning with the broader goal of enhancing driver well-being through targeted ergonomic interventions.

The specific research objectives of the thesis includes:

1. Identify prevalent in-car lighting colour schemes through image analysis using K-means clustering to establish a data-driven foundation for experimental testing.

2. Examine the psychological and physiological effects of different lighting colours in a VR-based night-time driving simulation.

3. Collect both subjective (self-reported comfort and alertness) and objective (EEG-based brain activity) indicators to capture a comprehensive picture of driver responses.

4. Propose evidence-based recommendations for adaptive, user-centred in-car lighting systems that enhance night-time driving safety and comfort.

Chapter 2 Literature Review

2.1 Overview of Road safety Concerns at Night

Night-time driving presents significant and persistent safety challenges for all road users, including drivers, pedestrians, and cyclists (Ackaah et al., 2020; Wood, 2020). Despite reduced traffic volume during night hours, the risk of fatal accidents remains disproportionately high, with studies indicating that the likelihood of a fatal crash is up to three times greater at night than during the day, even when accounting for distances travelled (Wood, 2023). The risk to pedestrians is particularly alarming: they are up to seven times more likely to be involved in a fatal collision at night compared to the daytime (Griswold et al., 2011). Moreover, accidents that occur at night tend to be more severe, with a higher likelihood of fatalities and serious injuries, highlighting an urgent need for solutions that directly address the unique dangers of night-time driving (Alogaili and Mannering, 2022).

A primary factor contributing to this increased risk is driver distraction, which significantly reduces situational awareness and reaction times. Distraction, defined as a shift in attention from critical driving tasks to competing activities or stimuli, is particularly detrimental under night-time conditions where visibility and cognitive processing demands are already compromised. Data from the National Highway Traffic Safety Administration (NHTSA) shows that driver inattention contributes to approximately 25% of police-reported crashes, with distraction being a substantial factor (Lee et al., 2008). Distractions fall into three categories: manual, visual, and cognitive. Manual distractions involve removing one's hands from the steering wheel, visual distractions occur when drivers avert their gaze from the road, and cognitive distractions reflect mental engagement with non-driving-related thoughts or tasks (Gallahan et al., 2013). Each type of distraction poses unique risks, yet they intersect in ways that are particularly perilous in low-visibility conditions.

Despite considerable advancements in vehicle safety technology, the effectiveness of these measures remains mixed. For instance, Advanced Driver Assistance Systems (ADAS) have been developed to mitigate the effects of driver distraction by providing automated warnings or interventions. While ADAS can reduce accident risk, they are not foolproof and often rely on the driver's ability to respond quickly and effectively to alerts, which can be challenging when drivers are fatigued or visually strained at night (Antony and Whenish, 2021). Additionally, ergonomic improvements in dashboard design (Francois et al., 2024), control layouts (Ma et al., 2020), and seat positioning (Paruchuri and Kumar, 2015) have made driving more intuitive; however, these interventions primarily target manual and visual distractions and may fall short in addressing cognitive distractions, particularly during long night-time drives where mental fatigue is inevitable.

In-car lighting design, specifically tailored to address the unique demands of night-time driving, presents an underexplored opportunity to enhance driver concentration, comfort, and safety. Existing studies have shown that lighting characteristics—such as colour temperature, brightness, and positioning—can influence driver alertness and comfort levels (Mehri et al., 2024; Wood, 2020). However, much of this research remains limited in scope, often focusing narrowly on a few lighting attributes without considering the broader interaction between lighting, driver psychology, and physiological states. The potential for colour to improve alertness, reduce cognitive load, and alleviate visual strain is promising, yet understudied, and current design implementations lack empirical validation in real-world or simulated environments.

Critically, the balance between aesthetic appeal, comfort, and safety remains elusive in in-car lighting design. While ambient lighting is often marketed as a luxury feature, its impact on driver attention and alertness is rarely rigorously evaluated, leading to potential safety oversights. The psychological and physiological effects of various lighting colours and configurations are insufficiently understood, and few studies have investigated how these factors interact to influence driver performance over extended periods, especially under demanding night-time conditions. For instance, while blue and cyan lighting have been associated with alertness, excessive brightness or certain hues could exacerbate visual discomfort or even contribute to drowsiness if misapplied (Mehri et al., 2024). Similarly, red lighting, which can increase alertness in short bursts, may also elevate stress levels if overused, potentially compromising driver well-being (Hoffmann et al., 2010).

This critical gap in research underscores the need for a more nuanced, evidence-based approach to in-car lighting design. Addressing this gap requires a comprehensive investigation into how different lighting schemes impact both psychological and physiological responses, enabling a balanced design that prioritises safety while maintaining driver comfort. Ultimately, achieving this balance could lead to more effective design guidelines that go beyond aesthetics to actively contribute to driver alertness and reduced distraction, particularly under the demanding conditions of night-time driving.

2.2 Human Visual Perception

Human visual perception is a complex process that involves the coordination of multiple systems within the eye and brain, enabling the perception of light, colour, and detail. The human eye operates through two primary visual systems: Image-Forming (IF) and Non-Image-Forming (NIF) functions. The IF system is responsible for generating images, allowing humans to perceive details, shapes, and colours. Within this system, rod and cone cells in the retina play distinct roles: rod cells are highly sensitive to low light and are essential for night vision, while cone cells are responsible for colour perception under well-lit conditions. These cells convert light into neural signals, which are processed by ganglion cells and transmitted to the brain's thalamus and visual cortex, where visual information is further interpreted and integrated (Westland et al., 2017; Solomon, 2021).

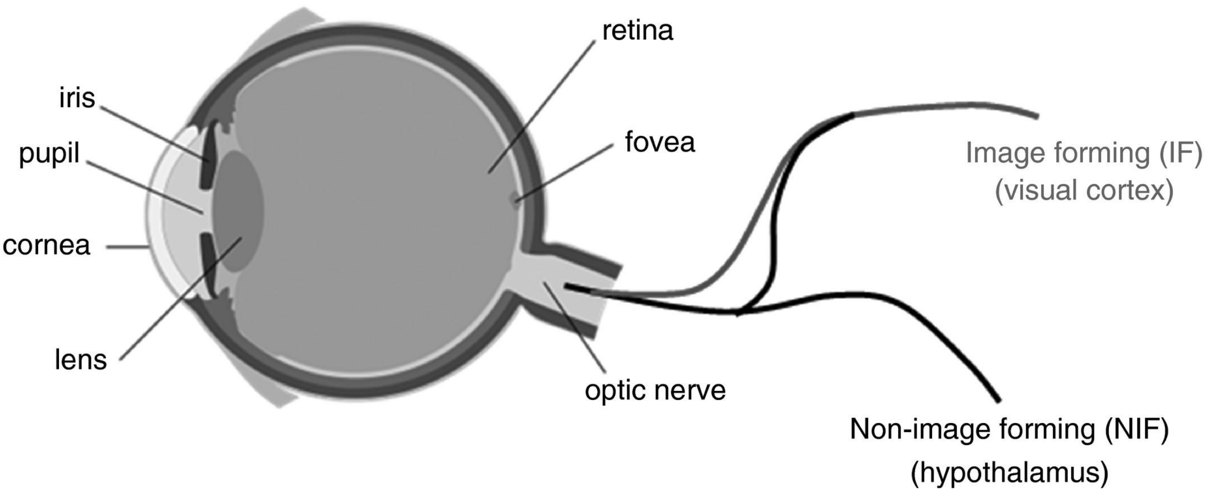


Figure 2.1 Diagram of the human eye showing the Image-Forming (IF) and Non-Image-Forming (NIF) pathways. The IF pathway enables image and colour perception, while the NIF pathway regulates physiological responses, such as circadian rhythms and alertness, through signals to the hypothalamus.

Historically, it was assumed that the eye's primary role was image formation. However, the discovery of melanopsin in the retinal ganglion cells introduced a new understanding of the eye's Non-Image-Forming (NIF) functions. Melanopsin-containing intrinsically photosensitive Retinal Ganglion Cells (ipRGCs) transmit light signals through the Retino-Hypothalamic Tract (RHT) to the Supra-Chiasmatic Nuclei (SCN), an area of the brain that regulates circadian rhythms and day-night cycles (Westland et al., 2017). This NIF pathway does not contribute to image formation but instead affects physiological processes like sleep-wake cycles, mood regulation, and alertness. This dual function highlights that light perception is not solely about visual clarity but also plays a crucial role in modulating human biology and behaviour.

The human perception of colour is intricately linked to both psychological and physiological responses. Colours can evoke various emotional and behavioural reactions, influencing how individuals perceive their environment and interact within it (Elliot and Maier, 2014; Xie et al., 2022). For instance, colours like red and blue are known to have opposed effects on emotions and physiological states. Red, often associated with arousal, dominance, and energy, can increase heart rate and stimulate alertness, making it suitable for environments where heightened attention is beneficial (Küller et al., 2006). Conversely, blue is linked with calmness and relaxation, potentially lowering stress levels and fostering focus in low-pressure situations (Dalke and Matheson, 2007). Such findings underscore the potential for leveraging specific colours in environments where emotional regulation and mental state are critical, such as vehicle interiors during night-time driving.

Human visual perception also changes significantly between day and night due to differences in lighting conditions and the eye's adaptation mechanisms. During daylight, cone cells dominate visual processing, allowing for vibrant colour perception and detailed image formation (Tovée, 2008; Arnkil, 2021). However, at night, rods become more active, which enhances sensitivity to light but limits colour perception. This shift means that colours appear less vivid, and drivers may struggle with visual clarity and contrast, especially under artificial lighting. Glare, reduced contrast, and the limited effectiveness of cones at low light levels collectively impair visual comfort and alertness during night-time driving (Wood et al., 2012; Edensor, 2017; Banerjee, 2019). These physiological limitations underscore the need for optimised in-car lighting that compensates for the eye's reduced colour sensitivity and supports visual comfort and cognitive alertness.

Understanding the interaction between light, colour, and perception is critical for designing in-car lighting that accommodates these physiological and psychological factors. The NIF pathway's sensitivity to certain wavelengths suggests that specific colours could be used to enhance alertness or calmness without compromising visual clarity. For example, recent research suggests that cool colours like blue and cyan, which are effective at stimulating the melanopsin response, may enhance alertness in night-time settings, potentially benefiting driver performance (Knez, 2001). However, excessive use of certain colours, such as red, which can evoke strong emotional responses like aggression or heightened arousal, could have adverse effects in the confined space of a vehicle cabin (Küller et al., 2006).

2.3 Colour and Light

Colour and light are essential aspects of human perception, profoundly affecting both the visual and psychological experience of a space. Light, as a form of electromagnetic radiation, becomes visible when it falls within a specific wavelength range (approximately 400–700 nm). Our perception of colour is a result of light interacting with objects, where certain wavelengths are absorbed, and others are reflected or transmitted, giving rise to different hues (Elliot and Maier, 2012). Human colour vision operates through three types of light-sensitive cells in the retina, known as cones. These cones exhibit broad spectral sensitivity with peak responses around 430 nm, 540 nm, and 570 nm, corresponding to our three-dimensional perception of colour (Figure 2.2). The visual attributes of colour are typically described as lightness, chroma, and hue. Under low light conditions (scotopic vision), the cones do not receive enough stimulation, and vision relies on rod cells. In these conditions, colours are not perceived, and vision is limited to shades of grey—this represents true colour blindness. However, the term "colour blindness" is more commonly used to refer to difficulties with colour discrimination, which occur when one type of cone is missing (dichromacy) or when a cone's wavelength sensitivity is altered (anomalous trichromacy) (Chichilnisky and Wandell, 1995). In artificial environments such as vehicle interiors, manipulating light and colour is not only a tool for aesthetics but also a functional necessity, as it can enhance visibility, improve mood, and support physiological processes vital for tasks like driving.

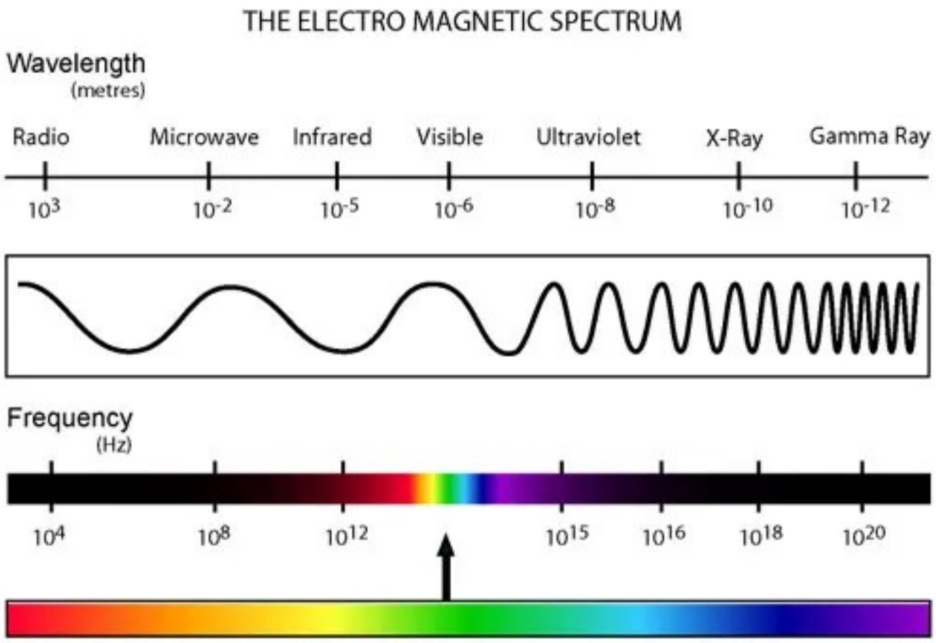


Figure 2.2 The visible spectrum (Holtzschue, 2012).

Light sources vary significantly in their spectral composition, resulting in different colour characteristics that can influence perception and performance. For instance, natural daylight offers a balanced, full-spectrum light that is optimal for colour perception, while artificial sources, such as LEDs, are often engineered to emphasise specific wavelengths to achieve desired colour effects. This manipulation of light is particularly relevant in enclosed environments like vehicle cabins, where lighting must balance visual comfort with the functional demands of driving (Boyce, PR and Smet, 2014). Understanding these foundational principles of colour and light provides a basis for assessing the suitability of different lighting designs, especially under the unique constraints of night-time driving.

Colour temperature is a fundamental property of light that describes its perceived warmth or coolness, measured in Kelvin (K). Originating from the concept of a "black body radiator," colour temperature categorises light based on the temperature at which a theoretical object emits similar colour tones (Lin, Jing, 2020). Lower colour temperatures (e.g., 2700–3000 K) emit warm, yellowish tones, similar to incandescent light, while higher temperatures (e.g., above 5000 K) produce cooler, bluish tones, akin to daylight. This measure is crucial for designers because it enables the tailoring of artificial lighting to meet specific functional or psychological needs, whether in offices, homes, or vehicles.

To quantify colour temperature in practical applications, designers often rely on the correlated colour temperature (CCT) metric, which approximates the “temperature” of light sources that deviate slightly from the black-body curve but maintain similar perceptual qualities (Choudhury, 2014). Devices such as spectrometers and colorimeters measure CCT by analysing spectral distribution, allowing for precise calibration of lighting systems (Elliot and Maier, 2012). In automotive lighting, where small differences in colour temperature can significantly impact driver alertness and visual comfort, CCT provides a practical tool to engineer lighting conditions that align with safety and comfort objectives. However, CCT alone does not capture all aspects of light quality, such as colour rendering and distribution, suggesting that this metric may need to be supplemented by other measurements for more nuanced design considerations (Boyce, PR and Smet, 2014).

The influence of colour temperature extends beyond mere aesthetics, affecting visual comfort, cognitive performance, and emotional responses (Mahnke, 1996; Chinazzo et al., 2021). Cool light (above 5000 K), which emits a bluish tone similar to daylight, has been shown to enhance alertness and support cognitive functions such as concentration and reaction time, making it suitable for tasks that require sustained attention (Lin, J et al., 2020). Studies indicate that cooler lighting enhances visual clarity by increasing contrast, which is particularly beneficial in low-light conditions where colour discrimination and depth perception are compromised (Boyce, PR and Smet, 2014; Smolders and de Kort, 2017). This effect is of particular relevance for night driving, where maintaining driver alertness is paramount for safety. However, excessive exposure to cool light, especially in a confined vehicle cabin, may induce eye strain and discomfort, creating a potential trade-off between alertness and long-term comfort (Martinsons et al., 2024).

Warmer light (below 3000 K), on the other hand, evokes a yellowish hue associated with relaxation and comfort, commonly used in residential or hospitality environments to foster a soothing atmosphere (Veitch and Newsham, 2000). This type of lighting has been shown to lower stress levels and even reduce heart rates, creating an environment conducive to relaxation (Dalke and Matheson, 2007). While such attributes may benefit passengers, in the context of driving, warmer lighting could reduce the driver's state of alertness, posing a potential risk to safety. The challenge, therefore, lies in balancing comfort with the functional need for vigilance in high-risk scenarios such as night-time driving.

A further consideration is how colour temperature shapes perceptions of the environment beyond physical comfort. Cooler colour temperatures often create a sense of cleanliness, modernity, and high-tech sophistication, potentially enhancing the perceived quality of a vehicle's interior (Veitch and Newsham, 2000; Knez, 2001). In contrast, warmer colour temperatures may evoke feelings of luxury, intimacy, or even nostalgia (Shamsul et al., 2013). While these associations may seem secondary to functional considerations, they play a critical role in user satisfaction and engagement, influencing driver and passenger comfort on a psychological level. In high-end vehicles, for example, lighting design often leverages these emotional responses to reinforce brand identity and enhance the driving experience (Yang, Y. et al., 2024).

Despite these insights, the field lacks comprehensive research on how best to balance these conflicting attributes of colour temperature in enclosed spaces like vehicle cabins. While cooler light supports focus and reduces fatigue, it may be detrimental to comfort over prolonged exposure (Veitch and Newsham, 1998). Conversely, warm lighting may promote relaxation but risks impairing the alertness necessary for safe driving. Existing studies on colour temperature and lighting design often overlook the combined physiological and psychological demands of night driving, leading to gaps in understanding optimal lighting configurations (Wördenweber et al., 2007; Papinutto et al., 2020). This lack of research highlights the need for innovative, adaptable lighting systems in automotive design that can dynamically adjust colour temperature in response to situational demands, providing both safety and comfort.

In summary, colour temperature is a critical factor influencing visual comfort, cognitive function, and emotional perception, with cooler tones generally supporting alertness and warmer tones promoting relaxation. However, the ideal balance between these effects remains unclear, particularly for night-time driving scenarios. As automotive lighting design evolves, future research may explore colour temperature ranges that maintain safety without compromising comfort, potentially through adaptive lighting technologies. Such an approach would mark a significant advancement in the field, aligning with broader industry trends toward human-centred and safety-focused vehicle design.

2.4 Effects of Lighting on Cognitive Function and Alertness

Light colour and intensity are powerful factors influencing cognitive function and alertness, especially in demanding environments like vehicle cabins during night-time driving (Hafezparast Moadab, 2024). Cognitive load refers to the mental effort required to perform tasks, and driver alertness is critical for maintaining focus on the road. Research indicates that specific light colours and intensities can either heighten or diminish cognitive load and alertness levels, significantly impacting driving performance and safety (Kircher and Ahlstrom, 2012; Mehri et al., 2024).

Cooler light colours, such as blue and cyan, are generally associated with increased alertness and cognitive performance. Studies suggest that blue light, for instance, can stimulate higher levels of mental alertness by affecting the brain’s processing speed, attention span, and reaction times (Smolders and de Kort, 2017). This is partly due to blue light’s influence on the intrinsically photosensitive retinal ganglion cells (ipRGCs), which stimulate brain regions involved in arousal and alertness. In night-driving conditions, exposure to cooler light has been shown to improve reaction times and reduce drowsiness, making it particularly effective in supporting alertness and maintaining cognitive focus(Boyce, PR and Smet, 2014). However, some studies caution that prolonged exposure to blue light in confined environments, such as vehicle cabins, can lead to visual discomfort and increased cognitive load due to glare or overstimulation, potentially reducing its efficacy over time (Mehri et al., 2024).

In contrast, warmer light colours, such as yellow or amber, generally evoke a calming effect, lowering cognitive load and reducing stress. While this may create a comfortable environment for passengers, it can reduce the driver’s alertness levels, thereby posing a safety risk. Lower colour temperatures, associated with warmer hues, have been found to promote relaxation by reducing heart rate and inducing a sense of calm (Knez, 2001). While this effect is beneficial in settings where comfort is the priority, it is less ideal for tasks that demand sustained cognitive focus, such as night driving.

Consequently, warm light may contribute to cognitive disengagement or even drowsiness over time, which can be hazardous in a driving context (Shamsul et al., 2013).

Light intensity also plays a critical role in shaping cognitive responses and alertness. Higher intensity lighting is generally associated with increased alertness, as bright light enhances visual clarity and reduces eye strain, especially in low-light environments (Veitch and Newsham, 2000). Bright, high-intensity light can improve contrast and reduce the cognitive effort needed to process visual information, making it ideal for night-time driving (Smolders and de Kort, 2014). However, high-intensity light can also lead to increased cognitive load if it is too harsh, causing glare or overstimulation, which can impair long-term focus and visual comfort (Borragán et al., 2017). Lower intensity lighting, while generally less stimulating, is associated with reduced cognitive load and can create a more relaxed atmosphere. However, it may also lead to diminished alertness in conditions where sustained attention is essential. These findings suggest that both light colour and intensity should be carefully calibrated in vehicle interiors to support driver alertness without inducing excessive cognitive load or discomfort.(Phipps-Nelson et al., 2003)

Circadian rhythms are the natural physiological cycles that regulate sleep-wake patterns, alertness, and various metabolic processes. Governed by the body's internal clock, located in the suprachiasmatic nucleus (SCN) of the hypothalamus, circadian rhythms align with the 24-hour day-night cycle and are strongly influenced by light exposure(Czeisler et al., 1981). Exposure to light, particularly blue light, plays a crucial role in resetting or reinforcing the circadian clock, thereby regulating alertness levels and sleep patterns (Wahl et al., 2019). For drivers, understanding and managing circadian rhythms is essential, as these rhythms impact alertness levels, especially during night-time driving when the body’s natural tendency is to prepare for sleep.

During the evening and night, the body experiences a drop in core temperature and melatonin levels increase, promoting drowsiness and reducing cognitive alertness (Lewy et al., 1998). This circadian-driven dip in alertness creates a significant safety risk for night-time drivers, as it reduces their reaction times, decision-making abilities, and overall vigilance. Research has shown that the propensity for accidents increases during the circadian low, typically occurring between midnight and 6 a.m., when alertness is naturally at its lowest (ÅKERSTEDT, 1995). Thus, night driving requires interventions that counteract these physiological inclinations toward sleep.

Light exposure can mitigate the effects of the circadian low by stimulating alertness. Cooler light, especially in the blue wavelength range, suppresses melatonin production and can temporarily override the body's natural sleep signals, increasing alertness and cognitive performance even during night-time hours (Cajochen et al., 2005). For this reason, cool-coloured or blue light is often recommended in applications where heightened alertness is essential, such as in vehicle cabins during night-time driving. However, excessive reliance on blue light may disrupt the natural sleep cycle if drivers are exposed to it for prolonged periods, leading to long-term consequences such as circadian misalignment and reduced sleep quality (Chellappa et al., 2011).

While blue light has advantages for sustaining alertness during night driving, its application must be carefully balanced to avoid adverse effects (Holzman, 2010; Rodríguez-Morilla et al., 2018). Short bursts of exposure may effectively counter drowsiness and support vigilance without significantly disrupting circadian rhythms (Holzman, 2010). Conversely, continuous exposure to blue light could result in overstimulation, increasing cognitive load and causing eye strain, which could impair visual comfort and lead to fatigue over time (Rodríguez-Morilla et al., 2018). Therefore, an optimal approach might involve dynamically adjusting light colour and intensity in response to driving conditions and time of night, thereby supporting alertness while minimising the risk of circadian disruption.

In summary, light colour and intensity have significant impacts on cognitive load and alertness, with cooler, high-intensity light generally supporting alertness but potentially increasing cognitive load if not carefully managed. Circadian rhythms introduce additional complexity, as the body's natural tendency toward drowsiness at night poses challenges for night-time driving. Strategic use of cooler light colours and appropriate light intensities in vehicle interiors could help counteract these effects, providing temporary boosts to alertness when needed. However, the potential for circadian disruption suggests that automotive lighting design must balance short-term alertness with long-term physiological health, underscoring the need for adaptive lighting systems that respond to both the time of day and driver needs.

2.5 Psychological and Physiological Effects of Coloured Lights

The psychological and physiological effects of coloured lighting have become increasingly relevant in research, particularly for environments like vehicle interiors where driver focus, mood, and alertness are paramount (Fernandes et al., 2017; Peng and Jia, 2023). While colour has been shown to evoke specific emotional and cognitive responses, the application of coloured lighting in vehicle interiors presents unique challenges. These responses are mediated through complex interactions of physiological, psychological, and contextual factors, making the effects of coloured lighting highly variable and sometimes contradictory (Waldram, 1954).

The calming effects of blue and green light, for instance, are well-documented, with studies suggesting that these hues can reduce heart rate, lower blood pressure, and alleviate stress (Smolders & de Kort, 2017). Blue light, in particular, is noted for its capacity to improve alertness by stimulating brain regions involved in arousal (Cajochen et al., 2005). However, these effects are not universally positive; while blue light may temporarily enhance alertness, prolonged exposure can lead to overstimulation, eye strain, and even headaches, especially in confined spaces like vehicle cabins (Mehri et al., 2024). This contradictory role of blue light—stimulating alertness yet potentially causing fatigue over time—raises concerns about its suitability for continuous night-time driving (Rodríguez-Morilla et al., 2018). Moreover, blue light's association with coldness and sterility may reduce comfort, creating a sensory environment that feels harsh rather than supportive (Rodríguez-Morilla et al., 2018).

Red light, often associated with heightened arousal and alertness, also presents complex implications for driver safety. Studies have shown that red light can increase heart rate and activate the sympathetic nervous system, theoretically helping drivers remain alert (Küller et al., 2009). However, this arousing effect can backfire, contributing to increased stress, irritability, and fatigue over prolonged exposure. In night-driving scenarios, the stimulating nature of red light may exacerbate tension and anxiety, potentially leading to aggressive or impaired driving behaviour (Boyce, PR and Smet, 2014). Furthermore, while red light may momentarily counteract drowsiness, it lacks the cognitive benefits of cooler tones like blue, limiting its effectiveness in sustaining focus over longer periods (Pan et al., 2023). This dual nature of red light—

enhancing alertness but risking stress-related discomfort—challenges its appropriateness as a primary light source in vehicle interiors (Shoaib et al., 2021).

Yellow and amber lighting are often perceived as warm, comforting, and slightly stimulating, making them seemingly ideal for balancing relaxation with alertness. Yet, yellow light is not without drawbacks. Research indicates that prolonged exposure to yellow tones can cause visual discomfort and eye strain, particularly under low-light conditions (Veitch & Newsham, 2000). While yellow light may enhance mood and reduce tension, its potential to induce visual fatigue raises concerns for its use in vehicle settings where clarity and prolonged concentration are essential (Honrao, 2023). Additionally, while yellow light is associated with warmth and positivity, its psychological impact is often less intense and focused than that of blue or red, potentially limiting its utility in scenarios that require heightened vigilance, such as night driving (Zhou et al., 2023).

Another critical issue is the variability in individual and cultural responses to coloured lighting. Studies have shown that individual differences, such as age, personal preference, and cultural background, significantly influence how colours are perceived and tolerated (Ou et al., 2004). For example, while blue light is commonly associated with calmness in Western cultures, it may not evoke the same response across different demographic groups. This variation complicates efforts to establish a standardised approach to in-car lighting design that would universally enhance comfort and safety. In automotive contexts, where safety is paramount, this unpredictability in response undermines the reliability of colour-based lighting schemes, suggesting that a more nuanced, adaptable system may be necessary to accommodate diverse user needs and preferences.

Moreover, the psychological and physiological effects of coloured lighting are context dependent (Bedrosian and Nelson, 2013). For instance, while blue light is effective at enhancing alertness in office settings, the confined, enclosed environment of a vehicle cabin alters its impact, potentially amplifying discomfort or causing overstimulation (Rodríguez-Morilla et al., 2018). This contextual sensitivity suggests that findings from stationary environments may not be directly transferable to automotive settings, highlighting a research gap in understanding how spatial constraints and movement dynamics affect colour perception and response in vehicles. Without this understanding, the application of coloured lighting in vehicles remains speculative, raising ethical concerns about prioritising aesthetics or theoretical benefits over empirical evidence of safety and comfort.

The concept of adaptive or customizable lighting has been proposed as a potential solution, allowing drivers to select or adjust light colours based on their personal preferences or current needs. While promising, adaptive lighting also presents new challenges. The cognitive demands of adjusting lighting settings mid-drive could introduce distractions, thereby increasing accident risk. Additionally, allowing drivers to self-select lighting could inadvertently lead to choices that prioritise comfort over safety, such as favouring warm, dim lighting that promotes relaxation but diminishes alertness. Therefore, any move towards adaptive lighting must be carefully regulated to ensure that it supports alertness without imposing additional cognitive load on drivers (Khanh et al., 2023).

Ultimately, the psychological and physiological effects of coloured lighting highlight a complex balance between benefits and risks, particularly in the confined and dynamic context of vehicle interiors. While blue and green lighting may enhance alertness and calmness (Rodríguez-Morilla et al., 2018; Honrao, 2023), they carry the potential for overstimulation and discomfort, particularly over prolonged exposure. Red lighting, though capable of increasing arousal and alertness (Pan et al., 2023), may inadvertently heighten stress and aggression, while yellow tones, despite their comforting qualities, risk inducing visual fatigue in low-light conditions. The interplay of these effects, coupled with cultural and individual variability in colour perception, underscores the inadequacy of standardised lighting solutions for vehicles. Moving forward, automotive lighting design must focus on developing adaptive systems informed by robust evidence, balancing safety, comfort, and alertness without imposing additional cognitive load or distractions on drivers. These advancements must be guided by a deeper understanding of how colour affects mood, focus, and stress in the unique spatial and functional constraints of vehicle interiors.

2.6 Selection of Analytical Method: Justification for K-means Clustering

The K-means clustering algorithm was selected for this study due to its effectiveness in identifying dominant colour groupings within large visual datasets, providing a rigorous and objective basis for subsequent experimental design. As an unsupervised machine learning method, K-means partitions data into a predetermined number of clusters by iteratively minimising the Euclidean distance between data points and their respective centroids (Arthur and Vassilvitskii, 2006). This enables the detection of natural patterns in image data without prior labelling or human intervention, thereby reducing subjective bias. Compared with alternative clustering techniques such as hierarchical clustering or Gaussian mixture models, K-means is computationally efficient, scalable, and well suited to high-dimensional data such as RGB pixel values (Jain, 2010). Its application in visual design and perceptual research has been recognised for producing reliable and reproducible classifications of colour distributions (Miraftabzadeh et al., 2023). Incorporating this method allows the present study to extract dominant lighting hues from authentic automotive interiors, ensuring that the selected colour palettes are representative of real-world design trends. This data-driven approach enhances the validity of the subsequent experimental testing phases and strengthens the methodological foundation for investigating the perceptual and cognitive effects of in-car lighting.

2.7 Types of In-Vehicle Lighting System

In-vehicle lighting systems play a pivotal role in enhancing both functionality and user experience, particularly in environments where visibility and safety are critical, such as night-time driving (Portera, 2024). Modern vehicle interiors are equipped with a variety of lighting systems that serve functional, aesthetic, and psychological purposes. These systems range from dashboard lights and task-specific illumination to ambient lighting designed to influence mood and comfort (Möller et al., 2021). The interplay of these lighting elements reflects a growing emphasis on creating a holistic in-cabin experience that supports driver performance and passenger well-being.

