Roadway Illumination Level Assessment for Driver Safety and Comfort: A Multimodal Human Factors Evaluation of Visual Behavior, Physiological Arousal, and Driving Performance in a High-Fidelity Driving Simulator

by

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Author's Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

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Abstract

Nighttime driving remains a major road safety concern because reduced illumination can impair visibility, delay hazard detection, and increase visual strain. Although roadway lighting is intended to improve safety, greater brightness does not always produce better driving conditions. Excessive illumination may introduce glare, discomfort, and unnecessary energy use without meaningfully improving driver response. This thesis investigates how different nighttime illuminance levels influence driver safety and comfort by examining their relationship with multimodal safety-related measures, with the aim of identifying the illumination level that best supports visual detection, driving performance, physiological stability, and perceived visibility, comfort, and safety.

A controlled mixed-design experiment was led in a high-fidelity virtual driving simulator using a replicated real-world street environment under three nighttime illuminance levels, low, medium, and high, established in accordance with roadway lighting standards. Thirty licensed drivers participated in the study, equally divided between younger adults aged 20 to 45 years and older adults aged 65 years and above. Driver response was evaluated using a multimodal framework integrating eye-tracking (Time to First Fixation (TTFF), Dwell Time), simulator-based driving measures (PRT, Speed, Hazard-related Deceleration), physiological markers (Heart Rate (HR), Electrodermal Activity (EDA)), subjective ratings of perceived visibility, comfort, and safety, and qualitative feedback.

The results showed a clear relationship between illuminance level and driver response. Low illuminance was associated with delayed visual detection, slower hazard response, higher physiological arousal, and poorer ratings of visibility, comfort, and safety. Increasing illuminance from low to medium improved TTFF and PRT, enhanced perceived visibility and comfort, and supported greater physiological stability, whereas increasing illuminance from medium to high produced little additional benefit and occasionally introduced glare-related discomfort. Older adults showed higher physiological arousal and more conservative braking behavior than younger adults, but both age groups followed the same overall pattern across illuminance levels.

Overall, the findings show that effective nighttime roadway lighting is not achieved by maximizing brightness, but by selecting an illumination level that supports visual effectiveness, driver response, comfort, and physiological stability. Among the conditions examined, medium illuminance provided the most favorable overall balance for safer and more efficient driving. These findings provide practical guidance for roadway lighting design and planning by suggesting that moderate illumination may offer the most effective balance between safety, comfort, and physiological stability.

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Dedication

This thesis is dedicated to my beloved family. Your love has been the foundation of every step of this journey. To my parents, thank you for your sacrifices, your faith in me, and the strength you instilled in me from the very beginning. To my husband, thank you for your patience, love, and unwavering belief. To my children, you are the light of my life and my deepest source of joy, motivation, and strength. This work belongs to all of you as much as it does to me.

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List of Abbreviations

Abbreviation	Definition
AVRIL	Autonomous Vehicle Research and Intelligence Laboratory
DBQ	Driver Behavior Questionnaire
EDA	Electrodermal Activity
GPS	Global Positioning System
HR	Heart Rate
LiDAR	Light Detection and Ranging
MSSQ-Short	Motion Sickness Susceptibility Questionnaire, Short Form
PPG	Photoplethysmography
PRT	Perception Response Time
REB	Research Ethics Board
SCL	Skin Conductance Level
TTFF	Time to First Fixation

CHAPTER 1

Introduction

1.1 Motivation

Nighttime driving remains one of the most hazardous conditions in road transportation, with collision and fatality rates per distance traveled substantially higher than during daytime conditions [1], [2], [3], [4]. Reduced illumination degrades contrast sensitivity, target detection, and hazard recognition, directly impairing drivers' ability to respond safely to road stimuli [5], [6], [7]. These visual constraints pose significant safety concerns for vulnerable road users, particularly cyclists and pedestrians, who experience a disproportionately higher risk of involvement in nighttime collisions [2], [5], [8].

Nighttime driving risk is strongly shaped by mesopic visual conditions, where reduced luminance limits visual acuity, contrast perception, and hazard detection, with these effects becoming more pronounced in the presence of age-related visual decline or other visual impairments [9], [10], [11]. Simulated visual impairment studies have shown that even modest reductions in visual capability can substantially worsen nighttime driving performance, including sign recognition, hazard avoidance, and pedestrian detection [9]. Together, these findings show that nighttime driving safety is closely tied to the quality and adequacy of roadway illumination [3], [9], [11].

Despite this well-established relationship between illumination and performance, nighttime driving safety cannot be explained by visibility alone. Drivers frequently overestimate their visual capabilities under low-light conditions and do not always adopt adequate compensatory behaviors, such as reducing speed or increasing visual scanning [12], [13]. At the same time, roadway lighting practice often assumes that increasing brightness will improve safety, even though excessive illumination may also introduce glare, discomfort, and cognitive strain.

Prior research has shown that reduced lighting can impair speed control, lane keeping, and stimulus recognition, yet the physiological and perceptual mechanisms underlying these effects remain insufficiently understood. In particular, the extent to which different illumination levels influence autonomic arousal, gaze behavior, and perceived visual comfort has not been systematically examined under controlled nighttime driving conditions[3], [13], [14] This limitation is important because safe nighttime driving

depends not only on whether hazards are visible, but also on how drivers visually process the environment, how they physiologically respond to it, and how comfortable and confident they feel while driving.

This gap limits the development of lighting systems that are aligned with human visual and cognitive capabilities. A clearer understanding of drivers' physiological, visual, and perceptual responses to varying illumination levels is therefore essential for informing evidence-based roadway lighting design and improving nighttime driving safety, particularly for aging populations who experience amplified declines in mesopic visual function and increased glare sensitivity [2], [3], [12], [13].

1.2 Research Objectives

The purpose of this study was to investigate how nighttime roadway illumination influences driver response within a controlled, high-fidelity virtual driving environment. Specifically, the study examined whether different illumination levels affect physiological activation, visual attention, subjective perceptual experience, and objective driving performance, and whether these effects differ between younger and older adult drivers. Informed by the literature reviewed in Chapter 2, the study was designed to address the need for an integrated, multimodal assessment of nighttime driving under realistic simulated roadway conditions.

The specific objectives were to:

1. Evaluate physiological response by examining whether low, medium, and high illumination levels influence autonomic activation, as reflected in Heart Rate (HR) and Electrodermal Activity (EDA).
2. Assess visual attention and driving performance by examining how illumination level influences hazard-related visual attention and driving response, measured using Time to First Fixation (TTFF), dwell time, Perception Response Time (PRT), pre-hazard speed, and hazard-related deceleration.
3. Assess subjective perceptual response by examining participants' ratings of visibility, comfort, and safety under each illumination condition, supported by qualitative feedback related to clarity, glare, and ease of driving.
4. Examine age-related differences by comparing the physiological, visual, perceptual, and driving-performance responses of younger and older adults across the three illumination conditions.
5. Determine whether illumination effects follow a non-linear pattern by examining whether improvements across the measured outcomes occur primarily from low to medium illumination, with comparatively smaller changes from medium to high illumination.

6. Identify the illumination condition that provides the most favorable overall balance of visual effectiveness, driving response, physiological stability, and perceived comfort through an integrated interpretation of the multimodal findings.

1.3 Research Hypotheses

This study was guided by the following hypotheses regarding the effects of nighttime roadway illumination on physiological response, subjective perception, visual behavior, and driving performance in a controlled virtual driving environment:

- H1. Illumination level will significantly influence autonomic response, as reflected in HR and EDA.
- H2. Changes in physiological response across illumination levels will not necessarily be linear, suggesting that increases in illumination may produce diminishing effects beyond a certain level.
- H3. Subjective ratings of visibility, comfort, and safety will differ across illumination conditions, with higher illumination generally expected to be associated with more favorable ratings.
- H4. Participants' qualitative descriptions of visibility, glare, and ease of driving will be broadly consistent with the quantitative subjective ratings across illumination conditions.
- H5. Lower illumination will be associated with less efficient visual behavior, reflected in longer TTFF and longer dwell time relative to higher illumination conditions.
- H6. Lower illumination will be associated with poorer driving performance, reflected in longer Perception Response Time (PRT), weaker hazard response, and less appropriate speed adaptation relative to higher illumination conditions.
- H7. Older adults will demonstrate greater physiological demand and more cautious or altered driving responses than younger adults across illumination conditions.
- H8. The effects of illumination on physiological response, visual behavior, subjective perception, and driving performance may differ in magnitude between younger and older adults.
- H9. Patterns observed across physiological, subjective, visual, and driving-performance measures will collectively help identify which illumination condition provides the most supportive overall driving environment.

1.4 Thesis Overview

The remainder of this thesis is organized as follows:

- Chapter 2 reviews the literature relevant to nighttime driving, including nighttime vision, roadway illumination, aging and visibility, simulator-based driving research, eye-tracking and visual behavior, and physiological measurement in driving studies.
- Chapter 3 describes the study methodology, including participant recruitment, experimental design, simulator environment, illumination conditions, physiological instrumentation, eye-tracking systems, and the procedures used for collecting and processing subjective, physiological, visual, and behavioral data.
- Chapter 4 outlines the analytical approach used to evaluate physiological, visual, kinematic, subjective, and qualitative outcomes, including the statistical procedures used to assess the effects of illumination and age-group differences.
- Chapter 5 presents the study findings across all outcome domains and discusses their implications for roadway lighting and driver safety. It also addresses the study limitations and provides recommendations for future research.

CHAPTER 2

Literature Review

2.1 Introduction

This chapter reviews the literature relevant to nighttime driving and roadway illumination, with emphasis on human vision under low-light conditions, driver performance, visual attention, physiological and subjective response, and simulator-based research. It also considers age-related differences in nighttime driving and the role of spatially accurate virtual environments in improving simulator realism. The chapter concludes by identifying the key research gaps that motivate the present study.

2.2 Human Vision and Perception at Night

Nighttime driving presents a substantially greater visual challenge than daytime driving and is associated with higher crash and fatality risk, particularly for vulnerable road users such as cyclists and pedestrians [3], [4], [13]. A central reason for this increased risk is the marked reduction in usable visual information under low illumination. As luminance decreases, contrast is reduced, detection distances become shorter, and hazards are recognized later, limiting the time available for safe driving responses [2], [3]. These limitations affect the detection of critical roadway elements, including lane boundaries, road signs, pedestrians, and other hazards, thereby increasing visual demand during nighttime driving [3], [15].

Nighttime driving commonly occurs under mesopic lighting conditions, in which both rod and cone photoreceptors contribute to visual perception. Under these conditions, drivers generally experience reduced visual acuity, lower contrast sensitivity, and slower visual processing than under daytime conditions[12], [16], [17]. As a result, the ability to detect and interpret visual stimuli declines, with important consequences for hazard recognition and safe vehicle control [3], [13]. These limitations tend to intensify with age, as older adults often exhibit poorer nighttime visual acuity and increased sensitivity to glare, both of which can impair nighttime driving performance [12], [18], [19]. These limitations may be further compounded by age-related cognitive changes, such as slower processing speed and reduced attentional capacity, which also play an important role in hazard perception during nighttime driving [20], [21], [22]. In this context, conventional photopic visual acuity measures are often insufficient for evaluating nighttime driving ability, whereas mesopic visual acuity and glare sensitivity appear to be more relevant

indicators. This distinction is important because standard daytime visual assessments may fail to capture the functional limitations drivers experience under nighttime roadway illumination [12], [18], [19].

Nighttime visual performance can be further degraded by visual impairments such as cataracts or refractive blur, which reduce the recognition of road signs, delay hazard detection, and impair pedestrian visibility [9]. At the same time, the literature shows that pedestrian conspicuity can be improved through retroreflective materials configured to highlight biological motion, thereby enhancing pedestrian detection under low-light conditions, including among drivers with visual impairment [3], [13]. Another major challenge is glare, particularly from oncoming headlights, which can produce visual discomfort, reduce visibility, and temporarily disrupt visual performance. This effect is especially problematic for older drivers and has been shown to substantially reduce pedestrian detection during night driving [23].

Beyond reduced acuity and glare sensitivity, nighttime perception is also affected by the overall impoverishment of visual information available in low-light environments. Under these conditions, drivers must interpret scenes with less reliable detail, reduced contrast, and weaker object separation, making visual search and object identification more difficult [13], [19]. Collectively, these limitations show that nighttime driving is not simply daytime driving under lower light, but a qualitatively different visual task shaped by reduced sensory input and increased perceptual uncertainty [23].

In summary, human vision and perception at night are characterized by reduced visual acuity, impaired contrast sensitivity, greater glare vulnerability, and poorer recognition of roadway hazards, particularly under mesopic lighting conditions. These constraints are amplified by age-related changes in visual function and by visual impairment, making nighttime driving especially demanding. This visual degradation provides the foundation for understanding how roadway illumination influences driver perception, performance, and safety under nighttime conditions and supports the need to examine driver response under controlled nighttime illumination levels [3], [11], [12], [13]. Because much of this visual difficulty arises under mesopic conditions, the following section examines mesopic vision and its functional implications for nighttime driving in greater detail.

2.3 Mesopic Vision and Visual Function Under Nighttime Roadway Illumination

Nighttime driving places the visual system in a luminance range that does not align with purely photopic or scotopic functioning. Photopic vision operates under daylight or high-luminance conditions, mediated by cones that provide high acuity and color perception. Scotopic vision governs very low-light conditions and relies on rods, which are highly sensitive to luminance but offer limited spatial detail and no color

information. Roadway lighting rarely places the visual system fully in either of these states; instead, nighttime driving relies primarily on mesopic vision in which both rods and cones contribute to visual processing [8], [12], [15], [24], [25], [26], [27].

Mesopic vision is associated with reduced visual acuity and lower visual efficiency relative to photopic conditions (Black et al., 2025). The transition into the mesopic region has direct implications for driving performance. As luminance decreases from photopic levels toward low mesopic levels (approximately 1 to 0.01 cd/m²), contrast sensitivity and reaction time decline sharply, reducing the visual system's ability to detect low-contrast or fine-detail targets [29], [30]. These impairments are particularly critical in driving tasks that depend on rapid identification of road hazards, road signs, and changes in roadway alignment. Under these conditions, the visual system also undergoes a spectral shift toward rod-driven sensitivity, known as the Purkinje shift, which further diminishes cone-mediated color and detail perception and makes hazards and signage more difficult to detect as luminance decreases [29]. Mesopic vision is influenced by multiple interacting factors, including rod–cone interactions, changes in Postreceptoral pathways, spectral sensitivity shifts, and the spatial and temporal properties of the visual system, making nighttime visual performance far more variable and difficult to predict than under photopic conditions [26], [31]

These mesopic visual challenges are often exacerbated by age-related changes. Older adults typically experience poorer contrast sensitivity, slower adaptation to darkness, and greater difficulty recovering from glare, all of which further reduce the amount of usable visual information available in low-light settings [3], [18], [32], [33], [34], [35] These deficits become particularly evident under mesopic and glare-related nighttime driving conditions [28]. Recent high-fidelity simulator and naturalistic driving studies demonstrate that these mesopic-specific deficits distinct from standard daylight acuity directly predict driving impairment. [18] found that reduced mesopic contrast sensitivity in drivers over sixty was significantly associated with greater lateral lane instability, speed fluctuations, and delayed reaction times, largely independent of their daytime visual acuity. Similarly, Kimlin et al., [19] and Green et al. [36] observed that older drivers with greater mesopic glare sensitivity required significantly more time to detect pedestrians and recognize road signs, with performance decrements emerging at luminance levels typical of roadway lighting [37], [38].

Crucially, these functional deficits translate into tangible safety outcomes. Owsley et al. [34] established that mesopic contrast sensitivity is a strong predictor of prospective crash risk in older adults[39], whereas standard photopic measures show little to no association with collision rates. This dissociation explains why older drivers who meet legal acuity requirements may still report substantial

difficulty maintaining lane position or detecting hazards at night [13], [40]. In response to these perceived deficits, observational data confirm a pattern of self-regulation: older adults with impaired contrast sensitivity or low-luminance complaints deliberately restrict their driving exposure, avoiding nighttime trips and high-demand traffic conditions to compensate for their visual vulnerability [41], [42].

Overall, mesopic vision defines the functional visual context in which most nighttime driving occurs. Compared with photopic vision, it is associated with reduced acuity, lower contrast sensitivity, slower visual processing, and greater susceptibility to glare, with these effects becoming more pronounced in older drivers. These limitations are central to understanding how roadway illumination influences hazard detection, driver performance, and age-related differences under nighttime driving conditions.

2.4 Streetlighting and Safety

Streetlighting is one of the principal engineering measures used to improve nighttime road safety by increasing visibility and supporting earlier detection of hazards under low-light conditions. Its importance lies in the fact that nighttime driving occurs when visual performance is already constrained, requiring drivers to respond to the roadway environment with reduced and less reliable visual information. Appropriate streetlighting can improve the visibility of lane boundaries, pedestrians, roadside objects, and roadway geometry, thereby support safer driving performance and reduce the likelihood of delayed responses to hazards [2], [3], [6] .

However, the relationship between streetlighting and safety is not simply linear. Insufficient illumination reduces contrast, shortens detection distance, and delays recognition of hazards, increasing visual demand and crash risk, particularly for pedestrians and other vulnerable road users [2], [3]. At the same time, excessive illumination may also impair safety by producing discomfort glare or disability glare, both of which can reduce visual comfort and interfere with hazard perception, especially among older drivers and other visually vulnerable populations [18], [19]. These findings suggest that both under-lighting and over-lighting can compromise safe nighttime driving.

In addition to illumination level, the safety value of streetlighting depends on the quality and distribution of light across the roadway environment. Poor lighting uniformity and abrupt transitions between bright and dark areas increase visual adaptation demands and may delay hazard detection by forcing the visual system to repeatedly adjust to changing luminance levels. More balanced and uniform lighting conditions can reduce these adaptation effects and support more stable visual processing,

particularly at locations requiring rapid hazard recognition, such as intersections, pedestrian crossings, and curved roadway segments [2], [13].

Streetlighting may also influence driver behavior indirectly. Drivers do not consistently adapt their behavior to account for decreased visibility [43], and brighter environments may sometimes be interpreted as inherently safer, leading to overconfidence or insufficient speed adjustment [13]. This indicates that the safety benefit of roadway illumination should not be evaluated solely in terms of visibility, but also in relation to its effects on driver behavior, comfort, and response to hazards.

Overall, the literature indicates that streetlighting is essential for nighttime safety, but its effectiveness depends on achieving a balanced level of illumination that improves visibility without introducing glare, discomfort, or unnecessary visual strain. While the preceding sections discussed the visual mechanisms underlying nighttime perception, this section highlights the role of roadway illumination as an engineering measure for improving safety. The following section examines how age-related changes may influence driver performance under these nighttime lighting conditions.

2.5 Aging, Visibility, and Nighttime Driving Performance

Aging is an important factor in nighttime driving because many of the visual and perceptual functions required for safe performance decline with age, particularly under low-light conditions. As discussed in previous sections, age-related changes in contrast sensitivity, glare sensitivity, and dark adaptation can reduce the amount of usable visual information available during nighttime driving. Although many older adults continue to meet legal daytime visual acuity standards, nighttime driving often reveals functional limitations that are not captured by conventional daytime assessments. These limitations include reduced contrast sensitivity, slower dark adaptation, greater susceptibility to glare, and decreased ability to detect low-contrast hazards, all of which can impair performance in nighttime roadway environments [11], [18], [19], [44].

One of the most significant age-related challenges is the reduced efficiency of visual processing under mesopic conditions. Compared with younger drivers, older adults generally require higher luminance to achieve similar levels of visual performance and often experience greater difficulty detecting pedestrians, road signs, and roadway features at night [18], [19]. These impairments are compounded by slower glare recovery and reduced ability to adapt to changes in luminance, particularly in environments with non-uniform lighting or oncoming headlights. As a result, older drivers may experience delayed hazard recognition and greater difficulty maintaining stable vehicle control under nighttime conditions.

These age-related visual, perceptual, and cognitive limitations translate into measurable differences in driving behavior and safety-related performance. Previous research has shown that older drivers often exhibit slower reaction times, greater lane instability, and less efficient responses to hazards at night, even when daytime visual acuity remains within acceptable limits [13], [18], [40]. In some cases, these deficits are associated with more cautious driving patterns, including lower speeds and increased self-regulation, while in other cases they may result in delayed or less effective responses to sudden hazards [41], [45]. This suggests that age-related decline affects not only visual capacity, but also cognitive processing and the way drivers adapt behaviorally to reduced nighttime visibility.

Importantly, aging does not simply reduce performance uniformly across all conditions. Rather, age-related effects may become more pronounced under specific illumination ranges where visual demands increase, and glare sensitivity becomes more disruptive. This makes age an especially relevant factor in studies examining nighttime roadway illumination, as the effect of lighting may differ not only in magnitude but also in the way it interacts with hazard perception, comfort, and driver response. For this reason, comparing younger and older adults is essential for understanding whether nighttime illumination supports both groups equally or whether certain lighting conditions are more favorable for one group than the other.

Overall, the literature indicates that older drivers face greater challenges in nighttime roadway environments influenced by changes in vision associated with aging, glare recovery, and low-light processing. In the context of this research, examining age-related differences helps clarify whether different illumination levels influence driver perception, attention, physiological response, and driving performance differently across age groups.

2.6 Driving Performance Under Nighttime Illumination

Driving is a complex perceptual and behavioral task requiring the continuous integration of visual input, decision-making, motor control, and sustained attention. Under nighttime conditions, these demands increase because reduced luminance, limited contrast, and glare reduce the quality of visual information available for safe driving. Driver performance at night is influenced by the combined effects of reduced visibility, increased visual workload, and limitations in human visual processing under low illumination conditions. Compared with daytime driving, nighttime environments provide less reliable visual information, requiring drivers to detect hazards, interpret roadway features, and make driving decisions with reduced contrast and shorter detection distances. These limitations can affect several aspects of driving behavior, including hazard recognition, reaction time, vehicle control, and speed regulation [2], [3], [11], [13], [46].

One of the most critical aspects of nighttime driving performance is the ability to detect hazards and respond in time to avoid potential collisions. Reduced illumination can delay the detection of pedestrians, cyclists, and roadway obstacles, particularly when targets are low contrast or poorly illuminated. As a result, drivers often require more time to recognize hazards and initiate braking or steering responses under nighttime conditions. Studies have shown that hazard perception and reaction time are strongly influenced by visibility and lighting conditions, with poorer illumination associated with slower responses and increased safety risk [2], [13]. PRT refers to the duration from the initial presentation of a hazard to the driver's first measurable physical reaction, such as braking or releasing the accelerator. As a behavioral measure, it reflects how quickly drivers detect, process, and respond to safety-critical events under varying illumination conditions.

Nighttime illumination also influences driver speed behavior and self-regulation. When visual information becomes less reliable, drivers may adjust their speed to compensate for reduced visibility and increased uncertainty in the driving environment. Previous research has shown that drivers often adopt lower speeds under low-light conditions as a compensatory strategy to maintain safety margins and increase the time available to respond to unexpected hazards [11], [13]. Although reduced visibility would be expected to encourage compensatory slowing, prior studies suggest that drivers do not always reduce speed sufficiently under low-light conditions, indicating incomplete adaptation to degraded visibility [13]. However, such behavioral adjustments are not always sufficient to offset the limitations imposed by reduced illumination, particularly when hazards appear suddenly or when the visual environment contains glare or uneven lighting.

