Investigating Non-Image-Forming (NIF) effects of lighting for pedestrians after dark

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Abstract

A key purpose of road lighting is to allow road users to proceed safely. On minor roads, road lighting is designed to meet the needs of pedestrians and cyclists. Current guidelines for designing outdoor lighting focus on their visual needs: it is not known whether they are in line with the ongoing understanding of non-image-forming (NIF) effects and the unwanted side effects of road lighting. The NIF effects of light are psychological, physiological and behavioural effects of light. One such effect is that light with a peak around the blue range of the light spectrum can improve alertness and cognitive performance. Alertness is the state of being ready to see, understand, and act in a particular situation. Enhancing alertness could make pedestrians more alert to potential hazards, enhance visibility and improve visual perception in detecting dangerous objects. A lack of alertness may contribute to road traffic collisions (RTCs) and pedestrians sustaining injuries from falls.

In this thesis, two laboratory experiments were conducted to investigate the NIF effects of road lighting in a context representing pedestrians. The aim of the experiments was to explore the effect of lighting on pedestrian alertness and melatonin levels in the evening, using lighting conditions typical of outdoor lighting. 80 participants were recruited, and trials were conducted in pairs. Four dependent variables (DVs) were measured: reaction time (measured via Psychomotor Vigilance Task (PVT)), subjective alertness (assessed via Karolinska Sleepiness Scale (KSS)), melatonin levels (collected via saliva samples) and skin temperature (measured via iButtons).

The results of the first experiment did not suggest an effect of changes in lighting on any of the four DVs. The null finding supports the results of Bhagavathula *et al.*[113] and Gibbons *et al.*[114] However, it was not certain whether the null finding meant no effect, or rather that the experiment was insufficient to reveal an effect. This was tested in the second experiment by using more extreme variations in test conditions. The same protocol and DVs were used as in the first experiment, excluding the skin temperature measures. The results of the second experiment suggested that for melanopic equivalent daylight illuminance (EDI) of up to 10.7 lx, there was no effect on alertness or melatonin level, confirming the findings of previous studies.[113,114] Increasing the melanopic EDI to almost 100 lx revealed a significant reduction in reaction time, an increase in subjective alertness and a decrease in melatonin level. Changing position from sitting to standing increased melatonin concentration. Walking at a moderate speed significantly shortened reaction time and enhanced subjective alertness.

The results of this thesis do not suggest that lighting on minor roads has a significant impact on the alertness or melatonin level of pedestrians and thus would not affect the choice of optimal lighting conditions.

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Declaration

*I, **Aysheh Alshdaifat**, confirm that the Thesis is my own work. I am aware of the University's Guidance on the Use of Unfair Means (www.sheffield.ac.uk/ssid/unfair-means). This work has not been previously been presented for an award at this, or any other, university.*

Glossary

Adaptation luminance is the average luminance of objects and surfaces in the immediate vicinity of an observer, used to estimate the visual range. It is also known as adaptation level, adaptation illuminance, brightness level, field brightness or field luminance.[A]

Adaptation is the process by which the visual system is modified by previous and present exposure to stimuli of varying illuminance, luminance and SPD values.[B]

Attention is the ability to prioritise one type of information over another. The brain avails maximum resources to deal with this prioritised information.[C,D]

Auditory cognition involves cognitive processes based on auditory information such as speech, sounds, vocalising emotions, musical ability, recognising unique voices, reading subtitles with foreign audio and others.[D]

Auditory localisation is the localisation of sound sources that requires the auditory system to determine the sound direction and its distance.[E]

Awareness is the continuous monitoring of one's thoughts and perceptions.[D] It is possible to be aware of something without being explicitly conscious of it.[C]

Biological clocks are an organism's innate timing device. They're composed of specific molecules (proteins) that interact in cells throughout the body. Biological clocks are found in nearly every tissue and organ.[F]

Correlated colour temperature (CCT) refers to the colour of white light that correlates with the colour of light emitted by a black body at a specific temperature measured in Kelvin (K).[G]