Dashboard lights are among the most critical components of in-vehicle lighting systems (Figure 2.3) (Möller et al., 2021). Positioned within the driver's immediate field of vision, these lights illuminate key instruments such as speedometers, tachometers, and fuel gauges, ensuring that essential information remains easily accessible, even in low-light conditions (Chen, F. and Kuo, 2022). Historically, dashboard lights were designed with basic functionality in mind, typically employing white or green hues for optimal legibility (Chen, F. and Kuo, 2022). However, modern designs increasingly incorporate adjustable brightness and colour schemes, enabling drivers to tailor lighting to their preferences and reduce glare or distraction. While effective for their intended purpose, overly bright or poorly designed dashboard lights can contribute to visual discomfort or cognitive overload, particularly during extended periods of driving at night (Boyce, PR and Smet, 2014).

Figure 2.3 Dashboard Lights (Chris Simmance, 2024).

Task-specific lighting systems, such as map lights or reading lights (Figure 2.4), are designed to provide localised illumination without disrupting the driver's focus. These lights are often positioned strategically to minimise glare and ensure that the cabin environment remains functional without compromising safety (Ishihara et al., 2021). For instance, warm white or amber tones are commonly used in these systems to create a comfortable yet unobtrusive glow, allowing passengers to read or access items without affecting the driver's concentration (Sarkarian, 2021). However, task-specific lighting can inadvertently cause distraction if poorly positioned, leading to reflections on windows or unintended illumination of the driver's peripheral vision.

Figure 2.4 Task-specific light (image sourced from: https://www.birminghammail.co.uk/motoring/motoring-news/drivers-given-new-internal-lights-30640334)

Ambient lighting represents a more recent innovation in vehicle interior design, focusing on enhancing the aesthetic and emotional appeal of the cabin (see Figure 2.5). This type of lighting often includes strips or panels integrated into door panels, footwells, or the dashboard, with colours and intensities that can be customised by the user. Ambient lighting serves several purposes: it can improve spatial orientation within the vehicle, create a calming or energising atmosphere, and contribute to brand identity by using signature colour schemes (Flannagan and Devonshire, 2012). For example, cooler tones such as blue or cyan are often used to convey a sense of modernity and sophistication, while warmer tones such as amber or red are associated with luxury and intimacy (Küller et al., 2009). Despite these benefits, ambient lighting requires careful calibration, as overly bright or poorly chosen colours can inadvertently distract the driver or create visual discomfort.

Figure 2.5 Ambient light (image sourced from: https://www.sevensmartauto.com.au/car-ambient-lighting/)

The selection of colours in in-vehicle lighting systems reflects their intended psychological and functional effects. Commonly used colours include white, blue, green, red, and amber, each chosen for its unique properties and associations (Hilliard, 2013; Birren, 2016). White light is versatile and neutral, often employed in task lighting or dashboards to ensure clarity and legibility. Blue and green hues, known for their calming and alertness-enhancing effects, are frequently used in ambient lighting and dashboards, particularly for night-time driving scenarios (Smolders & de Kort, 2017). However, prolonged exposure to cooler tones can induce visual fatigue, highlighting the need for balanced application. Red light, associated with heightened arousal and visibility, is often used in warning indicators or subtle ambient lighting. While effective in capturing attention, red lighting must be used judiciously to avoid overstimulating the driver and increasing stress levels (Knez, 2001). Amber and yellow tones, meanwhile, are used for their warm and inviting qualities, often in task or ambient lighting to reduce glare and improve visual comfort, though excessive use can lead to eye strain in dark environments (Veitch & Newsham, 2000).

While these systems and colour choices have advanced significantly in recent years, gaps remain in understanding how different types of lighting interact to influence driver performance, mood, and safety (Weirich et al., 2022a; Weirich et al., 2022b; Weirich et al., 2023). For instance, the integration of dynamic or adaptive lighting systems that adjust based on external conditions, driver behaviour, or circadian rhythms offers potential but remains underexplored. Additionally, the potential trade-offs between aesthetic appeal and functional efficacy highlight the importance of evidence-based design in automotive lighting systems (Flannagan and Devonshire, 2012; Luo and Luo, 2018). Moreover, standardised approaches fail to account for individual differences in colour perception, emotional response, and visual fatigue, leading to inconsistent experiences across users (Knez, 2001; Smolders and de Kort, 2017). The limited integration of adaptive or intelligent lighting technologies highlights a broader research gap: the absence of data-driven methods to design lighting systems that dynamically balance alertness and relaxation in real-time. Addressing these shortcomings, the present study adopts a machine-learning and VR-based approach to derive evidence-informed lighting schemes that enhance both safety and perceptual comfort during night-time driving. Moving forward, a deeper understanding of how various lighting types and colours influence cognitive, emotional, and physiological responses will be essential for optimising in-cabin environments to support both safety and comfort.

2.8 Impact of In-Vehicle Coloured Lights on Driving

The use of coloured lighting in vehicle interiors has a significant impact on driving performance, particularly in how it influences driver attention, distraction, and visual capabilities (Flannagan and Devonshire, 2012; Blankenbach et al., 2020). While coloured lighting can enhance the driving experience by improving mood and alertness, it also presents challenges, including the potential for distraction, interference with night vision, and interaction with external lighting conditions (Hafezparast Moadab, 2024; Portera, 2024). Understanding these effects is crucial for designing in-vehicle lighting systems that enhance safety without compromising performance.

Coloured lighting can affect driver attention and distraction in profound ways. Certain colours, such as blue or green, are associated with improved concentration and reduced mental fatigue, making them effective for maintaining driver focus during extended periods (Smolders & de Kort, 2017). However, their application must be carefully managed, as overly intense or poorly positioned coloured lights can become sources of distraction. For example, brightly coloured ambient lighting in peripheral vision can draw attention away from the road, increasing reaction times and the likelihood of driver errors (Boyce, PR and Smet, 2014). Additionally, red lighting, commonly used for its ability to enhance alertness, has been found to increase physiological arousal, which may amplify stress levels and reduce decision-making efficiency in high-pressure situations (Küller et al., 2009). The dual role of coloured lighting—enhancing attention while posing a risk of distraction—illustrates the need for precise calibration and thoughtful placement within the vehicle interior.

Studies investigating the correlation between coloured lighting and driver error rates provide mixed results, highlighting the complexity of its effects (Owsley and McGwin Jr, 2010). Research has shown that cool-toned lighting, such as blue or cyan, can reduce errors associated with drowsiness by improving driver vigilance and reaction times (Lin, J et al., 2020). Conversely, warmer colours, such as yellow or amber, while effective at creating a calming atmosphere, have been associated with increased error rates due to their tendency to reduce alertness and cognitive engagement (Knez, 2001). Furthermore, the intensity of coloured lighting plays a significant role; excessively bright lights, regardless of colour, can overstimulate the driver, leading to visual discomfort and lapses in concentration. These findings suggest that while coloured lighting can mitigate certain risks, it may also introduce new challenges, necessitating a balanced approach tailored to specific driving conditions and individual needs.

The impact of coloured lighting on night vision and visibility is another critical consideration. Night vision relies heavily on the eye’s rod cells, which are highly sensitive to low light but lack colour perception (Cao, 2017). The introduction of coloured lighting in vehicle interiors can interfere with this natural adaptation process. For instance, blue light, while beneficial for alertness, can scatter more readily in the atmosphere, creating glare that reduces visibility and increases the risk of accidents (Boyce, PR and Smet, 2014). Similarly, red light, although less likely to disrupt night vision, can distort the perception of objects in low-light environments, particularly when transitioning between in-cabin and external lighting conditions (Cajochen et al., 2005). These effects are further compounded by the interaction between in-vehicle and external lighting, such as streetlights or oncoming headlights. Bright or mismatched in-cabin lighting can create reflections on the windscreen, exacerbating glare and diminishing the driver’s ability to see clearly in critical situations.

The interaction between in-vehicle lighting and external lighting conditions also poses significant challenges. At night, drivers must frequently adjust their focus between the dim environment outside and the relatively well-lit interior of the vehicle. Poorly designed coloured lighting can intensify this transition, leading to momentary vision impairment and delayed reaction times (Kompier et al., 2020). For example, cool-toned lighting inside the vehicle may clash with the warmer tones of streetlights, causing perceptual inconsistencies that distract the driver or reduce visual acuity (Veitch & Newsham, 2000). Conversely, well-integrated lighting systems that account for external conditions can help reduce these effects by maintaining consistent illumination levels and minimising glare.

Despite advancements in lighting technology, research on the optimal use of coloured lighting for improving night vision and minimising distraction remains limited. Adaptive lighting systems, which adjust colour and intensity based on driving conditions, offer potential solutions but require further investigation (Schmidt et al., 2007; Portera, 2024). These systems could dynamically balance the need for alertness with visual comfort, responding to changes in external lighting conditions and the driver's physiological state. Additionally, studies examining the long-term effects of coloured lighting on driver performance are necessary to establish guidelines that prioritise safety while enhancing the driving experience (Portera, 2024).

While coloured lighting in vehicles has the potential to improve driver focus and reduce errors, its impact on distraction, night vision, and interaction with external lighting conditions underscores the complexity of its effects. Careful consideration of colour, intensity, and placement is essential to maximise benefits and mitigate risks. Future research should explore adaptive lighting technologies that dynamically respond to environmental and physiological factors, ensuring that in-vehicle lighting systems support both safety and comfort under diverse driving conditions.

2.9 Existing Methods for Evaluating Colour Impacts on Humans and their suitability for this study project

Understanding how lighting influences driver comfort and alertness requires methodological approaches that capture both subjective experience and objective psychophysiological responses. Existing research in driving, cognitive ergonomics, and lighting science employs a wide array of techniques, each offering different strengths, limitations, and degrees of suitability for controlled experimental investigation. This section critically reviews nine major methodological approaches—self-reported questionnaires, behavioural performance metrics, EEG, heart-rate variability, electrodermal activity, eye-tracking, melatonin sampling, VR simulation, and field-based driving studies—to identify which methods are most appropriate for the present study. By examining how each technique has been applied in empirical research, this section establishes a rigorous methodological foundation for selecting the most suitable tools for analysing in-car lighting effects.

2.9.1 Self-reported questionnaires

Self-reported questionnaires are widely used in driving research to capture perceived sleepiness, comfort, alertness, and subjective workload—measures that cannot be accessed through physiological indices alone. Radun et al. (2022) demonstrated the value of subjective ratings in a real-road study where drivers repeatedly completed the Karolinska Sleepiness Scale (KSS) during a 52.5 km night-time highway drive; increases in KSS scores closely mirrored deteriorations in lane-keeping and blink behaviour. Similarly, Schreier et al. (2015) employed KSS in a prolonged monotonous driving simulation, showing systematic increases in self-reported sleepiness that aligned with degraded steering stability and reaction times. These studies illustrate that validated questionnaires provide a reliable window into drivers' internal states and are sensitive to subtle changes in alertness, making them essential for research examining how lighting influences perceived comfort and vigilance.

2.9.2 Behavioural performance measures

Behavioural indicators such as lane-keeping, steering variability, speed maintenance, and reaction time are frequently used as functional measures of driving performance. Ahlström et al. (2018), in a field study comparing daytime and night-time driving, found that increased sleepiness corresponded with larger lane deviations and less stable speed control. Anund et al. (2017) also used real-world bus-driving data to relate line-crossing frequency to driver sleepiness, demonstrating that even small increases in subjective sleepiness lead to quantifiable behavioural degradation. These studies show that performance-based metrics are useful for identifying the safety implications of altered driver state, although they remain indirect indicators of comfort and alertness. For studies focused primarily on perceptual experience—such as assessing in-car lighting effects—behavioural metrics provide complementary but not sufficient evidence on their own.

2.9.3. Electroencephalography (EEG)

EEG is one of the most sensitive and frequently used physiological measures for assessing vigilance, drowsiness, and cognitive state during driving. Gibbings et al. (2022)showed that even mild sleep restriction leads to measurable increases in theta and alpha power during simulated driving, correlating with unsafe driving behaviours. Di Flumeri et al. (2022) developed a neurophysiological “drowsiness index” using EEG signals, demonstrating that EEG can detect the transition into drowsiness well before performance failures occur. Arefnezhad et al. (2022) extended this by modelling instantaneous drowsiness levels continuously during simulation, confirming EEG’s ability to capture real-time fluctuations in alertness. This evidence demonstrates that EEG is ideally suited for studies investigating lighting-induced changes in driver alertness, offering an objective, high-resolution complement to subjective questionnaires.

2.9.4. Heart rate and heart-rate variability (HR/HRV)

Heart-rate metrics have been widely used to index mental workload, stress, and arousal during driving. Arutyunova et al. (2024) used HRV features to classify cognitive workload across multiple simulated driving conditions, showing predictable reductions in HRV with increased task demand. Czaban et al. (2025) compared HRV responses between real-world and simulated driving environments to assess simulator validity, finding that HRV changes reliably mirrored shifts in driver load. Although HR/HRV measures are physiologically informative, they are influenced by respiration, posture, emotional state, and environmental stressors, making them less specific to perceptual comfort or lighting changes. Therefore, they serve as supportive but non-primary indicators for lighting-focused research.

2.9.5. Electrodermal activity (EDA)

EDA is commonly used in simulator studies to assess sympathetic arousal and emotional activation. Mwange et al. (2022) tracked EDA during prolonged simulator exposure, showing how arousal levels stabilised over time as drivers adapted to the simulated environment. Nahid et al. (2024) recorded EDA using wearable sensors during real-world driving, demonstrating its sensitivity to emotional arousal and aggressive driving tendencies. A recent distraction study further showed that EDA increases under higher traffic complexity and cognitive load. Although EDA is responsive to arousal changes, its variability across individuals and sensitivity to temperature, hydration, and sensor placement reduce its reliability for detecting subtle lighting effects, limiting its suitability for this study's aims. (Halin et al., 2025)

2.9.6. Eye-tracking and pupillometry

Eye-tracking has been widely applied in driving studies to measure gaze behaviour, attention allocation, and cognitive load. Palinko and Kun (2011) conducted an influential simulator study in which both illumination level and cognitive demand were manipulated, demonstrating that pupil diameter reflects both photic and workload effects—making interpretation challenging when lighting is the independent variable. More recent work has used eye-tracking to analyse visual attention distribution across signage and dashboard displays during night driving. While eye-tracking is powerful for attentional research, its strong sensitivity to luminance makes it difficult to distinguish cognitive effects from lighting-induced pupil responses, reducing its suitability for experiments directly manipulating in-car lighting conditions. (2024)

2.9.7. Melatonin and circadian measures

Melatonin assessment has been used to study the biological impact of night-time lighting, particularly its influence on circadian rhythms. Gibbons et al. (2022) tested the effects of solid-state roadway lighting by collecting salivary melatonin samples across different lighting conditions; results indicated that typical road lighting levels do not significantly suppress melatonin. Chen et al. (2020) used field measurements and circadian models to predict melatonin suppression from urban night-time lighting, showing that most real-world exposures cause only modest effects. Although highly relevant for long-term circadian research, melatonin sampling is invasive, time-consuming, and generally insensitive to short-duration, low-intensity exposures typical of vehicle interiors, making it unsuitable for this VR-based experimental design.

2.9.8. Virtual reality (VR) simulations

VR is increasingly used for controlled, immersive investigation of lighting and environmental factors on driving behaviour. Wang et al. (2025) used VR to examine how lighting conditions influenced pedestrian gap acceptance and crossing behaviour. He et al. (2022) explored the combined effects of emotional state and lighting on drivers' turning decisions within a controlled simulated night environment. Chen et al. (2024) used a high-fidelity simulator to test how correlated colour temperature and illuminance influence driver alertness and found systematic differences in performance and perceived fatigue under different lighting spectra. VR also supports virtual prototyping of automotive lighting systems. (2010) Together, these studies show that VR provides the ecological realism and environmental control required for precise manipulation of in-car lighting, making it a central method for your research.

2.9.9. Field studies

Field studies examine how lighting affects drivers in real traffic environments, offering high ecological validity. Sandberg et al. (2011) conducted naturalistic night-time driving studies measuring lane drifting, blink duration, and sleepiness ratings, providing robust evidence of how fatigue develops under real-night conditions. Liu et al. (2025) examined how seasonal variation and urban lighting affect alertness across both day and night. Although these studies demonstrate the real-world relevance of lighting effects, field experiments lack the precise stimulus control required to manipulate interior lighting colours safely and systematically, limiting their suitability for early-phase experimental work. Such studies serve better as follow-up validation once controlled VR research has established the specific lighting parameters of interest.

Overall, the reviewed methods vary widely in suitability for examining how in-car lighting affects driver comfort and alertness. Self-reported questionnaires, EEG, and VR simulations constitute the strongest methodological combination for this study. Questionnaires provide essential insight into perceived comfort and alertness—the core experiential outcomes of interest. EEG offers a sensitive, objective index of vigilance capable of capturing subtle lighting-induced changes. VR simulation provides a controlled yet ecologically realistic environment for systematically manipulating lighting conditions during simulated night-time driving. In contrast, HRV, EDA, eye-tracking, melatonin sampling, and field studies present interpretability, feasibility, or safety limitations that misalign them with the study's aims. Together, EEG, questionnaires, and VR form a methodologically rigorous triad that maximises internal validity, ecological realism, and conceptual relevance to the human factors of automotive lighting.

2.10 Evaluating the Realism and Validity of VR Simulators for Driving Research

Driving-simulator validity has long been framed in terms of absolute validity (numerical equivalence of measures in simulator and field) and relative validity (same direction/magnitude of effects across conditions), with foundational treatments distinguishing these criteria for behavioural comparability (Wynne et al., 2019). Contemporary systematic evidence indicates that about half of direct comparison studies achieve absolute or relative validity, while roughly a third do not—underscoring that validity is contingent on scenario design, metrics and users rather than guaranteed by fidelity alone (Wynne et al., 2019). In other words, high visual fidelity does not automatically confer validity; rather, task structure, measurement strategy and calibration determine whether simulator behaviour maps to on-road behaviour (e.g., speed choice, lane-keeping, braking initiation) (Aksan et al., 2016; Klüver et al., 2016; Wynne et al., 2019). These reviews and multi-simulator studies therefore support a conditional claim: VR/simulator platforms can be valid when they are instrumented with appropriate behavioural and psychophysiological measures and when scenarios replicate the perceptual–cognitive demands of the target context.

At the study level, numerous comparisons report behavioural convergence for speed regulation, lane position and manoeuvre timing, and demonstrate both relative and absolute validity across different simulator configurations and driving tasks (e.g., single vs multi-screen/HMD, urban vs highway) (Klüver et al., 2016; Branzi et al., 2017; de Frutos et al., 2023). Importantly, these papers also document where divergence occurs (e.g., over-cautious speeds or altered braking thresholds), which is typically traced to visual flow, field-of-view and risk perception differences—factors that can be mitigated through careful scenario calibration, practice drives, and metric selection. This body of work motivates the use of behaviourally anchored outcomes (e.g., lateral control variability, reaction latencies) alongside subjective scales to triangulate realism.

Beyond behaviour, VR reliably evokes presence and affective responses that are relevant to driving—provided cybersickness is managed. HMD-based VR tends to increase spatial presence and emotional intensity compared with non-immersive displays, strengthening ecological plausibility when studying perceptual comfort and alertness (Voinescu et al., 2023; Gabes and Mühlberger, 2024). At the same time, cybersickness can compromise data quality; pre-exposure oculomotor exercises and design choices (stable frame-rate, appropriate FOV) reduce symptoms and help preserve presence, which in turn predicts usability and task engagement (Voinescu et al., 2023). Taken together, the presence/sickness literature supports a design-for-immersion, control-for-tolerance approach that enhances the likelihood of authentic cognitive–emotional states during simulated night driving.

Implications for the present thesis. The reviews and comparative studies justify employing a VR driving model as a controlled yet ecologically meaningful platform for investigating in-car lighting at night—provided that (i) outcome measures include behavioural indices with prior evidence of simulator–road correspondence, (ii) subjective comfort/alertness scales are used to capture experiential realism, and (iii) immersion is supported while cybersickness is minimised and monitored. To operationalise these conditions, this thesis pairs immersive VR with self-report instruments and EEG for convergent validity and implements stimulus-validation checks (perceived realism of lighting/textures) to address the very contingencies highlighted in the validation literature. This strategy aligns with evidence that simulator validity is achievable when measurement, scenario and user factors are explicitly engineered rather than assumed.

Chapter 3 Methodology

3.1 Research Design and Overall Methodology

Selecting an appropriate research methodology is fundamental to achieving reliable and valid insights that address the research question and objectives effectively (Saharan et al., 2020). In this thesis, the methodology was carefully designed to support a multi-phase investigation into how in-vehicle coloured lighting affects driver alertness, comfort, and safety during night-time driving. This chapter 3 outlines the overall methodological framework, which includes both a data-driven analysis of colour choices in automotive interiors (Chapter 4) and a controlled experimental study examining the psychological and physiological impacts of these lighting conditions (Chapter 5 and 6). The specific and detailed methods for colour selection, VR model development, and data analysis can be found in chapter 4 to 6, respectively.

To establish an appropriate methodology, it is essential to identify the purpose and scope of the research. As noted by previous research, research purpose can be classified into four types: exploration, description, explanation, and prediction (Chen, Y., 2021). This thesis spans both *description* and *explanation*. The data-driven analysis in Chapter 4 provides a descriptive understanding of current trends in in-vehicle colour choices, while the experimental study in Chapter 5 and 6 seeks to explain how these colours affect drivers' psychological and physiological states. This thesis applies these strategies across two complementary studies: Table 3.1 summarises these research purposes.

Table 3.1 The Four Types of Research Purpose (adapted from Blaikie, 2000).

Type	**Description**
Exploration	Discovers new insights or hypotheses when knowledge is limited.
Description	Aims to provide an accurate account of specific characteristics or effects.
Explanation	Investigates causal relationships and underlying mechanisms.
Prediction	Anticipates future occurrences based on current knowledge.

In addition to defining the research purpose, a suitable research strategy is essential to structure the approach taken to achieve these aims (Hennink et al., 2020). Research strategies can be classified into inductive, deductive, retroductive, and abductive, with each approach suited to different types of inquiry (Blaikie, 2000; Noor, 2008). This thesis employs a combination of inductive and deductive strategies within a mixed-methods framework, integrating quantitative data from image analysis and physiological measurements with qualitative insights from subjective assessments. Table 3.2 presents an overview of these strategies.

Table 3.2 Research Strategies (adapted from Blaikie, 2000).

Strategies	Research Category	Aim	Approach
Inductive	Quantitative	Identify patterns & establish descriptions.	Gather data, summarise findings, and build insights from observed patterns.
Deductive	Qualitative	Test existing theories / hypotheses.	Deduce hypotheses, model theories, and conduct experiments.
Retroductive	Mixed	Understand underlying mechanisms.	Develop hypotheses based on observed patterns and test through modelling.
Abductive	Qualitative	Explain social meanings through observation.	Observe behaviours and interpret social meanings, leading to theory development.

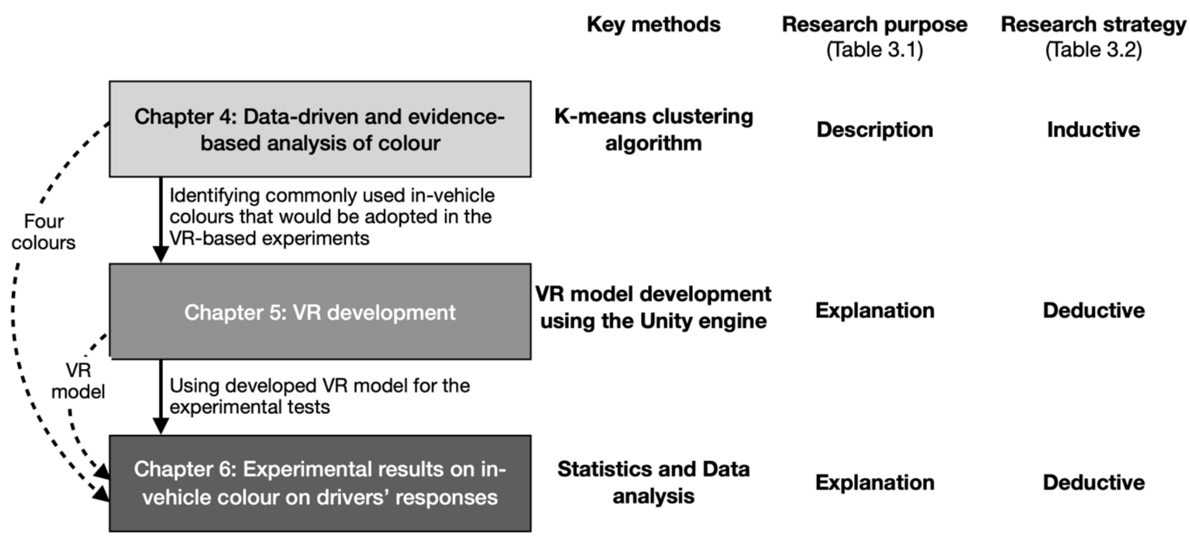


Figure 3.1 Research methodologies for chapter 4-6 of this project.

Applying the specific purposes and strategies outlined above, Figure 3.1 illustrates the methodologies adopted in this study. For example, Chapter 4 identifies and analyses the common colour schemes in automotive interiors through K-means clustering of image data (description purpose and inductive strategy). Building on these findings, Chapter 5 applies the explanatory phase by employing VR technology to construct controlled night-time driving environments, thereby enabling the systematic testing of selected lighting conditions. Finally, chapter 6 continues the explanatory phase noted in Table 3.1 by integrating subjective and physiological measures. Consistent with the mixed-methods framework in Table 3.2, it combines EEG recordings with self-reported questionnaires to evaluate drivers' comfort and alertness under different lighting conditions. Specifically:

Stage 1: Colour selection for the car interiors

The first stage of the research (presented in Chapter 4) employs a data-driven methodology to analyse colour choices in car interior lighting using a dataset of images collected from various online sources.

The primary objective of this stage is to identify prevalent colour schemes and assess their alignment with principles of colour psychology, particularly regarding their potential effects on driver alertness and comfort. To systematically examine colour preferences and trends within automotive interior design, this study adopts a data-driven approach grounded in machine learning analysis. The K-means clustering algorithm is employed to categorise the dominant hues from a dataset of 174 interior lighting images (Chapter 4), as it offers an objective, replicable means of identifying underlying colour groupings within large visual datasets. Unlike manual coding or subjective classification, K-means provides an unsupervised statistical framework that partitions image data into meaningful clusters based on colour similarity, thereby reducing human bias and enhancing analytical precision (Miraftabzadeh et al., 2023). This quantitative method establishes an empirical foundation for identifying the most prevalent lighting tones used across contemporary vehicles. The resulting clusters form the basis for subsequent experimental work, in which these colour schemes will be evaluated within a controlled VR environment to investigate their psychological and physiological impacts on driver comfort and alertness.

The findings establish a foundation for understanding industry design practices and inform the selection of colour schemes for experimental testing in Chapter 5.

Stage 2: VR model development and experimental campaign

The second stage, presented in Chapter 5 and 6, shifts to a more explanatory approach, examining how specific coloured lighting conditions affect drivers' psychological and physiological responses.

This study employs a controlled experimental design using a virtual reality (VR) simulation to recreate night-time driving scenarios under various lighting conditions identified from chapter 4, including purple, green, blue, and dark.

To evaluate the perceptual and cognitive effects of interior lighting under controlled yet ecologically valid conditions, this study developed a custom-built virtual reality (VR) prototype simulating a night-time driving scenario. The prototype was constructed using the Unity game engine and a head-mounted display (HMD) interface, replicating the visual and spatial characteristics of a standard car interior. This approach enables dynamic manipulation of lighting parameters—such as hue, correlated colour temperature, and luminance intensity—while maintaining experimental consistency across participants.

The rationale for adopting a VR-based experimental platform rests on three key considerations. First, VR offers experimental control unavailable in real-world testing, where environmental variables such as weather, traffic, and road illumination introduce unwanted noise. Second, VR provides high ecological validity, allowing participants to experience the perceptual context of driving in a safe, immersive environment. Prior research has demonstrated the reliability of VR in reproducing authentic driving responses and emotional states comparable to those observed in field conditions. Third, by integrating interactive scripting functions—including a “Car Light Controller” system coded in C#—the setup allows real-time adjustment of lighting attributes, supporting fine-grained comparison between colour conditions (e.g., blue, green, pink, and dark modes).

This prototype functions as a controlled experimental platform for investigating how in-car lighting influences visual comfort and alertness. Its modular structure facilitates synchronisation with physiological data collection tools such as EEG and enables consistent replication of test conditions across participants. The design also addresses limitations identified in previous research, notably the difficulty of manipulating interior lighting safely during real-world night driving. By using the VR prototype, this study achieves a balance between experimental precision and perceptual realism, advancing methodological rigor in automotive lighting research.

During the experiments, participants first provided consent, completed the Farnsworth-Munsell 100 Hue test, and were fitted with VR glasses and EEG equipment, followed by a brief dark adaptation and practice drive. The Farnsworth–Munsell 100 Hue Test was selected because it provides a quantitative assessment of fine-grained hue discrimination across the entire visible spectrum (Farnsworth, 1957; Vingrys and King-Smith, 1988). Unlike standard colour-vision screening tools such as the Ishihara plates—which detect primarily congenital red–green deficiencies and offer only categorical classifications (Birch, 1993; Cole, 2004)—the FM100 Hue Test measures continuous variations in chromatic sensitivity and can detect even mild perceptual differences among observers with otherwise “normal” colour vision (Kinnear and Sahraie, 2002). Given that this study requires participants to differentiate subtle shifts in interior lighting hue, the FM100 provides a more appropriate and methodologically rigorous way of ensuring that perceptual differences are attributable to the lighting manipulations rather than unmeasured variability in colour discrimination ability.

For each of the four lighting conditions (presented in Latin Square order), they underwent a cycle of dark adaptation, a VR-based PAD test, a 5-minute driving task, and post-session questionnaires rating comfort and alertness. After completing all conditions, the equipment was removed and the experiment concluded.

Participants’ responses are measured through both subjective assessments and objective physiological metrics, including brain activity, heart rate variability, and emotional response scales. Multiple software tools and statistical methods are applied for data analysis to ensure a comprehensive evaluation of the results. For example, EEG data were processed and analysed using MATLAB and the EEGLAB toolbox, while subjective assessment data were analysed using SPSS, with a particular focus on MANOVA to evaluate the effects of lighting conditions on various dependent variables.

By combining these measurements, the study offers a detailed understanding of the relationship between in-car lighting and driver alertness and comfort. This phase utilises a deductive approach, testing hypotheses about colour effects based on established theories in environmental psychology and ergonomics. The detailed experimental setup and data analysis methodologies are presented in chapter 5 and chapter 6, respectively.

3.2 Ethical Considerations

Throughout this research, ethical principles are prioritised to ensure participant safety and autonomy. Each participant will provide informed consent, understanding that they can withdraw from the study at any point. Specific precautions are taken to address any potential risks associated with the VR environment, including the potential for discomfort or motion sickness. Additionally, all participants will receive a thorough debrief following their participation, with access to a summary of the study's findings.

In line with best practices for data management, all data collected, including self-reported questionnaires, EEG recordings, and VR interaction data, will be stored securely on hard drives, password-protected systems. Personal identifiers will be removed, and data will be anonymised to ensure confidentiality. Access will be restricted to the research team only, and data will be retained for the period required by institutional guidelines before being securely destroyed. These measures ensure compliance with the University of Leeds' data protection policies, upholding both ethical and legal responsibilities in handling sensitive participant information.

This research was approved by the University of Leeds Ethical Committee (FAHC 23-046), ensuring adherence to institutional standards and guidelines for research involving human participants.

Chapter 4 A Data-Driven and Evidence-Based Analysis of Colour Choices and Driver Safety

4.1 Introduction

The role of ambient lighting in automotive interiors is increasingly recognised as a critical factor in influencing driver comfort, mood, and alertness—key components of safe driving, especially under night-time conditions (Wang, C., 2024). Night driving presents unique challenges due to limited visibility and the need for sustained visual and cognitive engagement (Kimlin et al., 2017; Williams, 2018). While vehicle design has traditionally focused on physical ergonomics, there is a growing interest in how environmental factors, such as interior lighting colour schemes, can be optimised to support driver well-being and performance (Caberletti et al., 2010; Weirich et al., 2022a). This chapter addresses the impact of in-car lighting on driver visual comfort and alertness, contributing to the overall aim of this thesis to explore how in-car lighting affects night-time driving experiences.