In addition to reaction time and speed regulation, nighttime illumination can affect vehicle control and lane stability. Reduced contrast and limited visual cues may make it more difficult for drivers to maintain accurate lane positioning or anticipate roadway geometry, especially on curves or in environments with inconsistent lighting. Experimental and simulator studies have shown that degraded nighttime visibility can lead to increased lane variability and less stable vehicle control, reflecting the greater perceptual demands placed on drivers in low-light conditions [13], [40].

Driving simulator research has become an important tool for investigating driver behavior under controlled nighttime illumination conditions. High-fidelity simulators allow researchers to manipulate lighting levels while maintaining consistent roadway environments, enabling systematic evaluation of driver responses such as reaction time, speed adjustments, and visual attention patterns. These controlled environments make it possible to isolate the effects of illumination from other confounding factors present

in real-world driving studies [3]. Simulator-based research therefore provides valuable insights into how different lighting conditions influence driver perception, behavior, and safety-related performance.

Overall, the literature indicates that nighttime illumination plays a critical role in shaping driver performance. Reduced lighting can delay hazard detection, slow driver responses, alter speed regulation, and increase the perceptual demands required to maintain safe vehicle control. Understanding how drivers respond to different illumination levels is therefore essential for evaluating the effectiveness of roadway lighting and for identifying conditions that support safer nighttime driving performance.

2.7 Visual Attention, Hazard Perception, and Eye-Tracking

Visual attention plays a central role in safe driving because drivers must continuously monitor the roadway environment and allocate visual resources to detect potential hazards. Effective driving requires rapid visual scanning of the forward roadway, mirrors, and surrounding environment to identify pedestrians, cyclists, vehicles, and roadway features that may require immediate response. At night, this task becomes more demanding because reduced illumination limits visual contrast and increases uncertainty in the driving scene, making hazard detection more dependent on resourceful visual attention strategies [2], [3], [13], [47].

Hazard perception refers to the ability to anticipate, detect, and respond to potentially dangerous events in the driving environment. It is widely recognized as a key component of driving safety and is commonly evaluated using measures such as hazard perception reaction time, hazard hit rate, and eye-fixation-based indicators including fixation probability, fixation reaction time, fixation duration, and fixation variance [48]. It depends on both visual processing and attentional allocation, as drivers must identify relevant cues and interpret them quickly enough to initiate appropriate responses. Reduced illumination can impair hazard perception by lowering contrast and decreasing the visibility of pedestrians and other road users, particularly when targets appear in peripheral vision or are poorly illuminated. Previous studies have shown that drivers often require longer detection times for hazards under nighttime conditions, which can delay braking or evasive maneuvers and increase crash risk [3], [13].

Eye-tracking has become an important method for examining visual attention and hazard perception during driving tasks. By recording eye movements, fixation locations, and gaze patterns, eye-tracking systems allow researchers to evaluate how visual attention is allocated by drivers across various areas within the driving environment. Measures such as fixation duration, dwell time, and gaze frequency provide insight into the visual strategies drivers use when scanning the roadway and responding to potential hazards. These

metrics help reveal whether drivers are focusing on relevant roadway regions or diverting attention to secondary areas within the vehicle environment [49], [50], [51].

Eye-tracking studies have demonstrated that experienced drivers tend to exhibit more efficient visual search patterns, characterized by shorter fixation durations and more strategic scanning of critical roadway regions. In contrast, less experienced or visually challenged drivers may show longer fixations, narrower visual scanning patterns, or delayed attention to hazards. Under nighttime conditions, these visual attention patterns may change as drivers attempt to compensate for reduced visibility, sometimes leading to increased visual concentration on the forward roadway while reducing monitoring of peripheral areas [11], [51]. Low-light conditions may also narrow gaze distribution and reduce attention to peripheral regions, which can delay hazard detection and reduce situational awareness in dynamic driving environments [3], [11], [52].

Importantly, eye-tracking provides objective measures of driver attention that complement traditional performance metrics such as reaction time or vehicle control. By combining eye-movement data with behavioral driving measures, researchers can better understand how drivers detect hazards and how visual attention contributes to safe or unsafe driving responses. For this reason, eye-tracking has become a widely used tool in driving simulator research to assess the connection between visual attention, hazard perception, and driver behaviour under different environmental conditions, including nighttime illumination.

2.8 Physiological and Subjective Responses to Nighttime Illumination

Driver responses to nighttime illumination are not limited to observable driving performance but also involve physiological and subjective reactions that reflect cognitive workload, stress, and visual comfort. Low-light environments can increase perceptual demand by requiring drivers to interpret roadway information with reduced contrast and limited visual cues. These conditions may elevate mental effort and physiological arousal as drivers attempt to maintain situational awareness and respond to potential hazards. Measuring physiological and subjective responses can therefore provide additional insight into how lighting conditions influence driver experience and performance beyond traditional behavioral indicators [3], [53], [54].

Physiological measures are commonly used in driving research to evaluate changes in driver arousal and workload. Indicators such as HR, Heart Rate Variability (HRV), and EDA reflect autonomic nervous system responses [55]associated with cognitive demand, stress, and attentional engagement. HR is commonly used as an indicator of arousal and mental demand, whereas EDA is particularly sensitive to changes in stress, attentional engagement, and momentary workload. For example, increased task difficulty

or perceived risk during driving has been associated with changes in HR and elevated EDA, reflecting heightened physiological activation as drivers respond to demanding situations [53], [56]. These measures allow researchers to examine how drivers physiologically react to different driving environments, including variations in lighting conditions.

In nighttime driving contexts, physiological responses may increase when visibility is reduced or when drivers experience greater uncertainty in detecting hazards. Low illumination and glare can increase visual strain and attentional demand, potentially leading to elevated physiological arousal as drivers allocate additional effort to monitor the roadway and maintain safe vehicle control. Conversely, improved illumination may reduce perceptual demand and physiological stress by increasing visibility and supporting more efficient hazard detection. In addition to low illumination, excessive brightness may also elevate physiological strain when glare or visual discomfort increases the effort required to process the roadway environment. These physiological responses provide valuable information about the internal state of the driver, which may not always be captured through driving performance metrics alone.

In addition to physiological indicators, subjective assessments are frequently employed to evaluate drivers' perceptions of comfort, visibility, and safety across different lighting conditions [57]. Self-report measures allow participants to describe their perceived workload, visual clarity, and level of confidence while driving. Such subjective evaluations are particularly valuable in human factors research because they capture the experiential dimension of driving, including perceived visual comfort and difficulty, which may influence driver behavior and safety outcomes [53].

Combining physiological measurements with subjective evaluations provides a more comprehensive understanding of driver response to nighttime illumination. While physiological signals offer objective indicators of arousal and workload, subjective reports provide insight into drivers' perceptions of visibility and comfort. Together, these complementary measures help reveal how lighting conditions influence both the internal state of the driver and their perceived driving experience, contributing to a more complete evaluation of nighttime roadway illumination. Importantly, physiological and subjective responses do not always align, and this divergence can itself be informative, revealing differences between drivers' perceived comfort and their underlying physiological state.

2.9 Simulator-Based Nighttime Driving Research

Driving simulators have become an important research tool for studying driver behavior under controlled and repeatable conditions. Unlike field studies conducted on public roads, simulators allow researchers to

manipulate environmental variables such as illumination, roadway geometry, and hazard scenarios while maintaining consistent experimental conditions across participants. This level of control makes simulators particularly useful for investigating how drivers respond to different lighting conditions and how those conditions influence hazard detection, visual attention, and driving performance [58], [59]

Nighttime driving research presents several practical challenges when conducted in real-world environments. Field experiments involving low illumination conditions can be difficult to standardize because roadway lighting, traffic conditions, and environmental factors vary across locations and time. In addition, introducing controlled hazards in real traffic environments raises significant safety and ethical concerns. Driving simulators address these limitations by providing a safe and controlled setting in which nighttime driving scenarios can be replicated consistently while allowing researchers to systematically vary environmental conditions, roadway features, and hazard events [58], [59].

High-fidelity driving simulators are especially valuable for studying driver perception and response under nighttime illumination because they allow precise control of visual environments while capturing detailed behavioral data. Simulator platforms can record multiple aspects of driver behavior, including speed, acceleration, braking responses, lane position, and reaction time to hazards. These data provide objective measures of driver performance and allow researchers to examine how lighting conditions influence driving behavior across different scenarios [59].

Another advantage of simulator-based research is the ability to integrate additional measurement technologies that are difficult to implement in real-world driving studies. Eye-tracking systems can be used for a variety of purposes to examine visual attention [60], while physiological sensors can capture indicators of driver workload and arousal. The integration of these measurement systems allows researchers to explore the associations among visual attention, physiological responses, and driving performance [19] under controlled nighttime illumination conditions.

Despite these advantages, simulator studies must also consider potential limitations such as simulator adaptation, motion sickness, and differences between simulated and real-world driving behavior. To address these concerns, many studies include familiarization drives and controlled experimental protocols to ensure that participants become comfortable with the simulator environment before the experimental tasks begin. When properly designed, driving simulator experiments provide reliable and valid insights into driver behavior and have become widely accepted in transportation safety and human factors research [3], [58], [59].

Overall, simulator-based research offers a safe and effective method for examining how drivers respond to different nighttime illumination conditions. By allowing controlled manipulation of lighting levels while capturing detailed behavioral, visual, and physiological data, driving simulators provide valuable insights into the mechanisms through which roadway illumination influences driver perception, response, and safety-related performance.

2.10 Spatial Data for Realistic High-Fidelity Driving Simulator Environments

While the primary emphasis of this study is on the human factors of nighttime driving, the realism of the virtual driving environment is an important consideration in simulator-based research. Traditional driving simulator studies often rely on simplified roadway scenes and generalized lighting conditions that may not accurately represent the spatial distribution of roadway infrastructure or streetlighting systems. Such simplifications can reduce the transferability of experimental findings because driver responses may differ when the visual environment does not closely resemble real-world driving conditions [58], [59].

Recent advances in geospatial data collection and remote sensing technologies have made it possible to capture highly detailed spatial information about roadway environments. Technologies such as LiDAR scanning, aerial imaging, and geospatial mapping enable the accurate representation of roadway geometry, surrounding infrastructure, and environmental features with high spatial resolution. These datasets can be used to construct detailed virtual environments that more closely replicate real-world roadway settings, including roadway layout and the placement of roadside assets [61], [62].

Incorporating spatially accurate environmental information into driving simulators can improve the realism of virtual driving scenarios and enhance the ecological validity of simulator experiments. By reflecting actual roadway characteristics rather than simplified virtual scenes, these environments can provide a more representative context for examining driver behavior and responses to roadway conditions. As a result, spatially informed simulator environments offer a valuable approach for studying driver perception and performance under controlled experimental conditions while maintaining a closer connection to real-world driving environments [3], [59].

2.11 Literature Synthesis and Research Gap

The literature reviewed in this chapter shows that nighttime driving is shaped by reduced visibility, mesopic visual limitations, glare, and age-related declines in visual function. These factors influence hazard detection, response time, vehicle control, and overall safety. Prior studies also indicate that roadway

illumination affects not only driving performance, but also visual attention, physiological arousal, and subjective perceptions of visibility, comfort, and safety. Together, these findings show that nighttime driving is a multidimensional problem that cannot be adequately understood through any single outcome alone.

Despite these contributions, several important gaps remain in the literature:

- Most previous studies have examined nighttime driving using a single outcome domain, such as driving performance, visibility, eye movements, or physiological response, rather than integrating these measures within a multimodal framework.
- Limited research has simultaneously evaluated behavioral, visual-attentional, physiological, and subjective responses to different graded nighttime illumination levels within the same controlled study.
- The relationship between illumination level and driver response remains insufficiently understood, particularly whether performance and experience improve continuously with increasing brightness or begin to stabilize beyond a medium level of illumination. This question has practical importance for roadway lighting design because it relates to how lighting adequacy may be improved without assuming that brighter conditions always produce proportional safety benefits.
- Age-related differences in response to nighttime illumination remain underexplored, especially in studies that compare younger and older drivers using the same controlled conditions and multimodal measures.
- Many previous studies have examined nighttime driving under simplified or generalized simulation conditions which may not fully account for the complexity inherent in real-world roadway environments.
- Few studies have used high-fidelity driving simulators developed from digitally reconstructed real-world roadway settings, including roadway assets, actual light locations, and measured lighting characteristics, while also collecting synchronized performance, eye-tracking, physiological, and subjective data.
- The relationship between subjective perception and objective response remains unclear, particularly whether drivers' perceived comfort and visibility align with their physiological state and actual driving performance.

Accordingly, the present study addresses these gaps by examining how different nighttime illumination levels influence driver performance, visual attention, physiological response, and subjective experience in a high-fidelity driving simulator. The study was conducted in a simulator environment developed from a digitally reconstructed real-world roadway setting, including roadway assets, actual light locations, and measured lighting conditions, rather than a simplified virtual scene. It also compares these responses between younger and older drivers using an integrated multimodal framework and examines whether the effects of illumination suggest a threshold beyond which additional brightness offers limited benefit.

CHAPTER 3
Methodology

3.1 Introduction

This chapter examines how nighttime roadway illumination influences driver responses in a controlled virtual environment using a high-fidelity driving simulator. The study investigates the effects of three illumination levels, representing low, medium, and high roadway brightness, on drivers' visual, physiological, and behavioural responses, as well as their perceived visual comfort and safety. The simulated roadway incorporated standard Canadian design elements to support a realistic nighttime driving context. To address these objectives, the methodology combined a controlled experimental design with multimodal data collection, including simulator performance measures, eye-tracking indicators, physiological recordings, and post-drive ratings. A mixed design was employed, with illumination considered a within-subjects factor, while age group was specified as a between-subjects factor. The analyses were designed to examine whether illumination level and age group influenced the physiological, subjective, visual-attention, and driving-performance outcomes, and whether these effects varied across hazard scenarios where applicable.

3.2 Methodological Assumptions

Interpretation of the findings in this study rests on several methodological assumptions. First, the fixed-base high-fidelity driving simulator was expected to reproduce the essential visual characteristics of nighttime driving with sufficient realism to elicit natural driver responses [63]. While the simulator cannot replicate the full sensory complexity of real-world driving, the reconstructed roadway, developed via aerial site mapping to reflect Canadian roadway geometry in Waterloo, Ontario, is assumed to preserve the relative perceptual differences required for valid comparisons across the experimental illumination conditions.

Second, the multimodal measures are assumed to provide valid and complementary indicators of the driver's state. It is expected that simulator telemetry (the kinematic mode) accurately captures physical driving responses through measures of speed, PRT, and deceleration. Similarly, eye-tracking data (the visual mode) is assumed to reflect genuine visual attention allocation and response timing through TTFF

and dwell time. Furthermore, wearable sensor recordings (the physiological mode) are treated as reliable indices of autonomic arousal through HR and EDA, while post-drive questionnaires (the subjective mode) accurately reflect participants' conscious evaluations of visual comfort and perceived safety.

Finally, it is assumed that participants remained attentive and engaged throughout the experimental sessions and responded to the simulated nighttime environments in a consistent and natural manner. The illumination levels were also assumed to be perceptually distinct enough to produce measurable variation across the four response modes. Together, these assumptions support interpretation of the effects of nighttime roadway illumination within a controlled simulation setting.

3.3 Research Design

This study employed a mixed factorial design to examine the effects of nighttime roadway illumination on driver response. For the physiological and subjective measures, illumination level served as the within-subject factor and age group as the between-subject factor. For the visual attention and driving performance measures, a three-way mixed design was used, with driving scenario included as a second within-subject factor to account for differences in hazard context across scenarios.

Illumination was tested at three levels, classified as low, medium, and high, corresponding to progressively increasing roadway lighting intensity within the simulator, approximately 100 to 150 cd for low, 200 to 250 cd for medium, and 300 to 350 cd for high, and each participant experienced all three conditions. To represent a range of realistic nighttime driving situations, four roadway scenarios were presented under each illumination level. The order of scenarios was randomized to reduce sequence effects, resulting in a total of twelve driving trials per participant.

This design allowed illumination effects to be examined within the same participant while also supporting comparison between age groups. In addition, the inclusion of driving scenario in the visual attention and driving performance analyses provided a more detailed assessment of how different hazard contexts influenced driver response under varying nighttime illumination conditions.

3.3.1 Ethical Approval

This study was reviewed and approved by the University of Waterloo Research Ethics Board (REB #46838). All participants provided written informed consent after receiving a clear explanation of the study objectives, procedures, physiological measurements, and any potential risks associated with simulator use. Participation was entirely voluntary, and participants retained the right to withdraw from the study at any

time without any negative consequences. A compensation amount of $15 CAD for approximately one hour of participation was approved by the REB. All collected data were de-identified using coded numerical identifiers and stored on secure, encrypted servers in accordance with institutional data security requirements. Simulator sessions were monitored to support participant safety, and participants were permitted to pause or discontinue the session if they experienced discomfort.

3.3.2 Power Analysis and Sample Size Determination

An a priori power analysis was conducted using G*Power version 3.1.9.7 to estimate the sample size required for the planned mixed repeated-measures ANOVA [64] . The analysis reflected the study design, with illumination level (low, medium, high) specified as the within-subject factor and age group (younger and older adults) specified as the between-subject factor. The expected effect size was set to $f = 0.25$, corresponding to a medium effect size [65] . The significance level was set at $\alpha = 0.05$, and the desired statistical power was $1 - \beta = 0.85$. A conservative correlation of r = 0.50 among repeated measures was assumed to reflect moderate consistency across illumination conditions.

Table 1. Power analysis parameters used to estimate sample size.

Parameter	***Value***	***Justification***
Effect Size (f)	0.25	Medium effect size [65].
Significance Level (α)	0.05	Standard threshold.
Desired Power	0.85	Adequate for medium effects
Achieved Power	0.84	Exceeds the conventional 0.80 threshold.
Total Sample Size	30 Participants	Final recruited sample with balanced age groups
Repeated Measures	3 Illumination Levels	Each participant completed all conditions
Groups	Younger (20–45), Older (65+)	Age based between subjects' factors
Correlation Among Measures	0.50	Assumed moderate consistency across trials

Based on these parameters, the G*Power analysis indicated that a minimum sample of $n = 32$ participants would be required to achieve the target power of 0.866. The final recruited sample consisted of $n = 30$ participants, with balanced representation across the two age groups ($n = 15$ per group), which was consistent with the planned recruitment target for the study. A post hoc power calculation yielded an

achieved power of 0.841, exceeding the commonly accepted threshold of 0.80 for detecting medium-sized effects at $\alpha = 0.05$ level [66]. This sample size was therefore considered adequate for the planned analyses.

The parameters used in both the priori and post hoc calculations as demonstrated in Table 1, including the effect size, significance level, desired power, number of groups, number of repeated measurements, and assumed correlation among conditions. Together, these values provide empirical justification for the selected sample size and offer a reference point for sample size planning in future research.

3.4 Participants

A total of thirty adults participated in the study. Participants were assigned to one of two age groups, younger adults (20 to 45 years) and older adults (65+ years), to examine age-related differences in response to nighttime roadway illumination.

3.4.1 Recruitment and Eligibility Criteria

Seventy individuals were screened, and 30 participants were enrolled based on predefined eligibility criteria intended to support participant safety and data quality. Recruitment was conducted through university email lists, posters placed in high-traffic campus locations, including the Student Life Centre and the Engineering foyer, and the University of Waterloo Research in Aging Participant Pool (WRAP), which served as the primary source for older adult recruitment.

Eligibility criteria required participants to hold a valid Ontario G2 or G driver's licence for at least two years, report regular nighttime driving experience, and have normal or corrected-to-normal vision. Individuals were excluded if they reported colour blindness, severe cardiac conditions, a history of seizures, or high susceptibility to motion sickness in virtual or simulated environments. These criteria were established to support safe participation and the reliability of the visual, physiological and behavioural and perceptual data collected during the study [67].

3.4.2 Demographic Characteristics

The final sample consisted of thirty adults divided evenly across two age groups. The younger group included fifteen participants aged 20 to 45 years ($M = 29.5, SD = 6.2$), and the older group included fifteen participants aged 65 to 82 years ($M = 72.7, SD = 5.8$). Gender distribution was balanced, with 53 percent male and 47 percent female. Demographic information was collected using a brief demographic questionnaire (Appendix A) [67].

Driving experience reflected the expected age-related pattern. Younger adults reported fewer years of licensed driving ($M = 7.5$, $SD = 4.4$) than older adults ($M = 53.6$, $SD = 9.5$). Annual mileage (km/year) was distributed across comparable reporting ranges in both groups, with most participants reporting between 5,000 and 10,000 km/year, as shown in Table 2.

Motion-sickness susceptibility was assessed using the (MSSQ-Short [68], see Appendix C), and scores were low across the sample ($M = 6.2, SD = 4.3$), consistent with adult low-susceptibility norms [69], [70]. Descriptively, MSSQ scores appeared similar across age groups.

The age ranges selected for this study align with documented differences in visual function and driving experience, as aging is associated with reduced acuity, lower contrast sensitivity, and slower dark adaptation [71], [72], [73], [74], [75], [76].

Table 2. Demographic characteristics of the study sample

Characteristic	***Younger Adults (n = 15)***	***Older Adults (n= 15)***
Age (Years)	20 to 45; M = 29.5, SD = 6.2	65 to 82; M = 72.7, SD = 5.8
Gender	7 Males (47%), 8 Females (53%)	9 Males (60%), 6 Females (40%)
Driving experience (Years)	M = 7.5, SD = 4.4)	M = 53.6, SD = 9.5
Annual mileage (km/year)	<5,000: 33%	<5,000: 20%
	5,000–10,000: 40%	5,000–10,000: 53%
	>15,000: 27%	>15,000: 27%
Vision correction	None: 80%	None: 7%
	Glasses: 13%	Glasses: 67%
	Contacts: 7%	Contacts: 27%
Prior simulator experience	20%	0%
DBQ completed	Yes	Yes

3.5 Apparatus and Instrumentation

3.5.1 Driving Simulator

The study was conducted in the Autonomous Vehicle Research and Intelligence Laboratory (AVRIL) at the University of Waterloo using a VI-grade STATIC driving simulator as shown in Figure 1. The simulator

consists of a full Chevrolet Traverse SUV cabin equipped with original equipment manufacturer steering, pedals, and gear controls, allowing participants to interact with a realistic vehicle interface. The system also includes an active seat with a five-point harness that provides seat-integrated haptic feedback and resistance cues linked to vehicle dynamics [67].

Visual information was displayed on a 278-degree cylindrical projection system operating at 120 Hz, providing a wide field of view that included the forward roadway, dashboard, side mirrors, and rear-view perspectives. Auditory feedback was delivered through a 5.1-channel surround sound system. Together, the visual, auditory, and haptic components supported an immersive and controlled driving environment consistent with simulator-based human factors research [67], [77].