Cerebral cortex is the area in the brain that is associated with our highest mental capabilities.[H]

CIE standard illuminant D65 is a relative spectral distribution of radiant flux representing a phase of daylight with a correlated colour temperature of approximately 6500 K.[B]

Circadian rhythm is any periodic variation in a physiological, physical, mental and behavioural activity that repeats at approx. 24-hour intervals, responding primarily to light and darkness in an organism's environment. such as the sleep-wake cycle; the word comes from the Latin phrase "circa diem," which means "around a day".[C,F]

Cognition refers to all mental processes that lead to thoughts, knowledge and awareness. The underlying mechanisms are called cognitive processes that govern cognitive functions. The word cognition comes from the Latin word "*cognoscere"* which means "get to know".[D]

Cognitive relates to the mental process involved in knowing, learning and understanding things.[I]

Cognitive ageing refers to how our cognitive functioning changes in performance as we age.[I]

Cognitive function is a broad term that refers to mental processes involved in the acquisition of knowledge, manipulation of information and reasoning. Cognitive functions include the domains of perception, memory, learning, attention, decision-making and language abilities.[J]

Cognitive functioning is mental processes that gather and process information and allow us to carry out tasks. It includes memory, reasoning and attention, to name a few.[I]

Cognitive impairment refers to the difficulty in remembering, concentrating and decision making, or to the situation where the cognitive task takes significantly more time thanexpected relative to the specific person's ability.[I]

Cognitive load is the relative demand imposed by a particular task in terms of mental resources required. Also called mental load or mental workload.[C]

Cognitive performance refers to the performance of the mental processes of perception, learning, memory, understanding, awareness, reasoning, judgment, intuition and language.[C]

The cognitive process refers to the mental functions involved in obtaining, storing, interpreting, manipulating, transforming and using knowledge. These processes include activities such as attention, perception, learning and problem-solving. They are commonly explained through basic theories such as dual-task theory and are often used interchangeably with mental processes.[C]

Coordinate auditory and visual information refers to using simultaneous visual and auditory information to coordinate task performance.[K]

Co-ordinating perception and action (Perception-action coupling) refers to the cyclical cause-and-effect relationship between perception and movement. This is done to accomplish specific actions in relation to particular tasks.[L]

Diffuse reflectance is the scattering of light from a surface in many different directions. When light strikes a surface, it can be absorbed, transmitted through the material, or reflected. In the case of diffuse reflectance, the light is reflected in many directions rather than being reflected at a single angle.

Distractibility refers to difficulty in maintaining attention or a tendency to be easily diverted from the matter at hand.[C]

Divided attention refers to the attention to two or more channels of information at the same time, so that two or more tasks may be performed concurrently. It may involve the use of just one sense (e.g., hearing) or two or more senses (e.g., hearing and vision).[C]

Focus attention refers to directing attention to either one channel of information or another.[M]

Glare is a visual perception created when external light becomes scattered within the eyes to cast a hazy veil over the retinal surface, thus reducing the ability to see.[N]

Illuminance is the density of incident luminous flux with respect to area at a point on a real or imaginary surface.[B]

Inattentional blindness is a failure to notice unexpected but perceptible stimuli in a visual scene while one's attention is focused on something else in the scene. This phenomenon occurs even when items are visible for several seconds.[C]

Luminance is the density of luminous intensity with respect to a projected area in a specified direction at a specified point on a real or imaginary surface.[B]

Lux (lx) is a unit of illumination that is defined as the level of direct illumination on a surface located one meter away from a uniform point source with an intensity of one candle, or equivalently, as one lumen per square meter.