As part of a data-driven, evidence-based approach, this study focuses on identifying prevalent colour choices in vehicle interiors and examining their potential psychological effects. By analysing a large dataset of car interior images sourced from the internet, this study uses the K-means clustering algorithm to identify dominant hues commonly employed in ambient lighting. These colours are systematically evaluated against established principles of colour psychology to assess their potential impact on visual comfort and alertness, thereby contributing foundational insights that will inform subsequent stages of this research.

The results of this chapter will serve as a preliminary guide for designing in-car lighting schemes that will later be tested within a controlled VR environment. The VR prototype will simulate in-car lighting conditions, enabling controlled experimentation on driver experiences of visual comfort and alertness under different lighting schemes. Thus, this chapter lays the groundwork for the more immersive, experimental investigations that follow, where drivers' subjective experiences and physiological responses will be assessed.

The objectives of this chapter are to (1) explore the most common ambient lighting colours used in car interiors, (2) evaluate the alignment of these colours with colour psychology research related to comfort and alertness, and (3) identify promising colour schemes to be tested in a VR simulation. This chapter ultimately contributes to the thesis's broader aim by identifying initial colour schemes that could be further refined and experimentally tested for enhancing driver comfort and alertness during night-time driving.

4.2 Research Question and Objectives

The primary research question guiding this chapter is: How does in-car lighting influence driver visual comfort and alertness during night-time driving? This question seeks to uncover the ways in which specific lighting colours used in vehicle interiors may support or hinder a driver's ability to remain visually comfortable and alert in low-light driving conditions, where optimal attentiveness is crucial for safety. By exploring this question, the study aims to contribute to a deeper understanding of the impact of ambient lighting on driver well-being and performance, ultimately informing automotive design practices that prioritise safety and comfort.

To address this question, the study outlines four key objectives (OB):

The OB1 is to identify and analyse the most common ambient lighting colours used in car interiors through a data-driven approach. By employing a systematic methodology to gather and analyse image data from a diverse range of sources, the study seeks to establish a comprehensive overview of prevalent colour choices in current automotive interior lighting. In this context, a systematic methodology refers to a transparent and replicable process that follows a logical sequence, ensuring that data are collected, organised, and analysed in a consistent manner. This objective is foundational to understanding the landscape of design practices within the industry and provides a basis for examining how these choices align with psychological theories of colour.

The OB2 is to examine the potential psychological effects of these commonly used colours on driver visual comfort and alertness. Certain colours, such as blue and cyan, are known for their alertness-enhancing properties, while others, like red or yellow, may have complex effects that vary depending on intensity and exposure duration. By investigating these effects, OB2 aims to assess the suitability of various colours for supporting driver comfort and sustained attention during night driving at a theoretical level.

The OB3 is to assess the alignment of these prevalent colour choices with established principles of colour psychology, with a specific focus on their applicability to night-time driving. Colour psychology provides valuable insights into how specific hues can influence mood, cognitive state, and physiological responses. This objective aims to determine whether the dominant colour schemes identified through data analysis correspond with these principles, particularly regarding the requirements of night driving, where visual clarity and alertness are paramount.

Finally, the OB4 is to identify initial colour schemes to be tested in a VR environment, which will be developed as part of the broader thesis research.

4.3 Research Design

This study adopts a data-driven and evidence-based research design. A dataset of 174 images of car interiors was collected from online sources using the Fatkun image downloader, then filtered to retain only images representative of ambient lighting under night-time conditions. A total of 174 photographs was selected for analysis following a rigorous screening process to ensure accurate representation of night-time vehicle interiors. Preliminary clustering tests showed that this dataset size provided stable and reproducible colour groupings, with additional images contributing little new chromatic information. Selecting 174 images therefore offered an optimal balance between representativeness and computational efficiency while supporting a reliable extraction of dominant colour schemes.

To analyse these images, the K-means clustering algorithm (Verevka, 1995; Sahu and Parvathi, 2013) was employed to identify dominant colour schemes. K-means was selected because it is a widely used and computationally efficient unsupervised learning method, particularly effective for extracting representative colour palettes from complex images. Unlike hierarchical clustering or density-based methods, K-means is well suited to large datasets, where the objective is to identify a manageable number of representative colour groups (Sinaga and Yang, 2020).

The clustering process followed several steps. First, each image was converted into the CIELAB colour space, which offers perceptual uniformity by aligning more closely with how humans perceive colour differences than standard RGB. From each image, pixel values were sampled to reduce computational load while still capturing representative colour information. These sampled pixels were then grouped into clusters using K-means, which partitions data into k groups by minimising the distance between each pixel and its assigned cluster centroid. The number of clusters was determined using the Elbow Method, which evaluates the trade-off between within-cluster variance and model simplicity. Based on this analysis, k = 10 was selected as the optimal balance, ensuring that the main variations in hue were captured without over-fragmenting the data.

The resulting centroids provided a set of dominant colours across the dataset, representing the most frequently occurring hues in contemporary vehicle interiors. These colour clusters were then compared with established findings in colour psychology to evaluate their potential effects on visual comfort and alertness. This provided an empirical foundation for selecting candidate colours for experimental testing in the VR phase of the research.

4.4 Results

To systematically analyse the prevalent colours used in car interior lighting, this study applied the K-means clustering algorithm. This algorithm is highly suitable for identifying dominant colour schemes in large datasets and is widely used in image processing to group similar colours (Burney and Tariq, 2014). By leveraging this technique, the study aimed to obtain a representative set of colours commonly used in automotive interiors, which could then be evaluated for their potential effects on driver visual comfort and alertness.

The K-means clustering algorithm operates by partitioning the data, in this case, pixels from car interior images, into a specified number of clusters, k. Based on the Elbow Method, which evaluates the balance between within-cluster variance and simplicity, ten clusters were selected as the optimal number. This choice of k=10 allows for a comprehensive representation of key colours within the dataset, capturing essential variations in hue while remaining interpretable in the context of human visual perception (Barnes, 2024).

The algorithm follows an iterative process to form clusters. Initially, k centroids are randomly chosen as the centres of each cluster. Each pixel in the image dataset, which was transformed into the CIELAB colour space to better reflect human colour perception, is then assigned to the nearest centroid based on the Euclidean distance. This distance calculation helps determine which centroid each pixel colour most closely resembles, grouping similar colours together. The assignment is based on the formula:

$$j = \arg\min_{j} \|x_i - \mu_j\|^2$$

where x_i is the data point (the colour of each pixel) and μ_j is the centroid of cluster j. After all pixels are assigned to their nearest centroids, the centroids are recalculated by averaging the positions of all pixels within each cluster:

$$\mu_j = \frac{1}{|C_j|} \sum_{x_i \in C_j} x_i$$

This process of reassigning pixels to the nearest centroids and recalculating the centroids continues iteratively until the centroids stabilise, meaning the clusters no longer change significantly. This iterative approach ensures that the resulting clusters accurately represent the dominant colours within the dataset.

Using K-means clustering, this research identified ten dominant colours across the dataset of car interior images. The analysis revealed a palette that includes shades of blue, cyan, purple, pink, red, and yellow, which are commonly used in vehicle interior lighting (as shown in Figure 4.1). These colours were then cross-referenced with established research on colour psychology to explore their potential impacts on driver visual comfort and alertness.

Figure 4.1 Dominant interior light colours extracted by K-means clustering.

For example, blue and cyan are associated with increased alertness and reduced drowsiness (Sahin and Figueiro, 2013; Souman et al., 2018), making them suitable choices for night-time driving environments where sustained attention is critical. Red, while potentially enhancing alertness, may increase stress if used in prolonged exposures (Figueiro et al., 2016), suggesting that it may be better suited for short bursts or accent lighting rather than primary illumination. Purple and pink, associated with calmness and relaxation, could be beneficial for passenger comfort but require further investigation to determine their suitability for supporting driver focus. Yellow, known for creating warmth, can also cause visual strain with extended exposure, raising considerations for its careful application (Smolders and de Kort, 2014; Lok et al., 2018).

The results of this analysis provide a structured overview of common colour schemes in automotive interiors, highlighting specific colours that may support or hinder visual comfort and alertness in low-light driving. By identifying these colour schemes, this study lays the groundwork for the next phase of research within this thesis, where these findings will inform the design of a VR environment. In this VR setup, drivers' responses to different lighting conditions can be experimentally tested, allowing for a controlled evaluation of how each colour influences visual comfort and alertness. This data-driven analysis of interior lighting thus forms an essential foundation for the experimental investigations that follow in subsequent chapters.

4.5 Discussion and Conclusion

The findings of this study reveal significant insights into the colour schemes commonly used in car interior lighting and their potential implications for driver visual comfort and alertness. By applying a data-driven approach through K-means clustering, this research identified ten dominant colours, including blue, cyan, purple, pink, red, and yellow, which were further evaluated in the context of existing principles of colour psychology. These findings contribute to a foundational understanding of the role of ambient lighting in automotive interiors and inform future experimental studies in this thesis. However, critical reflections on the results and methodology highlight several considerations and opportunities for further exploration.

Blue and cyan hues emerged as promising options for enhancing driver alertness, aligning with existing research that associates these colours with increased cognitive engagement and reduced drowsiness (Lin, J et al., 2020; Spence, 2020). These findings reinforce their suitability for environments requiring sustained attention, particularly night-time driving. However, the extent of their benefits may depend on additional variables such as intensity, saturation, and duration of exposure, which were not accounted for in this study. Previous studies have highlighted that excessively bright or saturated blue lighting can cause glare or visual discomfort, potentially undermining its positive effects on alertness (Boyce, Peter et al., 2003). Future research must address these nuances to optimise the application of blue and cyan in vehicle interiors.

Red lighting, while frequently associated with heightened alertness and arousal, presents a more complex case (Figueiro et al., 2016). Although short-term exposure to red light has been shown to enhance reaction times and stimulate cognitive activity, prolonged exposure may increase stress levels, leading to driver discomfort or reduced performance (Mahnke, 1996; Hoffmann et al., 2010). These findings suggest that red lighting may be more appropriate for accent lighting or brief activations rather than sustained use in vehicle interiors. This underscores the importance of balancing physiological arousal with psychological comfort when designing in-car lighting systems.

Purple and pink hues are underexplored in the context of automotive lighting. While these colours are generally associated with calmness, relaxation, and reduced aggression, there is limited empirical evidence regarding their specific effects on drivers (Küller et al., 2009). This research identifies a gap in the literature, suggesting the need for targeted studies to evaluate whether these colours can promote a balanced state of relaxation and attentiveness that supports safe driving. Similarly, yellow lighting, known for its associations with warmth and positivity, raises potential concerns regarding visual strain during prolonged use (Boyce, Peter et al., 2003). These findings highlight the trade-offs that must be considered when incorporating yellow into automotive lighting, particularly in scenarios where extended visual engagement is required.

The methodology employed in this study, while robust in identifying dominant colour trends, also presents certain limitations. The reliance on digital images sourced from online platforms may not fully capture real-world lighting conditions, as variations in image quality, exposure, and resolution can influence the accuracy of the colour data. Moreover, the use of K-means clustering, although effective for identifying prevalent colours, provides a generalised representation rather than precise replications of lighting as experienced in practice. These limitations suggest the need for experimental validation in controlled environments, such as the VR simulation proposed in subsequent chapters. VR offers the advantage of replicating real-world conditions while allowing for controlled manipulation of variables, enabling a more comprehensive assessment of the psychological and physiological effects of in-car lighting.

Critically, the study highlights the broader implications of strategic colour design in vehicle interiors. The alignment of certain colours, such as blue and cyan, with established psychological principles underscores their potential to enhance driver safety and comfort. However, the divergence in the effects of other colours, such as red, purple, and yellow, calls attention to the complexity of lighting design in automotive contexts. It is essential for future research to consider not only the immediate effects of these colours but also their long-term impact on driver behaviour and well-being, as prolonged exposure to suboptimal lighting conditions could lead to fatigue, stress, or reduced performance.

In conclusion, this study provides a structured, data-driven analysis of dominant colour schemes in car interiors and their potential impacts on driver visual comfort and alertness. By identifying key colours and evaluating their psychological effects, this research lays the groundwork for further experimental validation within a VR environment. While the findings offer valuable insights, the study also highlights the need for nuanced investigations that address the complexities of lighting design in real-world contexts. Future research should focus on integrating these findings with practical applications, refining in-car lighting systems to support both safety and well-being during night-time driving. This work contributes to the broader discourse on human-centred design in automotive interiors, offering a pathway toward evidence-based strategies for improving driver and passenger experiences.

Chapter 5 Development and Implementation of the Virtual Reality Setup

5.1 Introduction

This chapter outlines the design, creation, and implementation of the Virtual Reality setup used in this research to study the effects of in-car lighting on driver comfort and alertness during night-time driving. The VR simulation provided a safe and controlled environment for replicating night-time driving conditions, enabling precise manipulation of lighting variables. By leveraging Unity, a powerful game development engine, and integrating lighting and environmental assets, the VR setup was meticulously crafted to achieve both realism and experimental rigour.

5.2 VR Environment Design

The VR setup was built using the Unity engine, a widely used platform for developing interactive 3D environments. The virtual environment consisted of two primary components: the car interior and the driving track.

The car interior (see Figure 5.1) was modelled to replicate a modern passenger vehicle cabin through a staged process. A generic passenger vehicle interior model obtained from the Unity Asset Store was used as the base mesh and then refined to meet the requirements of this study. The geometric layout of major components, including the dashboard, steering wheel, centre console, seats, and side panels, was first blocked out using simplified 3D primitives to establish the correct scale and proportions. These were then refined with imported models and adjusted against manufacturer specifications and reference photographs to ensure realism. Once the geometry was in place, high-resolution textures and material shaders were applied to replicate typical interior surfaces such as leather, fabric, and plastic. This step enhanced visual authenticity while maintaining a controlled and consistent environment. Finally, the interior was configured with designated ambient lighting zones embedded in areas such as the dashboard and side panels, enabling systematic variation of colour and intensity during the experiment. Proportions and viewing angles were carefully calibrated so that participants experienced the cabin at a life-size scale when viewed through the VR headset.

The virtual driving track (see Figure 5.2) was constructed to represent a rural night-time environment, following a similar iterative approach. The process began by defining a continuous road layout with curves and lane markings to simulate realistic driving demands. The surrounding terrain was shaped into rolling hills and fields, providing spatial depth and peripheral context. Surface patterns, vegetation, and roadside features were then added sparingly to enhance ecological validity while minimising distractions. In the final stage, the environment was adjusted to night-time conditions with minimal external lighting, ensuring that in-car illumination was the primary visual factor influencing participants' perception.

The completed VR environment was rendered at 2880 × 1600 resolution, with a 90 Hz refresh rate using the HTC VIVE Pro headset. The system was powered by a high-performance PC, ensuring smooth rendering and reducing the risk of simulator sickness. This immersive setup allowed participants to experience the driving task at full scale with natural head movements, supporting both subjective evaluation and EEG-based physiological measurements.

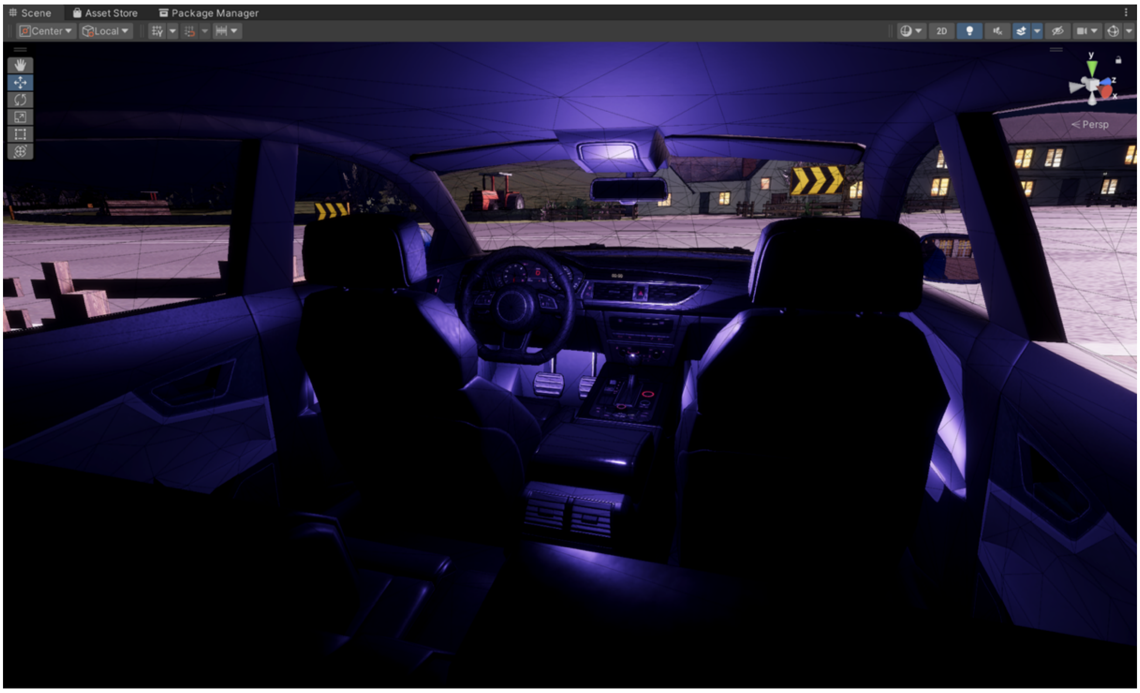


Figure 5.1 Shows the interior of the virtual car, highlighting the dashboard, seats, and steering wheel. The textures and lighting reflect real-world materials to enhance visual realism and participant engagement.

Figure 5.2 Provides a top-down view of the driving track layout. The combination of road curves, elevation changes, and ambient scenery ensured a realistic and challenging driving experience.

5.3 Lighting System Integration

The VR setup was designed to test various lighting conditions by incorporating a dynamic lighting system controlled through Unity. Figure 5.3 illustrates the custom Car Light Controller script, which was developed to manage the experimental lighting conditions in the VR cabin. The Unity Inspector (left side in Figure 5.3) provided an interface where parameters including Light Colour, CCT, and Intensity could be defined, along with a list of the individual interior light objects (e.g., dashboard and side panels). The associated code (right side in Figure 5.3) ensured that these values were applied consistently and simultaneously across all light sources.

The coding logic was structured around functions including SetColor and UpdateLights, which received the target colour or correlated colour temperature (CCT) and propagated the change to all referenced lights. Within UpdateLights, a foreach loop iterated over each light object, updating its colour and intensity values in a single operation. In cases where CCT was specified, a conversion routine translated the input into RGB colour space before being applied. This centralised approach ensured that lighting transitions occurred instantly and uniformly, without discrepancies between different cabin zones.

By managing colour, intensity, and CCT within a single controller, the system created distinct and reproducible ambient lighting scenarios corresponding to the four experimental conditions: dark, blue, green, and pink. When the script triggered a new condition, participants perceived an immediate and consistent shift in the interior atmosphere. For instance, a sudden transition from dark to blue or from green to pink. Because the updates occurred atomically within one frame, these transitions were perceptually seamless and free from distracting flicker or gradual fade. This design guaranteed that differences in user experience were attributable to the intended lighting manipulations rather than technical artefacts.

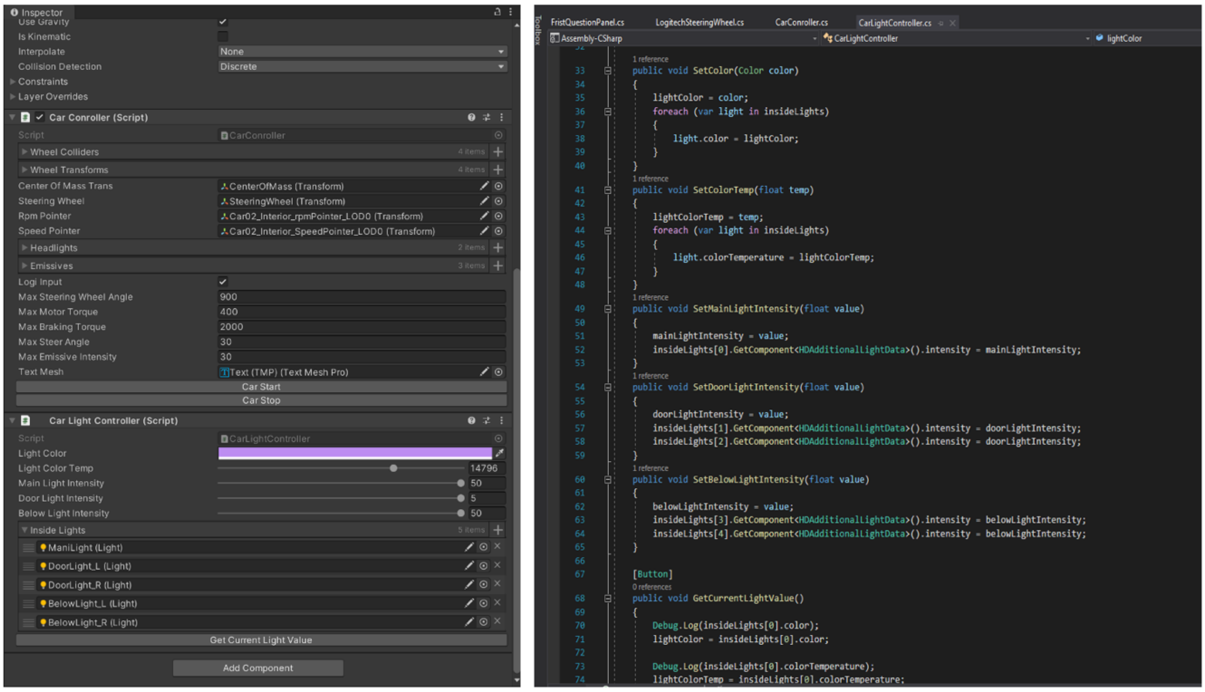


Figure 5.3 Displays the Unity interface with the Car Light Controller script, which facilitated the precise control of in-car lighting. Variables such as "Light Colour," "Light Colour Temp," and individual light intensities could be modified in real-time to suit the experimental needs.

In this way, the integration of parameter controls in the Inspector with coding elements and foreach directly translated into controlled environmental effects. The programming ensured that each lighting condition produced a coherent and perceptually salient experience, enabling participants to clearly distinguish the scenarios. This technical precision underpinned the validity of the study by linking implementation details to participants' subjective impressions of comfort and interior quality, as well as their physiological responses during the driving task.

5.4Participant Interaction in VR

Participants engaged with the VR simulation using a Logitech steering wheel and pedal setup (see Figure 5.4), providing a tactile and interactive driving experience. This integration allowed participants to navigate the virtual track while experiencing different lighting conditions.

Figure 5.4 Participants performing the driving task in the VR setup, simulating night-time conditions with interactive controls and varied in-car lighting for data collection.

5.5 Challenges and Limitations

While the VR setup provided a robust and controlled platform for investigating the effects of in-car lighting during night-time driving, it was not without its challenges and limitations. One notable limitation was the absence of multisensory feedback. The simulation focused primarily on visual and interactive elements, omitting auditory and tactile cues such as engine noise, ambient sound, or road vibrations. These sensory factors are integral to real-world driving experiences and could influence participants' cognitive and emotional responses. Their absence in the VR simulation may have impacted the ecological validity of the experiment, potentially limiting the generalisability of the findings to actual driving scenarios. Another challenge was posed by hardware constraints. The performance of the VR system, while sufficient to deliver a visually convincing experience, had to be carefully optimised to avoid issues such as motion sickness or lag. These limitations required a balance between visual fidelity and system performance, particularly for ensuring participant comfort during extended sessions. Although the hardware supported a high degree of immersion, it underscored the technical demands of achieving both realism and functionality within VR environments. Finally, the complexity of the virtual environment was intentionally limited to maintain experimental control. While the track was designed with detailed visuals and lighting effects, dynamic elements such as varying weather conditions, traffic, or unexpected events were excluded. Although this simplification helped isolate the effects of in-car lighting, it reduced the environmental complexity that drivers encounter in real-world scenarios. This trade-off highlights a key tension in experimental design: the need to balance control and realism. Future research could address these limitations by integrating multisensory feedback, utilising more advanced hardware, and incorporating additional environmental variables to further enhance the ecological validity of VR-based investigations.

Chapter 6 Effects of In-Vehicle Coloured Lighting on Drivers' Psychological and Physiological Responses

6.1 Introduction

The psychological and physiological effects of ambient lighting within vehicles are critical considerations for enhancing both driver safety and overall comfort. While previous studies, including those outlined in this thesis, have established a foundational understanding of how specific colours may influence visual comfort and alertness, further investigation is required to assess how these lighting conditions directly impact drivers' emotional and cognitive states. Such an investigation is particularly relevant for night-time driving, where reduced visibility and prolonged attention requirements place unique demands on drivers.

This chapter focuses on evaluating the effects of in-vehicle-coloured lights on drivers' psychological and physiological responses. By leveraging a controlled VR environment, this study explores how different lighting schemes influence mood, stress levels, attentiveness, and cognitive load during simulated night-time driving scenarios. The VR environment provides an experimental platform to examine lighting effects under consistent, repeatable conditions while capturing subjective assessments and physiological metrics such as brain activity, heart rate variability, and emotional response scales. This approach allows for a holistic understanding of the interplay between in-car lighting and driver performance.

The findings from this chapter aim to bridge the gap between theoretical insights from earlier research and practical applications in automotive design. By combining subjective and objective measures, the study contributes to the broader discourse on human-centred design, providing actionable recommendations for in-car lighting schemes that optimise driver well-being and alertness under low-light conditions.

6.2 Research Question and Objectives

This chapter investigates the impact of in-vehicle coloured lighting on drivers' psychological and physiological responses, focusing on the specific challenges of night-time driving. The research is guided by the central question: How do different in-vehicle coloured lighting conditions affect drivers' psychological and physiological responses, particularly during night-time driving? This question seeks to uncover how ambient lighting can influence drivers' emotional states, stress levels, cognitive engagement, and physical responses, contributing to a deeper understanding of how lighting design can enhance both safety and comfort.

To address this question, the study is framed by four key objectives. The OB1 is to evaluate the psychological effects of different coloured lighting conditions on drivers. This involves examining how various lighting schemes influence mood, stress, and emotional states during simulated night-time driving. The goal is to determine whether certain colours can alleviate stress or foster emotional well-being, thereby improving the overall driving experience.

The OB2 focuses on assessing the physiological responses of drivers to various lighting schemes. Using measures such as brain activity, heart rate variability, and emotional response scales, this objective aims to explore how lighting conditions impact cognitive load, stress levels, and alertness. By integrating these physiological metrics, the study provides objective evidence of how coloured lighting interacts with drivers' physical and cognitive states.

The OB3 is to identify lighting conditions that optimise both alertness and comfort. This involves synthesising insights from subjective assessments and physiological data to pinpoint specific colour schemes that support driver performance and well-being. The findings are expected to reveal how lighting design can balance the need for sustained attention with the creation of a comfortable in-car environment.

Finally, the OB4 seeks to refine and validate the use of colour in automotive lighting design. By integrating findings from this chapter with those from earlier research, this objective aims to provide evidence-based recommendations for in-car lighting schemes that enhance safety and well-being during night-time driving. These insights will contribute to a more human-centred approach to automotive interior design, addressing both functional and experiential needs.

Together, these objectives establish a comprehensive framework for exploring the interplay between coloured lighting and drivers’ psychological and physiological responses. The findings from this chapter will not only expand the theoretical understanding of in-car lighting effects but also offer practical guidance for designing lighting systems that prioritise driver safety and comfort.

6.3 Experimental Design

6.3.1 Participants

To ensure robust and generalizable findings, this study recruited 24 participants, balanced evenly by gender and representing diverse national backgrounds. The sample size of 24 participants was selected based on established practice in within-subject psychophysical and VR studies, where samples of approximately 20–30 participants are sufficient to achieve adequate statistical power for detecting medium effect sizes while maintaining tight experimental control and feasibility (Adams and Osgood, 1973; Ou et al., 2004). Participants were required to be over the age of 18 and have normal colour vision, verified using the Farnsworth-Munsell 100 Hue test, to ensure accurate responses to colour stimuli.

Recruitment was conducted through a multi-faceted approach to reach a diverse pool of participants. This included outreach via personal networks and online platforms such as social media groups (WeChat and Instagram) and forums dedicated to automotive technology and environmental topics. Additionally, posters and flyers were distributed across various locations to attract participants from different backgrounds, further enhancing the diversity of the sample. All participants passed the Farnsworth-Munsell 100 Hue test, demonstrating that they had normal colour vision and no obvious deficiencies. While specific ages were not recorded individually, participants fell within the typical student age range of approximately 18–35 years. This range was considered appropriate for the purpose of this study, as individuals in this age group generally share comparable cognitive and physiological characteristics relevant to driving tasks, such as attention, reaction time, and visual perception. Therefore, we do not expect age-related variability within this range to have had a significant influence on the experimental results.

All procedures complied with the ethical guidelines set by the University of Leeds. Ethical approval for this study was granted by the university's ethics committee under reference number FAHC 23-046 23, ensuring that all participant interactions and data handling followed established ethical standards.

6.3.2 Experimental Protocol

Participants begin by providing consent and completing the Farnsworth-Munsell 100 Hue test to assess their colour vision. They then don HTC Pro VR glasses and an EEG device. Subsequently, participants started to sit in the driver's seat of the driving prototype and perform a practice drive.

For each lighting condition, participants go through a structured sequence. They a 3-minute dark adaptation period, followed by a PAD (Pleasure, Arousal, Dominance) test to assess their emotional state using VR-displayed emoticons, selected with a controller. Participants then engage in a 5-minute driving session under the current lighting condition. This procedure - adaptation, PAD test, and 5-minute driving - is repeated across all four lighting conditions, following the Latin Square order to mitigate order effects (see Figure 6.1).

The decision to use a 5-minute driving duration in each lighting condition was made from a practical perspective: shorter driving sessions help to minimise motion sickness, or discomfort that may arise in a VR environment, while still allowing sufficient time for participants to engage with the driving task and experience the lighting conditions. Although real-world driving often involves longer journeys, the aim of this experiment was to capture the immediate effects of lighting conditions on alertness and comfort. Future studies may extend the driving duration to investigate sustained impacts of in-vehicle lighting during prolonged driving.

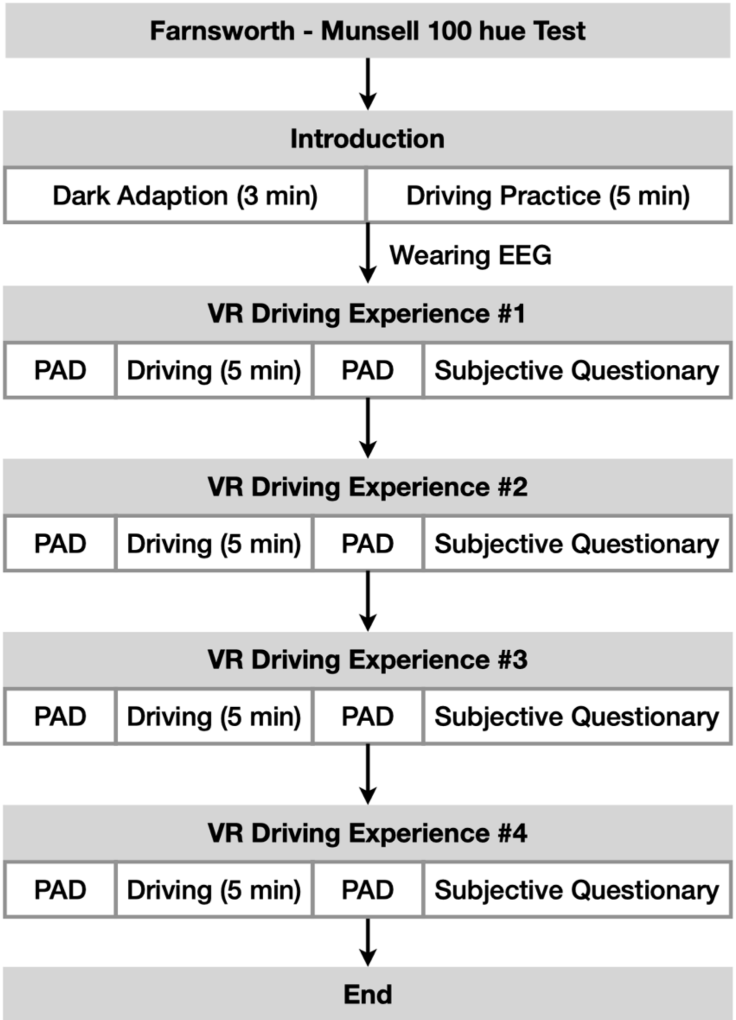


Figure 6.1 Experimental protocol

After each driving session, participants complete a PAD questionnaire and a follow-up survey with thirteen questions, rating their experience of the lighting condition on a scale from -5 to +5. Upon completion of all driving sessions and questionnaires, the VR and EEG equipment is removed, and the experiment concludes.