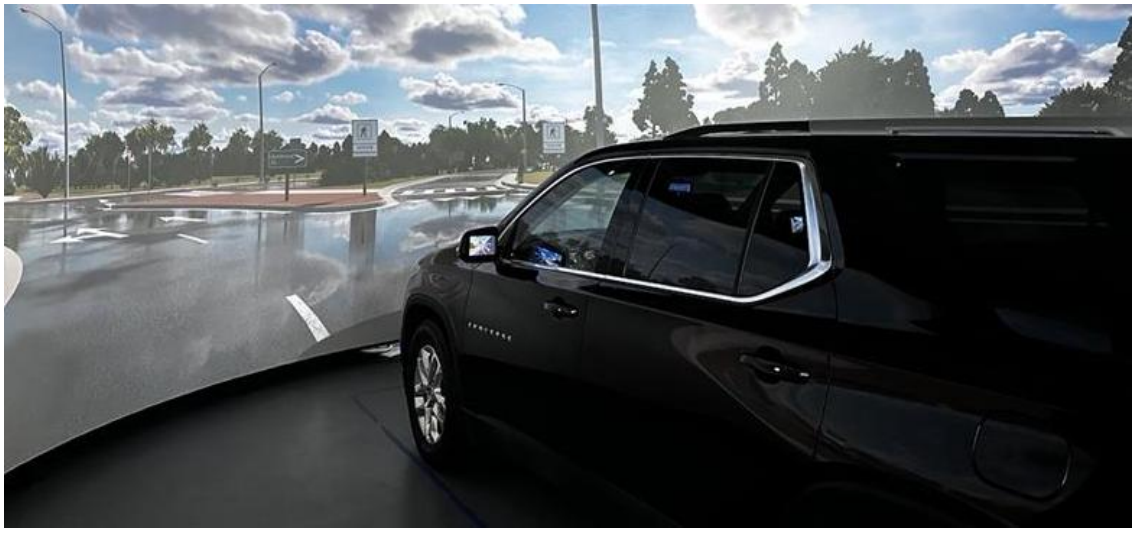


Figure 1 Autonomous Vehicle Research and Intelligence Laboratory (AVRIL) at the University of Waterloo using a VI-grade STATIC driving simulator with a digitally replicated real-world environment.

3.5.2 Physiological Sensors

Physiological data were collected using the Empatica EmbracePlus multisensory wearable device, which was worn on the participant's non-dominant wrist [67], [78]. The device uses a multi-wavelength reflectance Photoplethysmography (PPG) sensor to measure blood-volume pulse at a raw sampling rate of 64 Hz. HR values were obtained from the device's onboard processing pipeline as shown in Figure 2. While the underlying physiological signals were recorded at higher sampling frequencies, the processed HR output used for this study was available at a resolution of one value per minute. Valid pulse-rate values range from 24 to 240 bpm, with an approximate resolution of 1 bpm [79].

EDA was recorded using ventral skin-conductance electrodes embedded in the device. Raw EDA was sampled at 4 Hz, and the onboard algorithm produced Skin Conductance Level (SCL) estimates using non-overlapping 60-second windows [79], resulting in one SCL value per minute. Valid SCL outputs range from 0.01 to 100 μS, although missing segments may occur during periods of reduced skin contact or device movement.

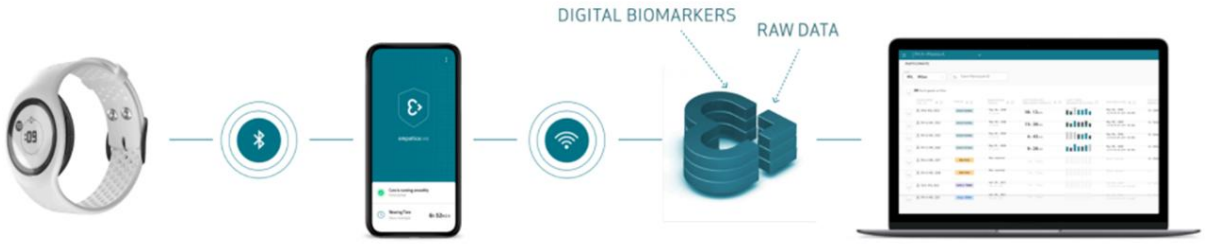


Figure 2 Data workflow of the Empatica EmbracePlus system, showing the wearable device transmitting physiological signals to a smartphone, which uploads raw data and processed digital biomarkers to the Care Portal for monitoring and analysis [79].

Together, these physiological measures provided continuous indicators of autonomic arousal throughout the driving task. All physiological data were processed using the device's motion-tolerant filtering pipeline, uploaded through the Empatica Care App, and time-aligned with simulator event logs to support synchronization with driving sessions.

3.5.3 Eye-Tracking System

Eye-tracking data were collected using the Ergoneers Dikablis Professional system, a binocular pupil–corneal reflection device as shown in Figure 3 that records gaze behaviour at sampling rates up to 60 Hz with an average accuracy of approximately 0.5° visual angle. The system captures real-time gaze coordinates and pupil diameter using dual eye cameras (648 × 488 pixels) and a high-definition scene camera providing a 76° horizontal and 58° vertical field of view at 1920 × 1080 pixels and 30 frames per second.

The lightweight headset (approximately 52 g) is designed to minimize discomfort and is compatible with prescription eyewear [67], [77], [80], [81]. Gaze behaviour and fixation data were logged continuously and synchronized with simulator events through the D-Lab software. These data were processed and analyzed to capture drivers' visual attention during hazard events. Specifically, the eye-tracking data were

used to extract TTFF, Dwell Time on hazards, and overall fixation distributions across predefined areas of interest.



Figure 3 Ergoneers Dikablis Glasses 3 eye-tracking system used in the study, showing the headset and recording unit (left) and the front-view worn configuration (right).

3.5.4 Ambient Illumination

Ambient illumination in the simulator room was controlled prior to data collection to maintain a consistent nighttime testing environment. The AVRIL simulator space is fully enclosed with blackout curtains, allowing ambient light to be reduced to very low levels. During laboratory setup, illumination inside the simulator cabin was measured using a calibrated digital lux meter as shown in Figure 4 positioned at driver eye height near the steering wheel. Ambient light levels were maintained between approximately 0.2 and 0.4 lux, ensuring that the simulated roadway lighting remained the primary source of visual illumination. This controlled lighting condition helped preserve the consistency of the experimental illumination manipulation throughout the study.



Figure 4 URCERI Handheld digital illuminance meter used to measure ambient light levels during simulator setup.

3.5.5 Subjective Evaluation Questionnaire

To capture participants' subjective perceptions within the multimodal study design, a 9-item questionnaire was administered immediately after each illumination condition. Responses for all items were recorded on a 5-point Likert scale and were combined to form a unified measure of the driver's perceptual experience under simulated nighttime lighting. The questionnaire items were developed specifically for this study to assess two conceptual components: perceived visibility, and perceived safety and comfort.

Cronbach's alpha was calculated to evaluate internal consistency for each lighting condition, yielding reliability values that indicated acceptable coherence across the nine items. This supported their aggregation into a single composite measure of perceived visibility, safety, and comfort as shown in the Appendix B.

3.5.6 Open-Ended Qualitative Feedback

To complement the quantitative Likert-scale ratings, qualitative data were collected through open-ended questions embedded within the same post-drive questionnaire, as shown in Appendix B. These prompts allowed participants to elaborate on their experiences of visibility, perceived safety, and visual comfort in their own words. They also provided an opportunity for drivers to describe specific challenges encountered, such as glare or difficulty detecting hazards, under different nighttime lighting levels.

These responses provided additional context for interpreting the structured quantitative scores. Qualitative responses were examined for recurring themes and summarized descriptively across illumination conditions to support interpretation of the quantitative results.

3.6 Experimental Variables

3.6.1 Independent Variables

This study included three independent variables: illumination level, age group, and driving scenario. The primary within-subject variable was nighttime illumination, presented at three levels: low, medium, and high. These lighting conditions were implemented through predefined settings within the simulator environment. Each participant completed all three illumination conditions, and condition order was counterbalanced across participants to control for sequence effects and limit adaptation to anyone lighting level [67].

The between-subjects variable was age group, consisting of younger and older adult drivers. This factor was included to examine potential age-related differences in visibility, comfort, and driving response under nighttime illumination. For analyses involving eye-tracking and driving simulator measures, driving scenario was included as a secondary within-subject variable. Including scenario as a factor allowed the study to examine whether the effects of illumination varied across different roadway hazard contexts.

3.6.2 Dependent Variables

Four categories of dependent variables were analyzed: physiological measures, subjective ratings, visual attention metrics, and vehicle control performance. Each variable was operationally defined as follows:

A. Physiological Measures

The physiological outcome variables were mean heart rate (HR) and electrodermal activity (EDA), operationalized as skin conductance level (SCL). HR, expressed in beats per minute (bpm), was used as an indicator of cardiovascular arousal during the driving task. SCL, expressed in microsiemens (μS), was used as an indicator of sympathetic autonomic arousal. Both measures were obtained from the EmbracePlus wearable device and synchronized with simulator event logs so that condition-specific responses could be examined across illumination levels.

B. Subjective Ratings

Subjective experience was assessed using a 9-item post-condition questionnaire completed after each illumination level. Items were rated on a 5-point Likert scale, and responses were combined into a composite score representing perceived visibility, safety, and visual comfort under nighttime illumination. Higher scores reflected more favourable subjective evaluations of the driving environment. To complement these scaled responses, participants also completed four open-ended items that elicited qualitative feedback regarding perceived safety and visibility, difficulties detecting specific roadway elements, experiences of discomfort such as glare or eye strain, and recommendations for improving the lighting conditions.

C. Visual Attention Metrics

Visual attention was assessed using eye-tracking measures derived from gaze behaviour during the simulated driving task. TTFF was defined as the elapsed time from cue onset to the driver's first fixation on the relevant hazard target, such as the cyclist, pedestrian, construction worker, or merging vehicle. Dwell time was defined as the cumulative duration of fixations directed toward the hazard target within the event

window. In addition, fixation frequency was included as a descriptive indicator of visual monitoring behaviour, reflecting how often drivers shifted their gaze toward predefined secondary areas of interest, including the dashboard, side mirrors, and rear-view mirror, across illumination conditions. This measure was used to characterize how drivers distributed visual attention across vehicle-reference regions under different nighttime lighting levels.

D. Vehicle Control Performance

Vehicle control was assessed using simulator-derived kinematic measures. PRT represents the elapsed time from cue onset to the initiation of the driver's braking response. Pre-hazard speed was defined as the driver's average speed during the pre-hazard segment, before entering the hazard event window. To avoid contamination from initial acceleration and speed stabilization, the first 2 seconds of the pre-hazard segment were excluded from this calculation. This measure was used to represent the driver's steady approach speed before any hazard-related response or distraction occurred. Mean deceleration, expressed in m/s^2, was defined as the average deceleration recorded during the hazard segment. Maximum deceleration magnitude, also expressed in m/s^2, was defined as the peak deceleration recorded during the same hazard segment. Together, these measures were used to quantify the intensity of the driver's braking response to roadway hazards.

3.6.3 Controlled Variables

Several aspects of the simulator environment were held constant to reduce variability unrelated to the illumination manipulation. Road geometry, lane configuration, signage placement, and the timing and sequence of hazard events were kept identical across all lighting conditions. The simulator room was also maintained in a near-dark state, with ambient illumination held between 0.2 and 0.4 lux and verified prior to participant sessions.

Hardware configuration and data collection procedures were similarly standardized across all sessions. All participants used the same simulator cabin setup, received the same task instructions, and followed the same seating and control-adjustment procedures. Physiological and eye-tracking equipment were applied and calibrated using the same protocol for each participant. These controls helped support consistent experimental conditions and improved the validity of comparisons across illumination levels.

3.7 Driving Scenarios

Four distinct nighttime driving scenarios were developed to present consistent and repeatable hazard events across all illumination conditions. Each scenario consisted of a roadway segment approaching a roundabout and was designed to reflect a typical nighttime driving environment in the Waterloo region. To maintain experimental consistency, environmental features including road geometry, pole spacing, signage, and pavement markings were held constant across all scenarios. Participants drove along a corridor with a posted speed limit of 60 km/h.

Each scenario was structured into two segments: a pre-hazard approach segment and a hazard segment beginning at cue onset. The pre-hazard segment provided sufficient uninterrupted driving time for participants to establish a stable driving approach before the critical event began. The hazard segment extended from cue onset through the driver's interaction with the hazard before the roundabout entry. This structure was used to ensure a consistent and comparable event sequence across all scenarios and illumination conditions.

Each individual scenario lasted approximately 1.5 to 2 minutes, resulting in roughly 8 minutes of continuous driving per illumination condition. All participants completed the same four events under each illumination level, with both the illumination order and the sequence of scenarios randomized to reduce learning and sequence effects. Across the four scenarios, the primary hazard targets included a cyclist, a pedestrian, a construction worker, and a roadside vehicle. The scenarios were designed to examine driver responses to these hazards under varying nighttime illumination conditions while maintaining a consistent roadway context across events. Detailed descriptions of the four events are provided below, along with accompanying visuals. Although some figures are presented in daytime lighting for visual clarity, all experimental trials were conducted under simulated nighttime, clear-weather conditions with no additional environmental distractors.

3.7.1 Scenario 1: Bicycle Lane Incursion

In this scenario, the ego vehicle travels in the right lane while a cyclist proceeds in the adjacent bicycle lane. At a predefined point, the cyclist makes a brief lateral movement toward the driving lane, creating an unexpected incursion that serves as the hazard event. This scenario involved a cyclist as the primary hazard target and was designed to examine driver response to a sudden lateral movement near the travel lane. This scenario was designed to assess driver responses to a sudden lateral hazard near the travel lane under varying nighttime illumination conditions, as shown in Figure 5.

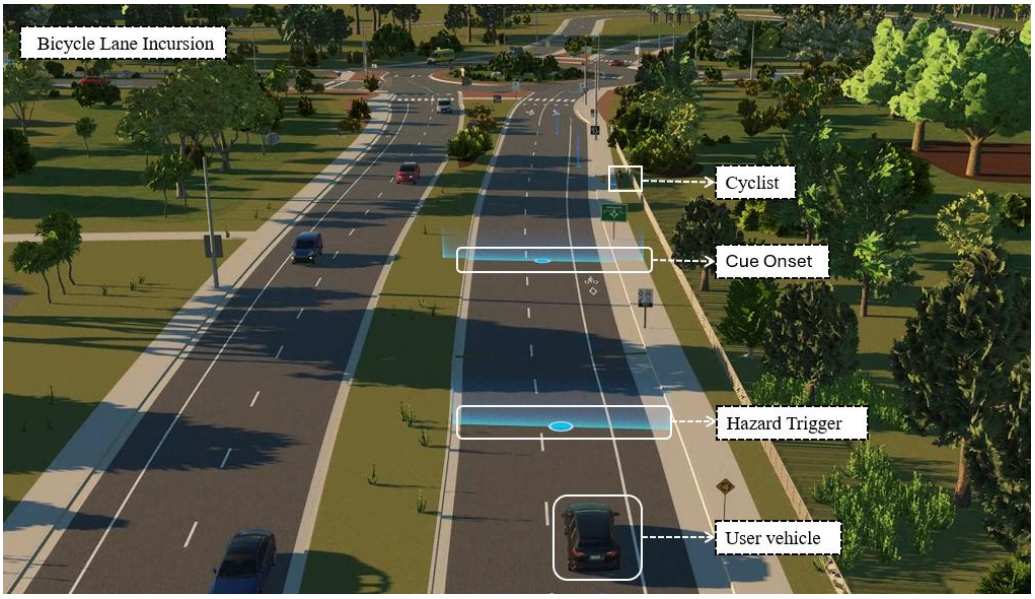


Figure 5. Cyclist briefly swerves into the lane to trigger rapid hazard recognition.

3.7.2 Scenario 2: Pedestrian Approaching Crosswalk

In this scenario, the ego vehicle travels in the right lane as it approaches a marked crosswalk. A pedestrian walks toward the crossing point and pauses at the curb without stepping into the roadway. This scenario involved a pedestrian as the primary hazard target and was designed to examine drivers' visual attention and response to a potential crossing-related hazard. This scenario was designed to examine drivers' visual attention and response to a potential pedestrian hazard, as shown in Figure 6.

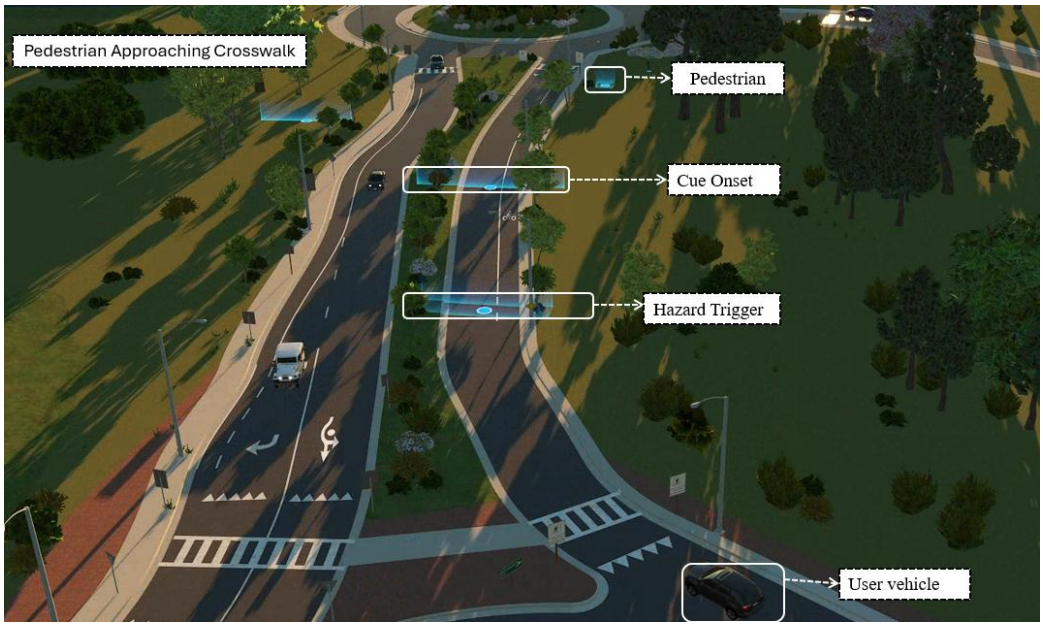


Figure 6. Pedestrian Approaching the Crosswalk

3.7.3 Scenario 3: Construction Work zone

In this scenario, the ego vehicle travels along a single-lane approach toward a roundabout entry. A construction worker stands near the roadside and is partially obscured by equipment, making the figure less visually prominent until the vehicle approaches. This scenario involved a construction worker as the primary hazard target and was designed to assess driver attention and response to a partially occluded roadside hazard. This scenario was designed to assess driver attention and response to a partially occluded roadside hazard, as shown in Figure 7.

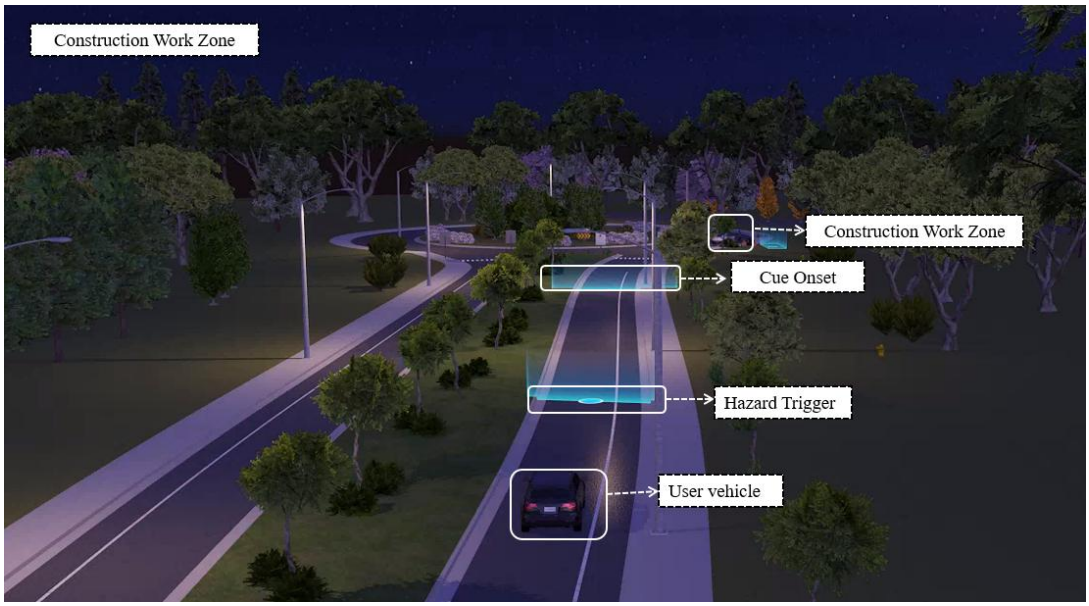


Figure 7. Construction Work Zone Event

3.7.4 Scenario 4: Roadside Vehicle Signaling to Merge

In this scenario, the ego vehicle travels along a single-lane roadway toward the roundabout entry. A stationary vehicle is positioned on the roadside ahead. As the ego vehicle approaches, the roadside vehicle activates its turn signal and slightly angles toward the lane, creating an early visual cue of a possible merge into traffic. This scenario involved a roadside vehicle as the primary hazard target and was designed to assess driver response to an emerging merge-related hazard. This scenario was designed to assess driver response to an emerging merge-related hazard, as shown Figure 8.

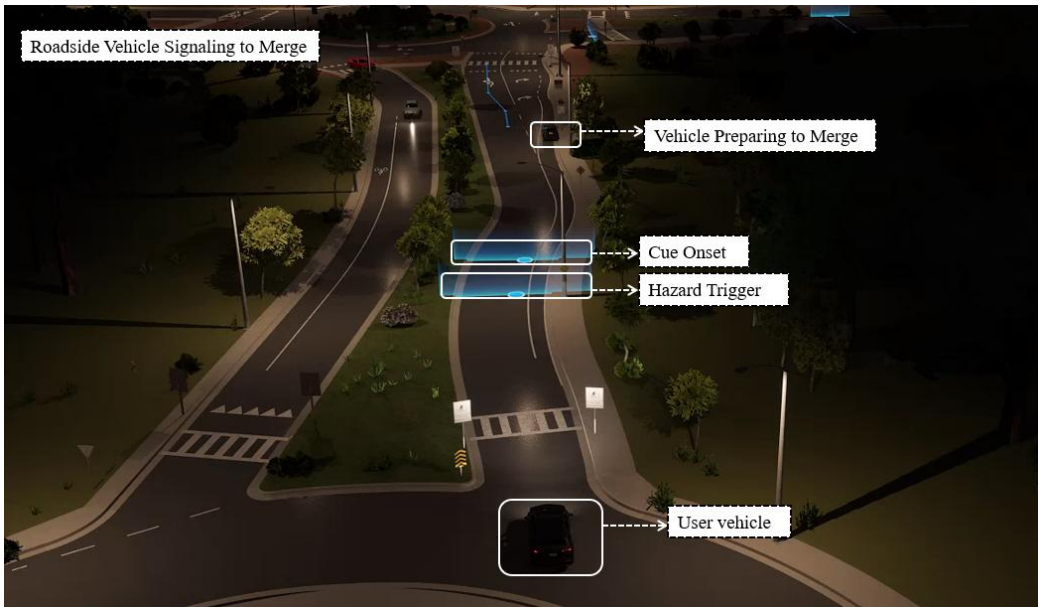


Figure 8. Roadside vehicle signalling to merge

3.8 Environment Development and Setup

The simulated driving environment was constructed using a roadway segment located near the University of Waterloo's student residential area. This corridor contains straight links and roundabout approaches that provide a realistic setting for examining nighttime visibility and perceived safety. Aerial mapping of the site was conducted using a DJI Matrice 300 RTK equipped with a downward-facing LiDAR scanner and high-resolution RGB camera as shown in Figure 9. These data produced georeferenced point clouds and Orthomosaic with centimeter-level accuracy, capturing roadway geometry, pole spacing, signage locations, elevation features, and surrounding roadside structures.