Master clock is a group of about 20,000 nerve cells (neurons) that form a structure called the suprachiasmatic nucleus (SCN). The SCN is located in a part of the brain called the hypothalamus and receives direct input from the eyes.[P]

Melanopic EDI is the illuminance of standard daylight (D65) at a point that provides equal melanopic irradiance as the test light. For example, a melanopic EDI of 100 lx means that the light source under evaluation produces the same amount of melanopsin-activating radiation as 100 lx of daylight at 6,500 K.[Q]

Memory is the ability to retain information or a representation of past experience based on the mental processes of learning or encoding, retention across some interval of time and retrieval or reactivation of the memory.[C]

Memory impairment is the loss of memory, such as the one associated with a memory disorder.[C]

N-back task is a widely used measure for the assessment of working memory function. participants are typically instructed to monitor a series of stimuli and to respond whenever a stimulus is presented that is the same as the one presented N trials previously. Common versions are 2-back and 3-back tasks, in which participants have to respond to stimuli that have been presented two or three trials earlier. Zero-back and 1-back versions are also often used as control conditions.[R]

Optical radiation is electromagnetic radiation at wavelengths between the region of transition to X-rays ($\lambda \approx 1$ nm) and the region of transition to radio waves ($\lambda \approx 1$ mm).[B]

Perception is the processing and interpretation of signals from the senses as well as signals generated internally by the brain.[D]

Perceptual tasks for a pedestrian, involves perceiving and understanding the surrounding traffic environment to make safe and informed decisions while walking.

Peripheral vision is the area of vision outside the centre of focus, which allows individuals to detect motion and objects in their surroundings without having to shift their gaze. The peripheral vision is crucial for situational awareness and can contribute to overall safety, especially in activities such as driving, sports and navigating crowded environments.

Reaction time is the time that elapses between the onset or presentation of a stimulus and the occurrence of a specific response to that stimulus.[C]

Road crossing is a complicated decision-making process and a key cognitive task that helps pedestrians avoid unsafe crossing behaviours.[S]

Short-term memory is the reproduction, recognition, or recall of a limited amount of material after a period of about 10 to 30 seconds.[C]

Spectral power distribution (SPD) displays or specifications of the monochromatic components of the radiation considered.[B] In other words, it is a measure that describes the intensity of light at each wavelength across the visible spectrum.

The Go-NoGo task is a cognitive task where the participants require participants to respond by pressing a button when they see a “go” signal and not respond when they see the “no-go” signal. The key behaviour measured in this experiment is the participants’ ability to withhold a response on No-go trials.[T]

Vigilance is a state of extreme awareness (careful attention) and watchfulness directed toward the environment, usually with salient, often toward potential threats (e.g. obstacle, enemy).[C]

Vigilance decrement in a vigilance task is a decrease in the number of targets detected that occurs after a short period on the task.[C]

Visual acuity is the ability of the eye to perceive spatial details at a given distance and is an important indicator of human vision and eye health.[U]

Visual cognition is cognitive processes based on visual and spatial information – colours, shapes, arrangements, locations, directions, gradients and stimuli-based details.[D]

Visual perception is the awareness of visual sensations that arise from the interplay between the physiology of the visual system and the internal and external environments of the observer.[C]

Visual search is the act of looking for a predefined target among other objects.[V]

Vitreous body or the eye’s vitreous body is a clear, gel-like substance that fills the cavity of the eye behind the lens and helps to stabilise the various retinal layers and retinal vasculature.[W]

Abbreviations

CBT – Core Body Temperature
CCT – Correlated Colour Temperature
DVs – Dependent Variables
EEG – Electroencephalogram
ipRGCs – Intrinsically Photosensitive Retinal Ganglion Cells
KSS – The Karolinska Sleepiness Scale
LED – Light-Emitting Diode
NIF – Non-Image-Forming
PVT – Psychomotor Vigilance Task
HRmax – Maximum Heart Rate
RGC – Retinal Ganglion Cells
RTCs – Road Traffic Collisions
SCN – Suprachiasmatic Nucleus