6.3.3 Lighting Conditions

This study investigates the effects of four distinct lighting conditions - dark (no ambient light), blue, green, and pink (see Figure 6.2) - on drivers' concentration and visual comfort during night-time driving, using an HTC VIVE Pro VR Headset. These colours were selected based on the results of the image analysis in Chapter 4, which identified them as prevalent in commercial vehicle interiors, and on previous literature linking them to differences in psychological and physiological responses. Each colour was applied consistently across the interior cabin environment (dashboard, side panels, and ambient strips). The lighting parameters were standardised, with intensity calibrated to a comfortable, non-glaring level suitable for night-time driving simulations (see Table 6.1 for detailed parameters, including hue, RGB values, and luminance settings). This ensured that the lighting differences experienced by participants were attributable to colour rather than unintended variations in brightness or contrast.

Figure 6.2 Virtual Reality Simulations of four distinct ambient lighting conditions: pink, green, blue, and dark.

Table 6.1 Lighting Conditions and Parameters

Lighting Condition	CCT (K)	RGB Values	Light Intensity
Purple Light	3500	(128, 0, 128)	3.37
Green Light	5000	(0, 128, 0)	1.00
Blue Light	6500	(0, 0, 255)	4.97
No Light (Dark)	N/A	(0, 0, 0)	0.00

6.3.4 Psychological Measures

To assess drivers' psychological responses to different in-vehicle lighting conditions, two primary psychological measures were utilised: the Visual Comfort Questionnaire and the PAD (Pleasure-Arousal-Dominance) scale, both administered within the VR environment. The Visual Comfort Questionnaire was designed to evaluate participants' subjective experience of visual comfort under various coloured lighting conditions, addressing factors such as eye strain, clarity, and overall comfort. This measure provides a direct assessment of how different lighting colours impact visual comfort, which is crucial for understanding potential applications in real-world driving scenarios.

The PAD scale, which measures Pleasure, Arousal, and Dominance, was used to capture the emotional and psychological states elicited by each lighting condition. The PAD model is a well-established tool in environmental psychology, frequently applied to evaluate emotional responses in experimental settings (Russell and Mehrabian, 1974). By examining Pleasure (positive or negative feelings), Arousal (level of alertness or excitement), and Dominance (sense of control or influence), the PAD scale offers a comprehensive understanding of how each lighting scheme may affect mood and alertness, both critical factors for night-time driving.

All responses were recorded directly within the VR environment to maintain immersion and provide contextually relevant assessments. This approach allowed participants to experience the lighting conditions as they would in a real driving scenario, thereby increasing the ecological validity of the findings.

6.3.5 Physiological Measures

To capture the physiological responses associated with each lighting condition, EEG (electroencephalography) was used as the primary measurement tool. EEG is a non-invasive technique for monitoring brain activity by recording electrical patterns across the scalp, making it suitable for detecting changes in cognitive load, alertness, and emotional states. The DSI-24 device was utilised in this study (see Figure 6.3). In this study, EEG data was collected to analyse participants' brainwave activity under different coloured lighting conditions, focusing on specific frequency bands (e.g., alpha, beta, theta, and delta) associated with relaxation, alertness, and cognitive processing.

The EEG data was recorded continuously during the VR simulation, allowing for real-time monitoring of changes in brain activity as participants experienced each lighting condition. This setup provided an objective measure of participants' alertness and mental engagement, complementing the subjective data collected from the Visual Comfort Questionnaire and PAD scale. EEG analysis focused on identifying patterns that correlate with psychological comfort and alertness, offering insights into the neural effects of in-vehicle coloured lighting.

Figure 6.3 DSI-24 Device

Together, these psychological and physiological measures provided a comprehensive assessment of how coloured lighting affects both subjective experiences and brain activity, thereby contributing valuable insights to the development of in-car lighting systems that prioritise driver comfort and safety.

6.3.6 Data Collection and Recording

Data collection for this study was conducted using a combination of objective physiological measures and subjective psychological assessments, all synchronised within the virtual reality (VR) simulation environment. The VR application facilitated automated data recording, ensuring consistency and accuracy across all experimental sessions.

Electroencephalography (EEG) was employed to capture real-time brain activity, focusing on frequency bands such as alpha (relaxation), beta (alertness), theta (drowsiness), and delta (deep relaxation). A 32-channel EEG system was used, with electrodes positioned according to the international 10–20 system. The VR simulation provided a controlled environment for recording EEG data, which was pre-processed to remove artefacts and normalised against a baseline condition (dark, no lighting). The VR application was designed to automatically log key experimental variables, such as lighting conditions, task performance, and user interactions. Data were recorded continuously throughout each session and exported as a text file (*.txt*) for subsequent analysis. This automated recording ensured precise time-stamped data synchronisation, eliminating the potential for manual errors.

Participants completed a standardised visual comfort questionnaire immediately following each lighting condition, capturing perceptions of comfort, glare, and lighting suitability for night-time driving. Responses were rated on a 5-point Likert scale. Emotional responses to each lighting condition were measured using the PAD scale, which assesses pleasure, arousal, and dominance. This scale provided insights into the emotional impacts of the lighting conditions experienced during the VR simulation.

The experiment was conducted in a controlled laboratory setting, with participants exposed to four lighting conditions (dark, green, purple, and blue) in a simulated night-driving environment. Each lighting condition lasted 5 minutes, with an additional 5-minute baseline measurement under the dark condition. Breaks were incorporated between conditions to minimise fatigue and ensure accurate data collection. The VR application automatically recorded and logged data from the simulation, including lighting parameters, task performance metrics, and environmental variables. The collected data, exported as text files, were formatted for compatibility with statistical analysis software, allowing for efficient data processing and analysis.

All data, including EEG recordings and VR-exported text files, were anonymised and stored securely on a university-approved server, adhering to ethical guidelines (University of Leeds reference number FAHC 23-046 23). Backup protocols ensured data integrity, and access was restricted to authorised researchers to maintain confidentiality. The automated data collection via the VR application, combined with EEG measurements and subjective assessments, provides a comprehensive dataset for evaluating the effects of coloured lighting on driver concentration and visual comfort. This approach enhances the efficiency and reliability of the data collection process, supporting robust analysis and interpretation.

6.3.7 Data analysis

The data analysis for this study involved the use of multiple software tools and statistical methods to ensure a comprehensive evaluation of the collected data. EEG data were processed and analysed using MATLAB and the EEGLAB toolbox, while subjective assessment data were analysed using SPSS, with a particular focus on MANOVA to evaluate the effects of lighting conditions on various dependent variables.

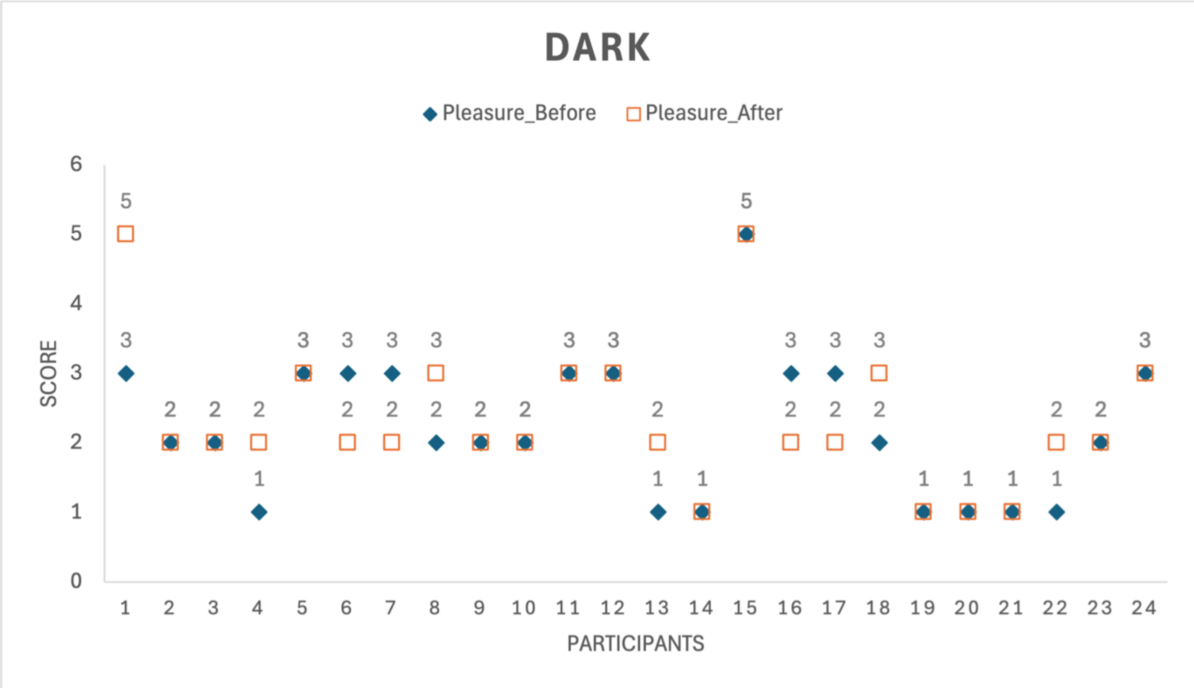
The EEG data were pre-processed in MATLAB using the EEGLAB toolbox, which included steps such as filtering, artefact removal, and segmentation. Frequency bands of interest—alpha, beta, theta, and delta—were extracted to assess the cognitive and emotional states of participants under each lighting condition. Preprocessing involved bandpass filtering to isolate these frequency bands, followed by independent component analysis (ICA) to remove artefacts such as eye blinks and muscle movements. Time-locked epochs corresponding to each lighting condition were then averaged to facilitate comparisons. The power spectral density (PSD) for each frequency band was computed, providing quantitative measures of brain activity across the experimental conditions.

Subjective assessment data, including responses to the visual comfort questionnaire and PAD scale, were analysed using SPSS. Descriptive statistics were calculated to summarise participants' ratings for each lighting condition. MANOVA was performed to examine the effects of the four lighting conditions (dark, green, purple, and blue) on multiple dependent variables, including visual comfort, pleasure, arousal, and dominance. This approach allowed for the simultaneous testing of differences across these measures while controlling for interdependencies between variables.

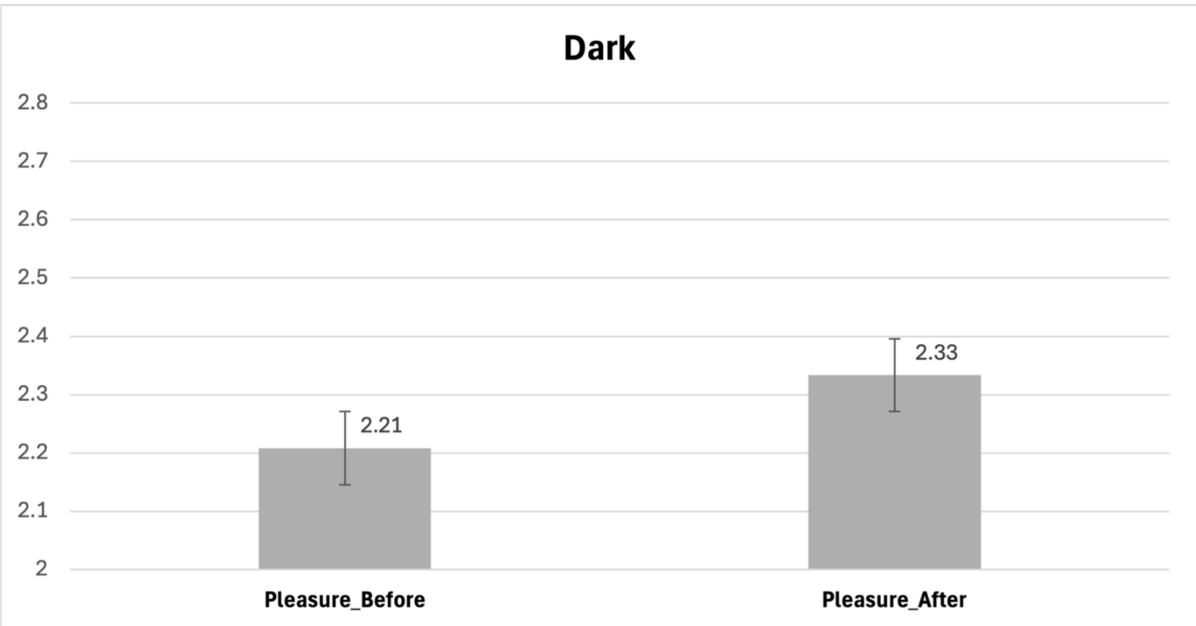
6.3.7.1 Results of Pleasure, Arousal, and Dominance Analysis

This section presents the findings from a MANOVA conducted to examine the effects of four distinct in-car lighting conditions—dark (no light), green, blue, and pink—on drivers' visual comfort and alertness during simulated night-time driving. Changes in PAD scores, collected before and after each driving session under the various lighting conditions, served as the primary measures. These scores provided insights into how each lighting condition influenced drivers' subjective experience of comfort, alertness, and control.

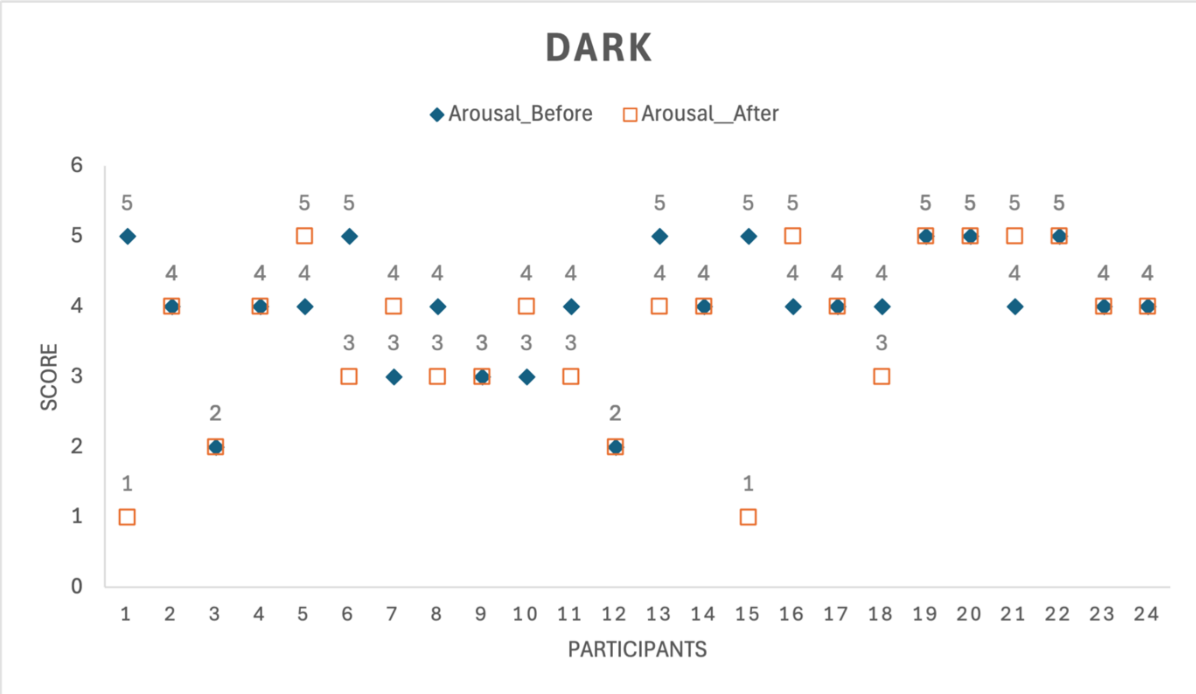
The results for the dark condition indicated no statistically significant changes across any of the PAD dimensions, suggesting that the absence of interior lighting had minimal impact on participants' subjective experiences during the driving task. The analysis for Pleasure showed no significant effect, $F(1, 23) = 0.016$, $p = 0.900$, $\eta^2 = .000$, F(1, 23) = 0.016, p = .900, η^2 = .000, indicating that participants' comfort levels remained largely consistent before and after driving in darkness. This is supported by the visual data presented in Figure 6.4 (a), where individual scores show minimal variation. While some participants reported slight increases or decreases in Pleasure, the overall average increased marginally from 2.21 to 2.33, as reflected in Figure 6.4 (b), which shows overlapping error bars and further underscores the statistical insignificance of this change. Similarly, Arousal scores demonstrated no significant change, $F(1, 23) = 1.099$, $p = .300$, $\eta^2 = .022$, F(1, 23) = 1.099, p = .300, η^2 = .022, highlighting that the absence of lighting had a negligible effect on participants' alertness. Although the raw data (Figure 6.4 (c)) revealed minor decreases in Arousal for certain individuals, the overall mean score decreased only slightly from 4.00 before driving to 3.63 afterwards, as illustrated in Figure 6.4 (d). The observed trend suggests that driving in complete darkness might contribute to a subtle decline in alertness for some participants, but the effect is neither consistent nor significant across the sample. For Dominance, the results were similarly stable, with no significant effect observed, $F(1,\ 23) = 0.016$, $p = .900$, $\eta^2 = .000$, F(1, 23) = 0.016, p = .900, η^2 = .000. Participants' perceived sense of control remained largely unchanged, as shown in Figure 6.4 (e), where most scores before and after the driving task were consistent. The average Dominance score experienced a negligible decrease from 3.75 to 3.71, with Figure 6.4 (f) showing overlapping error bars that further emphasize the lack of significant change. The individual data points similarly reveal only minor fluctuations, reflecting the overall stability of this dimension under the dark condition. In summary, the findings indicate that driving in complete darkness does not have a notable impact on participants' subjective experiences of comfort, alertness, or control. While slight individual variations were observed across the PAD dimensions, these changes were neither consistent nor statistically significant, suggesting that the absence of interior lighting has a neutral effect on driver psychology during night-time driving. These results highlight the limited influence of a dark environment on driver performance and well-being, providing a baseline for comparison with other lighting conditions.



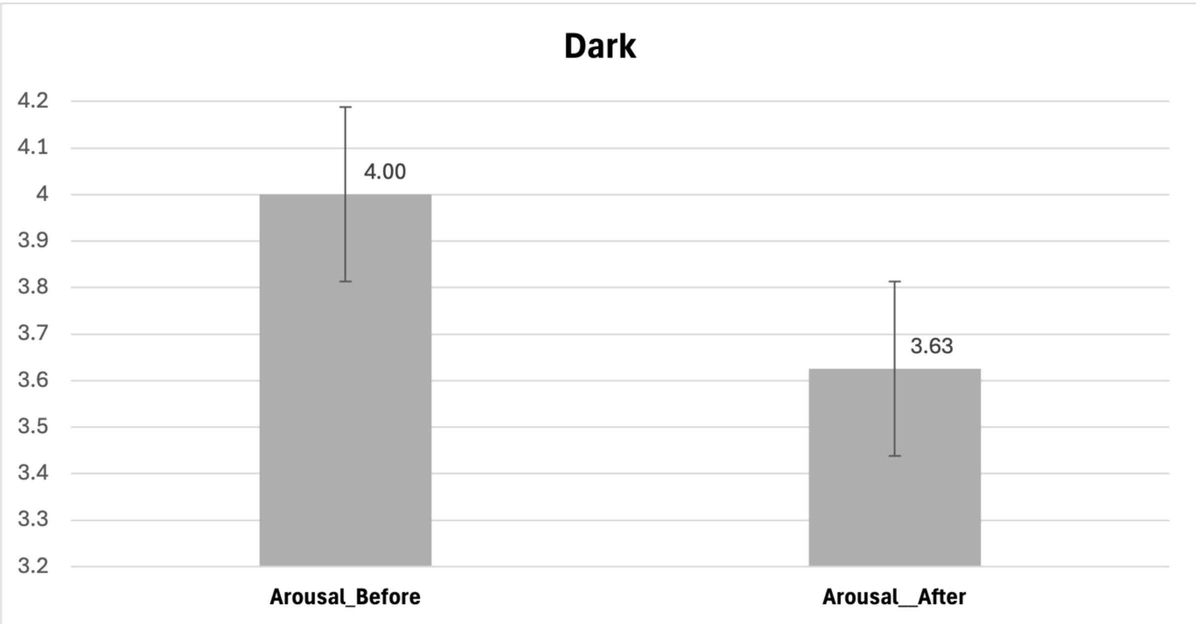
(a)



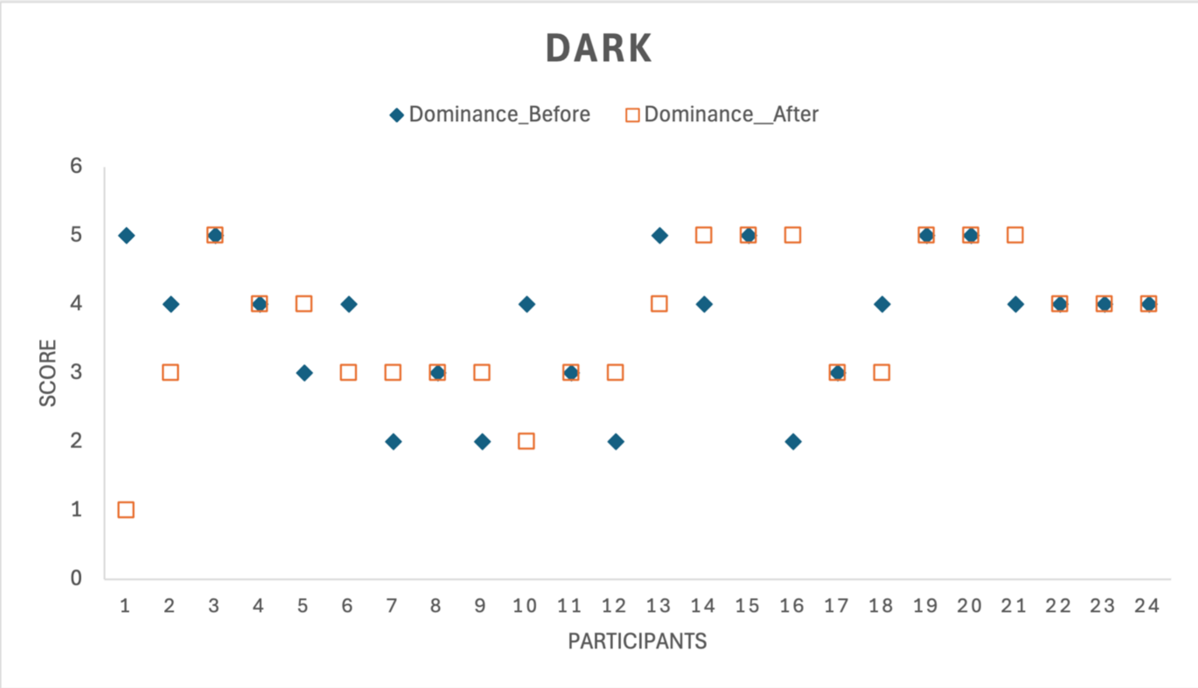
(b)


DARK
Arousal_Before
Arousal__After
SCORE
PARTICIPANTS

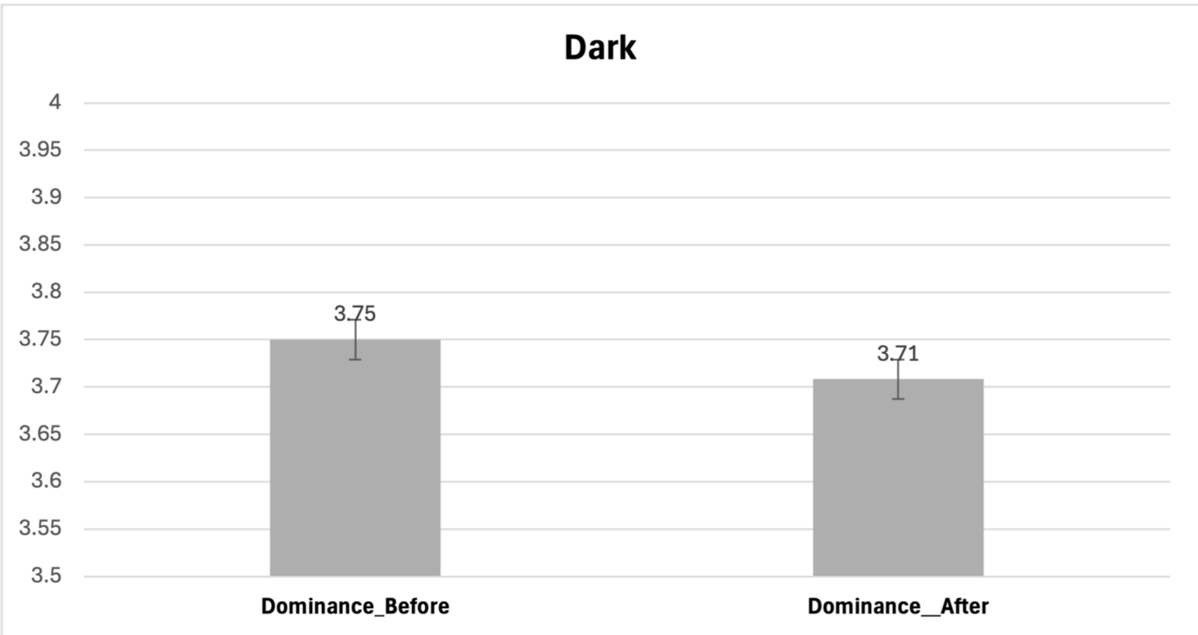
(c)


Dark
4.00
3.63
Arousal_Before
Arousal__After

(d)



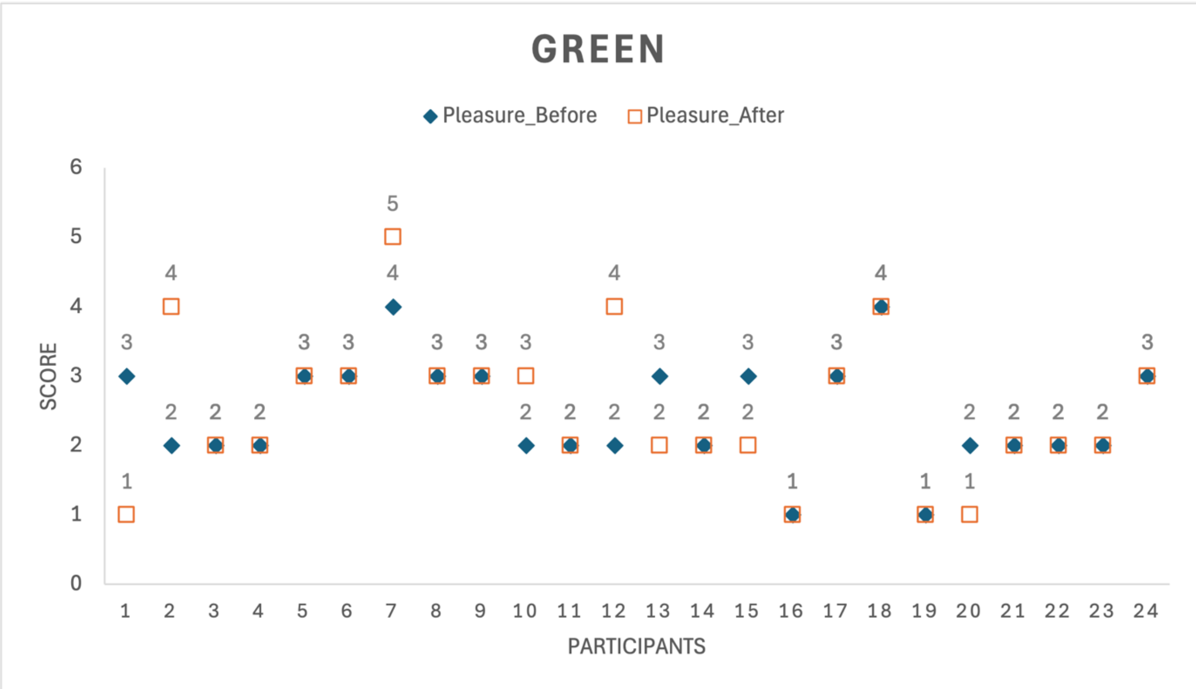
(e)



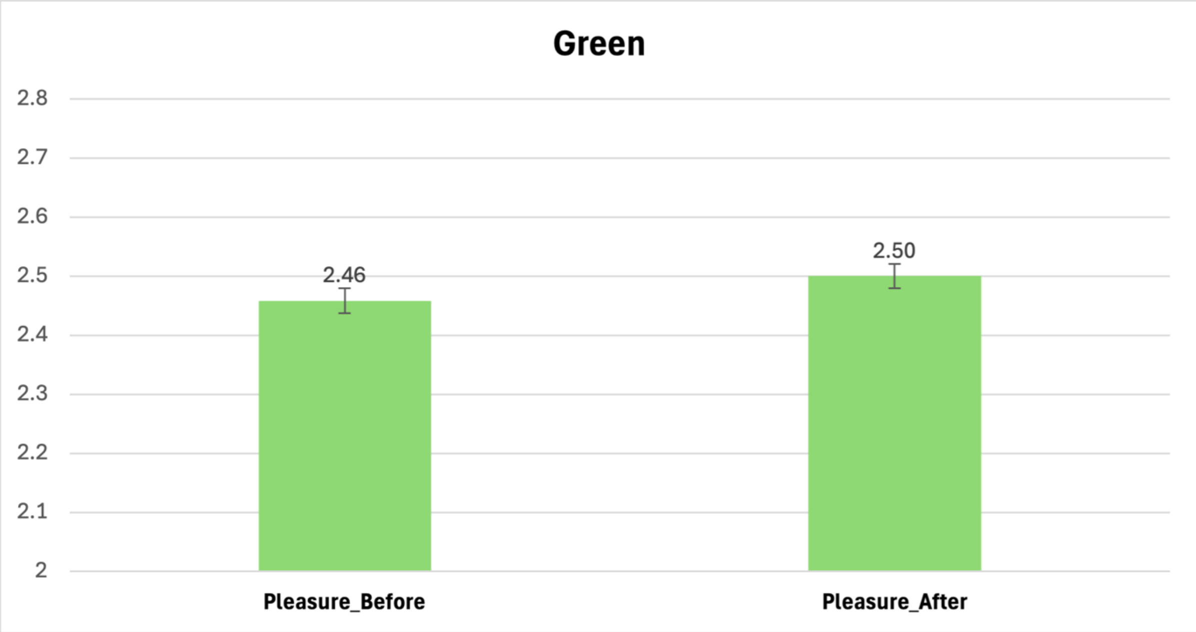
(f)

Figure 6.4 Participant-level and average scores for Pleasure (a & b), Arousal (c & d), and Dominance (e & f) before and after driving under the dark condition. (a), (c), and (e) display individual variability, while (b), (d), and (f) present mean scores with standard error bars, illustrating overall stability across all PAD dimensions.