Figure 9. Nighttime roadway lighting and mapping survey (left) and daytime aerial mapping (right) both conducted using the DJI Matrice 300 RTK drone for digital twin reconstruction of the study environment.

The roadway was reconstructed in MathWorks RoadRunner by modelling alignment, lane configuration, intersection layout, and fixed roadside elements directly from the UAV-derived data. Canadian regulatory and warning signs were added manually following national guidelines. The completed scene was exported to the VI-Grade ModKit and WorldSIM platforms, where scenario logic, hazard triggers, and nighttime illumination controls were implemented. The resulting environment preserves the spatial and structural characteristics of the real corridor, functioning as a conceptual digital twin that supports controlled experimental manipulation. The final simulation environment used in the study is shown in Figure 10.



Figure 10. Daytime 3D-model reference view (Left), Nighttime simulator reconstruction scene (Right) in the study.

3.9 Illumination Setup

Three nighttime illumination levels were implemented to examine how changes in roadway brightness under controlled simulator conditions. Illumination was controlled using the candela-based intensity parameters in the Unreal Engine lighting system within VI-Grade ModKit.

Although these parameters use the unit candela, they represent stable engine-defined intensity values used to systematically manipulate brightness within the high-fidelity virtual environment. Field illuminance measurements collected at the reference site provided a realistic indication of the illumination range encountered along comparable roadways and guided the separation of the Low, Medium, and High conditions. These observations supported the conceptual alignment of the simulated levels with the relative lighting distinctions described in ANSI/IES RP-8 [82].

Ensuring that the resulting scenes remained ecologically meaningful while preserving full experimental control. Beam geometry, pole spacing, light distribution, and correlated colour temperature (CCT) were held constant across all conditions, with a fixed CCT of 4000 K was selected based on evidence that neutral-

white light (≈ 3500–4000 K) supports stable visibility, perceptual comfort, and cognitive performance during nighttime driving [83], [84].



Figure 11. Low, Medium, and High Illumination Levels in the Driving Simulator Scene

Only luminous intensity varied across conditions, producing perceptually distinct nighttime scenes while maintaining ecological validity. In the simulator, the Low, Medium, and High conditions corresponded to approximate intensity settings of 100 to 150 candela (cd), 200 to 250 cd, and 300 to 350 cd, respectively (*Figure **11***). These values were used as conceptual analogues of realistic roadway-lighting categories within the constraints of the simulation engine.

3.10 Experimental Procedure

All experimental sessions were conducted individually in the AVRIL laboratory following a standardized protocol and lasted approximately one hour. At the beginning of each session, participants completed the informed consent process, followed by the Motion Sickness Susceptibility Questionnaire Short Form (MSSQ-Short; Appendix C) and a brief demographic questionnaire (Appendix A). Eligibility was also reconfirmed at this stage, including visual correction, simulator tolerance, and nighttime driving experience. Participants were subsequently introduced to the simulator and completed a 5 to 10 minute familiarization drive to gain comfort with the steering controls, pedals, mirrors, and general vehicle handling as shown in Figure 12. This familiarization segment included no hazards and no illumination manipulations. After familiarization, the EmbracePlus physiological sensor and the Ergoneers eye-tracking headset were fitted and calibrated, and signal quality was verified, as shown in Figure 13.

Table 3 Illumination conditions and hazard scenario presentation across experimental configurations

Illumination Block 1	***Scenario Sequence***	***Illumination Block 2***	***Scenario Sequence***	***Illumination Block 3***	***Scenario Sequence***
Low	Bicycle Pedestrian Construction Merging	Medium	Pedestrian Construction Merging Bicycle	High	Construction Merging Bicycle Pedestrian
Medium	Construction Merging Bicycle Pedestrian	High	Merging Bicycle Pedestrian Construction	Low	Pedestrian Bicycle Construction Merging
High	Pedestrian Construction Merging Bicycle	Low	Construction Merging Bicycle Pedestrian	Medium	Merging Bicycle Pedestrian Construction

A five-minute resting baseline was then recorded in a quiet, low-stimulus environment while the participant was seated comfortably in the simulator cabin. During this period, participants were instructed to relax, minimize movement, and keep their eyes closed to allow HR and EDA to stabilize before the driving task began. The experimental drive then proceeded under the three illumination conditions, with both the order of illumination levels and the order of scenario presentation counterbalanced across participants to reduce sequence and adaptation effects. Illumination conditions and hazard scenarios were presented using three predefined experimental configurations, as shown in Table 3. Participants were

randomly assigned to one configuration. Within each illumination condition, participants completed the same four nighttime scenarios, resulting in approximately eight minutes of driving per lighting session. Short rest breaks were provided between conditions to reduce carryover effects and allow participants to recover before continuing.

Throughout the session, physiological signals, eye-tracking data, and vehicle telemetry were recorded continuously and synchronized with simulator event logs for temporal alignment. Participants were instructed to drive normally, obey posted speed limits, and respond naturally to hazards. After each illumination condition, they completed the post-condition questionnaire assessing perceived visibility, safety, and visual comfort as shown in Appendix B. At the end of the session, the sensors were removed, participants were debriefed, brief feedback was collected, and compensation was provided.



Figure 12. Interior configuration of the VI-grade STATIC driving simulator vehicle cabin, showing the steering interface, dashboard displays, and driver seating used during the experimental sessions.



Figure 13. Demonstration of the instrumentation setup on (left) Nighttime simulator scene (right). (The individual shown is not a study participant; the image is included solely for demonstration of the equipment configuration)

CHAPTER 4
Results & Analysis

4.1 Introduction

This chapter presents the physiological, visual, behavioral, and perceptual findings associated with the three illumination levels in the simulated nighttime driving environment. Physiological responses, including HR and EDA, were examined across low, medium, and high illumination, with resting baseline comparisons included only for these measures. Visual attention and driving performance were assessed using eye-tracking metrics, including TTFF, dwell time, and descriptive fixation count, together with simulator-derived measures such as PRT, pre-hazard speed, mean deceleration, and maximum deceleration magnitude. Subjective ratings of visibility and comfort were also collected after each driving segment, alongside open-ended qualitative feedback describing participants' experiences of visibility, safety, and visual comfort. Age-group comparisons were conducted across outcome measures, and driving scenario was included as a factor for visual attention and driving performance outcomes. The chapter is organized by outcome domain, beginning with physiological responses, followed by visual attention and driving performance, and concluding with subjective and qualitative findings.

4.2 Data Overview

This chapter analyzes four categories of data collected under low, medium, and high illumination, with an additional resting baseline included only for the physiological measures. HR and EDA were recorded continuously, synchronized with the simulator timeline, and segmented by illumination level. EDA activity was analyzed using tonic SCL as an index of autonomic arousal.

Eye-tracking and vehicle kinematic data were also synchronized with specific hazard events in the simulator. Visual attention was assessed using TTFF and dwell time, with descriptive fixation count included to characterize gaze allocation across predefined areas of interest. Driving performance was evaluated using PRT, pre-hazard speed, mean deceleration, and maximum deceleration magnitude.

Subjective responses were obtained using a nine-item questionnaire completed after each illumination condition. Items were rated on a five-point Likert scale and analyzed as a composite measure of perceived nighttime comfort and safety. Internal consistency across illumination levels supported the use of this

composite score. Qualitative responses were collected through open-ended items embedded within the same post-drive questionnaire, allowing participants to elaborate on their experiences of discomfort such as glare or eye strain, and recommendations for improving the lighting conditions.

All variables were screened using Q-Q plots and Shapiro-Wilk tests to guide the selection of parametric or non-parametric models for each outcome. Physiological and subjective measures, aggregated across each illumination condition, were analyzed using a two-factor mixed-design ANOVA, with illumination specified as a within-subjects factor and age group as a between-subjects factor. By contrast, visual attention and driving performance measures, derived from specific hazard events, were analyzed using a three-factor mixed-design ANOVA, with illumination and scenario as within-subject factors and age group as the between-subject factor, to account for variation across hazard types. Qualitative responses were examined separately to identify recurring themes and were summarized descriptively across illumination levels to support interpretation of the quantitative findings. The following sections present the results by outcome domain, beginning with physiological responses, followed by visual attention, driving performance, and subjective and qualitative findings.

4.3 Physiological Results

4.3.1 Heart Rate (HR)

The distribution of HR values, measured in beats per minute (BPM), was first examined across the three illumination conditions. Visual inspection of the Q-Q plots for the low, medium, and high illumination levels as shown in *Figure 14* showed close alignment between the observed and expected theoretical quantiles. This was supported by non-significant Shapiro-Wilk tests for all illuminated conditions (all $p > .05$), indicating that the assumption of normality was satisfied and that parametric analyses were appropriate.

Descriptive statistics for HR across baseline, low, medium, and high illumination are presented in Table 4 for the full sample and by age group. Across the full sample, mean HR increased from baseline ($M = 73.12$ BPM, $SD = 11.63$) to low illumination ($M = 76.81$ BPM, $SD = 12.61$), declined at medium illumination ($M = 74.63$ BPM, $SD = 11.00$), and increased again under high illumination ($M = 76.14$ BPM, $SD = 12.12$).

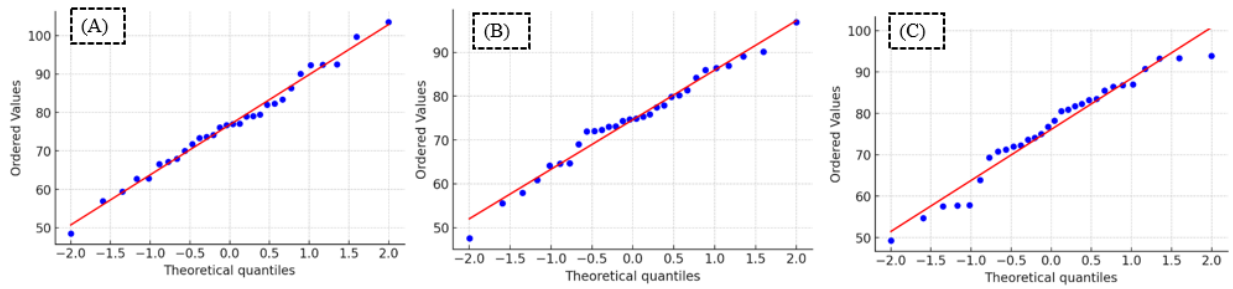


Figure 14. Q–Q plots for average heart-rate distributions under Low (A), Medium (B), and High (C) illumination.

Both age groups showed a similar directional pattern, although younger adults exhibited slightly higher heart-rate values overall. Variability was greatest under low illumination, particularly among older adults (SD = 15.07). These trends are illustrated in Figure 15.

Table 4 Mean HR (BPM) by illumination level for the full sample and both age groups.

Age Group	***Condition***	***Mean***	***Median***	***Std Dev***	***Range***
Full Sample	Baseline	73.12	73.60	11.63	43.20
	Low	76.81	76.85	12.61	55.00
	Medium	74.63	74.81	11.00	49.35
	High	76.14	77.54	12.12	44.65
Older Adults	Baseline	71.71	73.80	12.44	42.33
	Low	76.00	77.00	15.07	55.00
	Medium	72.49	73.00	12.67	49.35
	High	73.81	76.78	12.81	44.65
Younger Adults	Baseline	74.53	73.40	11.00	33.87
	Low	77.61	76.70	10.04	33.04
	Medium	76.77	75.90	8.96	33.51
	High	78.46	80.60	11.34	35.83

These observed trends were then examined using inferential analyses to determine whether the observed differences across conditions and age groups were statistically significant. A repeated-measures ANOVA was first conducted to test whether HR differed across baseline, low, medium, and high illumination. The analysis revealed a significant main effect of condition, $F\,(3, 87) = 5.94, p = .001, \eta p^2 \approx .170$, indicating that HR varied significantly across the full set of conditions.

A second repeated-measures ANOVA was conducted using only the low, medium, and high illumination levels to assess how HR varied across illuminated conditions. The analysis showed no significant differences among these three lighting levels, $F\ (2, 58)\ =\ 2.58, p\ =\ 0.085, \eta p^2\ =\ 0.082$. These findings suggest that the presence of illumination was associated with an increase in HR, whereas further increases in illumination intensity did not produce additional group-level changes.

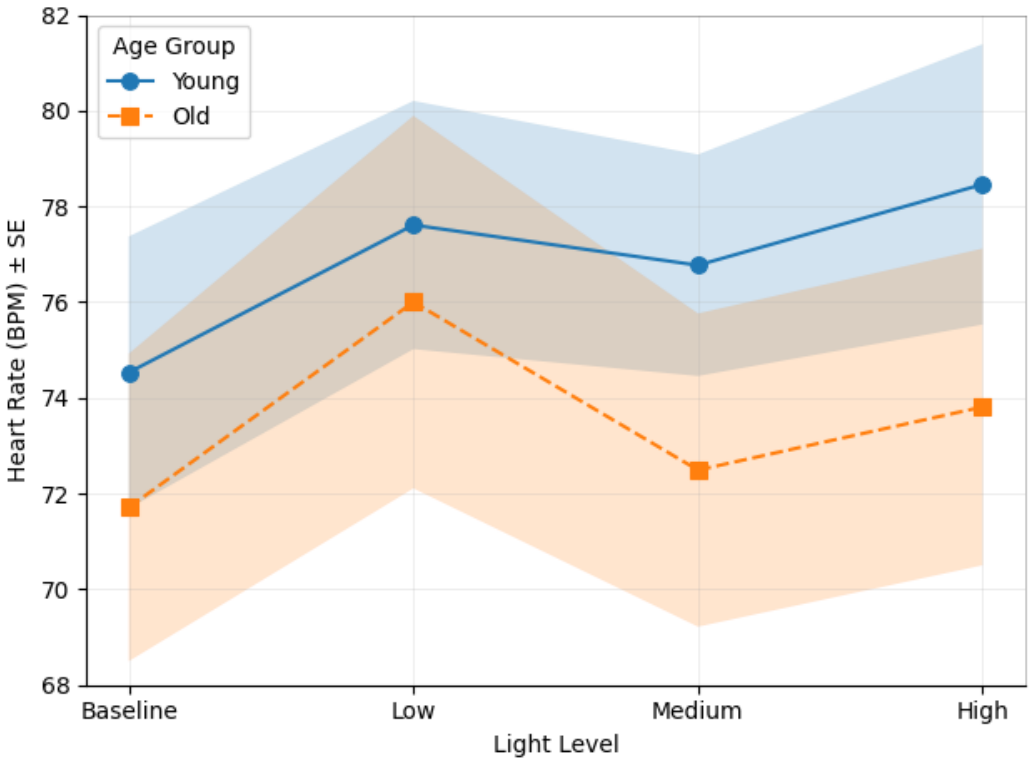


Figure 15. Mean HR changes across baseline and illumination levels by age group.

Post-hoc comparisons are presented in Table 5 supported this pattern across both the full sample and the age groups. Relative to baseline, HR increased significantly under low illumination for the full sample (+3.69 BPM, p < .001) and again under high illumination (+3.01 BPM, p = .018), while the increase at medium illumination was not significant (+1.51 BPM, p = .315). Younger adults showed the same pattern: a significant rise from baseline to low illumination (+3.08 BPM, p = .0037) and a smaller but still significant increase at high illumination (+3.93 BPM, p = .037), with no significant change at medium illumination (+2.24 BPM, p = .585). Older adults also demonstrated a significant increase from baseline to low illumination (+4.29 BPM, p = .020), but neither medium (+0.78 BPM, p = 1.000) nor high illumination (+2.10 BPM, p = .401) differed significantly from baseline.

Importantly, no significant differences emerged among the three illuminated conditions within any age group. Taken together, these results show that the introduction of illumination elevates cardiovascular activation, but increasing the intensity from low to high does not meaningfully change HR for the sample as a whole or for the younger and older adults considered separately. Holm–Sidak corrections were applied for the overall post-hoc comparisons to maintain statistical power, whereas Bonferroni adjustments were used for the age-specific analyses because the smaller subgroup samples required a more conservative approach to reduce Type I error.

Table 5 post-hoc pairwise comparisons for HR means (Holm–Sidak for overall; Bonferroni for age-specific analyses) [67]

Group	***Condition***	***Mean Difference***	***Adjusted p***	***Cohen's d***
Full Sample	Baseline → Low Light	+3.69	0.0003***	0.87
	Baseline → Medium Light	+1.51	0.315 n.s.	0.28
	Baseline → High Light	+3.01	0.018*	0.58
Younger Adults	Baseline → Low Light	+3.08	0.0037**	1.04
	Baseline → Medium Light	+2.24	0.585 n.s.	0.35
	Baseline → High Light	+3.93	0.037*	0.74
Older Adults	Baseline → Low Light	+4.29	0.020*	0.82
	Baseline → Medium Light	+0.78	1.000 n.s.	0.16
	Baseline → High Light	+2.10	0.401 n.s.	0.41

*Note: n.s. = not significant; * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.*

A two-factor mixed-design ANOVA was then conducted using the illuminated conditions only, with illumination as the within-subjects factor and age group as the between-subjects factor. The main effect of age group was non-significant, $F\,(1, 56) = 1.54$, $p = .22$, $\eta p^2 = .027$ and the age × illumination interaction was also non-significant, $F\,(2, 56) = 1.45$, $p = .24$, $\eta p^2 = .049$. These results indicate that age does not meaningfully influence heart-rate responses across the illuminated conditions. Younger and older adults follow statistically similar heart-rate patterns under low, medium, and high illumination (all $p > .05$).

4.3.2 Electrodermal Activity (EDA)

Electrodermal Activity, indexed using tonic SCL, was examined to assess physiological arousal across the illumination conditions and between age groups. Because SCL reflects sympathetic nervous system activation, it was used to evaluate changes in autonomic arousal under different nighttime lighting levels.

This section first assesses the distributional properties of the SCL data and then presents the descriptive and inferential results across baseline and illuminated conditions.

Normality of EDA values under the low, medium, and high illumination conditions was assessed using Shapiro-Wilk tests and visual inspection of Q-Q plots. All three illuminated conditions showed significant departures from normality (all $p < .05$), and the Q-Q plots showed the positive skew typically observed in tonic skin conductance data. A logarithmic transformation, $\ln(x + 1)$, reduced the degree of skewness but did not fully normalize the distributions. Because non-normality remained, EDA was analyzed using non-parametric methods.

Descriptive statistics for tonic EDA across baseline, low, medium, and high illumination are presented in Table 6 for the full sample and by age group. Across the full sample, mean SCL was lowest at baseline (M = 1.09 μS, SD = 1.64) and increased under all illuminated conditions, with the highest value observed under low illumination (M = 4.48 μS, SD = 6.06), followed by high illumination (M = 3.36 μS, SD = 4.25) and medium illumination (M = 3.21 μS, SD = 4.88). Both age groups showed higher SCL under illuminated conditions than at baseline, although older adults exhibited higher overall SCL values and a more pronounced increase across conditions. Variability was also substantial across illumination levels, particularly under low illumination. These trends are illustrated in Figure 16.

Table 6. Mean SCL (μS) across baseline and illumination levels for the full sample and age groups

Age Group	***Condition***	***Mean (μS)***	***Median***	***SD***	***Range***
Full Sample	Baseline	1.0939	0.2750	1.6418	5.57
	Low	4.4750	2.2556	6.0629	26.37
	Medium	3.2097	1.2200	4.8767	22.27
	High	3.3634	1.3206	4.2508	16.04
Older Adults	Baseline	1.3525	0.8480	1.4941	4.87
	Low	6.4046	5.8812	4.7202	14.73
	Medium	4.3320	1.7900	5.6861	22.23
	High	4.7504	3.3838	4.6423	15.56
Younger Adults	Baseline	0.8353	0.0660	1.7910	5.57
	Low	2.5455	0.1025	6.7738	26.37
	Medium	2.0873	0.1300	3.7725	12.58
	High	1.9763	0.1113	3.4285	8.93

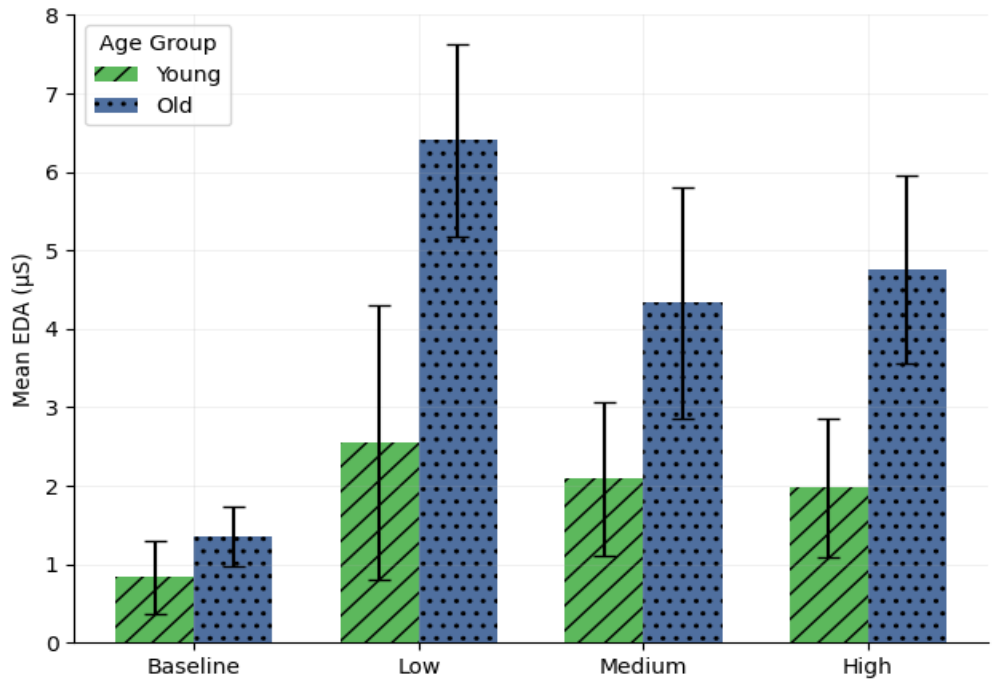


Figure 16. Mean SCL across baseline, low, medium, and high illumination levels for younger and older adults.