Chapter 1

Illuminating the night: Pedestrian safety and road lighting

1. Illuminating the night: Pedestrian safety and road lighting

1.1. Introduction

Road lighting is installed to alleviate impairments to human vision after dark and plays a critical role in road user safety. Its influence on the visual realm is well-documented and explored, yet its impact extends beyond simply lighting the way after dark. Light also has non-image-forming (NIF) effects on humans,[1] also known as non-visual effects. The NIF effects of light refer to the ability of light to regulate numerous neuro-physiological, neuro-endocrine and neuro-behavioural processes that play a crucial role in health and well-being.[2,3] For pedestrians, alertness and melatonin suppression are particularly key NIF effects because of their potential impact on pedestrian safety and well-being.[4,5]

While the visual aspects of road lighting have been widely researched,[6,7] investigation of the NIF effects is only at its beginning. This thesis seeks to improve our understanding of the effects of road lighting on specific aspects of NIF effects: pedestrians' alertness and melatonin level in the evening.

1.2. Light: A brief overview

Light is the narrow band within the spectrum of electromagnetic radiation that stimulates the human sense of vision (see Figure 1.1). It is thus known as visible light and also as optical radiation. The human eye perceives electromagnetic radiation within wavelengths ranging from about 360 nanometres (nm) to 780 nm.[8]

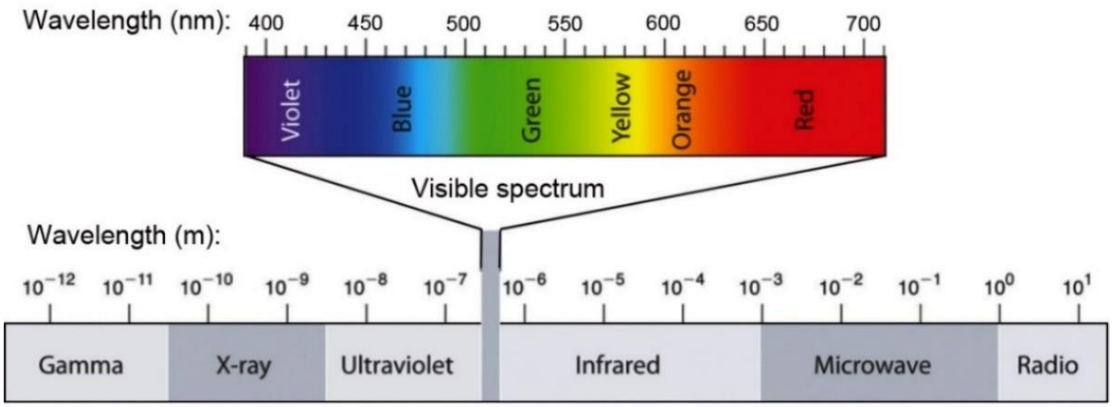

Figure 1.1 The wavelength ranges of electromagnetic radiation. The visible spectrum is the narrow band with wavelengths between 360 nm and 780 nm. [Source: modified by the author, after Averill.[9]]

Light possesses a dual nature, functioning as both an electromagnetic wave with variable frequency and wavelength and as discrete units of energy known as photons.[10] These describe the characteristics of light that could be used to explore how the visual system interacts with light. When determining the sensitivity of the visual system to light, such as the minimum threshold for light detection, it is common to reference light in terms of photons.[11,12] On the topic of colour perception, light is usually discussed with reference to its wavelength measured in nanometres (nm);[13,14] with one nm being equivalent to 10^{-9} meters. For instance, the human eye preserves short wavelengths (around 430 nm to 460 nm) as blue light, while longer wavelengths (around 560 nm to 580 nm) are perceived as red light.[9,10,15]

1.3. Vision: Understanding the operation of the human visual system

Vision is a complex process that involves the eye, the visual pathway and the brain.[7,9,10,16-18] In humans, vision starts by capturing the photons that enter the eye by passing through the cornea, a transparent protective layer at the front of the eye (see Figure 1.2).