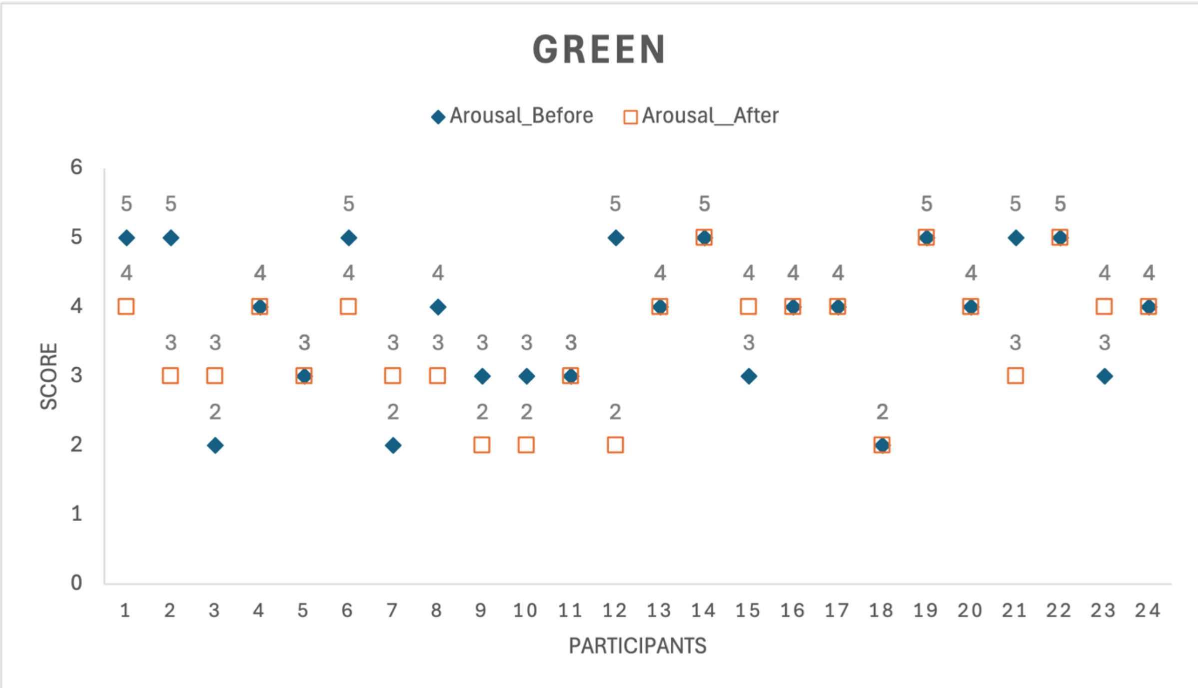
In the green lighting condition, the statistical analysis revealed no significant effects across the PAD dimensions, as shown in Figure 6.5 (a) to (f). Specifically, Pleasure scores showed no statistically significant change, $F(1, 23) = 0.090$, $p = .766$, $\eta^2 = .002$ (Figure 6.5 (a) and (b)), indicating that green lighting neither enhanced nor reduced the drivers' subjective comfort. Similarly, Arousal scores did not exhibit a significant difference, $F(1, 23) = 1.322$, $p = .256$, $\eta^2 = .026$ (Figure 6.5 (c) and (d)), suggesting that the green lighting had minimal impact on drivers' alertness. Furthermore, Dominance scores remained stable under the green lighting condition, $F(1, 23) = 0.089$, $p = .767$, $\eta^2 = .002$ (Figure 6.5 (e) and (f)), indicating that this lighting configuration did not alter participants' perceived sense of control. Collectively, these results suggest that green lighting offers a neutral effect on drivers' subjective comfort, alertness, and control, which could position it as a balanced lighting option with minimal influence on driver experience.



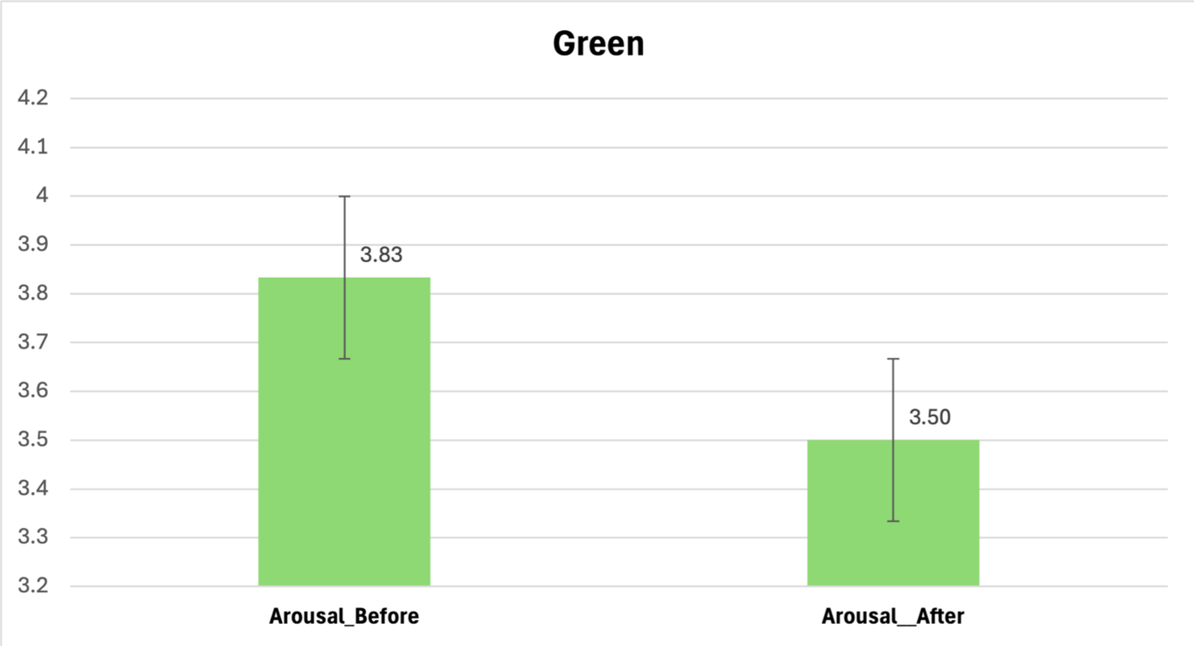
(a)


Green
2.8
2.7
2.6
2.5
2.4
2.3
2.2
2.1
2
2.46
2.50
Pleasure_Before
Pleasure_After

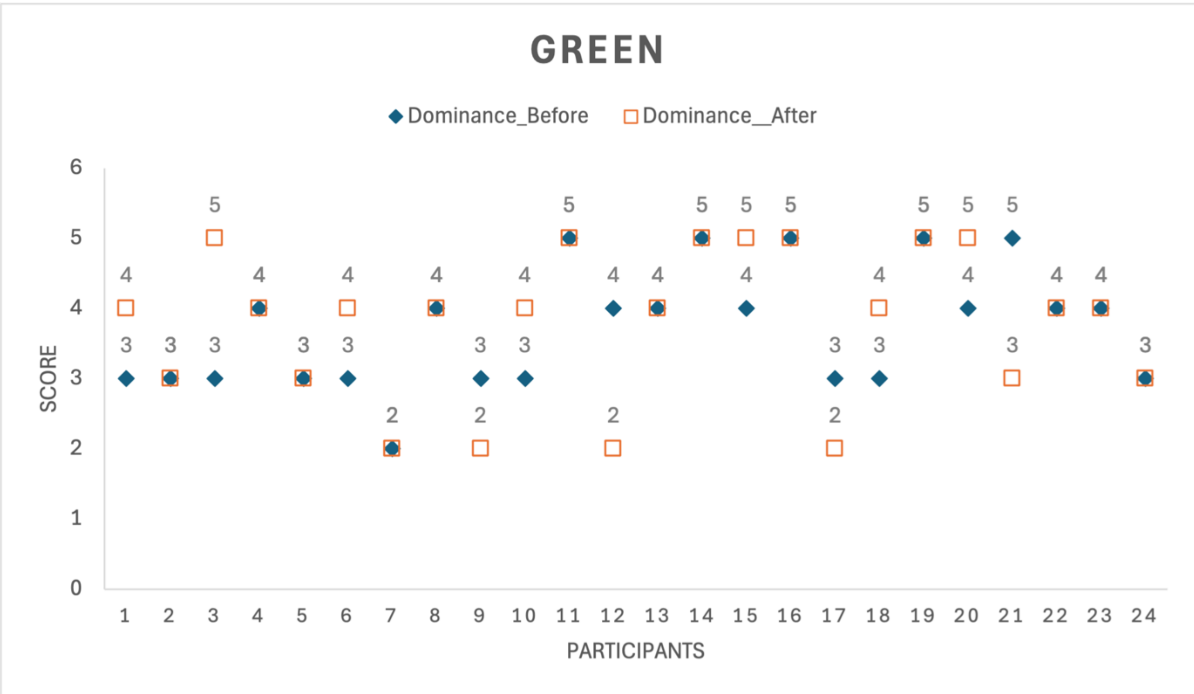
(b)


GREEN
Arousal_Before
Arousal__After
SCORE
PARTICIPANTS

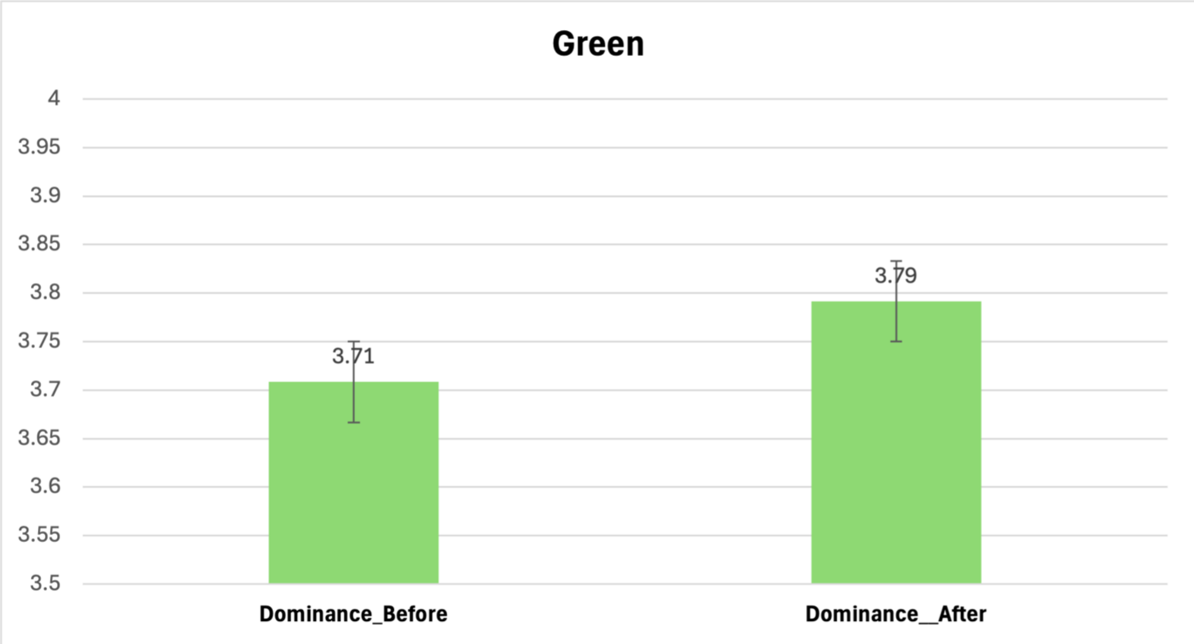
(c)


Green
4.2
4.1
4
3.9
3.8
3.7
3.6
3.5
3.4
3.3
3.2
3.83
3.50
Arousal_Before
Arousal__After

(d)


GREEN
Dominance_Before
Dominance__After
SCORE
PARTICIPANTS
0
1
2
3
4
5
6
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24

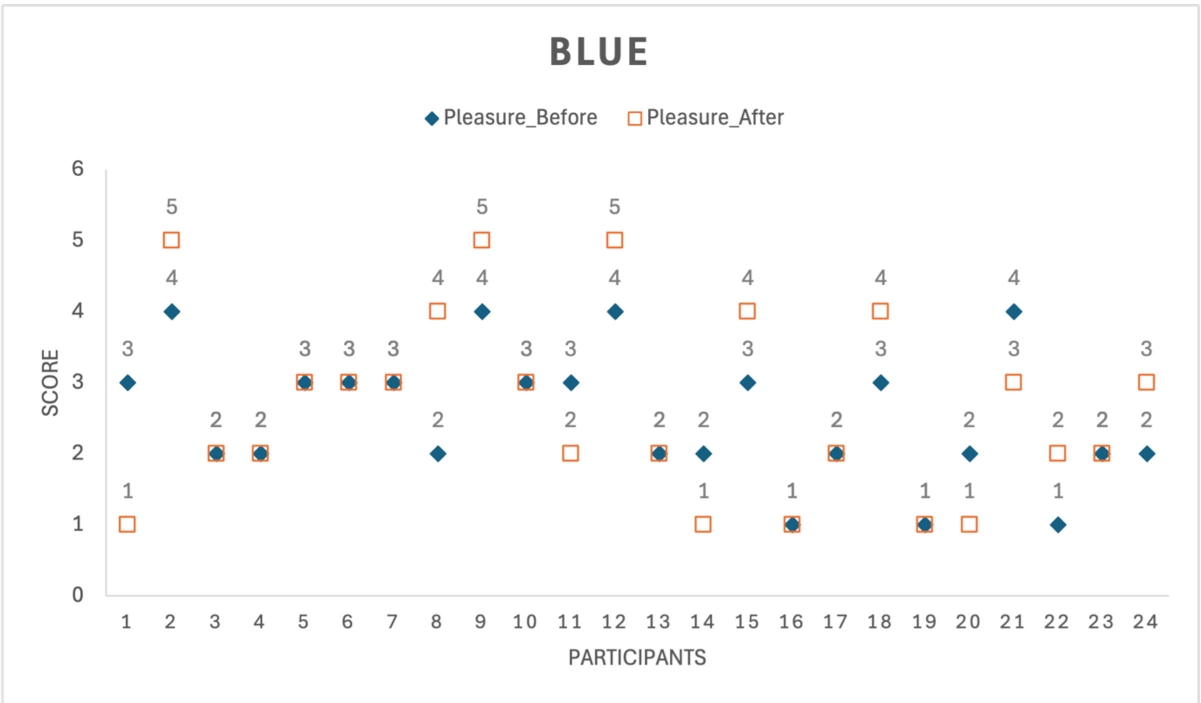
(e)



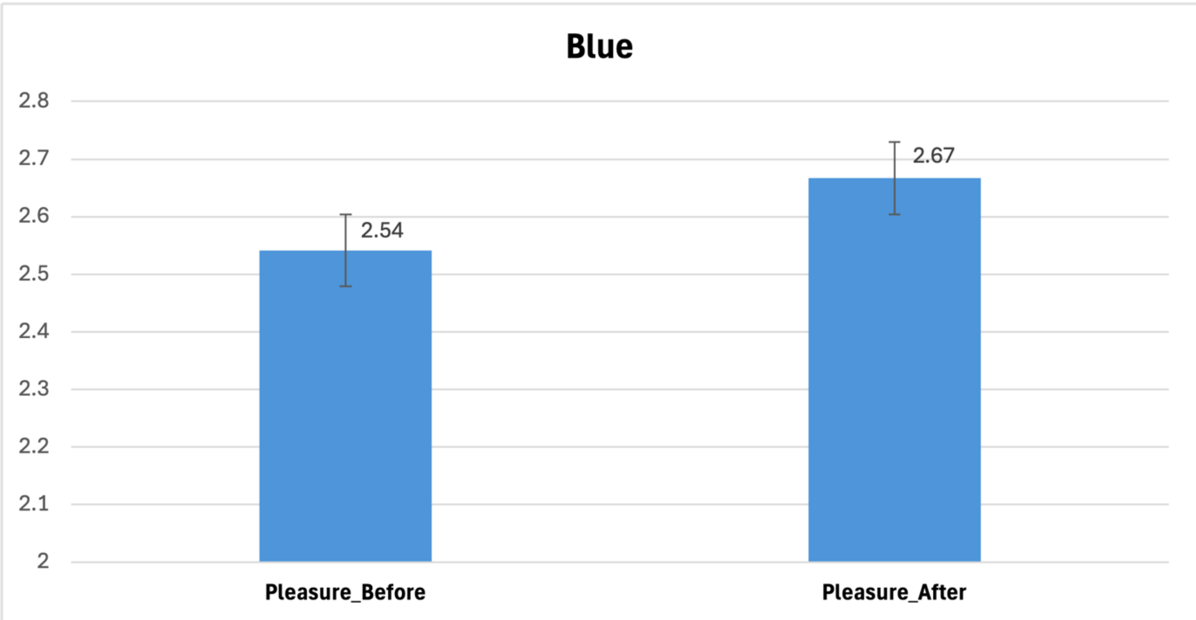
(f)

Figure 6.5 Green lighting condition results for Pleasure (a & b), Arousal (c & d), and Dominance (e & f) dimensions. Scatter plots (a, c, e) represent individual participant scores before and after exposure, while bar charts (b, d, f) depict mean scores with error bars indicating standard error. Statistical analyses indicate no significant changes across these dimensions under the green lighting condition.

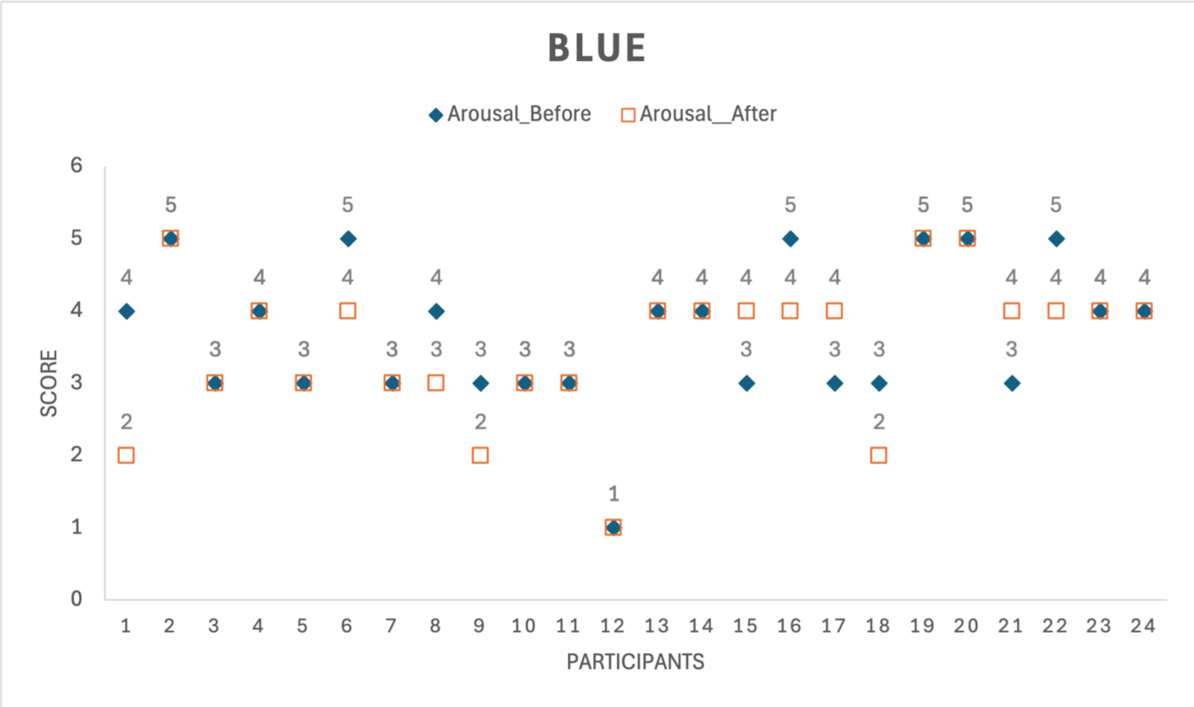
Under blue lighting conditions, the analysis revealed no statistically significant effects across any of the PAD dimensions (Figure 6.6 (a) to (f)). For the Pleasure dimension, the results indicated no significant change, $F(1,23)=0.247$, $p=.622$, $\eta^2=.005$, suggesting that blue lighting neither enhanced nor diminished participants' sense of comfort (Figure 6.6 (a) and (b)). Similarly, Arousal scores showed no significant difference, $F(1, 23) = 0.173$, $p = .679$, $\eta^2 = .003$, indicating a limited influence of blue lighting on driver alertness (Figure 6.6 (c) and (d)). Dominance scores also remained stable, $F(1, 23) = 0.074$, $p = .787$, $\eta^2 = .001$, implying that blue lighting did not affect drivers' perceived control during the task (Figure 6.6 (e) and (f)). While previous research has linked blue light to increased alertness and improved cognitive performance, the findings from this study suggest that such effects were not observed under the specific experimental parameters employed, underscoring the importance of contextual factors in determining lighting effects.


BLUE
Pleasure_Before
Pleasure_After
SCORE
PARTICIPANTS

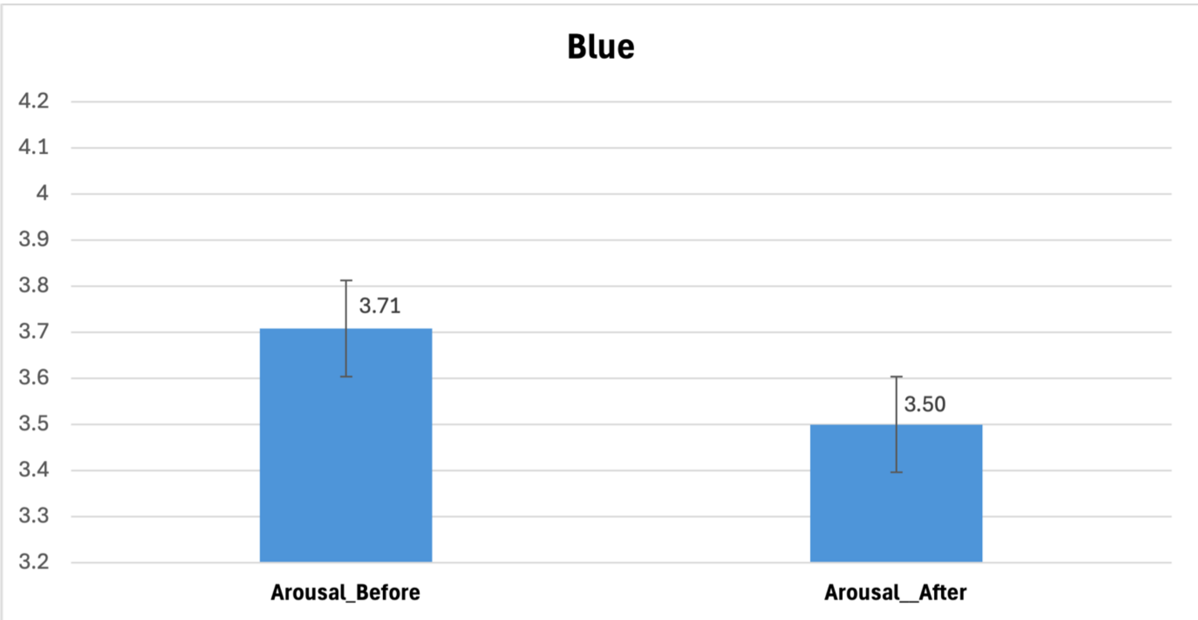
(a)


Blue
2.54
2.67
Pleasure_Before
Pleasure_After

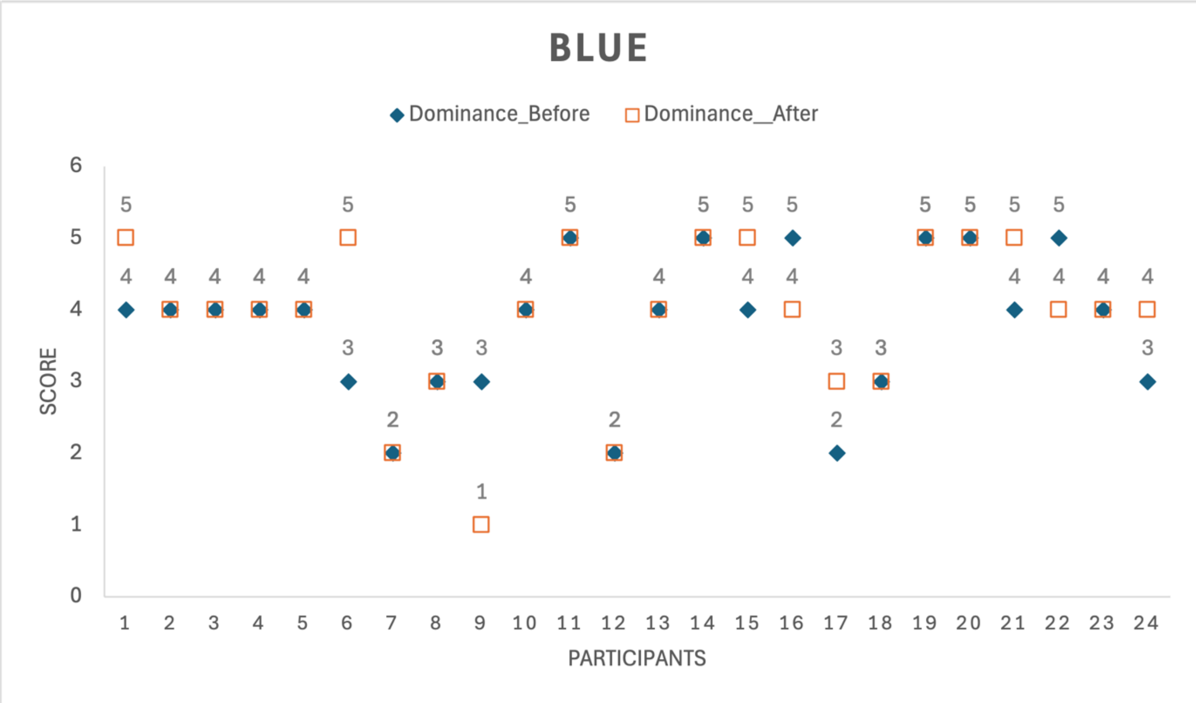
(b)


BLUE
Arousal_Before
Arousal__After
SCORE
PARTICIPANTS
0
1
2
3
4
5
6
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24

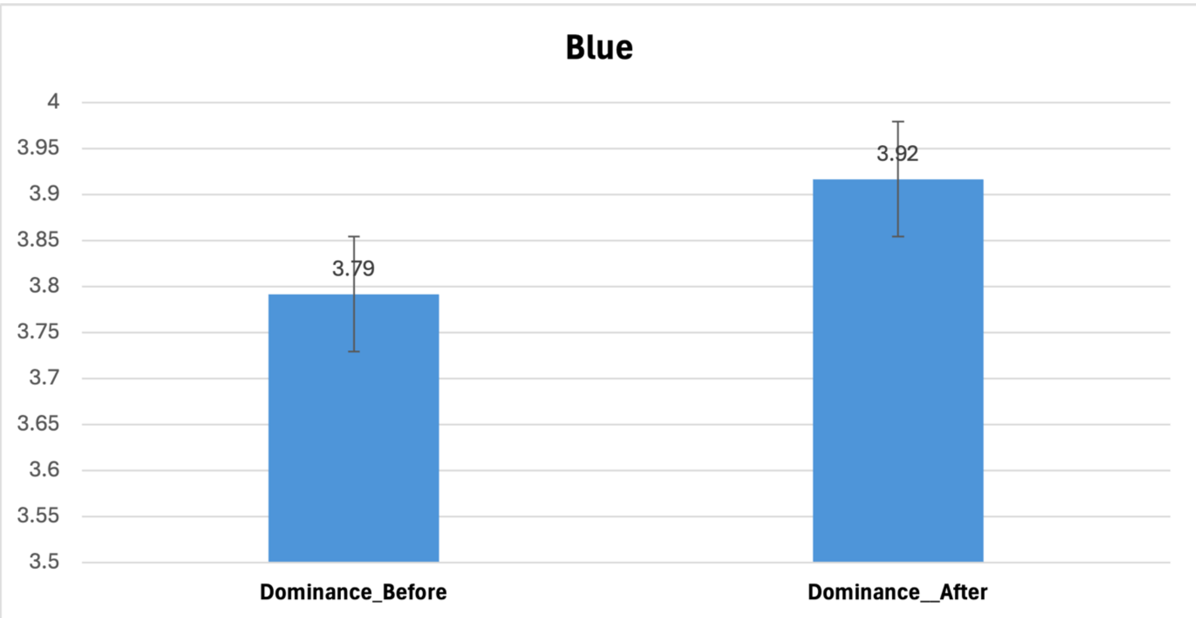
(c)


Blue
4.2
4.1
4
3.9
3.8
3.7
3.6
3.5
3.4
3.3
3.2
3.71
3.50
Arousal_Before
Arousal__After

(d)



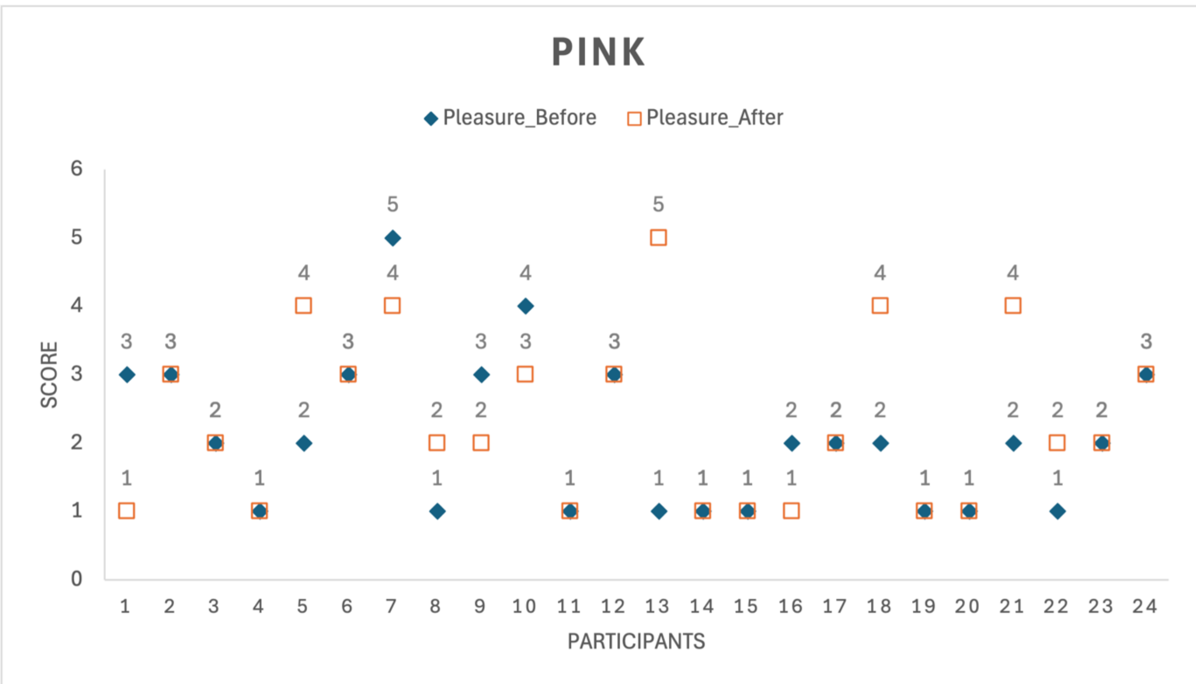
(e)



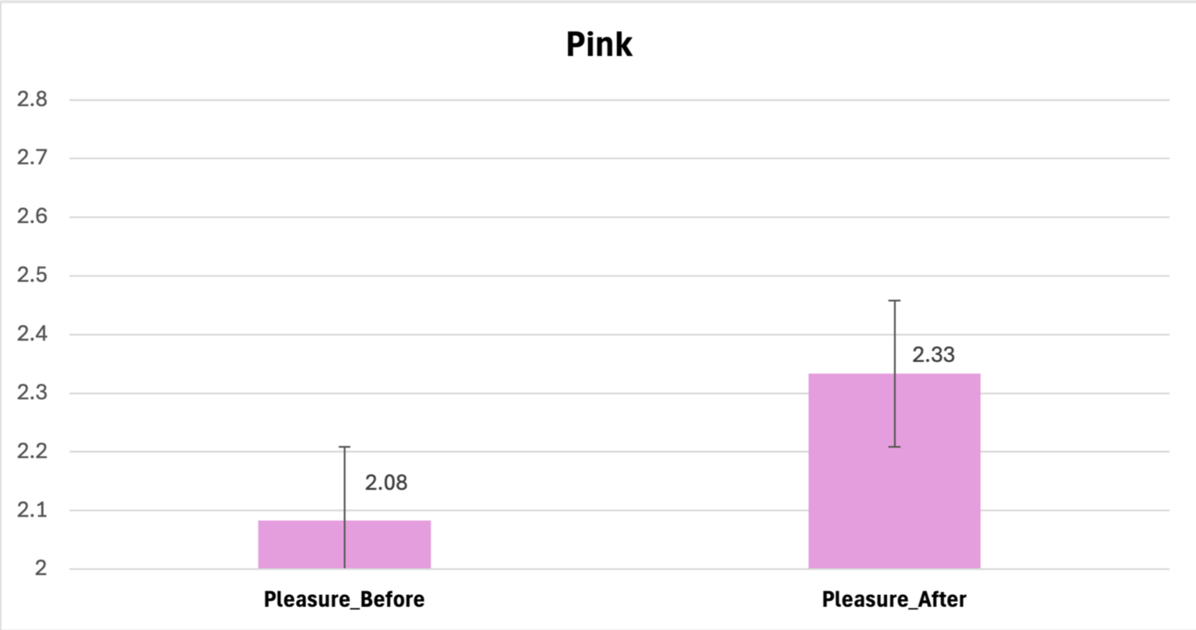
(f)

Figure 6.6 Changes in Pleasure, Arousal, and Dominance (PAD) scores under blue lighting conditions. (a) Individual participant scores for Pleasure before and after exposure. (b) Mean Pleasure scores with standard error bars. (c) Individual participant scores for Arousal before and after exposure. (d) Mean Arousal scores with standard error bars. (e) Individual participant scores for Dominance before and after exposure. (f) Mean Dominance scores with standard error bars. Statistical analysis indicated no significant changes across all dimensions of the PAD framework under blue lighting conditions.