EDA values violated the assumption of normality; accordingly, non-parametric procedures appropriate for within-subject data were employed. Comparison of baseline with the three illuminated conditions, low, medium, and high, using the Friedman test revealed a significant effect of illumination on sympathetic activation, χ^2 (3) = 39.96, p < .001, Kendall's W = 0.444. This result indicates a moderate overall shift in EDA across conditions, with the most pronounced increase observed between baseline and low illumination.

A second Friedman test using only the low, medium, and high illumination levels was then performed to assess differences among the illuminated conditions themselves. This analysis was not significant, χ^2 (2) = 4.07, p = .131, Kendall's W = 0.068, indicating that the three illuminated conditions did not differ reliably in their physiological impact.

Post-hoc comparisons Table 7 supported this pattern across both the full sample and the age groups. Relative to baseline, EDA increased significantly for the full sample under all three illuminated conditions. The largest shift occurred at low illumination (+3.39 µS, adjusted p < .001), followed by medium (+2.12 µS, adjusted p < .001) and high illumination (+2.27 µS, adjusted p < .001). These changes all showed large effect sizes, indicating a clear rise in sympathetic activation once lighting was introduced. To understand whether this pattern differed by age, the same comparisons were examined separately for younger and older adults.

Younger adults showed the same overall direction, although with smaller magnitude. EDA increased significantly from baseline to low illumination (+1.71 μS, adjusted p = .040), and the transitions from baseline to medium (+1.25 μS, adjusted p = .0004) and high illumination (+1.14 μS, adjusted p = .0004). No significant differences emerged among the three illuminated conditions. Older adults demonstrated a more pronounced physiological shift. EDA rose sharply from baseline to low illumination (+5.05 μS, adjusted p < .001), with not significant increases also observed at medium (+2.98 μS, adjusted p = .0905) and high illumination (+3.40 μS, adjusted p = .0545). Like the younger group, none of the illuminated levels differed significantly from each other after correction. This shows that the magnitude of change is larger in older adults, but the pattern is identical.

Overall, the post hoc comparisons indicate a clear and consistent pattern in which illumination was associated with elevated tonic sympathetic activity across participants. Holm–Sidak adjustments were applied to the full-sample comparisons to retain statistical power, whereas Bonferroni corrections were used for the age-specific analyses to provide a more conservative control of multiple comparisons.

Table 7. Post-hoc pairwise comparisons for SCL (μS) means (Holm–Sidak for overall; Bonferroni for age-specific analyses).

Group	***Comparison***	***Mean Diff (μS)***	***Adjusted p***	***r (effect)***	***Cohen's d***
Full Sample	Baseline → low	+3.3811	0.0001***	0.632	0.651
	Baseline → medium	+2.1157	0.0003***	0.517	0.506
	Baseline → high	+2.2694	0.0002***	0.531	0.615
Younger Adults	Baseline → low	+1.7102	0.0403*	0.495	0.292
	Baseline → medium	+1.2520	0.0004***	0.732	0.559
	Baseline → high	+1.1410	0.0004***	0.732	0.528
Older Adults	Baseline → low	+5.0520	0.0004***	0.732	1.280
	Baseline → medium	+2.9795	0.0905 n.s.	0.444	0.548
	Baseline → high	+3.3979	0.0545 n.s.	0.481	0.745

*Note: n.s. = not significant; * p < 0.05; **p < 0.01; ***p < 0.001.*

An aligned rank transform mixed ANOVA was conducted to examine whether age modified the illumination-related pattern in EDA, with illumination condition entered as the within-subjects factor and age group as the between-subjects factor. The age group × illumination interaction was not significant, $F(2, 84) = 2.74$, $p = .070$, $\eta p^2 = .061$, indicating that the pattern of change across the illuminated conditions was similar for younger and older adults. The main effect of illumination was also not significant, $F(2, 84) = 1.87$, $p = .160$, $\eta p^2 = .043$, which is consistent with the non-parametric results showing no reliable

differences among low, medium, and high illumination. In contrast, the main effect of age group was significant, $F(1, 84) = 32.26$, $p < .001$, $\eta p^2 = .277$, indicating that older adults exhibited consistently higher sympathetic activation than younger adults across the illuminated conditions.

This statistical profile reinforces the descriptive pattern. Illumination increases EDA relative to baseline, but differences among low, medium, and high levels remain small. Age changes the overall magnitude of EDA.

4.4 Visual Attention Results

4.4.1 Time to First Fixation (TTFF)

Time to First Fixation was examined to assess how illumination influenced the speed of visual hazard detection across scenarios and between age groups. TTFF represents the elapsed time between hazard onset and the driver's first fixation on the relevant hazard target.

Table 8. Mean ± SD TTFF by scenario and illumination level

Group	***Scenario***	***Low***	***Medium***	***High***
Full Sample	Bike	2.49 ± 0.82	1.93 ± 0.57	1.60 ± 0.71
	Pedestrian	1.07 ± 0.45	0.73 ± 0.33	0.83 ± 0.56
	Construction	2.33 ± 0.67	1.76 ± 0.83	2.09 ± 0.88
	Merging	1.69 ± 0.63	1.08 ± 0.33	1.17 ± 0.49
	Average	1.94 ± 0.51	1.37 ± 0.47	1.46 ± 0.45
Younger Adults	Bike	2.26 ± 0.60	2.02 ± 0.58	1.56 ± 0.77
	Pedestrian	1.20 ± 0.51	0.83 ± 0.26	0.95 ± 0.54
	Construction	2.07 ± 0.63	1.36 ± 0.42	1.41 ± 0.40
	Merging	1.88 ± 0.56	1.01 ± 0.36	1.11 ± 0.45
	Average	1.95 ± 0.40	1.40 ± 0.44	1.31 ± 0.43
Older Adults	Bike	2.75 ± 0.98	1.82 ± 0.56	1.66 ± 0.65
	Pedestrian	0.94 ± 0.38	0.63 ± 0.36	0.69 ± 0.56
	Construction	2.52 ± 0.66	2.16 ± 0.96	2.73 ± 0.70
	Merging	1.54 ± 0.65	1.14 ± 0.31	1.23 ± 0.53
	Average	1.93 ± 0.61	1.33 ± 0.51	1.62 ± 0.44

Descriptive statistics for TTFF across low, medium, and high illumination are presented in Table 8 for the full sample and by scenario. Across the full sample, hazard detection was slowest under low illumination (M = 1.94 s, SD = 0.51), improved under medium illumination (M = 1.37 s, SD = 0.47), and remained similar under high illumination (M = 1.46 s, SD = 0.45). This pattern was generally observed across scenarios, although the magnitude of the difference varied by hazard type. These trends are illustrated in Figure 17.

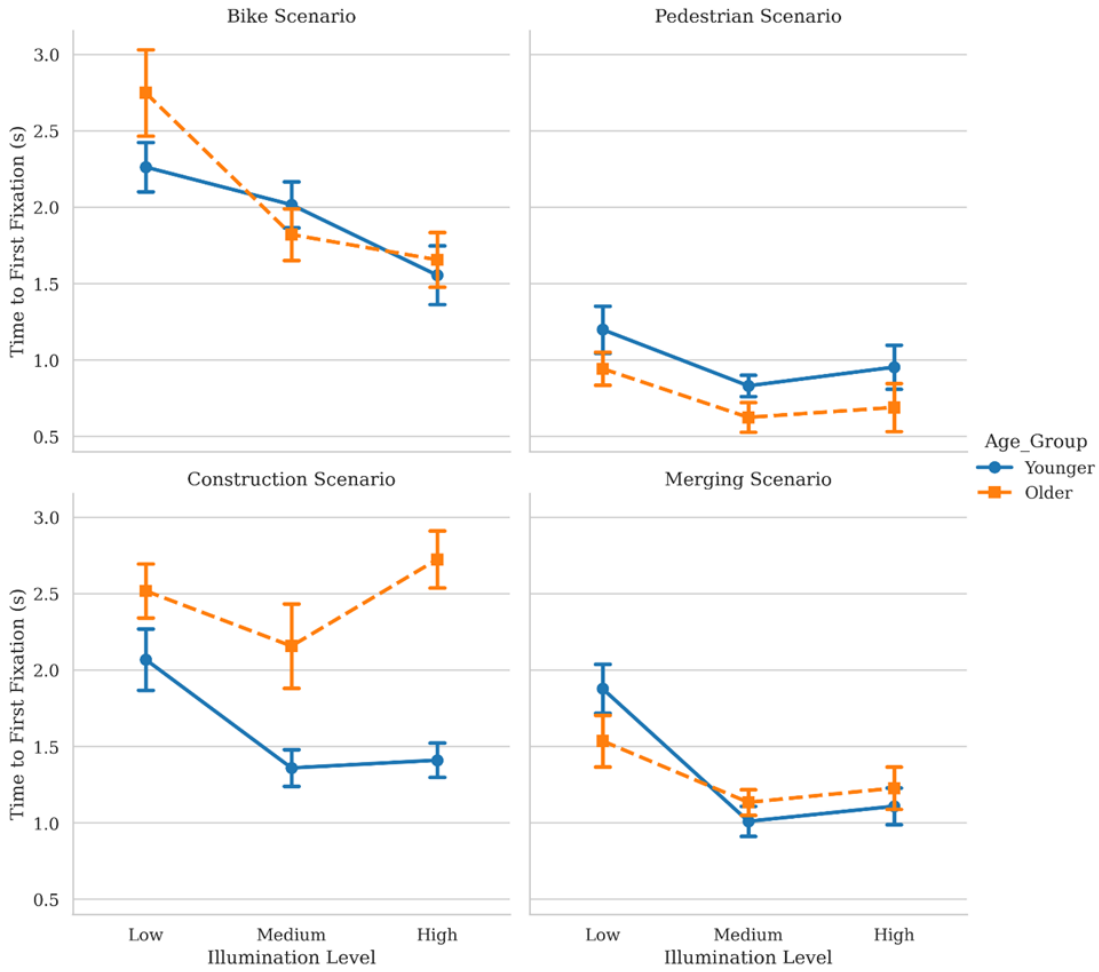


Figure 17. Mean TTFF across illumination levels by scenario and age group

Post hoc pairwise comparisons presented in Table 9 and Table 10 showed that the TTFF differences were driven primarily by transitions from low illumination to higher lighting levels for the full sample and age groups, respectively. In the full sample, significant reductions in TTFF were observed from low to medium illumination in the bike ($p = .0068$, $d = 0.783$), pedestrian ($p = .0034$, $d = 0.867$), construction ($p = .0117$, $d = 0.758$), and merging ($p < .001$, $d = 1.223$) scenarios. Significant low-to-high reductions were

also observed in the bike ($p < .001$, $d = 1.164$) and merging ($p = .0011$, $d = 0.925$) scenarios. No significant medium-to-high differences were identified in any scenario.

Age-specific comparisons followed the same general pattern but were more selective. Among younger adults, significant reductions in TTFF were observed in the bike, construction, and merging scenarios, particularly in comparisons involving low illumination, with large effect sizes throughout. Among older adults, significant differences were limited to the bike scenario, where TTFF was shorter under both medium and high illumination than under low illumination. Overall, these results indicate that the main improvement in visual hazard detection occurred when illumination increased from low to at least moderate levels, whereas increasing illumination from medium to high did not provide additional meaningful benefit.

Table 9. Post hoc pairwise comparisons and Cohen's d for TTFF across illumination levels by scenario in the full sample.

Group	***Scenario***	***Comparison***	***p-value***	***Cohen's d***
Full sample	Bike	Low vs. Medium	0.0068**	0.783
	Bike	Medium vs. High	0.06177 *n.s.*	0.515
	Bike	Low vs. High	0.000007***	1.164
	Pedestrian	Low vs. Medium	0.00337**	0.867
	Pedestrian	Medium vs High	0.42558 *n.s.*	0.217
	Pedestrian	Low vs High	0.10668 *n.s.*	0.467
	Construction	Low vs Medium	0.01166*	0.758
	Construction	Medium vs High	0.17088 *n.s.*	0.39
	Construction	Low vs High	0.28323 *n.s.*	0.304
	Merging	Low vs Medium	0.00004***	1.223
	Merging	Medium vs High	0.40234 *n.s.*	0.226
	Merging	Low vs High	0.0011**	0.925

*Note: n.s. = not significant; * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.*

To assess whether the observed differences in TTFF were statistically reliable, a three-factor mixed-design ANOVA was conducted. And the result revealed a significant main effect of illumination on TTFF, $F(2, 56) = 6.346$, $p = .002$, $\eta p^2 = .185$, indicating that hazard detection time differed across illumination conditions. A significant main effect of scenario was also observed, $F(3, 84) = 3.613$, $p = .013$, $\eta p^2 = .114$, indicating that TTFF varied across hazard types. The main effect of age group was not significant, $F(1, 28) = 0.373$, $p = .541$, $\eta p^2 = .013$, suggesting that younger and older adults did not differ in overall hazard detection speed.

Table 10. Post hoc pairwise comparisons and Cohen's d for TTFF across illumination levels by scenario in age groups.

Group	*Scenario*	*Comparison*	*p-value*	*Cohen's d*
Younger	Bike	Low vs Medium	0.2731 n.s.	0.416
Adults	Bike	Medium vs High	0.07151 n.s.	0.672
	Bike	Low vs High	0.00967**	1.016
	Construction	Low vs Medium	0.00497**	1.351
	Construction	Medium vs High	0.76023 n.s.	0.124
	Construction	Low vs High	0.00614**	1.281
	Merging	Low vs Medium	0.0001***	1.876
	Merging	Medium vs High	0.53754 n.s.	0.241
	Merging	Low vs High	0.00068***	1.533
	Pedestrian	Low vs Medium	0.02778*	0.946
	Pedestrian	Medium vs High	0.45117 n.s.	0.289
	Pedestrian	Low vs High	0.25899 n.s.	0.466
Older Adults	Bike	Low vs Medium	0.01199*	1.148
	Bike	Medium vs High	0.51656 n.s.	0.27
	Bike	Low vs High	0.003**	1.328
	Construction	Low vs Medium	0.26801 n.s.	0.446
	Construction	Medium vs High	0.09453 n.s.	0.685
	Construction	Low vs High	0.42993 n.s.	0.303
	Merging	Low vs Medium	0.04706*	0.773
	Merging	Medium vs High	0.57591 n.s.	0.21
	Merging	Low vs High	0.1682 n.s.	0.517
	Pedestrian	Low vs Medium	0.03836*	0.862
	Pedestrian	Medium vs High	0.72304 n.s.	0.138
	Pedestrian	Low vs High	0.20353 n.s.	0.524

*Note: n.s. = not significant; * p < 0.05; **p < 0.01; ***p < 0.001.*

Neither the Illumination × Scenario interaction, F (6, 168) = 1.649, p = .129, ηp^2 = .056, nor the Illumination × Age Group interaction, F (2, 56) = 2.489, p = .083, ηp^2 = .082, was significant. However, the Scenario × Age Group interaction was significant, F(3, 84) = 10.481, p < .001, ηp^2 = .272, as was the Illumination × Scenario × Age Group interaction, F(6, 168) = 2.402, p = .025, ηp^2 = .079, indicating that the effect of illumination on TTFF varied across specific hazard scenarios between the two age groups.

4.4.2 Dwell Time

Dwell time was examined to assess the total duration of visual attention allocated to a hazard after it was detected. Longer dwell times may reflect increased visual processing demand or greater attentional effort directed toward the hazard. Descriptive statistics for the full sample and both age groups are presented in Table 11. Across the full sample, dwell time was highest under low illumination (M = 2.39 s, SD = 0.57) and decreased under medium (M = 1.89 s, SD = 0.49) and high illumination (M = 1.87 s, SD = 0.42), indicating that the main reduction occurred when illumination increased from low to medium, with little further change from medium to high.

A similar pattern was observed across age groups, although the reduction was more pronounced among younger adults. Younger adults showed a steady decline in dwell time from low to high illumination (2.53 s to 1.67 s), whereas older adults showed a smaller reduction from low to medium illumination (2.24 s to 1.87 s) and a slight increase under high illumination (2.08 s). Overall, these descriptive results suggest that increasing illumination beyond medium did not meaningfully improve visual processing efficiency, and that age influenced the magnitude, but not the general direction, of the response. And the overall dwell-time trends across illumination levels and age groups are illustrated in Figure 18.

Table 11. Mean ± SD dwell time (s) by scenario and illumination level for the full sample and both age groups

Group	***Scenario***	***Low***	***Medium***	***High***
Full sample	Bike	3.04 ± 1.14	2.52 ± 0.80	2.32 ± 1.10
	Pedestrian	0.92 ± 0.51	1.00 ± 0.36	1.01 ± 0.54
	Construction	2.69 ± 1.36	2.68 ± 1.42	2.34 ± 1.10
	Merging	2.57 ± 0.86	1.63 ± 0.52	1.84 ± 0.74
	Average	2.39 ± 0.57	1.89 ± 0.49	1.87 ± 0.42
Younger adults	Bike	3.08 ± 1.00	2.45 ± 0.77	2.07 ± 1.01
	Pedestrian	0.90 ± 0.51	0.97 ± 0.45	0.91 ± 0.33
	Construction	2.84 ± 1.68	2.74 ± 1.91	2.14 ± 1.23
	Merging	2.67 ± 0.81	1.52 ± 0.54	1.71 ± 0.66
	Average	2.53 ± 0.61	1.90 ± 0.55	1.67 ± 0.43
Older adults	Bike	2.98 ± 1.33	2.62 ± 0.87	2.62 ± 1.16
	Pedestrian	0.93 ± 0.53	1.02 ± 0.25	1.12 ± 0.70
	Construction	2.58 ± 1.14	2.63 ± 0.74	2.53 ± 0.96
	Merging	2.50 ± 0.92	1.73 ± 0.51	1.95 ± 0.82
	Average	2.24 ± 0.50	1.87 ± 0.42	2.08 ± 0.32

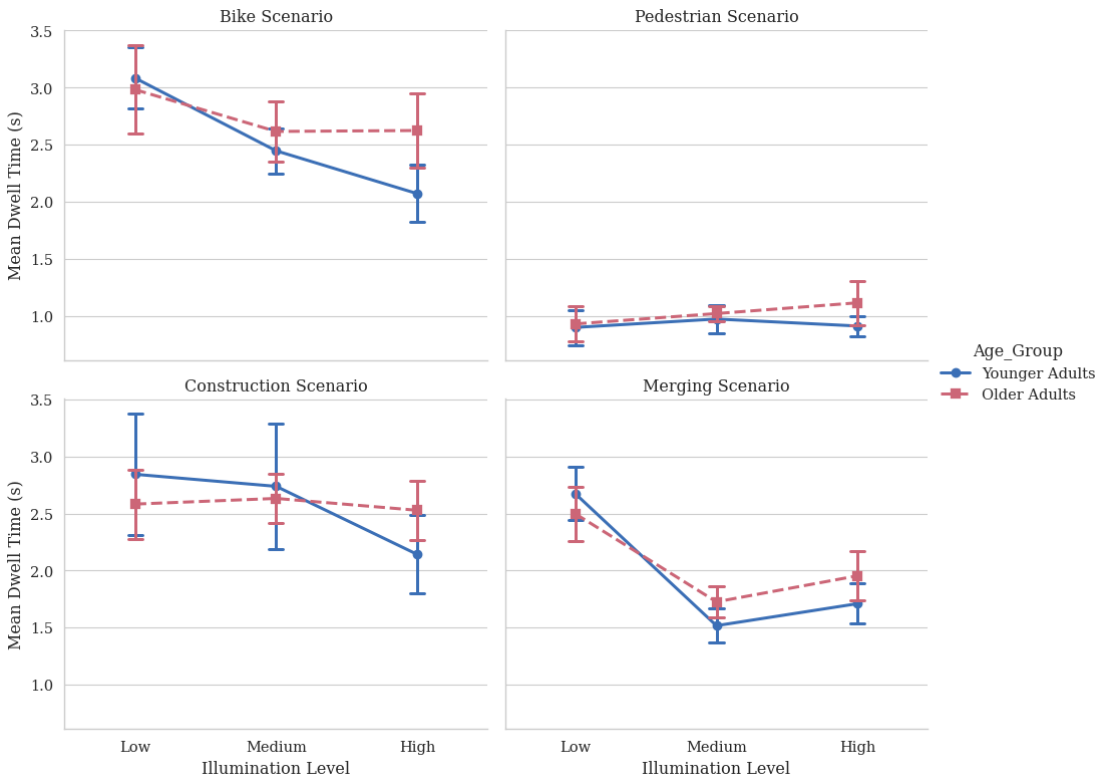


Figure 18. Scenario-specific dwell time patterns across illumination levels for younger and older adults

Post hoc pairwise comparisons presented in Table 12 and Table 13 showed that the significant dwell-time differences were concentrated in comparisons involving low illumination for the full sample and age groups, respectively. In the full sample, average dwell time was significantly shorter under medium illumination than under low illumination ($p < .001$, Cohen's $d = 0.947$) and under high illumination than under low illumination ($p < .001$, $d = 1.033$), whereas no significant difference was observed between medium and high illumination. At the scenario level, significant reductions were found only in the merging scenario, where dwell time was shorter under medium than low illumination ($p < .001$, $d = 1.337$) and under high than low illumination ($p = .0011$, $d = 0.923$).

Age-specific comparisons showed a similar overall pattern, but with fewer significant contrasts. Among younger adults, significant reductions in dwell time were observed in the bike scenario between low and high illumination ($p = .0103$, $d = 1.007$) and in the merging scenario between low and medium illumination ($p = .0003$, $d = 1.701$) and between low and high illumination ($p = .0027$, $d = 1.318$). Among older adults, the only significant comparison was in the merging scenario, where dwell time was shorter under medium than low illumination ($p = .0099$, $d = 1.031$). No medium-to-high differences were significant in either age group. Overall, these results suggest that the main reduction in dwell time occurred when illumination

increased from low to at least medium levels, while additional lighting beyond medium provided little further improvement. Age appeared to influence the strength of this effect more than its general direction.

Table 12. Post hoc pairwise comparisons and Cohen's d effect sizes for dwell time across illumination levels by scenario for the full sample

Group	***Scenario***	***Comparison***	***p-value***	***Cohen's d***
Full sample	Bike	Low vs Medium	0.06458 n.s.	0.524
	Bike	Medium vs High	0.45099 n.s.	0.205
	Bike	Low vs High	0.02131*	0.641
	Pedestrian	Low vs Medium	0.50688 n.s.	0.188
	Pedestrian	Medium vs High	0.9194 n.s.	0.027
	Pedestrian	Low vs High	0.52985 n.s.	0.18
	Construction	Low vs Medium	0.98763 n.s.	0.004
	Construction	Medium vs High	0.33583 n.s.	0.273
	Construction	Low vs High	0.31574 n.s.	0.284
	Merging	Low vs Medium	0.00001***	1.337
	Merging	Medium vs High	0.22887 n.s.	0.325
	Merging	Low vs High	0.0011**	0.923
	Average	Low vs Medium	0.00048***	0.947
	Average	Medium vs High	0.88289 n.s.	0.038
	Average	Low vs High	0.00016***	1.033

*Note: n.s. = not significant; * p < 0.05; **p < 0.01; ***p < 0.001.*

A three-factor mixed-design ANOVA was conducted to examine the effects of illumination, scenario, and age group on dwell time. As shown in Table 12and Table 13, significant main effects were observed for illumination, $F(2, 56) = 4.442$, $p = .0118$, $\eta p^2 = .125$, and scenario, $F(3, 84) = 5.145$, $p = .0015$, $\eta p^2 = .142$, indicating that dwell time varied across lighting conditions and hazard types. The main effect of age group was not significant, $F(1, 28) = 2.509$, $p = .1132$, $\eta p^2 = .075$, suggesting that younger and older adults did not differ significantly in overall dwell time. None of the interaction terms were significant, including Illumination × Scenario, Illumination × Age Group, Scenario × Age Group, and the three-way Illumination × Scenario × Age Group interaction (all $p > .05$). Together, these results indicate that both younger and older adults experienced the same visual struggle in low light and the same relief in medium light.