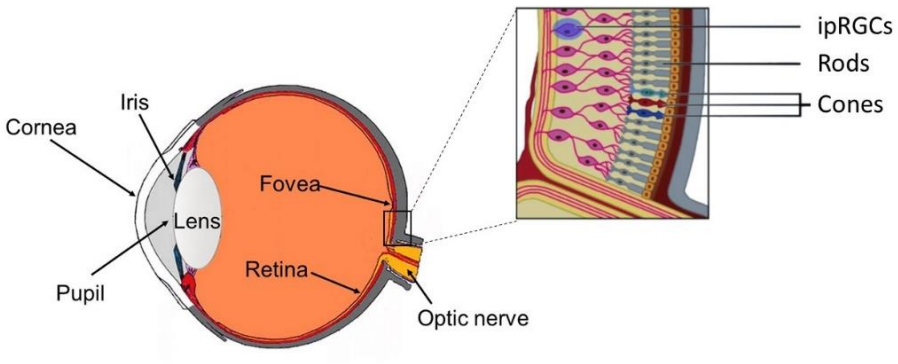

Figure 1.2 The horizontal section of the eye as seen from above. The pupil is the opening in the iris (left) and an overview of the retina photoreceptors (right). [Source: modified by the author, after Averill,[9] Tovée,[10] Kolb *et al.*,[16] Blume *et al.*,[3] Atchison and George.[18]]

After the cornea, the light reaches the pupil, which can constrict or dilate to regulate the amount of light entering the eye. The pupil is able to adjust with the help of the iris, the coloured part of the eye. After passing through the pupil, the light reaches the lens, which is located behind the pupil. The lens further adjusts the incoming light by changing its own shape, focusing the light rays onto the retina at the back of the eye. This flexible lens allows the eye to focus on objects at varying distances, ensuring clear vision.[9,10,16]

The retina is a thin tissue layer at the back of the eye that contains millions of specialised cells called photoreceptors, including rods and cones. Rods, which outnumber cones, are

more sensitive to low light conditions (low amount of photons, such as at dusk or under a starlit sky) and play a significant role in such environments. On the other hand, cones work best in well-lit surroundings (such as the outdoor light during the daytime) and are responsible for colour vision (Figure 1.2). Cones predominate in the fovea, which is 1.5 mm in diameter or approximately 5° wide at the back of the eye. The fovea is free of rods in its central 1° field.[18] Cones respond very rapidly to changes in light; even in dim light, when they are slowest, the time it takes for the cones to respond is less than 12 ms,[19] while it takes around 100 ms for rods.[20]

When light reaches the photoreceptors, it triggers chemical reactions that generate electrical impulses. These impulses are then transmitted to the optic nerve, a bundle of nerve fibers located at the back of the eye (a front view of the optic nerve appears in Figure 1.3 as the optic disc). The optic nerve carries these electrical impulses to the brain.[9,18] In the brain's visual cortex, the area of the cerebral mantle that processes visual information, the electrical signals received from the optic nerve are used to construct a cohesive representation of our visual surroundings.[21]

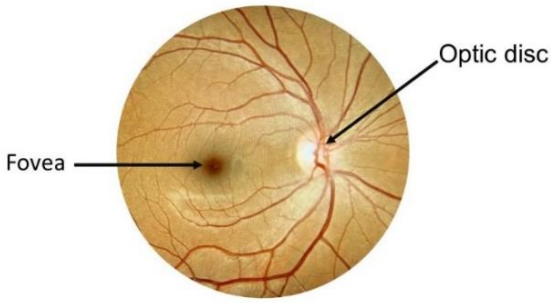

Figure 1.3 A vertical section of the eye, as seen from the front, shows the retina of a real human eye. The Fovea and optic disc locations are visible in the retina [The author's eye taken by Boots Opticians, Sheffield, UK, 2023]

1.4. Visual response after dark: Why does vision decrease after dark

There are three states of vision; photopic, mesopic and scotopic, characterised by adaptation luminance and dominant photoreceptor (Table 1.1).