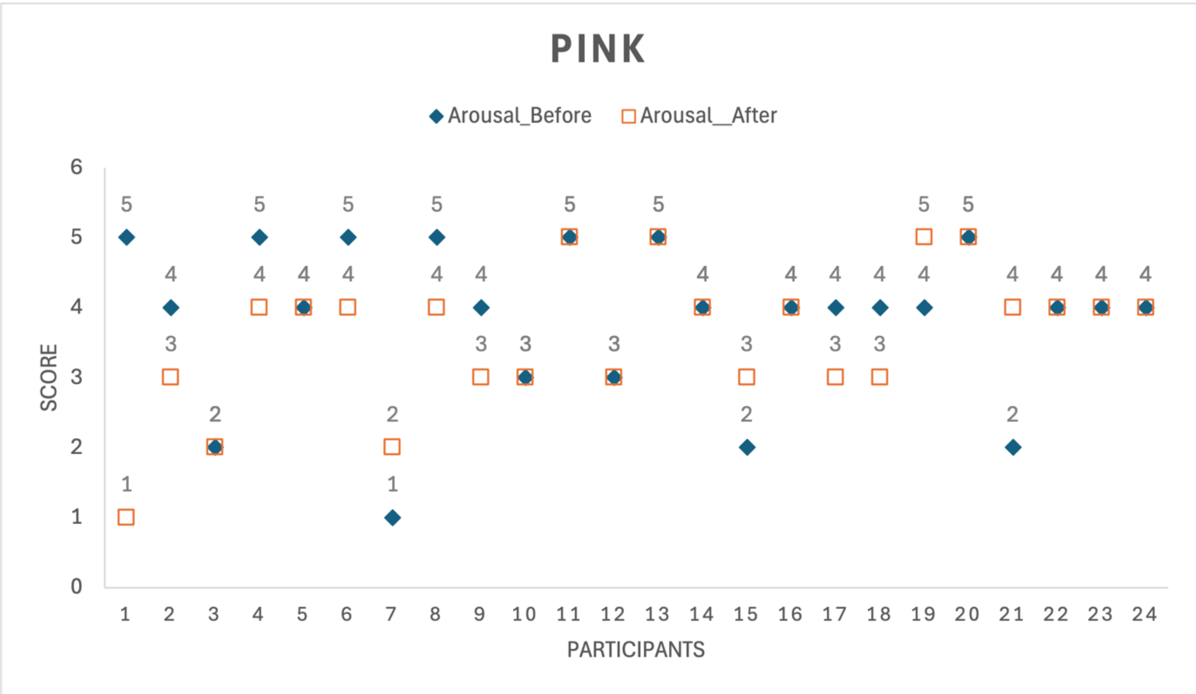
Under pink lighting, the analysis revealed no statistically significant changes across the PAD dimensions, suggesting its neutral influence on driver experience (Figure 6.7 (a) to (f)). For Pleasure, the results indicated no meaningful effect, $F(1, 23) = 0.342$, $p = .561$, $\eta^2 = .007$, signifying that pink lighting neither improved nor diminished comfort levels (Figure 6.7 (a) and (b)). Similarly, Arousal scores remained unaffected, $F(1, 23) = 0.268$, $p = .607$, $\eta^2 = .005$, demonstrating minimal influence on driver alertness (Figure 6.7 (c) and (d)). Dominance scores also showed no significant difference, $F(1, 23) = 0.061$, $p = .806$, $\eta^2 = .001$, indicating no alteration in drivers' perceived control or empowerment (Figure 6.7 (e) and (f)). These findings suggest that pink lighting, akin to green, offers a balanced environment that does not significantly enhance or detract from drivers' subjective comfort, alertness, or sense of control. Figure 6.7: Influence of pink lighting on participants' Pleasure (a & b), Arousal (c & d), and Dominance (e & f) scores, before and after the intervention. Error bars represent standard errors of the mean.



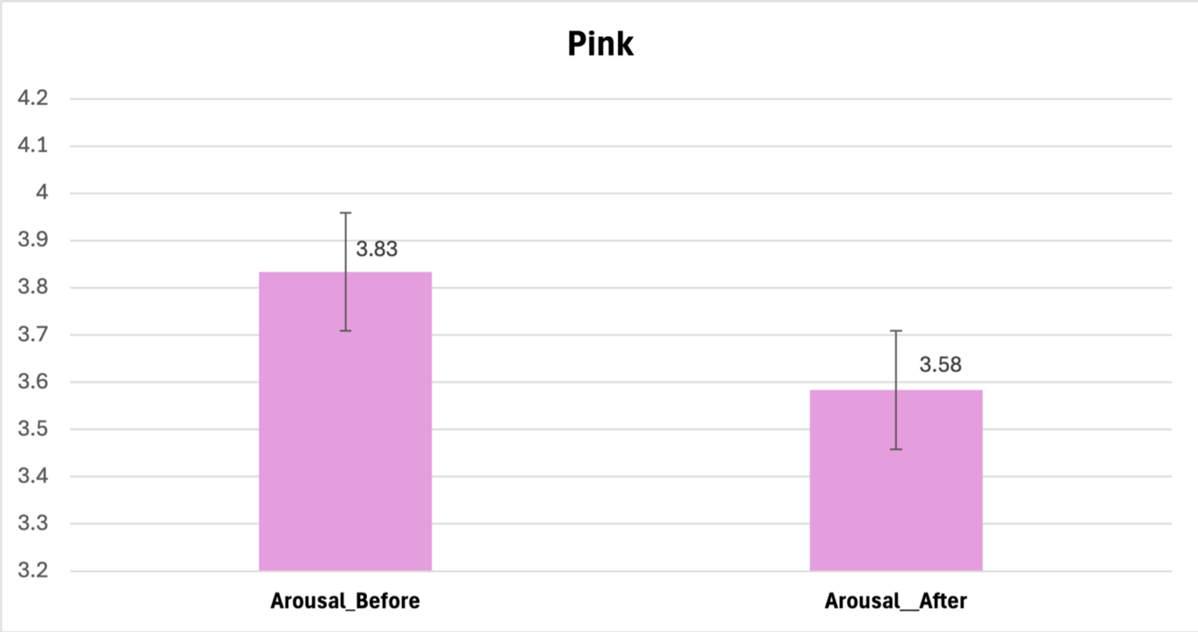
(a)


Pink
2.8
2.7
2.6
2.5
2.4
2.3
2.2
2.1
2
2.08
2.33
Pleasure_Before
Pleasure_After

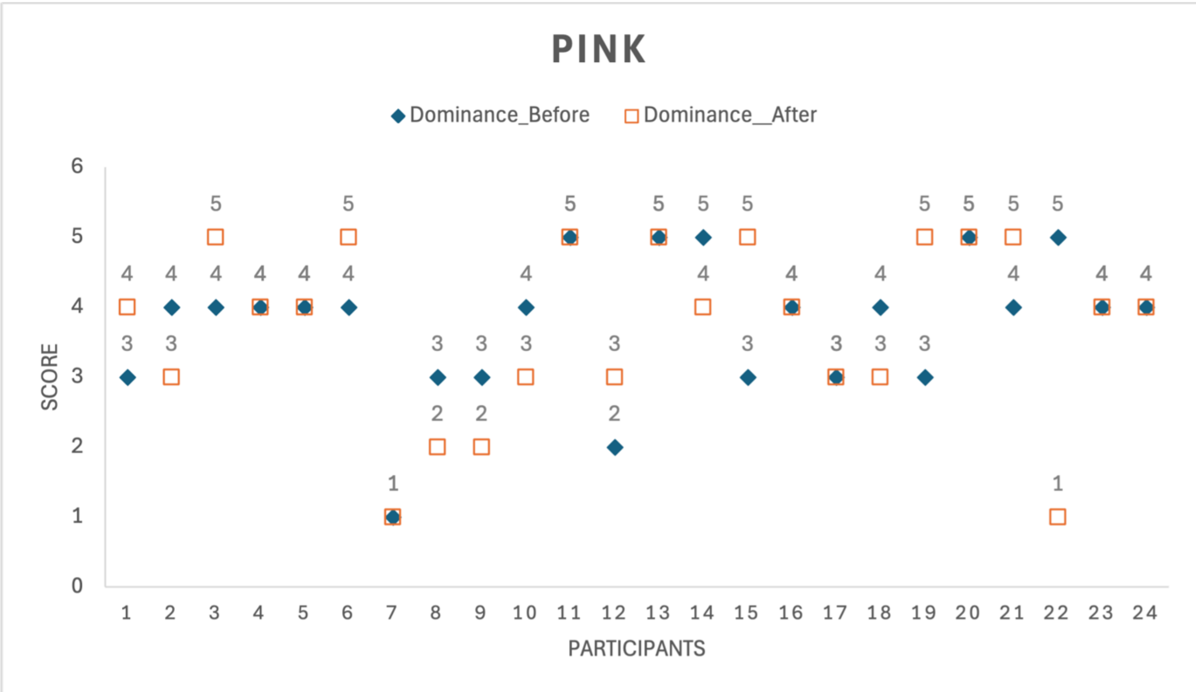
(b)


PINK
Arousal_Before
Arousal__After
SCORE
PARTICIPANTS
0
1
2
3
4
5
6
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24

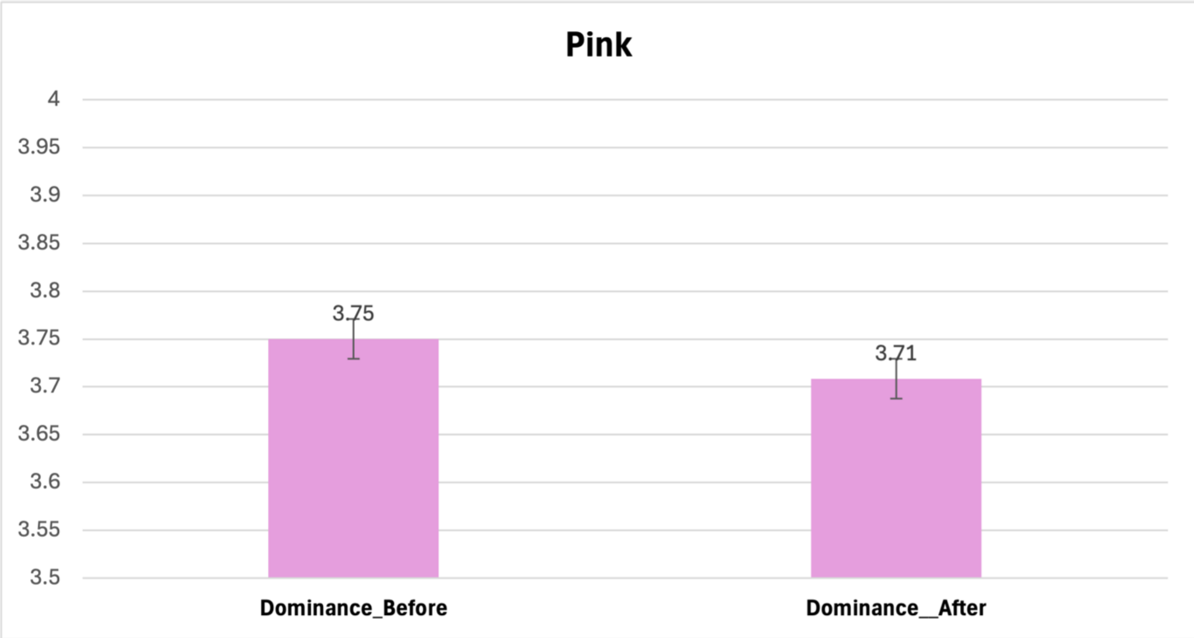
(c)


Pink
4.2
4.1
4
3.9
3.8
3.7
3.6
3.5
3.4
3.3
3.2
3.83
3.58
Arousal_Before
Arousal__After

(d)


PINK
Dominance_Before
Dominance__After
SCORE
PARTICIPANTS

(e)



(f)

Figure 6.7 Changes in participants' Pleasure (a & b), Arousal (c & d), and Dominance (e & f) scores under pink lighting conditions. Panels (a), (c), and (e) display individual scores before and after exposure, while panels (b), (d), and (f) illustrate the mean scores with error bars representing standard errors. Statistical analysis indicates no significant effects of pink lighting on any of the PAD dimensions.

The MANOVA results for the four lighting conditions (dark, green, blue, and pink) revealed no statistically significant changes in the PAD dimensions of Pleasure, Arousal, or Dominance. All p-values exceeded the conventional significance threshold of .05, and the effect sizes (partial eta squared) were negligible, indicating that the tested lighting conditions had minimal impact on drivers' subjective experiences of visual comfort or alertness during simulated night-time driving. These findings suggest that, under the parameters of this study, neither the presence nor the specific colour of in-car lighting notably influenced drivers' emotional or cognitive responses. Future research could explore larger sample sizes, extended exposure durations, varied lighting intensities, or alternative experimental designs to uncover potential subtle effects of in-car lighting on driver comfort and alertness.

6.3.7.2 Results of Between-Subjects Effects for Alertness Dimension

Alertness was measured through four core dimensions: distraction, concentration, tiredness versus activation, and sleepiness versus energy. These dimensions encapsulate drivers' subjective evaluations of their ability to stay focused and responsive during the driving task under different lighting conditions. The analysis for distraction showed no statistically significant differences between lighting conditions, $F(3,92) = 0.635$, $p = .594$, $\eta^2 = .02$, with an observed power of .178. This suggests that the presence or colour of in-car lighting did not meaningfully influence drivers' perceptions of being distracted from the driving task. Consequently, lighting was not a determining factor in distraction levels. Conversely, a significant effect of lighting condition was found for concentration, $F(3, 92) = 3.42$, $p = .021$, $\eta^2 = .10$, with an observed power of .753. This finding indicates that lighting plays a role in drivers' ability to maintain focus. Specific lighting colours or intensities may enhance concentration, aligning with hypotheses that well-designed lighting can support improved driver attention, particularly in night-time driving scenarios. For the tiredness versus activation dimension, no significant effect of lighting condition was observed, $F(3, 92) = 0.777$, $p = .510$, $\eta^2 = .025$, with an observed power of .211. This result suggests that lighting alone may not be sufficient to modulate drivers' perceptions of tiredness or activation levels in a meaningful way. Finally, lighting condition significantly influenced perceptions of sleepiness versus energy, $F(3, 92) = 3.031$, $p = .033$, $\eta^2 = .09$, with an observed power of .696. This suggests that some lighting conditions were perceived as more energizing, reducing feelings of sleepiness and promoting a greater sense of alertness. These findings highlight the potential for targeted lighting designs to counteract sleepiness and support driver vigilance during night-time driving.

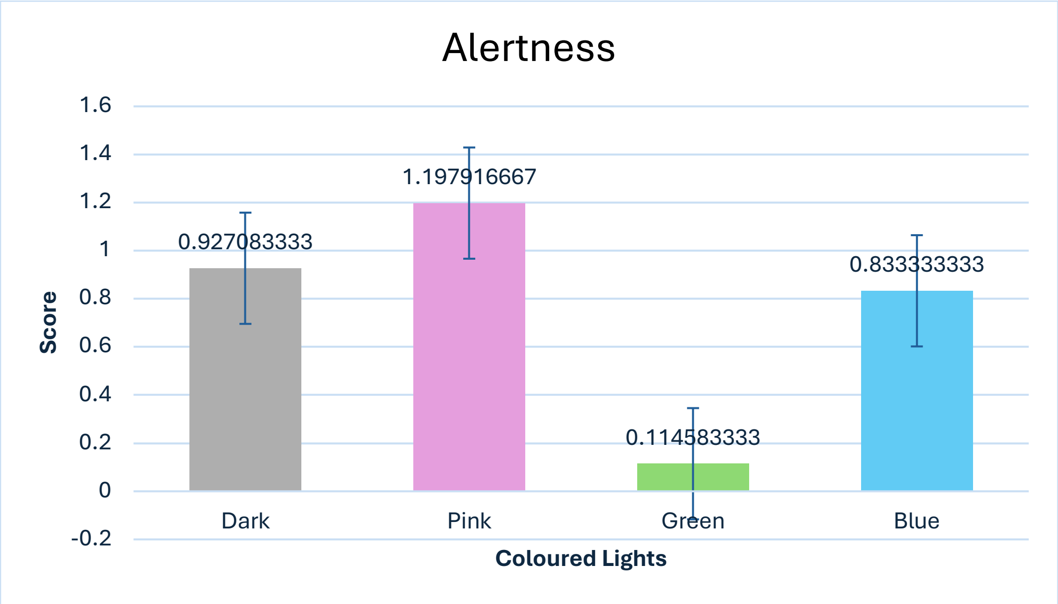


Figure 6.8 Mean alertness scores across four lighting conditions (Dark, Pink, Green, and Blue) with standard error bars. Alertness was assessed through dimensions including distraction, concentration, tiredness versus activation, and sleepiness versus energy.

In summary, the findings suggest that in-car lighting conditions have a measurable influence on drivers' perceptions of alertness, particularly in enhancing concentration and reducing feelings of sleepiness. Such lighting conditions may contribute to improved overall alertness, thereby supporting a safer driving experience during night-time conditions. However, perceptions of distraction and tiredness versus activation were not significantly affected by the lighting conditions examined, indicating that additional variables may need to be considered to comprehensively address these aspects of alertness. These results highlight the potential for optimising in-car lighting to target specific dimensions of alertness, ultimately fostering a safer and more focused driving environment.

6.3.7.3 Results of Between-Subjects Effects for Attractiveness Dimension

The MANOVA analysis revealed a significant main effect of lighting condition on perceived attractiveness, $F(3, 284)=6.61$, $p<.001$, $\eta^2= .07$. Descriptive statistics showed that pink lighting achieved the highest mean rating ($M = 1.39$, $SD = 2.71$), followed by blue ($M = 0.78$, $SD = 2.87$), dark ($M = 0.54$, $SD = 2.43$), and green ($M = -0.44$, $SD = 2.41$). Further analysis indicated that green lighting was rated significantly lower in attractiveness compared to pink and blue lighting, $F(3, 284) = 2.65$, $p < .001$, $\eta^2 = .05$. However, no significant differences were found between the dark condition and any of the coloured lighting conditions except green, suggesting that the absence of lighting was perceived similarly to most coloured lighting conditions. Additionally, pink and blue lighting were rated similarly, $F(3, 284) = 1.25$, $p = .051$, $\eta^2 = .04$, indicating that both colours offered comparable aesthetic appeal. In summary, the results demonstrate that in-car lighting significantly influences perceptions of interior attractiveness, with pink and blue lighting being perceived more positively than green. These findings suggest that strategic lighting choices, particularly the use of colours like pink and blue, can enhance passenger satisfaction by improving the aesthetic appeal of the vehicle interior.

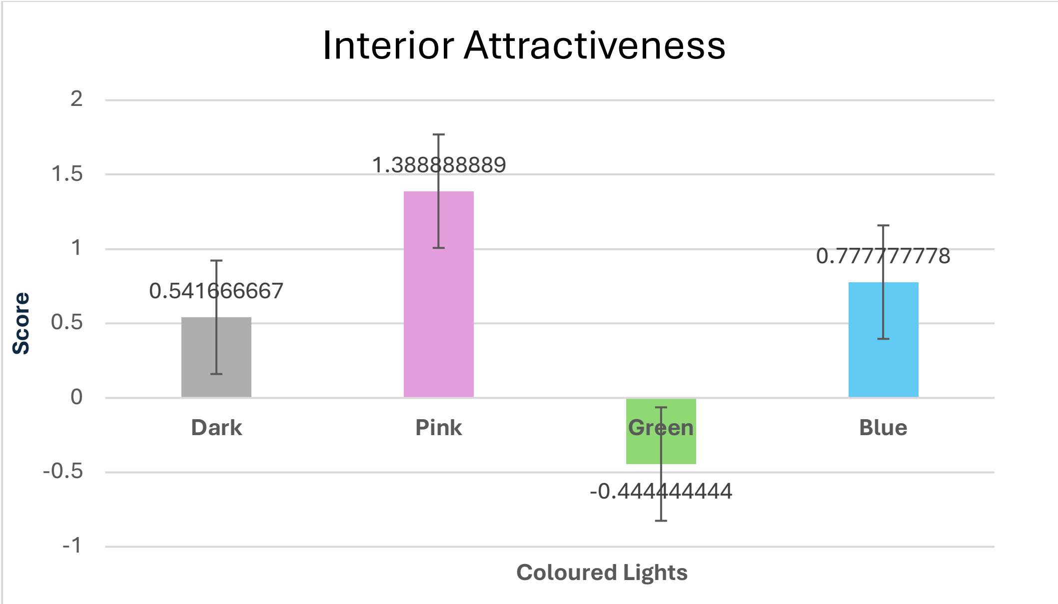


Figure 6.9 Mean interior attractiveness scores across four in-car lighting conditions (dark, pink, green, and blue). Error bars represent 95% confidence intervals. Pink lighting achieved the highest attractiveness ratings, followed by blue, dark, and green lighting. The MANOVA indicated a significant effect of lighting condition, with green lighting rated significantly lower in attractiveness compared to pink and blue.

6.3.7.3. Results for Perceived Interior Quality Dimension

To further examine the effects of different in-car lighting conditions on *Perceived Interior Quality*, a MANOVA analysis was conducted, comparing perceptions of interior quality across four lighting conditions: dark, green, pink, and blue. The results, illustrated in Figure 6.10, provide a visual representation of the mean perceived quality scores for each condition, indicating notable differences in aesthetic evaluations based on lighting colour. As shown in Figure 6.10, pink lighting received the highest mean rating for perceived interior quality (M = 1.25), suggesting that participants found this lighting condition to be the most aesthetically pleasing. The MANOVA results indicated a significant effect of lighting condition on perceived interior quality, F (3, 284) = 6.61, $p < .001$, $\eta^2 = .07$, confirming that lighting colour played a critical role in shaping participants' evaluations of the interior.

Green lighting, however, received the lowest mean rating (M = -1.40), suggesting it was generally perceived as the least attractive option for interior lighting. Statistical comparisons confirmed that green lighting significantly differed from both pink and blue lighting in terms of perceived interior quality. Blue lighting, with a positive mean score (M = 0.81), was rated higher than green lighting and moderately positively compared to the dark condition. However, while blue lighting appeared to enhance the perceived quality compared to the dark condition, this difference was not statistically robust, $F(3, 284) = 1.25$, $p = .051$, $\eta^2 = .04$. No significant differences were observed between pink and blue lighting conditions, suggesting that participants viewed both colours as similarly attractive in enhancing the interior quality. In summary, the MANOVA results indicate that lighting condition significantly influenced perceptions of interior quality, $F(3, 284) = 6.61$, $p < .001$, $\eta^2 = .07$, with pink lighting emerging as the most preferred option, followed closely by blue lighting. Conversely, green lighting was consistently rated the lowest, $F(3, 284) = 2.65$, $p < .001$, $\eta^2 = .05$, suggesting it may detract from the perceived quality of the vehicle's interior. The bar chart (Figure 6.10) visually supports these findings, highlighting the aesthetic appeal of pink and blue lighting over green and dark conditions. These results suggest that lighting choices, particularly the selection of pink or blue hues, could be strategically used to enhance drivers' and passengers' perception of interior quality.

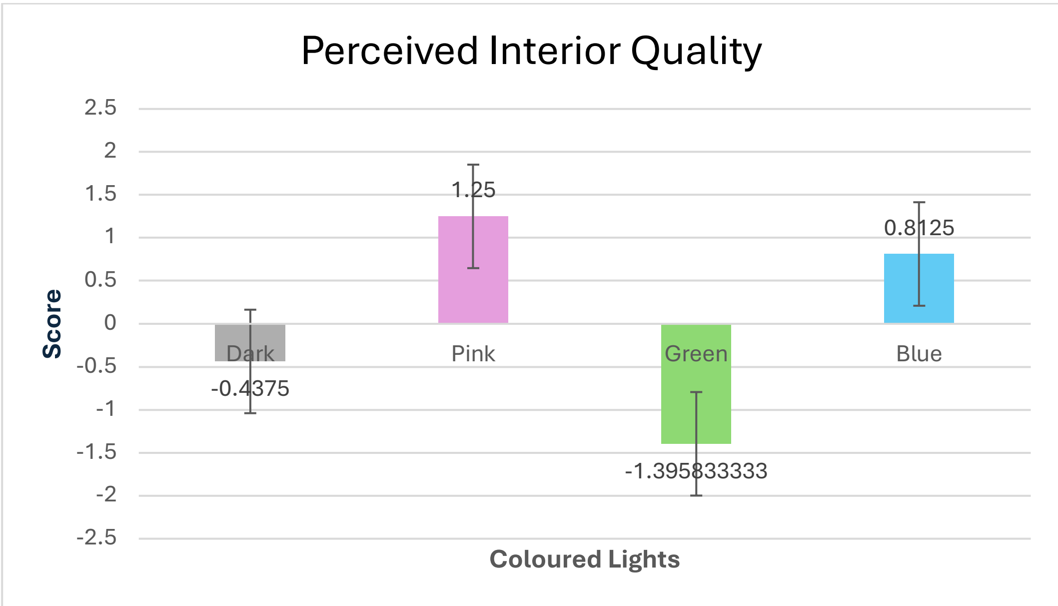


Figure 6.10 Mean perceived interior quality scores across four in-car lighting conditions (dark, pink, green, and blue). Pink lighting received the highest rating, significantly outperforming the dark and green conditions, while green lighting was rated the lowest. Blue lighting received moderately positive ratings but did not significantly differ from the dark condition. Error bars represent 95% confidence intervals.

6.3.7.4. Results for Functionality Dimension

The MANOVA analysis revealed a significant main effect of lighting condition on the functionality dimension, $F(3, 284) = 4.78$, $p = .003$, $\eta^2 = .05$. As shown in Figure 6.11, blue lighting received the highest mean functionality rating ($M = 1.13$), significantly outperforming the dark condition ($F(1, 284) = 6.73$, $p = .039$, $\eta^2 = .02$). This result suggests that blue lighting was perceived as enhancing functionality compared to an unlit (dark) interior, indicating its potential utility in improving functional aspects of the driving environment.

In contrast, the results indicated no significant differences in functionality ratings between the dark and pink lighting conditions ($F(1, 284) = 1.84$, $p = .275$, $\eta^2 = .01$), or between the dark and green lighting conditions ($F(1, 284) = 0.35$, $p = .878$, $\eta^2 = .001$). Similarly, there were no significant differences in functionality ratings among the coloured lighting conditions themselves: pink and green ($F(1, 284) = 0.89$, $p = .712$, $\eta^2 = .003$), pink and blue ($F(1, 284) = 0.83$, $p = .802$, $\eta^2 = .003$), and green and blue ($F(1, 284) = 2.67$, $p = .207$, $\eta^2 = .01$). These findings indicate that participants did not perceive substantial differences in functionality among the coloured lighting conditions, except for the clear advantage of blue over dark lighting.

The results demonstrate that blue lighting was perceived as significantly more functional than the dark (no light) condition, highlighting its potential to enhance functional aspects of the driving environment. However, pink and green lighting did not significantly differ from the dark condition, nor were there significant differences among the coloured lighting conditions themselves. These findings suggest that blue lighting may offer a distinct advantage in functionality, potentially supporting better visual engagement within the vehicle interior during driving, as illustrated in Figure 6.11.

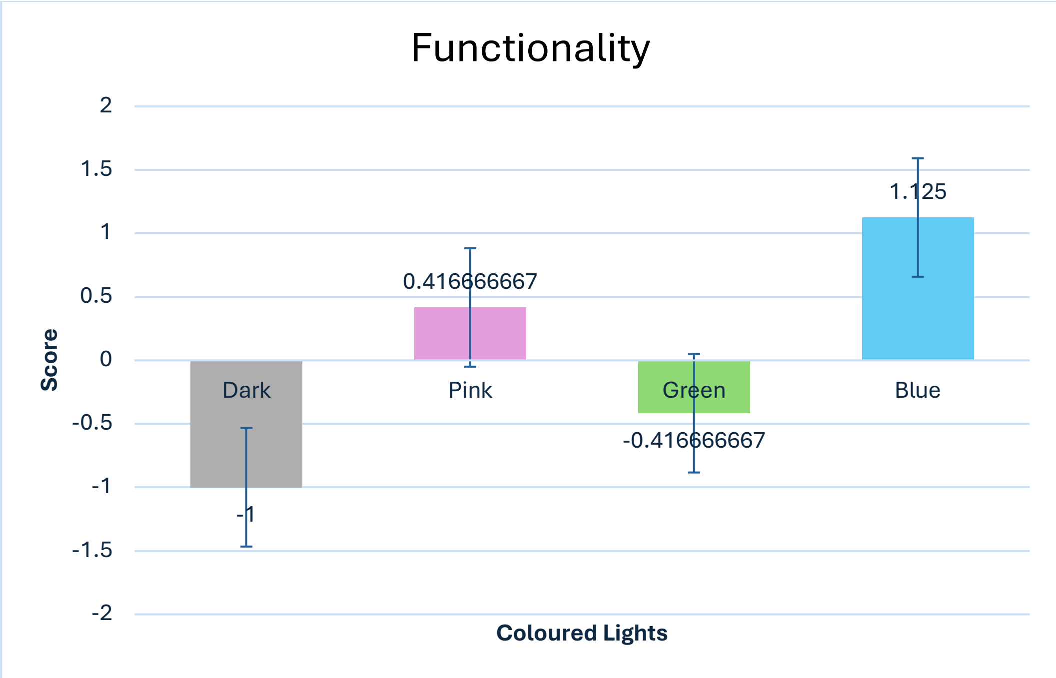


Figure 6.11 Mean functionality scores across different in-car lighting conditions (dark, pink, green, and blue), illustrating significant differences in perceived functionality. Blue lighting received the highest functionality rating, significantly outperforming the dark condition ($p = .039$), while no significant differences were observed among pink, green, and blue lighting. Error bars represent 95% confidence intervals.