Table 13. Post hoc pairwise comparisons and Cohen's d effect sizes for dwell time across illumination levels by scenario for both age groups

Group	*Scenario*	*Comparison*	*p-value*	*Cohen's d*
Younger adults	Bike	Low vs Medium	0.06501 n.s.	0.715
	Bike	Medium vs High	0.25638 n.s.	0.416
	Bike	Low vs High	0.01028*	1.007
	Construction	Low vs Medium	0.89306 n.s.	0.058
	Construction	Medium vs High	0.35962 n.s.	0.374
	Construction	Low vs High	0.25964 n.s.	0.487
	Merging	Low vs Medium	0.0003***	1.701
	Merging	Medium vs High	0.41429 n.s.	0.32
	Merging	Low vs High	0.00266**	1.318
	Pedestrian	Low vs Medium	0.70655 n.s.	0.154
	Pedestrian	Medium vs High	0.68436 n.s.	0.155
	Pedestrian	Low vs High	0.94294 n.s.	0.029
Older adults	Bike	Low vs Medium	0.44976 n.s.	0.321
	Bike	Medium vs High	0.98476 n.s.	0.008
	Bike	Low vs High	0.48128 n.s.	0.287
	Construction	Low vs Medium	0.8983 n.s.	0.051
	Construction	Medium vs High	0.76321 n.s.	0.12
	Construction	Low vs High	0.89266 n.s.	0.052
	Merging	Low vs Medium	0.00993**	1.031
	Merging	Medium vs High	0.38113 n.s.	0.331
	Merging	Low vs High	0.09853 n.s.	0.624
	Pedestrian	Low vs Medium	0.5719 n.s.	0.225
	Pedestrian	Medium vs High	0.64045 n.s.	0.182
	Pedestrian	Low vs High	0.46505 n.s.	0.297

4.4.3 Fixation Distribution

Visual attention allocation across the driving environment was summarized using fixation percentages for three predefined Areas of Interest (AOIs): the dashboard, side mirror, and rear-view mirror. Gaze distributions were tabulated separately for the pre-hazard and hazard segments across illumination levels, scenarios, and age groups, with descriptive results presented in Table 14 and Table 20. During the pre-hazard segment, fixations were generally more frequently recorded on the dashboard across conditions. For example, in the bicycle scenario, the full sample allocated 69.1%, 61.9%, and 81.0% of fixations to the dashboard under low, medium, and high illumination, respectively. Following hazard onset, fixation distributions varied across AOIs depending on the scenario, illumination condition, and age group. In some cases, hazard-segment fixations were concentrated within a single AOI, whereas in other cases they were

distributed across multiple AOIs. For instance, in the full sample, the construction scenario showed 100.0% side-mirror fixations under both medium and high illumination, while in the pedestrian scenario under low illumination, hazard-segment fixations were equally distributed across the dashboard, side mirror, and rear-view mirror (33.3% each). In some conditions, 0.0% fixation allocation was observed across all three AOIs, indicating that no fixations were recorded within the predefined AOI boundaries during that segment. These values are presented to summarize gaze distribution across vehicle-reference regions before and during hazard events.

Table 14. Percentage distribution of fixations across dashboard, side mirror, and rear-view mirror Areas of Interest (AOIs) during the pre-hazard and hazard segments by scenario, illumination level, and in full sample.

			Pre-Hazard Segment			***Hazard Segment***		
Age Group	***Scenario***	***Light***	***Dashboard***	***Side View Mirror***	***Rear View Mirror***	***Dashboard***	***Side View Mirror***	***Rear View Mirror***
Full Sample	Bike	Low	69.1 %	12.7 %	18.2 %	53.6 %	28.6 %	17.8 %
	Bike	Medium	61.9 %	19 %	19.1 %	30.8 %	53.8 %	15.4 %
	Bike	High	81 %	9.5 %	9.5 %	38.9 %	55.6 %	5.6 %
	Construction	Low	65.9 %	8 %	26.1 %	0 %	66.7 %	33.3 %
	Construction	Medium	64.2 %	11.9 %	23.9 %	0 %	100 %	0 %
	Construction	High	62.7 %	10.7 %	26.7 %	0 %	100 %	0 %
	Merging	Low	55.6 %	12.5 %	31.9 %	25 %	50 %	25 %
	Merging	Medium	58.3 %	15.5 %	26.2 %	0 %	100 %	0 %
	Merging	High	56.6 %	17 %	26.4 %	50 %	50 %	0 %
	Pedestrian	Low	42.1 %	28.9 %	28.9 %	33.3 %	33.3 %	33.3 %
	Pedestrian	Medium	32 %	36 %	32 %	20 %	40 %	40 %
	Pedestrian	High	23.8 %	28.6 %	47.6 %	50 %	50 %	0 %

Following hazard onset, fixation distributions varied across AOIs depending on the scenario, illumination condition, and age group. In some cases, hazard-segment fixations were concentrated within a single AOI, whereas in other cases they were distributed across multiple AOIs. For instance, in the full sample, the construction scenario showed 100.0% side-mirror fixations under both medium and high illumination, while in the pedestrian scenario under low illumination, hazard-segment fixations were equally distributed across the dashboard, side mirror, and rear-view mirror (33.3% each). In some conditions, 0.0% fixation allocation was observed across all three AOIs, indicating that no fixations were recorded within the predefined AOI boundaries during that segment. These values are presented to summarize gaze distribution across vehicle-reference regions before and during hazard events.

Table 15. Percentage distribution of fixations across dashboard, side mirror, and rear-view mirror Areas of Interest (AOIs) during the pre-hazard and hazard segments by scenario, illumination level, and by age group.

			Pre-Hazard Segment			***Hazard Segment***		
Age Group	***Scenario***	***Light***	***Dashboard***	***Side View Mirror***	***Rear View Mirror***	***Dashboard***	***Side View Mirror***	***Rear View Mirror***
Older adults	Bike	Low	79.2 %	4.2 %	16.6%	46.7 %	40 %	13.3 %
	Bike	Medium	41.7 %	25 %	33.3 %	0 %	100 %	0 %
	Bike	High	100 %	0 %	0 %	22.2 %	77.8 %	0 %
	Construction	Low	73.3 %	6.7 %	20 %	0 %	66.7 %	33.3 %
	Construction	Medium	68.6 %	11.4 %	20 %	0 %	0 %	0 %
	Construction	High	71.1 %	7.8 %	21.1 %	0 %	100 %	0 %
	Merging	Low	59.6 %	10.6 %	29.8 %	0 %	50 %	50 %
	Merging	Medium	59.2 %	14.3 %	26.5 %	0 %	0 %	0 %
	Merging	High	67.7 %	12.9 %	19.4 %	0 %	100 %	0 %
	Pedestrian	Low	47.1 %	23.5 %	29.4 %	50 %	50 %	0 %
	Pedestrian	Medium	28.6 %	28.5 %	42.9 %	0 %	100 %	0 %
	Pedestrian	High	50 %	0 %	50 %	0 %	0 %	0 %
Younger adults	Bike	Low	61.3 %	19.3 %	19.4 %	61.5 %	15.4 %	23.1%
	Bike	Medium	70 %	16.7 %	13.3 %	50 %	25 %	25 %
	Bike	High	74.2 %	12.9 %	12.9 %	55.6 %	33.3 %	11.1 %
	Construction	Low	58.1 %	9.3 %	32.6 %	0 %	0 %	0 %
	Construction	Medium	59.4 %	12.5 %	28.1 %	0 %	100 %	0 %
	Construction	High	54.1 %	13.5 %	32.4 %	0 %	0 %	0 %
	Merging	Low	48 %	16 %	36 %	50 %	50 %	0 %
	Merging	Medium	57.1 %	17.1 %	25.7 %	0 %	100 %	0 %
	Merging	High	40.9 %	22.7 %	36.4 %	100 %	0 %	0 %
	Pedestrian	Low	38.1 %	33.3 %	28.6 %	0 %	0 %	100 %
	Pedestrian	Medium	33.3 %	38.9 %	27.8 %	25 %	25 %	50 %
	Pedestrian	High	7.6 %	46.2 %	46.2 %	50 %	50 %	0 %

To evaluate whether fixation distribution across the dashboard, side mirror, and rear-view mirror varied as a function of illumination level, Chi-square tests of independence were conducted separately for each scenario and segment. The results are presented in Table 16. Across the full sample, no statistically significant association between illumination level and fixation AOI distribution was observed for any scenario during either the pre-hazard or hazard segments (all $p > .05$). For example, in the bicycle scenario,

the association during the pre-hazard segment was not significant, $\chi^2\,(2, N = 139) = 3.75, p = .153, Cramer's\ V = .16$. Similar non-significant patterns were observed across the construction, merging, and pedestrian scenarios. Effect sizes were generally small (Cramer's V ranging from .024 to .354), indicating limited practical differences in gaze allocation across illumination conditions. Some hazard segments contained too few observations to satisfy the minimum expected frequency requirements for the chi-square test. As a result, those comparisons were not evaluated and are reported as not available.

Table 16. Chi-square analysis of fixation distribution by age group across driving scenarios

		Pre-Hazard Segment				***Hazard Segment***			
Age Group	***Scenario***	***χ²***	***N***	***p-value***	***Cramer's V***	***χ²***	***N***	***p-value***	***Cramer's V***
Full sample	Bike	3.751	139	0.153	0.164	2.155	59	0.341	0.191
	Construction	0.187	230	0.911	0.028	—	6	—	—
	Merging	0.125	209	0.939	0.024	0.875	7	0.646	0.354
	Pedestrian	2.103	84	0.349	0.158	0.635	10	0.728	0.252
Younger adults	Bike	1.243	92	0.537	0.116	0.053	32	0.974	0.041
	Construction	0.227	112	0.893	0.045	—	1	—	—
	Merging	1.482	82	0.477	0.134	2.000	4	0.368	0.707
	Pedestrian	3.886	52	0.143	0.273	0.875	7	0.646	0.354
Older adults	Bike	10.841	47	0.004	0.480	4.230	35	0.121	0.348
	Construction	0.218	118	0.897	0.043	—	5	—	—
	Merging	0.694	127	0.707	0.074	—	3	—	—
	Pedestrian	0.858	32	0.651	0.164	—	3	—	—

Note: — Statistical tests were not computed where sample sizes were insufficient to meet chi-square assumptions.

When analyzed by age group, a significant association emerged only for older adults in the bicycle scenario during the pre-hazard segment, χ^2 (2, N = 47) = 10.84, p = .004, Cramer's V = .48, suggesting a moderate shift in fixation distribution across illumination levels. This indicates that older adults may have adjusted their pre-hazard visual scanning pattern across illumination conditions in this scenario, although this effect was not observed in the other scenarios. No other age-specific comparisons reached statistical significance. In several hazard-segment analyses, statistical testing could not be performed because one AOI category or illumination level contained zero observations, due to insufficient expected cell frequencies.

4.5 Driving Performance Results

Driving performance was examined to evaluate how illumination influenced vehicle control across the pre-hazard and hazard segments of the driving task. Because these outcomes included both anticipatory driving

measures and event-related response measures, they were analyzed across illumination level, scenario, and age group.

4.5.1 Perception Response Time (PRT)

Perception Response Time was examined to assess the interval between hazard onset, defined as the moment the hazard first became visible, and the driver's initial braking response. PRT therefore reflects the time required to convert hazard detection into a physical response. Descriptive statistics for PRT are presented in Table 17. Across the full sample, mean PRT was longest under low illumination (M = 2.01 s, SD = 0.52), shortest under medium illumination (M = 1.69 s, SD = 0.56), and slightly higher again under high illumination (M = 1.83 s, SD = 0.50), indicating that the main improvement occurred between low and medium illumination. The same general pattern was observed in both age groups, although the reduction was somewhat greater among younger adults. Scenario-level differences were most evident in the bike and merging events, whereas the pedestrian and construction scenarios showed weaker or less consistent illumination-related changes.

Table 17. Mean ± SD PRT (s) by scenario and illumination level for the full sample and both age groups

Group	*Scenario*	*Low*	*Medium*	*High*
Full sample	Bike	2.80 ± 1.03	2.46 ± 1.03	2.26 ± 0.73
	Pedestrian	1.35 ± 0.56	1.00 ± 0.65	1.33 ± 0.89
	Construction	2.08 ± 0.75	1.89 ± 0.64	2.15 ± 0.85
	Merging	1.93 ± 0.61	1.33 ± 0.37	1.59 ± 0.56
	Average	2.01 ± 0.52	1.69 ± 0.56	1.83 ± 0.50
Older adults	Bike	3.18 ± 1.13	2.75 ± 1.24	2.34 ± 0.53
	Pedestrian	1.32 ± 0.62	0.95 ± 0.84	1.30 ± 1.18
	Construction	2.00 ± 0.85	1.93 ± 0.85	2.39 ± 0.92
	Merging	1.83 ± 0.58	1.38 ± 0.39	1.58 ± 0.52
	Average	2.02 ± 0.61	1.78 ± 0.70	1.91 ± 0.56
Younger adults	Bike	2.42 ± 0.79	2.11 ± 0.60	2.17 ± 0.92
	Pedestrian	1.38 ± 0.52	1.04 ± 0.45	1.36 ± 0.59
	Construction	2.19 ± 0.64	1.85 ± 0.41	1.94 ± 0.76
	Merging	2.03 ± 0.65	1.27 ± 0.36	1.61 ± 0.61
	Average	2.00 ± 0.40	1.58 ± 0.33	1.75 ± 0.42

To further examine which illumination contrasts contributed to the observed PRT pattern, post hoc pairwise comparisons were conducted for the full sample. Post hoc pairwise comparisons for the full sample are presented in Table 18. Across scenarios, most pairwise differences in PRT were not statistically significant after correction. The only significant comparison was observed in the merging scenario, where PRT was shorter under medium illumination than under low illumination ($p = .00011$, Cohen's $d = 1.181$), indicating a large improvement in response speed.

Although several other comparisons showed moderate effect sizes, including the bike low-versus-high comparison ($d = 0.600$), the pedestrian low-versus-medium comparison ($d = 0.578$), and the average low-versus-medium comparison ($d = 0.600$), these did not reach statistical significance. Overall, these results suggest that the clearest illumination-related improvement in PRT occurred in the merging scenario, while the remaining scenario-level and average comparisons did not show reliable differences across lighting conditions in the full sample.

Table 18. Post hoc pairwise comparisons and effect sizes for PRT across illumination levels by scenario for the full sample

Scenario	***Comparison***	***Adjusted p***	***Cohen's d***
Bike	Low vs Medium	0.2280 n.s.	0.332
	Low vs High	0.0337*	0.6
	Medium vs High	0.4276 n.s.	0.216
Pedestrian	Low vs Medium	0.0424*	0.578
	Low vs High	0.9355 n.s.	0.023
	Medium vs High	0.1291 n.s.	0.428
Construction	Low vs Medium	0.3413 n.s.	0.281
	Low vs High	0.7877 n.s.	0.077
	Medium vs High	0.2425 n.s.	0.339
Merging	Low vs Medium	0.0001***	1.181
	Low vs High	0.0407*	0.577
	Medium vs High	0.0523 n.s.	0.552
Average	Low vs Medium	0.0237*	0.6
	Low vs High	0.1822 n.s.	0.349
	Medium vs High	0.2884 n.s.	0.277

A three-factor mixed-design ANOVA was conducted to examine the effects of illumination, scenario, and age group on PRT Significant main effects were observed for illumination, $F (2, 56) = 4.554$, $p = .011$,

$\eta p^2 = .140$, and scenario, $F(3, 84) = 7.271$, $p < .001$, $\eta p^2 = .206$, indicating that PRT varied across lighting conditions and hazard types.

The main effect of age group was not significant, $F(1, 28) = 0.320$, $p = .572$, $\eta p^2 = .011$, indicating that younger and older adults did not differ significantly in overall PRT. None of the interaction terms reached significance, including Illumination × Scenario, $F(6, 168) = 1.775$, $p = .100$, $\eta p^2 = .060$, Illumination × Age Group, $F(2, 56) = 1.257$, $p = .284$, $\eta p^2 = .043$, Scenario × Age Group, $F(3, 84) = 0.657$, $p = .578$, $\eta p^2 = .023$, and the three-way Illumination × Scenario × Age Group interaction, $F(6, 168) = 0.863$, $p = .521$, $\eta p^2 = .030$. Together, these findings suggest that both age groups showed a similar delay under low illumination and a comparable response-time benefit under medium illumination.

4.5.2 Pre-hazard speed

Pre-hazard speed was examined as the driver's average vehicle speed (km/h) during the pre-hazard segment, before the hazard became visible. It represents the steady approach speed prior to hazard onset and was used to assess whether anticipatory driving behavior varied across illumination conditions.

Table 19. Mean ± SD pre-hazard speed (km/h) by scenario and illumination level for the full sample and both age groups individually.

Sample	***Scenario***	***Low***	***Medium***	***High***
Full sample	Bike	42.26 ± 11.67	45.74 ± 11.52	40.95 ± 11.33
	Pedestrian	29.95 ± 8.50	30.69 ± 7.53	31.03 ± 6.03
	Construction	43.30 ± 10.12	44.41 ± 7.97	44.56 ± 7.70
	Merging	26.68 ± 8.12	25.78 ± 9.04	27.30 ± 6.58
	Average	34.66 ± 8.32	36.50 ± 6.57	35.67 ± 6.17
Younger adults	Bike	46.36 ± 8.58	50.90 ± 5.44	47.48 ± 5.83
	Pedestrian	33.09 ± 8.89	32.25 ± 9.72	34.10 ± 5.61
	Construction	48.81 ± 10.33	48.54 ± 5.17	48.16 ± 6.17
	Merging	31.43 ± 8.07	28.10 ± 11.58	31.13 ± 6.76
	Average	39.34 ± 7.83	40.33 ± 4.69	40.23 ± 3.81
Older adults	Bike	38.16 ± 13.17	41.26 ± 13.58	34.88 ± 11.96
	Pedestrian	26.57 ± 6.87	29.01 ± 3.82	27.73 ± 4.67
	Construction	38.64 ± 7.48	40.28 ± 8.29	40.97 ± 7.56
	Merging	22.28 ± 5.34	23.95 ± 6.29	23.73 ± 4.00
	Average	30.57 ± 6.52	33.14 ± 6.23	31.68 ± 4.97

Descriptive statistics for pre-hazard speed across illumination levels, scenarios, and age groups are presented in Table 22. Across the full sample, mean pre-hazard speed was lowest under low illumination (M = 34.66, SD = 8.32), increased under medium illumination (M = 36.50, SD = 6.57), and remained slightly lower under high illumination (M = 35.67, SD = 6.17). This pattern suggests a modest increase in pre-hazard driving speed under medium illumination, with limited additional change under high illumination.

A similar overall pattern was observed across age groups, although younger adults maintained higher speeds than older adults under all illumination conditions. Younger adults showed mean pre-hazard speeds of 39.34 (SD = 7.83), 40.33 (SD = 4.69), and 40.23 (SD = 3.81) under low, medium, and high illumination, respectively, whereas older adults showed mean values of 30.57 (SD = 6.52), 33.14 (SD = 6.23), and 31.68 (SD = 4.97). At the scenario level, the bike and construction scenarios showed the highest operating speeds overall, whereas the pedestrian and merging scenarios were associated with lower speeds.

These descriptive patterns suggest that illumination may have influenced steady driving behavior before hazard onset, while age was associated with overall speed level rather than a clear change in directional pattern. These trends are also illustrated in Figure 19, which shows the distribution and variability of pre-hazard speed across illumination levels for both age groups.

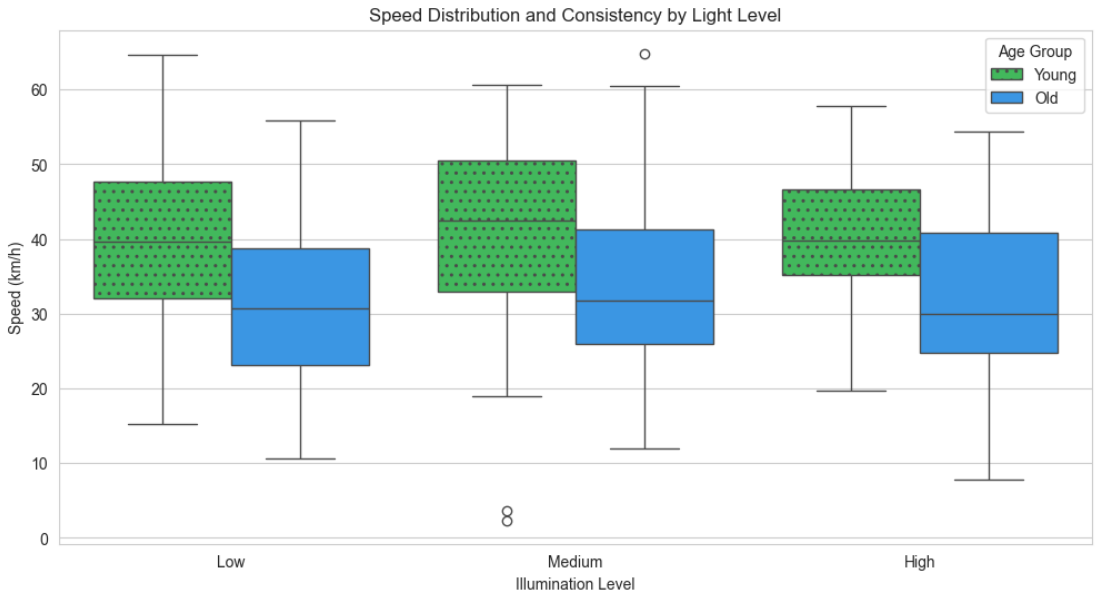


Figure 19. Distribution of pre-hazard speed (km/h) across illumination levels for younger and older drivers.

Post hoc pairwise comparisons were conducted to examine differences in pre-hazard speed across illumination levels within each scenario. None of the comparisons reached statistical significance after adjustment for multiple comparisons (all adjusted $p > .05$). This pattern was consistent across the bike, pedestrian, construction, and merging scenarios, and the effect sizes were small ($|d| \leq 0.34$), indicating that the numerical differences in speed across illumination levels were limited in magnitude.