Table 1.1 Definitions of photopic, mesopic and scotopic visions according to adaptation luminance and photoreceptor activity[22]

State of vision	Photopic	Mesopic	Scotopic
Adaptation luminance (L) ($cd.m^{-2}$)[a]	>5	5<L<0.005	<0.005
Dominant photoreceptors	Cones	Cones and rods	Rods

[a] Candela per square meter

The three states of vision are defined by the Commission Internationale de l'Éclairage (International Commission on Illumination; CIE) as follows: 1) Photopic vision is vision by the normal eye in which cones are the principal active photoreceptors. 2) Scotopic vision is the vision by the normal eye in which rods are the principal active photoreceptors. 3) Mesopic vision is the vision by the normal eye intermediate between photopic vision and scotopic vision.[23]

Road lighting tends to fall within the mesopic region. The high daylight levels are photopic conditions where the cones dominate vision, and these permit colour vision and fine resolution of detail. Under purely scotopic vision, the rods are the dominant photoreceptors; the fovea is blind, and colour is not perceived. Under mesopic vision, both the rods and cones are active, the relative contributions of each depending on adaptation level and light source spectrum: as the light level reduces from the upper to lower boundaries of the mesopic range, the cone contribution decreases and with that, the colour discrimination and resolution of foveal cone vision also decrease.

1.5. Road lighting in minor roads: How can the vision impairment that occurs after dark be counteracted

Road lighting is installed to offset the impairments to vision after dark. It is typically provided by lamps installed on posts positioned at a height approx. 6 m above ground level. These lamps are spaced at regular intervals of around 30 m along the roadside, conveniently placed near the edge of the road at the top of a lamp post**.** Figure 1.4 shows examples of road lighting on minor roads and pedestrian footpaths.

Figure 1.4 Examples of road lighting on a minor road (left) and pedestrian footpaths (middle and right) in Sheffield, the UK

Various types of lamps are utilised for road lighting, each emitting a different colour depending on its type. Figure 1.5 illustrates examples of various road lighting lamp types, including cool white Light-Emitting Diode (LED), halogen spotlight, neutral-warm LED, high-pressure sodium (HPS), mercury vapour and metal halide (MH) lighting.

Figure 1.5 Examples of the different types of light sources used for road lighting from left to right are 1) cool white LED, 2) halogen spotlight, 3) neutral-warm LED, 4) high-pressure sodium, 5) mercury vapour and 6) metal halide lighting. [Source: modified by the author, after Dudley *et al.*[24]].

Road lighting benefits road users after dark because it improves perceived safety for pedestrians, visibility and the probability of detecting and identifying hazards.[25] According to the CIE,[26] the three primary objectives of road lighting are 1) to allow all road users, including operators of motor vehicles, motorcycles, pedal cycles and animal-drawn vehicles, to proceed safely, 2) to allow pedestrians to see hazards, orientate themselves, recognise other pedestrians and give them a sense of security and 3) to improve the day-time and night-time appearance of the environment. These purposes primarily relate to aspects of visual performance and visual perception.

According to the British Standards BS5489-1:2020,[27] "*The main purpose of lighting for minor roads and areas associated with those roads is to enable pedestrians and cyclists to orientate themselves and detect vehicular and other hazards. It can allow pedestrians to recognise other pedestrians and feel more secure. It also has a wider social role, with the potential of helping to reduce the fear of crime and to discourage crime against people and property*."

1.6. Current lighting standards for minor roads: What we have now

The guidance documents are the foundation for the lighting designer's role in determining the appropriate road lighting conditions for a specific case. These documents can be either international, such as those from the CIE[26] or national, like British Standards as used in the UK.[27]

For minor roads, the design of road lighting should consider the needs of pedestrians and cyclists.[26,27] While slow-moving vehicles (speed ≤ 30 mph) are permitted on some minor roads, pedestrians and cyclists are considered the primary user group targeted by road lighting on these minor roads,[27] also called subsidiary roads or residential roads, including pedestrian areas and footpaths. This thesis adopts the term "road" lighting in accordance with the terminology of BS5489-1:2020.[27] “Road” lighting includes the lighting used on pedestrian paths, whether they are adjacent to vehicular routes or separate footpaths. There is no specific distinction between "road" and "street," and therefore, the term "road" is used consistently throughout this thesis.