6.3.7.5. Results for Perceived Safety Dimension

The MANOVA was conducted to examine the influence of coloured lighting conditions (dark, green, blue, and pink) on perceived safety during night-time driving. The results indicated a significant main effect of lighting condition, $F(3, 92) = 5.62$, $p = .001$, $\eta^2 = .16$, demonstrating that perceptions of safety were significantly affected by the lighting colour. Post hoc analysis revealed that pink lighting yielded the highest safety perception scores, significantly surpassing green lighting, $F(1, 92) = 6.43$, $p = .015$, $\eta^2 = .07$. Blue lighting also scored higher in perceived safety compared to green, although the effect did not reach significance, $F(1, 92) = 3.55$, $p = .064$, $\eta^2 = .04$. In contrast, dark lighting demonstrated no significant differences from other lighting conditions, indicating a neutral influence on safety perception. Figure 6.12 provides a visual representation of the mean perceived safety scores for each condition, including standard error bars. The results suggest that pink lighting enhanced perceived safety the most, while green lighting was rated the least safe. These findings underscore the role of colour choice in shaping driver confidence and comfort, with implications for optimising in-car lighting systems to promote a sense of safety during night-time driving.

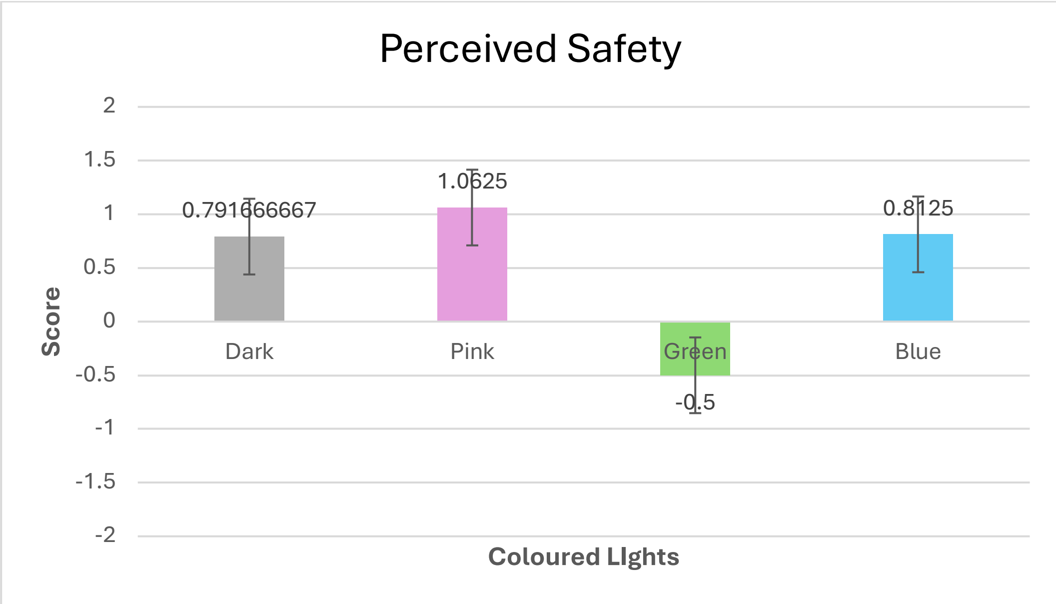


Figure 6.12 Mean perceived safety scores under different in-car lighting conditions (dark, pink, green, and blue). Pink lighting was perceived as the safest, while green lighting received the lowest safety ratings. Error bars represent standard errors.

6.3.7.5 EEG Results

The results of participants' brain activity reveal the nuanced effects of in-car lighting colours - blue, green, and pink - on driver alertness and visual comfort during dark, night-time driving conditions. By analysing EEG data and topographic maps across different frequency bands (alpha, beta, theta, and delta), this section explores the cognitive and emotional responses elicited by each colour, offering insights into how in-car lighting can be designed to enhance both comfort and focus during night-time driving.

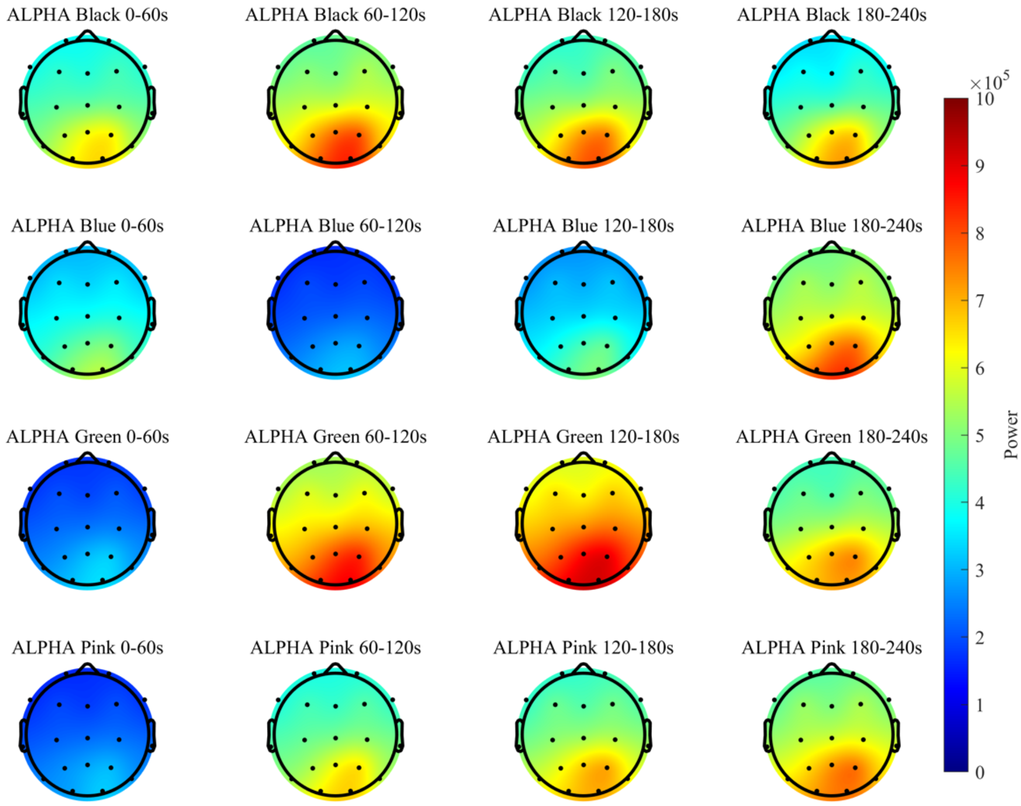


Figure 6.13 EEG Topographic Maps for Alpha Band under dark environment, blue, green, and pink lighting conditions across successive time intervals.

The EEG topographic maps in Figure 6.13 provide a fascinating look at the influence of different in-car lighting colours—black, blue, green, and pink—on driver alertness and visual comfort over time. Observing these maps, it becomes clear that in the absence of coloured lighting, alpha power consistently increases across all time intervals, particularly concentrated in the posterior regions of the brain. This pattern suggests that complete darkness promotes a state of relaxation, which could reduce mental engagement and alertness. Such a finding is aligned with previous studies that link higher alpha power to a relaxed mental state, indicating that while a dark environment may foster calmness, it may also impair focus, which could be detrimental to alertness in night driving. When analysing the blue lighting condition in Figure 6.13, an interesting deviation appears. While alpha power does increase slightly over time, it remains relatively lower than in the black condition. This suggests that blue lighting may help to counteract the natural relaxation response that darkness alone induces, helping drivers stay more alert. Blue light is known to have stimulating effects, which could make it a promising option for supporting prolonged focus in night-time driving. This aligns with broader research indicating that blue light can reduce alpha activity and promote wakefulness, which could be invaluable for maintaining driver alertness on long night journeys. In contrast, the green lighting condition in Figure 6.13 reveals a steady increase in alpha power over time, particularly after the 120-second mark, but this increase is less pronounced than in the black condition. Green light is often associated with calming effects, and this trend suggests that it may strike a balance, promoting a state of comfort without fully disengaging the driver's mental engagement. This balance could make green lighting suitable for scenarios where relaxation is desirable without a complete loss of focus, possibly making it more appropriate for areas of the vehicle where passengers are seated or for low-demand driving conditions. The pink lighting condition, on the other hand, exhibits a distinctive increase in alpha power, similar to green but reaching higher levels by the 180-second mark. This suggests that pink lighting may enhance the relaxation effect more intensely, possibly even more than green. While this might be beneficial in terms of comfort and reducing stress, it may not be ideal for sustained attention. This effect could potentially suit ambient lighting for passengers, where comfort is prioritised over focus, rather than for active driving scenarios. Collectively, the observations in Figure 6.13 suggest a clear trade-off between alertness and comfort depending on the colour of the in-car lighting. Blue lighting appears to be the most effective at maintaining alertness and could therefore be the optimal choice for in-car lighting during night driving. Green and pink lighting, while more relaxing, may be better suited to settings where comfort is the priority, such as rear seating or low-stress driving conditions. Additionally, the maps reveal that alpha power is predominantly concentrated in the posterior regions of the brain, which is associated with visual processing and attentional disengagement. This spatial distribution reinforces the idea that lighting choices influence not just the driver's overall alertness, but also the specific brain regions engaged during night driving. The practical implications of these findings are significant for in-car lighting design. To enhance night-time driving safety and comfort, car manufacturers might consider incorporating blue hues to promote driver alertness. Green and pink lighting, in contrast, could be selectively applied to support passenger comfort, fostering a relaxed atmosphere without overwhelming cognitive engagement. An adaptive lighting system that dynamically shifts colours based on driving conditions or user preferences could offer an ideal balance between comfort and attention. For instance, blue lighting could be prioritised during intense driving phases, while green or pink lighting could be introduced during breaks or more relaxed periods.

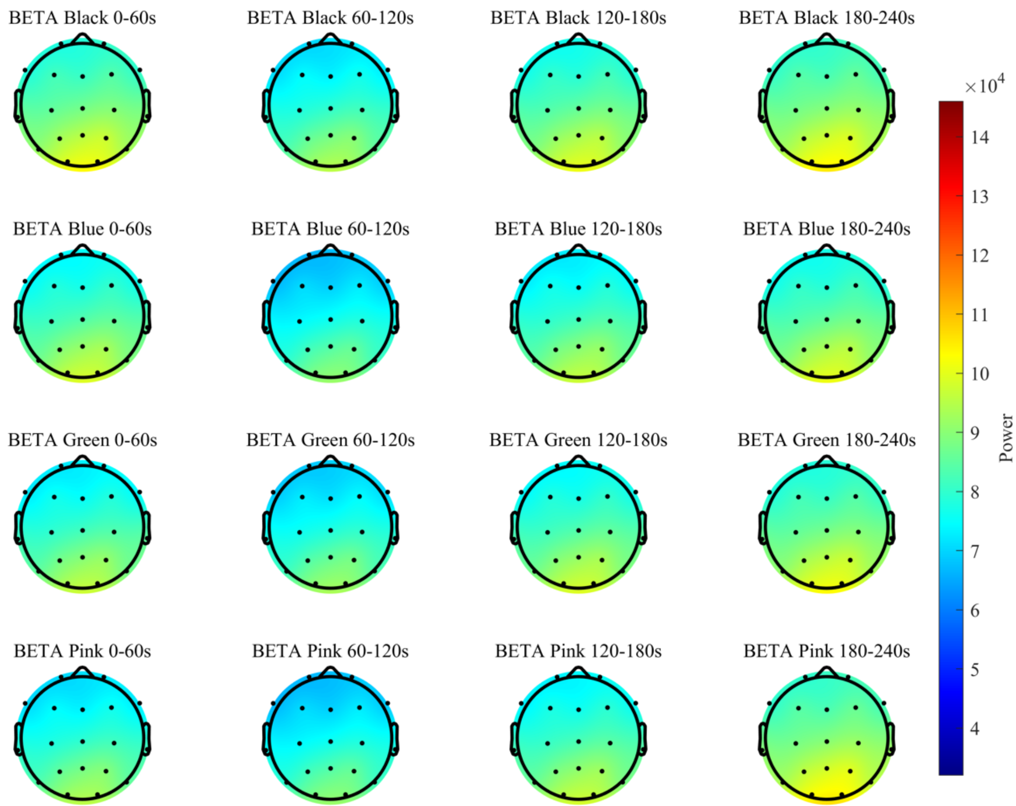


Figure 6.14 EEG Topographic Maps for Beta Band under dark environment, blue, green, and pink lighting conditions across successive time intervals.

In Figure 6.14, the EEG topographic maps illustrate the distribution of beta power across the scalp under dark, blue, green, and pink lighting conditions over successive time intervals. Beta waves are typically associated with alertness, concentration, and cognitive engagement, making their analysis crucial for understanding the effects of in-car lighting on sustained attention. Unlike the alpha band patterns observed in Figure 6.13, the beta power remains relatively low and consistent across all colour conditions and time intervals in Figure 6.14. This low beta activity suggests that none of the lighting conditions strongly enhance cognitive alertness or engagement over time, particularly in a dark driving environment where beta levels appear subdued. The lack of substantial beta power changes across conditions may indicate that these lighting colours have a limited impact on enhancing cognitive engagement in night-time driving scenarios, at least in terms of stimulating beta wave activity. When examining each colour condition in Figure 6.14, it appears that none significantly shifts beta power from baseline levels observed in the dark condition. In the black (dark) condition, beta power remains stable across the entire 240-second period, indicating that prolonged exposure to darkness does not stimulate beta-related alertness. Similarly, blue, green, and pink lighting do not show noticeable increases or shifts in beta activity, which suggests that these colours may not sufficiently stimulate cognitive engagement in a way that would be reflected in beta wave increases. This consistency in low beta activity across conditions implies that while coloured lighting may influence relaxation and comfort through alpha wave modulation (as seen in Figure 6.13), it might not be as effective for enhancing sustained attention or mental focus, which are typically represented by beta activity. These findings suggest that in-car lighting design for night-time driving may need to explore alternative strategies or lighting parameters if the goal is to directly promote cognitive engagement or alertness, as the current colour selections do not appear to increase beta-related alertness.

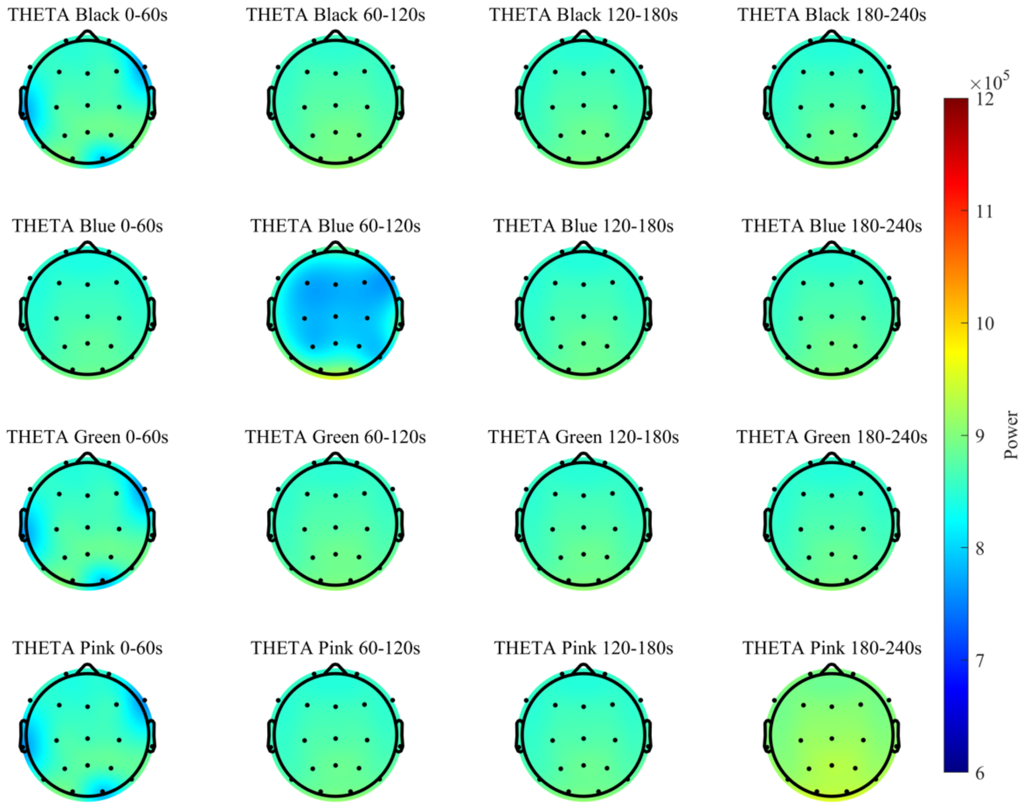


Figure 6.15 EEG Topographic Maps for Theta Band under dark environment, blue, green, and pink lighting conditions across successive time intervals.

In Figure 6.15, the EEG topographic maps illustrate the distribution of theta power across various lighting conditions—dark, blue, green, and pink—over different time intervals. Theta waves are typically linked to drowsiness, relaxation, and low cognitive activity levels, making them relevant for assessing the potential for drowsiness or a relaxed mental state in night driving scenarios. Starting with the dark condition, theta power remains relatively steady over time, showing only slight increases without significant shifts. This stability suggests that while darkness alone may create a calm atmosphere, it does not strongly promote drowsiness or high cognitive engagement. Under blue lighting, however, there is a noticeable increase in theta activity, especially between the 60-120 second mark. This suggests that blue light might, unexpectedly, induce a relaxed or mildly drowsy state within this period, as reflected in the elevated theta power. Although blue light is generally associated with alertness in the alpha and beta bands, the increased theta activity here indicates a more complex effect, where blue lighting could simultaneously promote alertness and relaxation. This balance might be beneficial for reducing stress without making the driver overly sleepy, though it suggests that blue light alone may not maintain optimal alertness over extended periods. Theta power under green lighting remains low and stable, with only minor increases over time, which aligns with green's calming effect without causing drowsiness. This pattern suggests that green lighting may support a calm yet somewhat more alert state than blue lighting, as it does not raise theta levels as much. This makes green lighting a viable choice for comfort without significantly affecting alertness or inducing drowsiness, fostering a balanced mental state that is relaxed yet attentive. In the case of pink lighting, theta power is similarly stable with slight increases over time, particularly around the 120-second mark. This pattern corresponds to pink's relaxing effect, indicating that it may promote comfort while keeping cognitive engagement minimal. While this might suit passengers seeking a comfortable setting, it may not be ideal for drivers who require sustained focus.

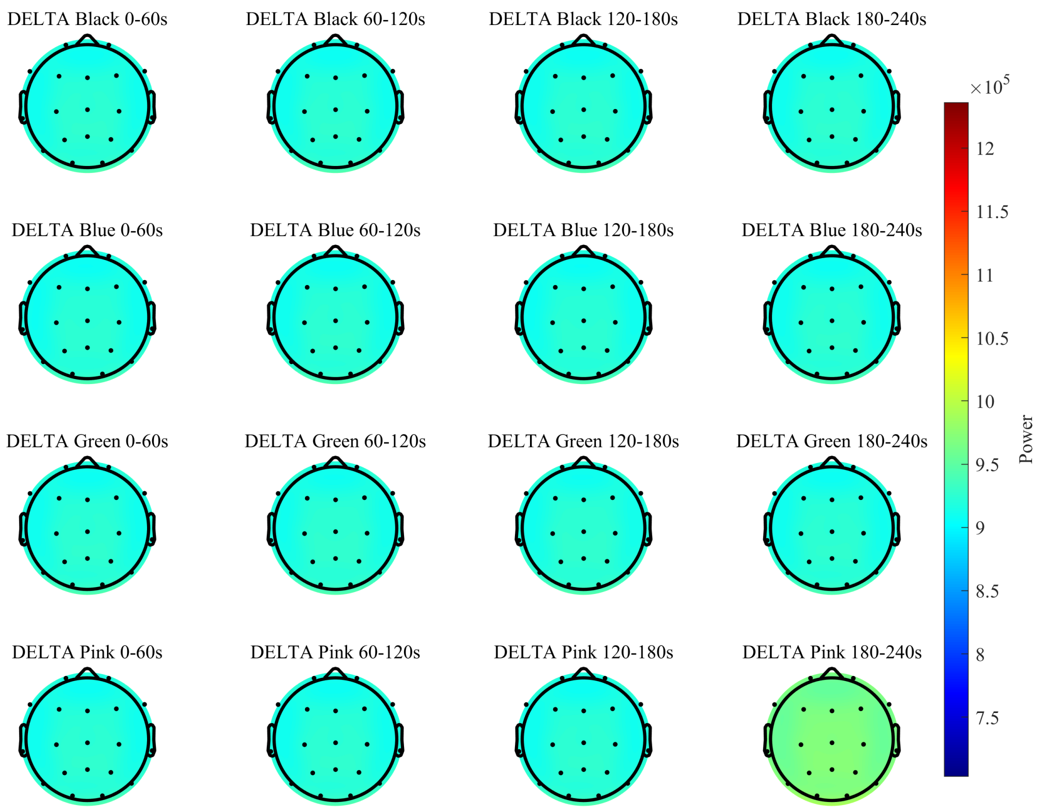


Figure 6.16 EEG Topographic Maps for Delta Band under dark environment, blue, green, and pink lighting conditions across successive time intervals.

Delta waves are generally associated with deep sleep and very low cognitive activity; thus, an increase in delta power could signify a state of deep relaxation or drowsiness, which would be undesirable for maintaining alertness in driving scenarios. In Figure 6.16, across all lighting conditions, delta power remains minimal and stable over time, showing no substantial variation across different colours or time intervals. Under the dark condition, delta power remains consistently low, suggesting that the absence of coloured lighting does not induce a state of deep relaxation or drowsiness. This stability in delta activity indicates that darkness alone does not produce the low arousal levels associated with deep relaxation, allowing for a calm yet alert mental state. In the blue, green, and pink lighting conditions, delta power also remains low and stable over time. This pattern suggests that none of these colours provoke a deep relaxation response that would elevate delta activity. Blue lighting, which has shown relaxing effects in other frequency bands, does not appear to increase delta power, meaning it may foster calmness without inducing drowsiness. Similarly, green and pink lighting, known for their calming effects, do not elevate delta power, indicating that they support relaxation without lowering alertness to a deeply relaxed or drowsy state. The consistently low delta activity across all conditions suggests that, while coloured lighting may influence relaxation or focus through other frequency bands, it does not trigger the deep relaxation state associated with heightened delta activity. This finding is encouraging for in-car lighting design, as it implies that coloured lighting can enhance comfort without reducing alertness through increased delta activity. Consequently, none of the lighting conditions are likely to adversely affect driver alertness from the perspective of delta wave activity.

The general results across Figures 6.13 to 6.16 suggest that different coloured lighting influences brainwave activity in ways that could affect relaxation and alertness in night driving. Blue lighting appears to balance relaxation with moderate alertness, as indicated by lower alpha and theta power, making it potentially suitable for supporting driver focus. Green and pink lighting, on the other hand, promote a calming effect without significantly boosting alertness, suggesting these colours may be better suited for passenger comfort rather than for drivers requiring sustained attention. Across all conditions, delta power remains stable, indicating that none of the lighting colours induce the deep relaxation or drowsiness associated with high delta activity. This stability supports the idea that coloured lighting can enhance in-car comfort without compromising driver alertness, highlighting the potential of adaptive lighting systems that adjust colour based on the driver’s needs and driving context.

6.4 Discussion and Conclusion

The psychological and physiological impacts of in-vehicle coloured lighting have become a critical area of investigation in automotive design, particularly in the context of night-time driving. This chapter has explored these effects through a rigorous experimental design incorporating both subjective and objective measures, including Pleasure, Arousal, Dominance scales, visual comfort questionnaires, and EEG data. The findings offer nuanced insights into how coloured lighting influences drivers' emotional states, cognitive engagement, and overall driving experiences, revealing both its potential and its limitations.

While the results provide actionable recommendations for automotive lighting design, they also raise questions about the complexities of integrating lighting schemes into vehicles for optimal outcomes. The analysis of emotional responses through PAD measures underscores the differential effects of coloured lighting. Pink lighting consistently elicited the highest pleasure scores, suggesting its potential to enhance comfort and foster positive emotional states during driving. However, its effects on arousal and dominance were limited, indicating that while it promotes relaxation, it may not sufficiently enhance alertness or a sense of control, both of which are critical for driver performance. This aligns with previous research suggesting that warmer tones often induce a calming effect but may detract from cognitive engagement (Mehta and Zhu, 2009). Blue lighting, on the other hand, demonstrated a tendency to enhance arousal, corroborating existing evidence linking blue light to cognitive stimulation and heightened wakefulness (Cajochen et al., 2005). Yet, its neutral impact on pleasure and dominance suggests that it may lack the capacity to balance comfort with alertness comprehensively. Green lighting showed minimal impact across all PAD dimensions, further emphasizing its role as a neutral influence on both emotional comfort and attentiveness. The dark condition, serving as a baseline, revealed negligible changes in PAD scores, highlighting that the absence of lighting neither significantly alleviates stressors nor enhances cognitive readiness during night-time driving.

The EEG analysis provided deeper insights into the physiological underpinnings of these subjective experiences, particularly in the context of brainwave activity across different frequency bands. Blue lighting demonstrated lower alpha power compared to the dark condition, signifying enhanced alertness and reduced relaxation. This finding aligns with previous studies highlighting the stimulating effects of blue light on cortical activity (Chellappa et al., 2011). However, the relatively stable beta power across all conditions suggests that none of the tested lighting schemes substantially boosted cognitive alertness or engagement, a critical limitation given the demands of night-time driving. Green and pink lighting, while promoting relaxation through elevated alpha activity, lacked the physiological indicators necessary for sustained attentiveness. Interestingly, theta and delta power remained low and stable across all conditions, indicating that none of the lighting configurations induced drowsiness or deep relaxation. This result is encouraging from a safety perspective, as it suggests that coloured lighting can enhance comfort without compromising drivers' alertness levels. These findings, while insightful, must be contextualized within the broader framework of human-centred design and automotive innovation.

The study's controlled VR environment allowed for consistent and repeatable conditions, providing robust data on how lighting schemes affect driver psychology and physiology. However, the limitations of this approach should not be overlooked. For instance, the ecological validity of VR simulations remains a contested issue, as real-world driving involves a multitude of dynamic factors that are difficult to replicate in controlled environments (De Winter et al., 2012). Moreover, the sample size of 24 participants, while adequate for psychophysical studies, limits the generalizability of the findings. The reliance on a homogenous group of individuals with normal colour vision also raises questions about the applicability of these results to more diverse populations, including those with colour vision deficiencies or different cultural perceptions of colour. The practical implications of these findings are significant but must be critically evaluated. Blue lighting emerges as the most effective for maintaining driver alertness, making it a promising option for night-time driving scenarios. However, its limited impact on pleasure and dominance suggests that it may need to be supplemented with other design elements to balance functionality with user experience. Pink and green lighting, while less effective in enhancing alertness, show potential for fostering comfort and improving perceived interior aesthetics. These insights align with the growing emphasis on multi-sensory design in automotive interiors, where lighting is increasingly integrated with other sensory modalities to create cohesive and engaging experiences (Spence, 2020). Nevertheless, the findings also highlight the challenges of optimizing in-car lighting systems. The lack of significant changes in beta power across conditions suggests that lighting alone may not be sufficient to sustain cognitive engagement during prolonged driving. This limitation points to the need for more sophisticated lighting strategies, such as dynamic or adaptive systems that respond to changes in driver state and environmental conditions. For example, lighting systems that dynamically adjust intensity and colour temperature based on EEG feedback could provide more targeted support for driver alertness and comfort. Such innovations, while technically feasible, raise questions about feasibility, cost, and user acceptability, particularly in mainstream automotive markets. In addition, the findings raise critical questions about the potential trade-offs between comfort and safety in automotive lighting design. While pink and green lighting enhance comfort and aesthetic appeal, their limited impact on alertness could render them less suitable for high-demand driving scenarios. Conversely, blue lighting, despite its benefits for alertness, may lack the warmth and engagement necessary for a truly human-centred design approach. These trade-offs underscore the complexity of integrating lighting into vehicles in ways that meet both functional and experiential needs. From a theoretical perspective, the results contribute to the broader discourse on the psychological and physiological effects of environmental lighting.

The study bridges gaps in the existing literature by combining subjective and objective measures, offering a holistic understanding of how coloured lighting affects driver performance and well-being. However, it also highlights the need for further research to uncover the nuanced interactions between lighting, emotion, and cognition. Future studies could explore larger and more diverse samples, varied lighting intensities and durations, and the integration of other sensory stimuli to build on these findings. The role of individual differences, such as age, gender, and cultural background, should also be examined to ensure that lighting systems are inclusive and adaptable to a wide range of users. In conclusion, this chapter provides valuable insights into the psychological and physiological effects of in-vehicle coloured lighting during night-time driving. While blue lighting shows promise for enhancing alertness, and pink and green lighting improve comfort and aesthetics, the findings reveal critical limitations and trade-offs that must be addressed in future research and design. By advancing our understanding of how lighting influences driver psychology and physiology, this study contributes to the development of more effective and human-centred automotive lighting systems. However, the complexities of real-world application and the challenges of balancing safety with comfort highlight the need for continued innovation and critical inquiry in this field.

Chapter 7 Discussion

This thesis presents an in-depth exploration of the interplay between in-car lighting design and its psychological and physiological effects on drivers, particularly under the demanding conditions of night-time driving. By integrating data-driven methodologies, controlled experimental approaches, and mixed-method data collection, the research addresses significant gaps in the understanding of how lighting influences driver safety, comfort, and overall well-being. Through a design methodological lens, this study advances the application of human-centred design principles, employing computational tools like machine learning and immersive technologies like VR to connect theoretical insights with practical automotive applications. However, a critical evaluation of these methods reveals strengths, limitations, and opportunities for future exploration, providing a nuanced perspective on this emergent field.

The methodological framework of this thesis exemplifies a quantitative, mixed-methods approach that prioritizes replicability, objectivity, and ecological validity. The initial phase employed K-means clustering, a computational technique widely recognized in design research for its efficiency in uncovering patterns within large datasets. This approach enabled the identification of dominant colour schemes in automotive interiors from a dataset of 174 images, offering a quantitative foundation for subsequent experimental investigations. While innovative, this method is not without limitations. The reliance on publicly available images introduces potential biases, as the dataset may lack representation of diverse cultural and market-specific design preferences. Moreover, while clustering effectively identifies trends, it lacks the contextual depth required to fully understand user preferences, aesthetic perceptions, or cultural influences on colour choice (Palmer et al., 2013). Future research could address these gaps by integrating participatory design techniques or ethnographic studies, which provide richer, user-centered insights into the contextual nuances of colour perception.

The experimental phase leveraged VR to simulate night-time driving scenarios, providing a controlled yet immersive platform to evaluate the psychological and physiological effects of different lighting conditions. VR technology is a powerful tool in design research, offering high ecological validity while ensuring participant safety during potentially hazardous conditions such as night-time driving. Consistent with prior studies validating VR's utility in simulating real-world environments (Kuliga et al., 2015), this study effectively replicated the visual and spatial dimensions of driving, enabling precise control over experimental variables such as lighting hue and intensity. Nonetheless, VR displays inevitably differ from real-world environments in terms of luminance, contrast, and colour rendering, which may affect visual adaptation and colour perception. This limitation is inherent to all VR-based research, and in the present study it was mitigated by applying the same calibrated settings across all participants, ensuring valid relative comparisons. More broadly, VR's inability to replicate multisensory stimuli, such as road vibrations or ambient sounds, further constrains its capacity to fully capture the real-world driving experience. These methodological considerations highlight the importance of complementing VR experiments with field studies to validate findings under dynamic, real-world conditions.

From a methodological perspective, the integration of subjective and objective measures represents a key strength of this research. Subjective assessments, such as self-reported comfort levels and emotional states measured through the PAD scale, provided insights into participants' personal experiences with different lighting conditions. These findings were augmented by objective physiological metrics, including EEG and heart rate variability, which offered deeper insights into the neural and autonomic responses underlying these experiences. This mixed-method approach aligns with best practices in human-centered design research, emphasizing the triangulation of data sources to capture the complexity of user experiences (Zimmerman et al., 2007). Nonetheless, reliance on self-reported data introduces potential biases, such as social desirability effects or variability in participants' interpretations of survey items. While EEG data mitigates some of these biases by offering objective neural correlates, the analysis of brainwave activity also presents challenges, including the difficulty of isolating lighting effects from individual differences or baseline cognitive states.