These results were consistent with the three-factor mixed-design ANOVA. No significant main effect of illumination was observed, $F(2, 56) = 2.722$, $p = .066$, $\eta p^2 = .089$, indicating that pre-hazard speed did not differ reliably across low, medium, and high illumination. By contrast, scenario showed a significant main effect, $F(3, 84) = 14.903$, $p < .001$, $\eta p^2 = .347$, indicating that drivers adjusted their speed according to hazard context. A significant main effect of age group was also observed, $F(1, 28) = 16.447$, $p < .001$, $\eta p^2 = .370$, showing that younger and older adults differed in overall driving speed. None of the interaction terms were significant, including Illumination × Scenario, $F(6, 168) = 0.778$, $p = .587$, $\eta p^2 = .027$, Illumination × Age Group, $F(2, 56) = 0.498$, $p = .608$, $\eta p^2 = .017$, Scenario × Age Group, $F(3, 84) = 1.023$, $p = .381$, $\eta p^2 = .035$, and the three-way Illumination × Scenario × Age Group interaction, $F(6, 168) = 0.468$, $p = .832$, $\eta p^2 = .016$.

Taken together, these findings indicate that illumination had limited influence on pre-hazard speed prior to hazard onset, whereas scenario and age were the primary sources of variation. In other words, drivers did not reliably reduce their pre-hazard speed under lower illumination, despite the poorer visual and response-related performance observed under those conditions.

4.5.3 Hazard-related deceleration

Hazard-related deceleration (m/s^2) was examined to assess the intensity of drivers' braking responses during the hazard segment. In this study, this measure is important because it reflects the magnitude of braking applied once a hazard was encountered and therefore provides an indicator of response intensity under different illumination conditions.

Descriptive statistics for mean hazard-related deceleration across illumination levels, scenarios, and age groups are presented in Table 20. Across the full sample, mean hazard-related deceleration varied only modestly across illumination levels, with values of 2.44 m/s^2 under low illumination, 2.52 m/s^2 under medium illumination, and 2.32 m/s^2 under high illumination. At the age-group level, clearer differences were observed. Older adults showed lower mean deceleration values across all illumination conditions,

ranging from 1.90 to 2.26 m/s², whereas younger adults showed consistently higher values, ranging from 2.71 to 2.83 m/s².

At the scenario level, the pedestrian scenario produced the highest deceleration values in both age groups, while the bike and merging scenarios generally showed lower braking intensity. Overall, these descriptive results suggest that age had a stronger influence on braking intensity than illumination level, while medium illumination was associated with only a slight increase in mean deceleration.

In addition to mean braking intensity, the maximum magnitude of hazard-related deceleration (m/s²) was examined to assess the strongest braking response applied during the hazard event. In the context of this study, this measure is useful because it reflects the severity of the braking maneuver under different illumination levels.

Table 20. Mean ± SD hazard-related deceleration (m/s²) by scenario and illumination level for the full sample and both age groups

Group	***Scenario***	***Low***	***Medium***	***High***
Full sample	Bike	2.31 ± 1.14	2.22 ± 1.29	1.86 ± 1.36
	Pedestrian	3.00 ± 1.78	3.21 ± 1.44	3.13 ± 1.95
	Construction	2.37 ± 0.88	2.40 ± 1.02	2.40 ± 1.34
	Merging	2.13 ± 1.06	2.11 ± 0.93	2.00 ± 0.81
	Average	2.44 ± 0.86	2.52 ± 0.87	2.32 ± 0.93
Older adults	Bike	2.05 ± 1.18	1.99 ± 1.12	1.19 ± 0.45
	Pedestrian	2.43 ± 1.54	2.57 ± 1.15	2.27 ± 1.22
	Construction	2.47 ± 0.71	2.24 ± 1.07	2.25 ± 1.35
	Merging	2.01 ± 0.62	2.19 ± 0.91	1.74 ± 0.62
	Average	2.21 ± 0.73	2.26 ± 0.73	1.90 ± 0.69
Younger adults	Bike	2.57 ± 1.08	2.49 ± 1.46	2.57 ± 1.64
	Pedestrian	3.54 ± 1.86	3.80 ± 1.47	3.92 ± 2.20
	Construction	2.25 ± 1.07	2.56 ± 0.98	2.55 ± 1.36
	Merging	2.26 ± 1.41	2.01 ± 0.99	2.28 ± 0.92
	Average	2.71 ± 0.94	2.83 ± 0.94	2.81 ± 0.96

Descriptive statistics for maximum hazard-related deceleration are presented in Table 21. Across the full sample, the highest average peak deceleration was observed under low illumination (M = 6.69 m/s², SD = 1.82), followed by medium illumination (M = 6.57 m/s², SD = 1.62) and high illumination (M = 6.34

m/s², SD = 1.74). This pattern suggests that drivers applied their hardest braking under low illumination, whereas the magnitude of peak braking changed only slightly between medium and high illumination.

A similar overall pattern was observed across age groups. Older adults showed the highest average peak deceleration under low illumination (M = 6.96 m/s², SD = 1.97), which declined under medium (M = 6.51 m/s², SD = 1.78) and high illumination (M = 6.17 m/s², SD = 1.63). Younger adults showed only modest variation across lighting levels, with values of 6.39 m/s² (SD = 1.66) under low illumination, 6.64 m/s² (SD = 1.48) under medium illumination, and 6.52 m/s² (SD = 1.90) under high illumination. Overall, these descriptive results suggest that lower illumination was associated with slightly stronger peak braking responses, while increasing illumination from medium to high did not meaningfully change the magnitude of the hardest braking response.

Table 21. Mean ± SD maximum hazard-related deceleration (m/s²) by scenario and illumination level for the full sample and both age groups

Group	***Scenario***	***Low***	***Medium***	***High***
Full sample	Bike	7.04 ± 2.82	6.36 ± 2.57	5.90 ± 2.85
	Pedestrian	6.56 ± 3.57	7.17 ± 2.96	7.00 ± 3.31
	Construction	6.74 ± 2.36	6.46 ± 2.35	6.36 ± 3.15
	Merging	6.68 ± 2.69	6.17 ± 2.10	5.96 ± 2.07
	Average	6.69 ± 1.82	6.57 ± 1.62	6.34 ± 1.74
Older adults	Bike	7.17 ± 3.43	6.52 ± 3.04	5.53 ± 2.56
	Pedestrian	5.92 ± 3.91	6.11 ± 3.21	6.32 ± 3.25
	Construction	7.82 ± 1.95	6.97 ± 2.84	6.57 ± 3.51
	Merging	7.59 ± 2.29	6.62 ± 2.00	5.84 ± 2.05
	Average	6.96 ± 1.97	6.51 ± 1.78	6.17 ± 1.63
Younger adults	Bike	6.92 ± 2.19	6.19 ± 2.00	6.30 ± 3.18
	Pedestrian	7.16 ± 3.26	8.15 ± 2.42	7.64 ± 3.36
	Construction	5.46 ± 2.22	5.94 ± 1.69	6.14 ± 2.85
	Merging	5.70 ± 2.82	5.60 ± 2.17	6.09 ± 2.17
	Average	6.39 ± 1.66	6.64 ± 1.48	6.52 ± 1.90

The effects of illumination, scenario, and age group on braking intensity were examined using separate three-factor mixed-design ANOVAs for mean hazard-related deceleration and maximum hazard-related deceleration. For mean hazard-related deceleration, illumination did not show a significant main effect, $F(2, 56) = 2.208$, $p = .110$, $\eta p^2 = .073$, indicating that average braking intensity did not differ reliably across

low, medium, and high illumination. A significant main effect of scenario was observed, $F(3, 84) = 2.818$, $p = .037$, $\eta p^2 = .091$, and age group also showed a significant main effect, $F(1, 28) = 7.875$, $p = .005$, $\eta p^2 = .220$, indicating that younger and older adults differed in their average braking intensity. None of the interaction terms were significant, including Illumination × Scenario, Illumination × Age Group, Scenario × Age Group, and the three-way interaction (all $p > .05$).

For maximum hazard-related deceleration, no significant main effects were observed for illumination, $F(2, 56) = 1.087$, $p = .337$, $\eta p^2 = .037$, scenario, $F(3, 84) = 0.452$, $p = .716$, $\eta p^2 = .016$, or age group, $F(1, 28) = 0.554$, $p = .457$, $\eta p^2 = .019$. Similarly, none of the interaction terms were significant (all $p > .05$), indicating that peak braking magnitude remained relatively stable across illumination levels, scenarios, and age groups. Taken together, these findings indicate that illumination had limited influence on braking intensity once the braking response was initiated. Although low illumination was associated with poorer visual detection and slower response timing, it did not produce reliable differences in either mean or maximum deceleration magnitude. In contrast, age-related differences were more evident, with younger adults showing stronger braking responses and older adults adopting more conservative and gradual braking profiles. This suggests that illumination may influence when braking begins, whereas age has a stronger effect on how hard driver's brake.

4.6 Perceptual Response Results

4.6.1 Quantitative Perceptual Results

Normality of the subjective ratings was assessed prior to statistical analysis. Shapiro Wilk tests showed no violations across the low, medium, and high illumination conditions (all $p > 0.05$), and the Q-Q plots followed the expected linear pattern. These results indicate that the composite scores were reasonably normally distributed. The resulting measure operated as a continuous variable suitable for parametric testing. Scale reliability was also evaluated to ensure that the items reflected a consistent underlying construct. Cronbach's alpha values were 0.900 for low illumination, 0.936 for medium illumination, and 0.848 for high illumination. These coefficients indicate strong internal consistency across all three conditions, supporting the use of the composite subjective score when comparing perceived safety and driving visibility across illumination levels

Descriptive statistics were then examined to explore overall patterns in perceived visibility, safety, and driving comfort across the three illumination conditions. For the full sample, subjective ratings of perceived safety and visual comfort increased from low to medium illumination and then decreased slightly at high

illumination. Participants rated low illumination as the lowest (M = 3.57, SD = 0.78). Ratings were highest under medium illumination (M = 4.30, SD = 0.61), and slightly lower under high illumination (M = 4.02, SD = 0.70). This shows that medium illumination was viewed as the most comfortable and supportive for safety and visibility. Looking at age groups, older adults showed the same overall pattern but with lower absolute ratings. Their subjective scores increased from 3.29 (SD = 0.84) at low illumination to 4.04 (SD = 0.75) at medium illumination, then decreased slightly at high illumination (3.85, SD = 0.77). Younger adults reported higher ratings across all lighting levels. Their scores followed the same shape, rising from 3.86 (SD = 0.67) at low illumination to 4.56 (SD = 0.38) at medium illumination before declining slightly at high illumination (4.19, SD = 0.59). Together, these descriptive results indicate that medium illumination produced the strongest perceived safety and visual comfort for both age groups, while low illumination was consistently rated lowest.

Building on these descriptive patterns, post hoc comparisons from Table 22 showed a consistent but bounded effect of illumination on perceived safety and visual comfort. In the full sample, only the contrast between High and Low illumination was statistically significant (adjusted $p = 0.0007$, $d = 0.76$). This reflects a clear improvement when moving from insufficient lighting to a well-lit environment. Medium illumination did not differ significantly from either Low ($p = 0.0529$) or High ($p = 1.000$), suggesting that once lighting reaches a moderate level, additional brightness does not meaningfully enhance subjective evaluations. The age group analyses followed the same structure with different magnitudes. Younger adults showed higher mean ratings with increasing illumination, but none of the pairwise comparisons were significant, indicating variability within the group rather than an absence of directional change. Older adults demonstrated a more pronounced pattern, with a significant improvement from Low to High illumination (adjusted $p = 0.0225$, $d = 0.81$). Medium illumination did not differ significantly from either Low or High, suggesting that both Medium and High were experienced as adequately supportive, with limited added benefit from increased brightness. Taken together, the results indicate that illumination level influences perceived safety and visual comfort, but improvements plateau beyond moderate lighting. The only reliably meaningful change occurs when shifting from low illumination to a well-lit condition.

These pairwise findings were supported by the overall inferential analyses. A repeated measures ANOVA showed a significant main effect of illumination on subjective ratings, $F(2, 58) = 31.84$, $p < .001$, $\eta p^2 = 0.523$. This indicates that participants' perceptions of safety and visual comfort differed reliably across the three lighting levels. Consistent with the descriptive patterns, subjective evaluations were lowest under low illumination, peaked at medium illumination, and declined slightly under high illumination. The large effect size shows that illumination level was a strong determinant of perceived comfort and visibility.

Table 22. Post-hoc pairwise comparisons of subjective ratings across illumination levels (Holm–Sidak for overall; Bonferroni for age-specific analyses)

Group	***Condition***	***Adjusted p***	***Cohen's d***
Overall	Medium → High Light	1.000 $^{n.s.}$	0.17
	Medium → Low Light	0.0529 $^{n.s.}$	0.59
	High → Low Light	0.0007***	0.76
Younger	Medium → High Light	1.000 $^{n.s.}$	0.48
	Medium → Low Light	0.4923 $^{n.s.}$	0.60
	High → Low Light	0.0526 $^{n.s.}$	0.43
Older	Medium → High Light	1.000 $^{n.s.}$	0.30
	Medium → Low Light	0.1599 $^{n.s.}$	0.76
	High → Low Light	0.0225*	0.81

*Note: n.s. = not significant; * p < 0.05; *** p < 0.001*

To further examine whether this pattern differed by age, a mixed ANOVA was conducted with Illumination as the within-subject factor (low, medium, high) and Age Group as the between-subject factor (younger, older). The overall illumination effect remained significant but smaller in magnitude when age was included, $F(2, 58) = 3.93$, $p = .023$, $\eta p^2 = .086$. There was no main effect of Age Group ($p = .855$), indicating that younger and older adults reported similar overall levels of perceived safety and driving visibility. The interaction between Age Group and Illumination was also non-significant ($p = .948$), showing that both groups followed the same directional pattern across lighting levels. These results indicate that the influence of illumination on subjective perceptions was consistent across age groups. Both younger and older adults rated low illumination lowest, showed the highest perceived support under medium illumination, and exhibited a modest decline at high illumination.

4.6.2 Qualitative Perceptual Results

Overview and Coding Approach: The post-session questionnaire included four open-ended questions for each lighting condition. Not all participants responded to every question, but all available comments were reviewed and coded to identify common patterns. The qualitative responses were analyzed using a thematic analysis approach. The analysis focused on describing how participants perceived visibility, safety, comfort, and potential improvements under different illumination levels. The analysis involved reviewing all responses, identifying the core idea of each comment, assigning one or more descriptive labels, grouping similar codes into broader thematic categories, and summarizing the findings across illumination

conditions. Each open-ended comment was coded by identifying its core idea and assigning one or more descriptive labels that reflected its meaning. Four themes were used in the analysis: visibility, safety, comfort, and suggestions. A fifth category, "blank", was applied when a participant provided no meaningful response, such as "none," "no comment," or an empty entry; these were treated as missing data. The coding process was conducted through researcher-led review and organization of responses in Excel, which was appropriate given the focused scope of the open-ended dataset and the predefined alignment of the questions with the study objectives. Using this structured framework allowed the qualitative findings to align directly with the quantitative measures of visibility, comfort, and perceived safety.

Overall Thematic Patterns: The final coded dataset consisted of 126 individual participant comments. Visibility-related observations were the most frequently reported (n = 36). Participants commonly described difficulty detecting pedestrians or signage under lower illumination conditions and reported clearer visual conditions under medium and high lighting levels. Safety-related perceptions were reflected in 22 comments (n = 22) and focused on driver confidence, hazard anticipation, and overall sense of control under different lighting intensities. Participant suggestions accounted for 24 comments (n = 24) and primarily involved requests for increased brightness, improved roadway coverage, or reduced glare from luminaires. Comfort-related feedback appeared less frequently (n = 12), addressing visual strain and general driving comfort, which were more often associated with higher illumination levels. Thirty-two responses were left blank (n = 32) or contained no substantive content, such as "no comment" or "none," and were treated as missing qualitative data rather than meaningful thematic responses.

Theme Distribution Across Illumination Levels: A descriptive count was conducted to examine how often each theme appeared under low, medium, and high illumination conditions. Table 23 summarizes this distribution.

Table 23 Illumination Distribution Theme

Theme	***Low***	***Medium***	***High***
Visibility	15	11	10
Safety	9	2	11
Comfort	4	4	4
Suggestions	14	6	4
Blank	8	13	11

Visibility comments appeared most frequently under low illumination, where participants commonly described difficulty detecting pedestrians, signs, and roadside hazards. Medium illumination generated

fewer specific remarks and more blank responses, suggesting that this condition was generally perceived as adequate and did not draw attention to major deficiencies. High illumination produced the greatest number of safety-related comments, indicating improved confidence and hazard awareness, but also prompted some concerns about glare and excessive brightness. Suggestions were most common under low illumination and primarily emphasized the need for greater brightness and wider roadway coverage.

Representative Participant Comments: Representative comments from each theme illustrate how participants described their experience, as shown below, using the anonymized participant identifiers originally assigned during the study.

- **Visibility**: "I couldn't see obstacles like bikers and children very well." (P4001)
  "Some pedestrians were difficult to see." (P2006)
- **Safety**: "Much more confident, felt safer, felt more aware." (P0630)
  "I felt extremely safe during these visibility conditions." (P0206)
- **Comfort**: "I felt comfortable under the conditions." (P2406)
  "It was okay. No strains." (P2606)
- **Suggestions**: "More lighting in the area beside the car (the roadside) would have helped my ability to see bikes or pedestrians." (P2316)
  "Implement measures to reduce glare on the road." (P0307)

Age Related Patterns: Age related differences in the open-ended responses were minimal. Both age groups mentioned similar issues with visibility, particularly under the low illumination condition, and both described the medium condition as generally adequate without requiring further explanation. Comments indicating discomfort or glare appeared in both groups as well, though older participants tended to mention glare more explicitly. Positive safety related remarks were present across ages and did not show a consistent directional trend. Overall, the qualitative responses did not show a clear age-based pattern.

Integration with Quantitative Findings: The qualitative findings aligned closely with the quantitative results. Comments related to poor visibility under low illumination reflected the lower subjective ratings observed in the Likert data, while the relative stability of responses under medium illumination supported its role as the most favorably perceived condition. High illumination was often associated with greater safety and confidence, consistent with the descriptive increase in perceived safety, although some participants also noted glare-related concerns. Overall, the open-ended responses helped explain the practical reasons behind participants' ratings and strengthened the interpretation of the quantitative findings.

CHAPTER 5
Discussion & Conclusion

5.1 Overview

This chapter interprets the findings of the study in relation to the research objectives, hypotheses, and literature reviewed in Chapter 2. The study examined how nighttime roadway illumination influences driver response in a high-fidelity driving simulator using a multimodal framework that included physiological response, visual attention, driving performance, and subjective perceptual response. By integrating these measures, the analysis provides a comprehensive evaluation of how different illumination levels affect driver behaviour and experience under nighttime conditions.

Overall, the findings show that illumination level meaningfully influenced driver response across multiple domains. Lower illumination was generally associated with delayed hazard-related visual attention, poorer driving performance, higher physiological activation, and less favourable subjective ratings of visibility, comfort, and safety. Increasing illumination from low to medium improved driver response across most measures, whereas increasing illumination from medium to high produced comparatively smaller changes. Taken together, these findings support the interpretation that nighttime roadway illumination may follow a threshold pattern in which medium illumination provides the most favourable overall balance between visibility, driving performance, physiological stability, and perceived comfort.

5.2 Visual Attention and Driving Performance

The visual attention and driving performance findings provide objective evidence that nighttime roadway illumination influenced hazard-related visual attention and driver response in the simulated driving environment. Illumination had a significant main effect on both TTFF, $F(2, 56) = 6.346$, $p = .002$, $\eta p^2 = .185$, and dwell time, $F(2, 56) = 4.442$, $p = .0118$, $\eta p^2 = .125$. Descriptively, TTFF was longest under low illumination ($M = 1.94$ s, $SD = 0.51$), improved under medium illumination ($M = 1.37$ s, $SD = 0.47$), and remained similar under high illumination ($M = 1.46$ s, $SD = 0.45$). Pairwise comparisons showed that the TTFF effect was driven mainly by comparisons involving low illumination. In the full sample, significant low-to-medium reductions were observed across all four scenarios, whereas additional low-to-high reductions were observed only in the bike and merging scenarios. No medium-to-high TTFF differences

were significant. This pattern indicates that the main gain in hazard localization occurred when illumination increased from low to medium rather than from medium to high.

Dwell time showed a similar pattern. Average dwell time decreased from 2.39 s under low illumination to 1.89 s under medium and 1.87 s under high illumination. In the full sample, both the low-to-medium and low-to-high comparisons were significant, whereas the medium-to-high difference was not. At the scenario level, the clearest reductions were observed in the merging scenario, where both medium and high illumination were associated with shorter dwell time than low illumination. Together, the TTFF and dwell-time findings indicate that reduced lighting delayed hazard localization and increased the amount of visual processing required, whereas illumination at least at the medium level supported more efficient visual attention.

Fixation distribution patterns were consistent with these findings, with gaze generally concentrated on the forward roadway during the pre-hazard segment. The chi-square analysis showed that illumination did not significantly alter fixation distributions across the dashboard, side mirror, and rear-view mirror AOIs in either segment for the full sample. This suggests that reduced lighting affected hazard localization and visual processing efficiency rather than overall scanning pattern. The only exception occurred among older adults in the bicycle scenario during the pre-hazard segment, where fixation distribution varied significantly across illumination levels.

Driving performance showed a related but somewhat more selective pattern. PRT showed a significant main effect of illumination, $F(2, 56) = 4.554$, $p = .011$, $\eta p^2 = .140$. Descriptively, average PRT was longest under low illumination ($M = 2.01$ s, $SD = 0.52$), shortest under medium illumination ($M = 1.69$ s, $SD = 0.56$), and slightly higher again under high illumination ($M = 1.83$ s, $SD = 0.50$). After correction for multiple comparisons, the only significant pairwise contrast in the full sample occurred in the merging scenario, where PRT was shorter under medium than low illumination. Even so, the descriptive pattern across scenarios remained consistent, with the largest improvement occurring between low and medium illumination.

By contrast, pre-hazard speed did not vary significantly across illumination conditions, $F(2, 56) = 2.722$, $p = .066$, $\eta p^2 = .089$, although it did vary significantly by scenario and age group. This suggests that participants did not reliably reduce their approach speed despite the poorer visibility and slower response timing observed under low illumination. Hazard-related deceleration also did not show a significant main effect of illumination, $F(2, 56) = 2.208$, $p = .110$, $\eta p^2 = .073$, indicating that illumination had a stronger

effect on when drivers visually localized hazards and initiated responses than on the intensity of the braking response itself.

Age-related differences were more evident in braking behaviour than in visual attention or response timing. Age group had a significant main effect on hazard-related deceleration, $F(1, 28) = 7.875$, $p = .005$, $\eta p^2 = .220$, with younger drivers generally showing stronger braking responses and older drivers adopting more conservative braking profiles. By contrast, age group did not show significant main effects for TTFF, dwell time, or PRT, indicating that both younger and older adults followed the same overall illumination pattern in hazard-related visual attention and response timing. This suggests that illumination mainly influenced when hazards were visually processed and when responses began, whereas age influenced how the braking response was physically executed.

Taken together, these findings show that illumination affected visual efficiency and behavioural response more strongly than speed choice or braking intensity. Across TTFF, dwell time, and PRT, the strongest improvements occurred from low to medium illumination, whereas medium-to-high differences were generally small or not significant. The absence of significant illumination effects on pre-hazard speed and hazard-related deceleration further suggests that lower illumination primarily impaired hazard localization and response timing rather than broader driving style. Overall, these results support the interpretation that medium illumination provided the most favourable level for hazard-related visual attention and driving response in the present study.

5.3 Physiological Results

The physiological results offer a clear picture of how nighttime illumination shaped autonomic activation during driving. Both HR and EDA increased when illumination was introduced, indicating heightened physiological readiness once participants entered the nighttime driving task. For HR, the repeated-measures ANOVA across baseline and the three illumination conditions showed a significant overall effect of condition, $F(3, 87) = 5.94$, $p = .001$, $\eta p^2 \approx .170$. Similarly, EDA showed a significant effect of condition in the nonparametric analysis, $\chi^2(3) = 39.96$, $p < .001$. Descriptively, both measures showed their largest increase when transitioning from baseline to low illumination, after which physiological activation remained elevated but relatively stable under medium and high illumination. This pattern suggests that illumination initially functions as an environmental cue that raises alertness and physiological readiness, but that increasing brightness beyond the lower illuminated range does not continue to amplify autonomic activation in a meaningful way.

This physiological pattern is consistent with the broader findings of the study. Under low illumination, drivers showed delayed hazard localization and slower response timing, indicating greater perceptual and attentional demand in the low-light driving environment. In that context, the pronounced shift from baseline to low illumination likely reflects the increased effort required to process roadway information under reduced visibility. Once illumination reached medium intensity, physiological activation remained above baseline but became more stable, suggesting that the roadway environment had become sufficiently visible to support driving without additional physiological escalation.

Age comparisons add another layer to this interpretation. Older adults showed descriptively higher baseline arousal and larger electrodermal shifts when illumination was introduced, reflecting greater autonomic activation rather than a different response pattern. Both age groups nevertheless followed the same general physiological trajectory, with the largest shift occurring from baseline to illuminated driving and relatively stable activation thereafter. Overall, these findings suggest a threshold-like physiological response: introducing light increased autonomic activation relative to baseline, but increasing illumination beyond a moderate level did not produce consistent additional benefit.

5.4 Perceptual Results

The perceptual findings showed a clear pattern across the three illumination levels. Subjective ratings differed significantly across conditions, $F(2, 58) = 31.84$, $p < .001$, $\eta p^2 = .523$. Participants rated low illumination least favourably, indicating poorer visibility, comfort, and safety, while medium illumination received the highest ratings. High illumination was also rated positively but did not meaningfully exceed the medium condition. This suggests that the main perceptual improvement occurred from low to medium illumination, whereas additional brightness provided limited added benefit.

This pattern was consistent with the broader study findings. Low illumination was associated with greater visual effort and reduced confidence, aligning with the delayed hazard localization and slower response timing observed in the objective measures. By contrast, medium illumination appeared to provide sufficient brightness without introducing additional strain. Although high illumination improved clarity for some participants, it did not substantially improve perceptual ratings relative to medium illumination.

Age-related patterns in the qualitative responses were minimal. Both younger and older participants described similar visibility challenges under low illumination, similar ease under medium lighting, and mixed impressions of the high condition. Older adults mentioned glare slightly more often, but not systematically. This matched the quantitative results showing no significant interaction between age and

illumination level. Taken together, the quantitative ratings and qualitative comments support the same conclusion: medium illumination provided the clearest and most comfortable nighttime driving environment. Low illumination required greater visual effort and reduced confidence, while high illumination offered no clear added perceptual benefit and may have introduced minor discomfort.

5.5 Integrated Interpretation Across Measures

Taken together, the visual, behavioural, physiological, and perceptual findings show a consistent pattern in how drivers responded to nighttime roadway illumination. Across outcome domains, the greatest improvement occurred when illumination increased from low to medium, whereas changes from medium to high were generally smaller and often not significant. This convergence supports a threshold-like interpretation in which illumination must reach an adequate level to support efficient hazard processing, stable physiological activation, and positive perceptual experience, while additional brightness beyond that level provides limited further benefit.

Under low illumination, drivers showed delayed hazard-related visual attention and slower response timing, while pre-hazard speed did not decrease significantly across lighting conditions. At the same time, physiological activation showed its largest shift at the transition into illuminated driving, and subjective ratings were least favourable, with participants frequently describing difficulty with visibility and hazard detection. Considered together, these findings indicate that low illumination imposed greater perceptual and attentional demand while providing the weakest overall support for safe and comfortable driving.

When illumination increased to the medium level, hazard-related visual attention became more efficient, behavioural response improved, and perceptual ratings reached their highest level, while physiological activation remained relatively stable. By contrast, increasing illumination from medium to high produced little additional improvement across the objective or subjective measures and, in the qualitative responses, occasionally introduced glare-related concerns. This overall pattern indicates that medium illumination provided the most favourable balance across the measured domains.

Age-related differences were more evident in the magnitude of some responses than in the overall pattern across illumination levels. Older adults showed more conservative braking behaviour and descriptively higher physiological activation in some conditions, whereas younger drivers generally showed stronger braking responses. However, both age groups followed the same overall trajectory across the three lighting conditions: low illumination produced the weakest outcomes, medium illumination produced the clearest improvement, and high illumination offered little additional benefit. This consistency suggests that

the threshold-like response to nighttime illumination was not confined to one age group, even though the intensity of some responses differed between younger and older drivers. To more clearly relate these findings to the research hypotheses presented in Section 1.3, Table 24 summarizes the degree of support observed for each hypothesis.

Table 24 Summary of support for the research hypotheses

Hypothesis	Outcome	Summary
H1	Partially supported	HR and EDA differed between baseline and illuminated conditions, but differences among low, medium, and high illumination were not consistently significant.
H2	Supported	Physiological responses did not change linearly across illumination levels, suggesting diminishing effects beyond a moderate level.
H3	Supported	Subjective ratings of visibility, comfort, and safety differed across illumination conditions, with low illumination rated least favorably.
H4	Supported	Qualitative feedback was broadly consistent with the quantitative subjective ratings across illumination conditions.
H5	Supported	Lower illumination was associated with less efficient visual behavior, including longer TTFF and longer dwell time in key scenarios.
H6	Partially supported	Lower illumination was associated with longer PRT, but speed adaptation and braking-related measures were limited or inconsistent.
H7	Partially supported	Older adults showed greater physiological demand and more conservative driving responses in some measures, particularly braking-related behavior.
H8	Not strongly supported	Illumination affected younger and older adults in broadly similar ways, with only limited evidence of age-related differences in the magnitude of illumination effects.
H9	Supported	The combined pattern of physiological, subjective, visual, and driving-performance findings indicated that medium illumination provided the most supportive overall driving environment.

5.6 Practical Implications

The findings of this study have clear implications for roadway lighting design, transportation planning, and sustainable infrastructure. Across the measured domains, the greatest benefit occurred when illumination increased from low to medium levels. Low illumination was associated with delayed hazard-related visual attention, slower response timing, stronger physiological activation, and less favourable perceptual ratings, while pre-hazard speed did not decrease significantly across lighting conditions. This suggests that insufficient lighting can impair hazard processing without producing a corresponding behavioural adjustment in speed, thereby reducing the overall margin of safety.

From a design perspective, the most important practical implication is the identification of a performance plateau at medium illumination. Medium illumination provided the most favourable overall balance across visual, behavioural, physiological, and perceptual measures, whereas increasing illumination from medium to high produced little additional benefit and, in some cases, introduced glare-related concerns in participant feedback. This indicates that effective roadway lighting should aim to provide adequate visibility and visual comfort rather than maximum brightness. In this sense, medium illumination can be understood as an ergonomic and energy-efficient target that supports hazard detection and sustained alertness without adding unnecessary physiological or perceptual burden.

These findings also support a more performance-based approach to lighting design. Rather than relying only on photometric criteria, roadway illumination can be evaluated in relation to human-response measures such as hazard-related visual attention, response timing, physiological stability, and perceived comfort. This approach is especially relevant for municipalities and transportation agencies seeking to balance safety, user experience, and sustainability. Because high illumination offered limited additional benefit, the results also support context-sensitive lighting strategies and energy-efficient dimming approaches that maintain adequate visibility while reducing unnecessary energy use, light pollution, and visual discomfort.

The age-related findings further strengthen the practical relevance of this conclusion. Although older adults showed more conservative braking behaviour and descriptively higher physiological activation in some conditions, both younger and older drivers followed the same overall response pattern across illumination levels. This suggests that a moderate illumination level may provide an appropriate balance of visibility, comfort, and safety for a broad range of roadway users.

5.7 Limitations and Directions for Future Research

Despite careful control of the experimental variables and a structured protocol designed to minimize noise during data collection, several methodological constraints still need to be acknowledged.

- Sample Size and group composition: The study included 30 participants, with 15 younger and 15 older adults. Although this was adequate for the within-subject design, it limited sensitivity to more subtle age-related differences and constrained the generalizability of the findings. In addition, although gender was recorded to describe the sample, the study was not designed or statistically powered to examine gender-based differences in driver response under varying illumination conditions. The study also did not explicitly control for differences in driving exposure or accumulated driving experience beyond the age-group classification. Future research should consider larger and more diverse samples with broader variation in age, gender, visual function, and driving experience.
- Simulator realism and environmental scope: The fixed-base driving simulator allowed precise control of illumination and hazard presentation, but it could not fully reproduce the sensory complexity of real nighttime driving. In addition, the study focused on one roadway setting under clear conditions. Future studies should examine a wider range of roadway environments, traffic conditions, and weather scenarios, and where possible include more immersive or field-based validation.
- Lighting parameters: The experiment used one spectral lighting condition and three illumination levels. This was appropriate for isolating the effect of illumination intensity, but it does not represent the full range of colour temperatures and spectral distributions used in practice. Future research should test multiple colour temperatures and a finer range of illumination levels to more clearly differentiate between adequate, optimal, and excessive illumination. While the current study identifies broad trends, a more granular scale would help define adequate lighting as the minimum safety threshold, optimal as the peak of driver comfort and performance, and excessive as the point of diminishing returns or increased glare emerge. This distinction is critical for better defining the optimal lighting range for nighttime driving.
- Measurement scope: The multimodal design captured physiological response, visual attention, driving performance, and perceptual response, but it did not include additional indicators such as HRV, EEG, extended-duration fatigue measures, or continuous lane-keeping metrics such as average lane position and standard deviation of lane position. The perceptual questionnaire was developed specifically for the experimental context to capture drivers' perceived visibility, and

perceived safety and comfort under the simulated illumination conditions. Because the study focused on hazard perception and response, so the behavioural analysis prioritized event-based measures rather than continuous lane-control metrics. Future research should examine longer driving sessions and broader physiological, cognitive, and vehicle-control indicators to better understand workload, vigilance, fatigue, and lane-keeping behaviour over time.

5.8 Conclusion

This study examined how nighttime roadway illumination influenced driver response across visual attention, driving performance, physiological activation, and perceptual experience in a high-fidelity driving simulator. Taken together, the findings showed a consistent pattern across these domains. Low illumination was associated with delayed hazard-related visual attention, slower response timing, stronger physiological activation, and less favourable ratings of visibility, comfort, and safety. At the same time, drivers did not reliably reduce their pre-hazard speed under lower illumination, indicating limited behavioural compensation for reduced visibility.

Increasing illumination from low to medium produced the clearest overall improvement. Medium illumination supported more efficient hazard localization, faster response timing, more favourable perceptual ratings, and relatively stable physiological activation. By contrast, increasing illumination from medium to high produced limited additional benefit across the measured outcomes and, in some cases, introduced qualitative concerns related to glare or unnecessary brightness.

Overall, the findings support the conclusion that nighttime roadway illumination operates in a threshold-like manner rather than a strictly linear one. Within the conditions examined in this study, medium illumination provided the most favourable overall balance between visibility, driver response, physiological stability, and perceptual comfort. These results highlight the importance of designing roadway lighting to achieve adequate and well-controlled illumination rather than simply maximizing brightness.

5.9 Recommendations

Based on the findings of this study, several recommendations can be made for roadway lighting design, transportation safety research, and future investigation of nighttime driving environments.

5.9.1 Recommendations for Roadway Lighting Design

Roadway lighting should prioritize adequate and consistent illumination rather than maximum brightness. Within the conditions examined in this study, medium illumination provided the most favourable balance of hazard visibility, driver response, physiological stability, and perceptual comfort. In practice, this supports the use of moderate, well-distributed lighting, particularly at locations with higher visual demand such as merges, intersections, and pedestrian crossings.

5.9.2 Recommendations for Transportation Policy and Infrastructure Planning

Transportation agencies and municipalities should consider adopting human-centred lighting approaches that evaluate illumination not only by photometric targets but also by driver response and comfort. Because both younger and older drivers followed the same overall pattern across illumination levels, a moderate illumination level may provide an appropriate balance of safety, comfort, and energy efficiency for a broad range of roadway users.

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Appendix A.

Demographic Questionnaire

This is a strictly confidential questionnaire. Only a randomly generated participant ID number, assigned by the research administrator, will appear on this questionnaire. Your information will be kept confidential. You may skip any questions you do not feel comfortable answering.

Participant ID: _____

(Research Administrator use only)

Section 1. Participant Information

1. What is your gender?

- ○ Man
- ○ Woman
- ○ Non-binary
- ○ Prefer to specify: _____
- ○ Prefer not to say

2. What is your date of birth?

Year: _____

Month: _____

3. Have you participated in a study at this laboratory in the past?

- ○ Yes
- ○ No

4. If yes, have you previously participated in any simulator-based studies?

- ○ Yes
- ○ No

Section 2. Driving History

5. How long have you been driving?

Years: _____

Months: _____

6. At what age did you get your driver's license?

Years: _____

Months: _____

7. What type of driver's license do you have?

- ○ G
- ○ G2

8. How many kilometers (km) have you driven in the past 12 months?

- ○ Less than 5,000 km
- ○ 5,000 to 10,000 km
- ○ More than 15,000 km

9. Do you normally wear eyeglasses or contact lenses while driving?

- ○ Yes, eyeglasses
- ○ Yes, contacts
- ○ No

Appendix B.

Post-Session Questionnaire

Thank you for participating in this experiment aimed at improving nighttime driving safety, reducing crashes, and making transportation safer. Please take a few minutes to share your thoughts and experiences.

Participant ID: _____

(Assigned by the researcher)

Section 1. Scenario Information

Which driving scenario did you complete?

○ Scenario 1

○ Scenario 2

○ Scenario 3

Section 2. Visibility

Scale: 1 = Strongly Disagree, 5 = Strongly Agree

I could clearly see road signs under this lighting condition.

1 ○ 2 ○ 3 ○ 4 ○ 5 ○

Pedestrians and objects were visible from a safe distance.

1 ○ 2 ○ 3 ○ 4 ○ 5 ○

I was able to maintain my lane position accurately.

1 ○ 2 ○ 3 ○ 4 ○ 5 ○

The lighting helped me recognize upcoming turns or intersections.

1 ○ 2 ○ 3 ○ 4 ○ 5 ○

Section 3. Perceived Safety and Comfort

Scale: 1 = Strongly Disagree, 5 = Strongly Agree

The lighting made me feel safe while driving.

1 ○ 2 ○ 3 ○ 4 ○ 5 ○

The lighting intensity was appropriate for driving.

1 ○ 2 ○ 3 ○ 4 ○ 5 ○

I experienced glare, eye strain, or discomfort.

1 ○ 2 ○ 3 ○ 4 ○ 5 ○

I had to adjust my driving due to poor visibility.

1 ○ 2 ○ 3 ○ 4 ○ 5 ○

I felt more stressed while driving under this lighting condition.

1 ○ 2 ○ 3 ○ 4 ○ 5 ○

Section 4. Open-Ended Feedback

How did the lighting affect your sense of safety and visibility?

Were there any specific elements (e.g., road signs, pedestrians) that were difficult to see?

Did you experience any discomfort (e.g., glare, eye strain, motion sickness)? If so, please describe.

What suggestions do you have for improving the lighting conditions?

Thank you. We appreciate your valuable feedback

Appendix C.

Motion Sickness Susceptibility Questionnaire

1. Please State Your **Age** ..... Years. *2.* Please State Your Sex (tick box) **Male** [ ] **Female** [ ]

This questionnaire is designed to find out how susceptible to motion sickness you are, and what sorts of motion are most effective in causing that sickness. Sickness here means feeling queasy or nauseated or actually vomiting.

Your CHILDHOOD Experience Only (before 12 years of age), for each of the following types of transport or entertainment please indicate:

3. **As a CHILD (before age 12),** how often you **Felt Sick or Nauseated** (tick boxes):

	Not Applicable - Never Travelled	**Never Felt Sick**	**Rarely Felt Sick**	**Sometimes Felt Sick**	**Frequently Felt Sick**
Cars					
Buses or Coaches					
Trains					
Aircraft					
Small Boats					
Ships, e.g. Channel Ferries					
Swings in playgrounds					
Roundabouts in playgrounds					
Big Dippers, Funfair Rides					
	t	0	1	2	3

Your Experience over the LAST 10 YEARS (approximately), for each of the following types of transport or entertainment please indicate:

4. **Over the LAST 10 YEARS,** how often you **Felt Sick or Nauseated** (tick boxes):

	Not Applicable - Never Travelled	**Never Felt Sick**	**Rarely Felt Sick**	**Sometimes Felt Sick**	**Frequently Felt Sick**
Cars					
Buses or Coaches					
Trains					
Aircraft					
Small Boats					
Ships, e.g. Channel Ferries					
Swings in playgrounds					
Roundabouts in playgrounds					
Big Dippers, Funfair Rides					
	t	0	1	2	3

Scoring the MSSQ- Short

Section A (Child) (Question 3)

Score the number of types of transportation not experienced (i.e., total the number of ticks in the 't' column, maximum is 9).

Total the sickness scores for each mode of transportation, i.e. the nine types from 'cars' to 'big dippers' (use the 0-3 number score key at bottom, those scores in the 't' column count as zeroes).

MSA = (total sickness score child) x (9) / (9 - number of types not experienced as a child)

Note 1. Where a subject has not experienced any forms of transport a division by zero error occurs. It is not possible to estimate this subject's motion sickness susceptibility in the absence of any relevant motion exposure.
Note 2. The Section A (Child) score can be used as a pre-morbid indicator of motion sickness susceptibility in patients with vestibular disease.

Section B (Adult) (Question 4)

Repeat as for section A but using the data from section B.

MSB = (total sickness score adult) x (9) / (9 - number of types not experienced as an adult)

Raw Score MSSQ-Short

Total the section A (Child) MSA score and the section B (Adult) MSB score to give the MSSQ-Short raw score (possible range from minimum 0 to maximum 54, the maximum being unlikely)

MSSQ raw score = MSA + MSB

Percentile Score MSSQ-Short

The raw to percentile conversions are given below in the Table 1 of Statistics & Figure 1. Use interpolation where necessary.

Alternatively a close approximation is given by the fitted polynomial where y is percentile; x is raw score

$y = a.x + b.x^2 + c.x^3 + d.x^4$

a = 5.1160923 b = -0.055169904
c = -0.00067784495 d = 1.0714752e-005

Table 1. Means and Percentile Conversion Statistics for the MSSQ-Short (n=257)

Percentiles Conversion	Raw Scores MSSQ-Short		
	Child Section A	Adult Section B	Total A+B
0	0	0	0
10	.0	.0	.8
20	2.0	1.0	3.0
30	4.0	1.3	7.0
40	5.6	2.6	9.0
50	7.0	3.7	11.3
60	9.0	6.0	14.1
70	11.0	7.0	17.9
80	13.0	9.0	21.6
90	16.0	12.0	25.9
95	20.0	15.0	30.4
100	23.6	21.0	44.6
Mean	7.75	5.11	12.90
Std. Deviation	5.94	4.84	9.90

Table note: numbers are rounded

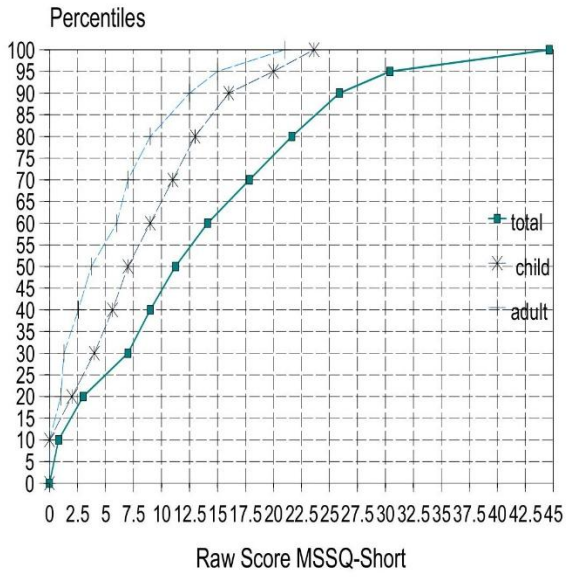


Figure 1. Cumulative distribution Percentiles of the Raw Scores of the MSSQ-Short (n=257 subjects).

Development, Normalisation & Validation of the MSSQ-Short (Golding, 2006)

Background Motion sickness susceptibility questionnaires (MSSQ), sometimes called motion history questionnaires, predict individual differences in motion sickness caused by a variety of stimuli. The original "Reason & Brand MSSQ" (Reason, 1968; Reason & Brand, 1975) had perhaps the best proven track record in the world for motion sickness research. It was subsequently revised, renormalized & revalidated (Golding, 1998). The aim was to develop a short version of the MSSQ, denoted "MSSQ-Short".

Methods Development used repeated item analysis, and various scoring methods of the MSSQ (Golding, 1998). Retained were: motion types (cars, boats, planes, trains, funfair rides, etc); corrections for motion type exposure with a much simplified format; sickness severity weightings; childhood versus adult experiences. New items such as visual/optokinetic items (cinerama, virtual reality, etc), were introduced but then excluded since they had low sickness prevalence & added little information. However they could become important in the future. Norms and percentiles were produced (n=257). Predictive validity used controlled motions representing all classes of motion sickness provocative stimuli (total n=178): cross-coupled (Coriolis); 0.2Hz frequency translational oscillation; off-vertical axis rotation (OVAR); visual-motion simulator.

Results Predictive validity for motion was median r =0.51. The relationship between MSSQ-Short and other non-motion sources of nausea and vomiting (e.g. headaches, food, stress, viral, etc) in the last 12 months was r=0.2 ($p<0.01$). Reliability: Cronbach's alpha was 0.87; Test-retest reliability was around r=0.9; Part A (child) with Part B (adult) was r=0.68.

Conclusions The MSSQ-Short provides reliability with an efficient compromise between length (reduced time cost) and validity (predicted motion susceptibility). Language variants include French, Italian, Spanish, Dutch, Flemish, German, Russian and Chinese.

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