The findings reveal complex and nuanced relationships between lighting conditions and driver responses, with significant implications for both design theory and practical application. Blue lighting was identified as the most effective in maintaining alertness, corroborating existing research on the stimulating properties of short-wavelength light (Chellappa et al., 2011; Cajochen et al., 2005). This effect was statistically supported by significantly higher alertness scores under blue lighting compared with the dark condition ($p = .04$; see Figure 6.8), as well as increased beta-band EEG activity, indicating greater cortical arousal. Also, it is consistent with findings in other contexts, such as workplaces and healthcare settings, where blue light has been shown to improve cognitive performance and reduce fatigue (Viola et al., 2008; Smolders and de Kort, 2014). However, its minimal impact on emotional comfort highlights a key trade-off. While blue light supports sustained focus, critical for high-demand driving tasks, it may fail to create a relaxing or welcoming ambiance, potentially detracting from its suitability in scenarios where emotional well-being and comfort are prioritized, such as leisure driving or passenger experiences. This trade-off aligns with earlier studies that underscore the potential for blue light to induce cognitive strain with prolonged exposure, especially in environments requiring a balance between functionality and comfort (Lunn et al., 2017).

Similarly, pink and green lighting demonstrated potential in enhancing emotional comfort and perceived interior quality, corroborating research that associates these hues with feelings of warmth, relaxation, and aesthetic appeal (Ou et al., 2004; Park and Farr, 2007). Pink lighting, in particular, received the highest ratings for interior quality ($M = 3.8$) and attractiveness ($M = 3.7$), often linked to soothing and restorative effects (Küller et al., 2009), performed well in creating a positive ambiance but fell short in maintaining alertness. Likewise, green lighting's association with calming and naturalistic effects (Boyce, PR and Smet, 2014) may explain its favorable ratings for emotional comfort. Nevertheless, green lighting was rated significantly lower in attractiveness ($M = 2.4$, $SD = 0.7$) and perceived safety compared with both pink and blue ($p < .05$; see Figures 6.9 and 6.12). Their weaker influence on alertness and cognitive engagement raises critical questions about their suitability for high-stakes or high-demand driving scenarios. This limitation is consistent with findings from lighting research in other domains, where green and pink light are noted for their emotional resonance but lack the physiological stimulation required to counter fatigue or maintain high levels of attentional control (Minguillon et al., 2017).

These findings echo broader challenges in design research, particularly the tension between meeting functional demands and delivering optimal experiential outcomes (Norman, 2004; Desmet and Hekkert, 2007). For example, while the design of healthcare environments emphasizes both comfort and functionality, studies have highlighted the difficulty of achieving this balance through lighting alone, often requiring the integration of multimodal stimuli (Van Hoof et al., 2021; Shukla, 2024). Similarly, automotive lighting must navigate the dual objectives of promoting safety and enhancing user experience, a challenge further complicated by individual differences in lighting preferences, cultural associations with colour, and contextual factors such as time of day or driving purpose (Mahnke, 1996). Critically, the results also underscore the importance of moving beyond a static approach to in-car lighting design. Adaptive systems, which dynamically adjust lighting parameters in response to real-time conditions or user inputs, have shown promise in reconciling these competing priorities. Studies in adaptive lighting systems in urban design and architecture, for instance, have demonstrated how dynamic lighting can enhance both functionality and ambiance, offering a model for application in automotive contexts (Gagliardi et al., 2018; Gagliardi et al., 2020). Furthermore, integrating lighting design with other sensory modalities—such as auditory or tactile cues—may provide a more holistic approach to addressing the diverse demands of drivers and passengers (Spence, 2020). In light of these findings, future research should delve deeper into the interplay between lighting and multimodal user experiences. Examining how adaptive systems and cross-sensory integrations can mitigate the limitations of single-colour lighting schemes is critical. Additionally, longitudinal studies that assess the long-term impact of specific lighting conditions on driver well-being and performance, particularly across diverse demographic groups and cultural contexts, would provide more robust evidence to guide design practice. By leveraging interdisciplinary approaches and emerging technologies, such as machine learning and real-time biofeedback systems, lighting design can evolve to better address the complex and often conflicting demands of modern driving environments.

EEG data offered valuable insights into the neural mechanisms underpinning the effects of different lighting conditions. Patterns of alpha and theta activity highlighted the relaxing properties of pink and green lighting, which aligns with prior research linking these brainwave patterns to reduced stress and enhanced emotional comfort

(Küller et al., 2009; Bazanova and Vernon, 2014). Conversely, the lower alpha power observed under blue lighting reflected its potential to sustain cognitive engagement, corroborating findings from studies on the stimulating effects of short-wavelength light on brain activity and alertness (Viola et al., 2008; Chellappa et al., 2011). However, the relative stability of beta and delta activity across conditions suggests that lighting alone may not sufficiently induce heightened alertness or deep relaxation, raising questions about its standalone efficacy in optimizing neural states for various driving contexts. These findings underscore the limitations of single-modal interventions in achieving comprehensive effects on driver well-being and performance. The stable beta and delta activity indicate that additional sensory inputs may be necessary to amplify the functional and experiential outcomes of lighting design. Integrating auditory or tactile stimuli, for instance, has been shown to complement visual inputs and enhance user engagement and comfort (Spence and Ho, 2008; Stavrinos et al., 2013). Such multimodal approaches could address the gaps observed in this study, offering a more holistic strategy for creating adaptive in-car environments tailored to diverse driving scenarios and user needs. The use of EEG, while offering rich and objective data, introduces practical challenges that merit critical consideration. The intrusiveness of the equipment, particularly in scenarios involving real-world driving, presents a barrier to its widespread application. Movement artefacts and discomfort caused by the sensors can compromise data quality, limiting the feasibility of EEG as a long-term or large-scale solution (Stavrinos et al., 2013). These constraints highlight the pressing need for the development of more user-friendly and minimally invasive physiological monitoring tools that can provide comparable insights without hindering the driving experience.

Critically, this research underscores the limitations of current automotive lighting systems, which often prioritize functional illumination over user experience. By demonstrating the psychological and physiological benefits of optimized lighting designs, this study advocates for a paradigm shift towards more adaptive and user-centered approaches in automotive design. Such systems could leverage real-time feedback from physiological sensors to dynamically adjust lighting based on drivers' cognitive and emotional states, aligning with emerging trends in adaptive vehicle technologies (Feng et al., 2020). However, implementing these systems faces challenges, including technical feasibility, standardization, and ethical considerations, such as ensuring equitable access and addressing potential over-reliance on automation. In conclusion, this thesis contributes significantly to the field of automotive ergonomics and lighting design by providing a detailed, evidence-based exploration of the effects of in-car lighting on driver well-being. By adopting a rigorous methodological approach, it advances our understanding of how lighting can be optimized to enhance safety, comfort, and alertness. However, it also highlights the complexities and trade-offs inherent in designing user-centered lighting systems, emphasizing the need for further research to address these challenges. Future studies should explore multimodal, adaptive lighting solutions that not only support functional performance but also enhance the overall driving experience, paving the way for more inclusive, dynamic, and human-centered automotive environments.

Chapter 8 Conclusion

This thesis provides a comprehensive exploration of the psychological and physiological impacts of in-car lighting under night-time driving conditions, addressing critical gaps in automotive lighting research and design. Through the integration of advanced methodologies, including machine learning, VR, and physiological data collection, the research offers evidence-based insights into how optimized lighting can enhance driver safety, comfort, and overall well-being. The findings contribute significantly to the field of automotive ergonomics and design by advancing the application of human-centred and adaptive design principles in the development of in-car environments.

The study's first phase employed machine learning techniques, specifically K-means clustering, to identify dominant colour schemes in automotive interiors. This data-driven approach offered a novel methodology for analyzing design trends and established a foundation for subsequent experimental testing. However, the limitations of relying on publicly available images and the lack of contextual depth highlight the need for more diverse datasets and user-centred qualitative methods in future research. Despite these challenges, this phase provided a valuable starting point for understanding industry practices and informed the experimental phase.

The experimental phase utilized VR to simulate night-time driving scenarios, enabling the controlled evaluation of lighting effects on drivers' psychological and physiological responses. This approach demonstrated the potential of VR as a methodological tool in design research, combining high ecological validity with the precision of experimental control. Findings from this phase revealed nuanced relationships between lighting conditions and driver responses. Blue lighting emerged as effective in maintaining alertness, while pink and green lighting enhanced emotional comfort and perceived interior quality. These insights underscore the trade-offs inherent in lighting design, emphasizing the need for adaptable solutions that balance functional and experiential goals.

The incorporation of mixed-methods data collection, combining subjective assessments with objective measures such as EEG and heart rate variability, added depth to the analysis. EEG data provided critical insights into the neural mechanisms underlying drivers' responses to lighting, revealing patterns of brain activity associated with relaxation, focus, and cognitive engagement. However, practical challenges related to the use of EEG in real-world driving scenarios highlight the need for less intrusive physiological monitoring tools in future applications.

This thesis also highlights the limitations of current automotive lighting systems, which often prioritize functionality over user experience. By demonstrating the psychological and physiological benefits of optimized lighting designs, this research advocates for a paradigm shift towards user-centred, adaptive lighting systems that dynamically respond to drivers' needs. Such systems have the potential to improve not only functional performance but also the overall driving experience, aligning with broader trends in adaptive and intelligent vehicle technologies.

While this research makes significant contributions, it also underscores areas for further inquiry. The limitations of VR in replicating the sensory richness of real-world environments and the challenges of isolating lighting effects from other variables point to the need for complementary field studies. Additionally, future research should explore multimodal approaches that integrate lighting with auditory and tactile stimuli, as well as the technical and ethical implications of adaptive systems.

In conclusion, this thesis advances the understanding of how in-car lighting can be optimized to enhance driver well-being under night-time conditions. By bridging theoretical insights with practical applications, it lays the groundwork for future innovations in adaptive, human-centred automotive design. The findings not only contribute to safer and more comfortable driving environments but also highlight the potential of emerging technologies to transform the way we design for human experiences in complex, dynamic contexts.

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Appendix A: Participant Consent Form & Ethics Approval

[Faculty of Arts,Humanities and Cultures]

UNIVERSITY OF LEEDS

Consent to take part in [Exploring the effects of coloured lighting design in alternative fuel vehicles interiors on car occupants' concentration]	Add your initials next to the statement if you agree
I confirm that I have read and understand the information letter dated [24/11/2023] explaining the above research project and I have had the opportunity to ask questions about the project.	
I understand that my participation is voluntary and that I am free to withdraw [at any time without giving any reason/ until [date]and without there being any negative consequences. In addition, should I not wish to answer any particular question or questions, I am free to decline. [If you drop out of the experiment, we will not retain any of your information.]	
I understand that members of the research team may have access to my anonymised responses. I understand that my name will not be linked with the research materials, and I will not be identified or identifiable in the report or reports that result from the research. I understand that my responses will be kept strictly confidential.	
I understand that the data collected from me may be stored and used in relevant future research in an anonymised form or I understand that the data I provide may be archived at name of archive.	
I understand that relevant sections of the data collected during the study, may be looked at by individuals from the University of Leeds or from regulatory authorities where it is relevant to my taking part in this research.	
I agree to take part in the above research project and will inform the lead researcher should my contact details change.	

Name of participant	
Participant's signature	
Date	
Name of lead researcher	Qian Cheng
Signature	
Date*	

*To be signed and dated in the presence of the participant.
Once this has been signed by all parties the participant should receive a copy of the signed and dated participant consent form, the letter/ pre-written script/ information sheet and any other written information provided to the participants. A copy of the signed and dated consent form should be kept with the project's main documents which must be kept in a secure location.

Template last updated 15/05/19 Page 1 of 1

Figure A.1 Participant Consent Form

Dear Qian,

FAHC 23-046 - Exploring the effects of coloured lighting design in alternative fuel vehicles interiors on car occupants' concentration

I am pleased to inform you that the above research ethics application has been reviewed by Faculty of Arts, Humanities and Cultures Research Ethics Committee and I can confirm a favourable ethical opinion based on the documentation received at date of this email.

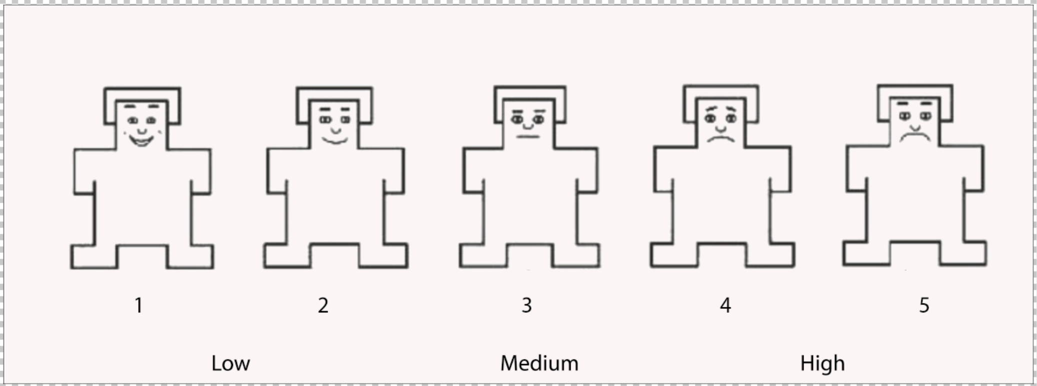
The reviewers had some comments for your consideration which are below, these do not impact your approval. If you decide to update any documents in response to these comments, please submit these to this email address for storage.

1. *The applicant could consider the need for aftercare, in the unlikely event that one of the eight participants requires it after taking part in the experiment(s).*

Please retain this email as evidence of approval in your study file.

Figure A.2 Ethics Approval

Appendix B: Questionnaires

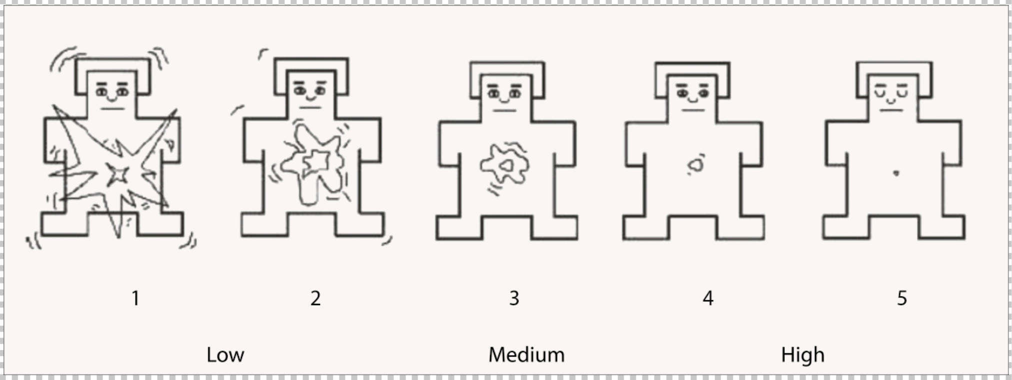


Pleasure

Meaning: This meaures how happy or unhappy you are in the car now.

Lowest Point: Very happy or pleased.

Highest Point: Very unhappy or pleased.

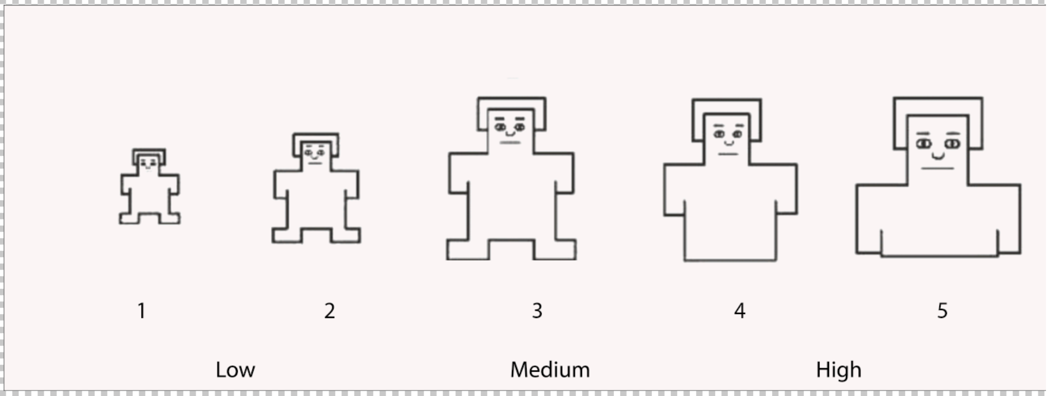


Arousal

Meaning: This mgauges how excited or calm you feel right now.

Lowest Point: Very excited or stimulated, possibly even nervious.

Highest Point: Very calm or relaxed, possibly even bored.



Dominance

Meaning: This assesses how in control or controlled you feel by the car's interior right now

Lowest Point: Feeling very controlled, as if you have no power

Highest Point: Feeling very in control, as if you are the one in charge.

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Figure B.1 PAD Questionnaire

Questions	Element (−5)	Element (5)	Marks										
			−5	−4	−3	−2	−1	0	1	2	3	4	5
1	Distracts me from driving	Keeps my attention on the driving											
2	Complicates concentration	Enables concentration											
3	Makes me tired	Activates me											
4	Makes me sleepy	Energizes me											
5	Has a really unpleasant light colour	Has a really pleasant light colour											
6	Is visually uncomfortable	Is visually comfortable											
7	I really disliked	I really liked											
8	Causes a small impression of interior space	Causes a big impression of interior space											
9	Looks cheap	Looks luxurious											
10	Gives a lesser quality impression	Gives a good quality impression											
11	Complicates the finding of other controls in the car interior	Facilitates the finding of other controls in the car interior											
12	Decreases the perceived safety	Increases the perceived safety											
13	Driving unconfidently	Driving confidently											

Figure B.2 Subjective questionnaire

Appendix C: Original Research Data

Multiple Comparisons

Dependent Variable: Driving_Attention

	(I) Coloured_Lights	(J) Coloured_Lights	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
Tukey HSD	Dark	Pink	-.27083	.34909	.865	-1.1716	.6300
		Green	.81250	.34909	.094	-.0883	1.7133
		Blue	.09375	.34909	.993	-.8071	.9946
	Pink	Dark	.27083	.34909	.865	-.6300	1.1716
		Green	1.08333*	.34909	.011	.1825	1.9841
		Blue	.36458	.34909	.723	-.5362	1.2654
	Green	Dark	-.81250	.34909	.094	-1.7133	.0883
		Pink	-1.08333*	.34909	.011	-1.9841	-.1825
		Blue	-.71875	.34909	.169	-1.6196	.1821
	Blue	Dark	-.09375	.34909	.993	-.9946	.8071
		Pink	-.36458	.34909	.723	-1.2654	.5362
		Green	.71875	.34909	.169	-.1821	1.6196
LSD	Dark	Pink	-.27083	.34909	.438	-.9572	.4156
		Green	.81250*	.34909	.020	.1261	1.4989
		Blue	.09375	.34909	.788	-.5926	.7801
	Pink	Dark	.27083	.34909	.438	-.4156	.9572
		Green	1.08333*	.34909	.002	.3969	1.7697
		Blue	.36458	.34909	.297	-.3218	1.0510
	Green	Dark	-.81250*	.34909	.020	-1.4989	-.1261
		Pink	-1.08333*	.34909	.002	-1.7697	-.3969
		Blue	-.71875*	.34909	.040	-1.4051	-.0324
	Blue	Dark	-.09375	.34909	.788	-.7801	.5926
		Pink	-.36458	.34909	.297	-1.0510	.3218
		Green	.71875*	.34909	.040	.0324	1.4051

Figure C.1 Original Data for Alertness subjective questions

Multiple Comparisons							
Dependent Variable: Interior_Attractiveness							
	(I) colours	(J) colours	Mean Difference (I–J)	Std. Error	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
Tukey HSD	Dark	Pink	-.84722	.43574	.212	-1.9733	.2789
		Green	.98611	.43574	.109	-.1400	2.1122
		Blue	-.23611	.43574	.949	-1.3622	.8900
	Pink	Dark	.84722	.43574	.212	-.2789	1.9733
		Green	1.83333*	.43574	<.001	.7073	2.9594
		Blue	.61111	.43574	.499	-.5150	1.7372
	Green	Dark	-.98611	.43574	.109	-2.1122	.1400
		Pink	-1.83333*	.43574	<.001	-2.9594	-.7073
		Blue	-1.22222*	.43574	.027	-2.3483	-.0961
	Blue	Dark	.23611	.43574	.949	-.8900	1.3622
		Pink	-.61111	.43574	.499	-1.7372	.5150
		Green	1.22222*	.43574	.027	.0961	2.3483
LSD	Dark	Pink	-.84722	.43574	.053	-1.7049	.0105
		Green	.98611*	.43574	.024	.1284	1.8438
		Blue	-.23611	.43574	.588	-1.0938	.6216
	Pink	Dark	.84722	.43574	.053	-.0105	1.7049
		Green	1.83333*	.43574	<.001	.9756	2.6910
		Blue	.61111	.43574	.162	-.2466	1.4688
	Green	Dark	-.98611*	.43574	.024	-1.8438	-.1284
		Pink	-1.83333*	.43574	<.001	-2.6910	-.9756
		Blue	-1.22222*	.43574	.005	-2.0799	-.3645
	Blue	Dark	.23611	.43574	.588	-.6216	1.0938
		Pink	-.61111	.43574	.162	-1.4688	.2466
		Green	1.22222*	.43574	.005	.3645	2.0799

Figure C.2 Original Data for Interior Attractiveness subjective questions

Multiple Comparisons

Dependent Variable: Perceived_Interiorquality

	(I) colour	(J) colour	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
Tukey HSD	Dark	Pink	-1.68750*	.48323	.003	-2.9401	-.4349
		Green	.95833	.48323	.198	-.2943	2.2109
		Blue	-1.25000	.48323	.051	-2.5026	.0026
	Pink	Dark	1.68750*	.48323	.003	.4349	2.9401
		Green	2.64583*	.48323	<.001	1.3932	3.8984
		Blue	.43750	.48323	.802	-.8151	1.6901
	Green	Dark	-.95833	.48323	.198	-2.2109	.2943
		Pink	-2.64583*	.48323	<.001	-3.8984	-1.3932
		Blue	-2.20833*	.48323	<.001	-3.4609	-.9557
	Blue	Dark	1.25000	.48323	.051	-.0026	2.5026
		Pink	-.43750	.48323	.802	-1.6901	.8151
		Green	2.20833*	.48323	<.001	.9557	3.4609
LSD	Dark	Pink	-1.68750*	.48323	<.001	-2.6408	-.7342
		Green	.95833*	.48323	.049	.0051	1.9116
		Blue	-1.25000*	.48323	.010	-2.2033	-.2967
	Pink	Dark	1.68750*	.48323	<.001	.7342	2.6408
		Green	2.64583*	.48323	<.001	1.6926	3.5991
		Blue	.43750	.48323	.366	-.5158	1.3908
	Green	Dark	-.95833*	.48323	.049	-1.9116	-.0051
		Pink	-2.64583*	.48323	<.001	-3.5991	-1.6926
		Blue	-2.20833*	.48323	<.001	-3.1616	-1.2551
	Blue	Dark	1.25000*	.48323	.010	.2967	2.2033
		Pink	-.43750	.48323	.366	-1.3908	.5158
		Green	2.20833*	.48323	<.001	1.2551	3.1616

Figure C.3 Original Data for Perceived Interior Quality subjective questions

Controls	Tukey HSD	Dark	Pink	-1.4167	.78268	.275	-3.4646	.6313
			Green	-.5833	.78268	.878	-2.6313	1.4646
			Blue	-2.1250*	.78268	.039	-4.1730	-.0770
		Pink	Dark	1.4167	.78268	.275	-.6313	3.4646
			Green	.8333	.78268	.712	-1.2146	2.8813
			Blue	-.7083	.78268	.802	-2.7563	1.3396
		Green	Dark	.5833	.78268	.878	-1.4646	2.6313
			Pink	-.8333	.78268	.712	-2.8813	1.2146
			Blue	-1.5417	.78268	.207	-3.5896	.5063
		Blue	Dark	2.1250*	.78268	.039	.0770	4.1730
			Pink	.7083	.78268	.802	-1.3396	2.7563
			Green	1.5417	.78268	.207	-.5063	3.5896
	LSD	Dark	Pink	-1.4167	.78268	.074	-2.9711	.1378
			Green	-.5833	.78268	.458	-2.1378	.9711
			Blue	-2.1250*	.78268	.008	-3.6795	-.5705
		Pink	Dark	1.4167	.78268	.074	-.1378	2.9711
			Green	.8333	.78268	.290	-.7211	2.3878
			Blue	-.7083	.78268	.368	-2.2628	.8461
		Green	Dark	.5833	.78268	.458	-.9711	2.1378
			Pink	-.8333	.78268	.290	-2.3878	.7211
			Blue	-1.5417	.78268	.052	-3.0961	.0128
		Blue	Dark	2.1250*	.78268	.008	.5705	3.6795
			Pink	.7083	.78268	.368	-.8461	2.2628
			Green	1.5417	.78268	.052	-.0128	3.0961
	Dunnett T3	Dark	Pink	-1.4167	.80289	.400	-3.6230	.7896
			Green	-.5833	.82952	.979	-2.8603	1.6936
			Blue	-2.1250	.82161	.074	-4.3808	.1308
		Pink	Dark	1.4167	.80289	.400	-.7896	3.6230
			Green	.8333	.74170	.834	-1.2015	2.8681
			Blue	-.7083	.73285	.909	-2.7186	1.3019
		Green	Dark	.5833	.82952	.979	-1.6936	2.8603
			Pink	-.8333	.74170	.834	-2.8681	1.2015
			Blue	-1.5417	.76193	.253	-3.6315	.5481
		Blue	Dark	2.1250	.82161	.074	-.1308	4.3808
			Pink	.7083	.73285	.909	-1.3019	2.7186
			Green	1.5417	.76193	.253	-.5481	3.6315
	Games-Howell	Dark	Pink	-1.4167	.80289	.304	-3.5604	.7271
			Green	-.5833	.82952	.895	-2.7960	1.6293
			Blue	-2.1250	.82161	.060	-4.3171	.0671
		Pink	Dark	1.4167	.80289	.304	-.7271	3.5604
			Green	.8333	.74170	.677	-1.1441	2.8108
			Blue	-.7083	.73285	.769	-2.6620	1.2453
		Green	Dark	.5833	.82952	.895	-1.6293	2.7960
			Pink	-.8333	.74170	.677	-2.8108	1.1441
			Blue	-1.5417	.76193	.194	-3.5726	.4893
		Blue	Dark	2.1250	.82161	.060	-.0671	4.3171
			Pink	.7083	.73285	.769	-1.2453	2.6620
			Green	1.5417	.76193	.194	-.4893	3.5726
	Dunnett t (2-sided)[a]	Dark	Blue	-2.1250*	.78268	.022	-3.9944	-.2556
		Pink	Blue	-.7083	.78268	.692	-2.5777	1.1610
		Green	Blue	-1.5417	.78268	.129	-3.4110	.3277

Figure C.4 Original Data for Functionality subjective questions

Multiple Comparisons							
Dependent Variable: Perceived_Safety							
	(I) colours	(J) colours	Mean Difference (I–J)	Std. Error	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
Tukey HSD	1.00	2.00	-.27083	.51829	.954	-1.6143	1.0727
		3.00	1.29167	.51829	.064	-.0518	2.6352
		4.00	-.02083	.51829	1.000	-1.3643	1.3227
	2.00	1.00	.27083	.51829	.954	-1.0727	1.6143
		3.00	1.56250*	.51829	.015	.2190	2.9060
		4.00	.25000	.51829	.963	-1.0935	1.5935
	3.00	1.00	-1.29167	.51829	.064	-2.6352	.0518
		2.00	-1.56250*	.51829	.015	-2.9060	-.2190
		4.00	-1.31250	.51829	.058	-2.6560	.0310
	4.00	1.00	.02083	.51829	1.000	-1.3227	1.3643
		2.00	-.25000	.51829	.963	-1.5935	1.0935
		3.00	1.31250	.51829	.058	-.0310	2.6560
LSD	1.00	2.00	-.27083	.51829	.602	-1.2932	.7516
		3.00	1.29167*	.51829	.014	.2693	2.3141
		4.00	-.02083	.51829	.968	-1.0432	1.0016
	2.00	1.00	.27083	.51829	.602	-.7516	1.2932
		3.00	1.56250*	.51829	.003	.5401	2.5849
		4.00	.25000	.51829	.630	-.7724	1.2724
	3.00	1.00	-1.29167*	.51829	.014	-2.3141	-.2693
		2.00	-1.56250*	.51829	.003	-2.5849	-.5401
		4.00	-1.31250*	.51829	.012	-2.3349	-.2901
	4.00	1.00	.02083	.51829	.968	-1.0016	1.0432
		2.00	-.25000	.51829	.630	-1.2724	.7724
		3.00	1.31250*	.51829	.012	.2901	2.3349

Figure C.5 Original Data for Perceived Safety subjective questions

Original data for subjective questionary can be found via:

https://leeds365-my.sharepoint.com/:f:/g/personal/ee20qc_leeds_ac_uk/EpWkTjHTAJlNvLxAobwbFa8BT98GoXxnpCqNGJnbLdAdcg?e=MWPsSA

Video records for VR driving tests:

https://leeds365-my.sharepoint.com/:f:/g/personal/ee20qc_leeds_ac_uk/Epbj_H_lMkRGkn-xSpuolPcBRFCUR1BHS2hTKf9llMys1g?e=pnFlYh

Appendix D: Publication

Conference paper: Cheng, Q., Xia, G., Henry, P., & Yu, L., 2024. Exploring in-car lighting design: A data-driven and evidence-based analysis of colour choices and driver safety. In *AIC 2024 Midterm Meeting Color Design, Communication and Marketing*, São Paulo, Brazil. Paper related to this thesis.

A Critical Analysis of In-car Lighting Design and Its Impact on Driver Alertness under Nocturnal Conditions

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Abstract

Driving at night presents greater challenges and risks than daytime driving, largely due to reduced visibility and the need for heightened attention and reaction capabilities (Abdulla et al., 2023). A comprehensive understanding of drivers' eye movements and how attention is distributed during nocturnal driving episodes is vital. Such insights could significantly inform the development and refinement of in-vehicle lighting technologies, enhancing safety in conditions mirroring night driving. Despite its importance, the understanding of drivers' precise gaze fixations and attention allocation under nocturnal conditions remains scant.

The ambient lighting within a vehicle's interior plays a pivotal role in influencing a driver's mood and attentiveness, factors critical to safe driving. Consequently, the investigation of in-car lighting colour schemes is of paramount importance. This study explores the prevalent colour choices in car interior lighting, utilizing a corpus of images acquired from the internet. We systematically compare our observations against the backdrop of established colour psychology, aiming to scrutinize the rationale and impact behind the selection of specific lighting colours within vehicles. Through the use of the Fatkun image downloader, we amassed a collection of 274 images, from which irrelevant material was diligently removed to ensure the focus and integrity of our analysis.

Employing MATLAB for data processing, we applied the K-means clustering algorithm to categorically identify and quantify the 10 most dominant colours featured in our dataset. This approach, aligned with human colour perception principles, allowed for the aggregation of colour data into coherent groups, facilitating the identification of predominant colour trends. Initial analysis revealed a preference for blue and purple hues in car interiors, a finding that necessitates a deeper exploration into the implications of such colour choices on driver well-being and vehicular safety.

Our research contributes to the broader discourse on automotive interior design, particularly in the context of night driving safety. By illuminating current trends in vehicle lighting colour selection and their potential psychological impacts, this study lays the groundwork for further inquiries into how strategic colour utilization within vehicles can enhance driving safety and overall passenger experience. This research will also provide a basis for coloured lighting selection for our experimental studies.

Keywords: *car interior lighting, road safety, driver attention, human-centric lighting design*