The recommended criteria for lighting on minor roads are known as the P-class.[26,27] These criteria define the amount of light using illuminance, with the average horizontal illuminance ranging from 2 lx to 15 lx on a surface (see Table 1.2). Given a surface having a diffuse reflectance of 0.2, these values correspond to luminances in the range of 0.13 cd.m^{-2} to 0.95 cd.m^{-2}, indicating that the pedestrian’s visual system will typically operate in the mesopic state.

Table 1.2 Illuminances for the P-class recommendations[26,28] and luminances determined assuming a diffuse surface reflectance of r = 0.2

P-class	**Average horizontal**		**Minimum horizontal**	
	Illuminance (lx)	Luminance (cd.m^{-2})	Illuminance (lx)	Luminance (cd.m^{-2})
P1	15	0.95	3	0.19
P2	10	0.64	2	0.13
P3	7.5	0.48	1.5	0.10
P4	5	0.32	1	0.06
P5	3	0.19	0.6	0.04
P6	2	0.13	0.4	0.03

The light level on an illuminated surface can vary due to factors such as the optical properties of the luminaire, as well as the height and spacing of the lamp posts. The light level is determined for each node in an array across the illuminated surface, with the average being the arithmetic mean of these values. In the P-class, the minimum illuminance for any node is set, and uniformity is defined as the ratio of minimum to maximum illuminance.

A particular lighting P-class is chosen according to several factors, such as travel speed, traffic volume, traffic composition, the presence of parked vehicles, ambient luminance and the requirement for facial recognition. While there is evidence that increases in traffic speed

and volume are associated with an increase in Road Traffic Collisions (RTCs), the extent to which different conditions of road lighting offset such increases is not known. In other words, the class selection factors are not well substantiated and do not appear to be founded in robust empirical evidence.[6,29] Moreover, there is a need to review the standards to align with ongoing developments in road lighting technology and developments in the understanding of vision and unwanted side effects of road lighting.[6]

1.7. Defining a pedestrian

A pedestrian is an individual who chooses to walk rather than use an alternative mode of transport, such as cycling or driving.[7] Walking means the act of going on foot,[30] of moving by repeatedly putting one foot in front of the other, allowing each foot to touch the ground before lifting the next.[31] Walking is considered a highly skilled performance and a complex human activity involving cognitive and perceptual processing[32] that requires coordinated and controlled movement, dynamic stability, motor and cognitive functions, and making a movement decision for safe ambulation.[33,34] Walking requires the pedestrian to choose the location of pending footfalls to ensure the continuation of locomotion and dynamic stability, especially on uneven terrain.[35]

1.8. Pedestrian vision after dark: Why this a critical consideration for pedestrians

The safety of pedestrians as they move through their surroundings depends largely on their ability to interpret sensory information, particularly visual input. This processed data plays a critical role in guiding pedestrians as they navigate both their immediate surroundings (step-by-step basis) and the more distant environment (route planning).[25,36-38]

Reduced visibility due to low ambient light levels is suggested to be a key causal factor of after-dark traffic-related pedestrian casualties.[39-41] In the scenario of crossing a road, the pedestrian needs to detect the presence of traffic, make judgments concerning the vehicle's movement, and take a crossing decision relating the time available to the time required to cross.[37,38] After dark, pedestrian visual functions like acuity and contrast detection deteriorate due to decreased light levels, and complex processes like visual search and motion perception get impaired, impacting the ability to deduct and avoid hazards.[39,42] Visual degradation leads to poor judgments of moving objects.[42] This impacts the pedestrian's estimation of the vehicle's speed and position, which leads to reducing the ability to find a proper gap for crossing roads.[40,43]

Pedestrians must ensure they are visible to drivers with sufficient time to allow a driver to react in case he must.[44] Pedestrians often underestimate the visibility problems drivers also encounter after dark.[40] This may lead pedestrians to overestimate a driver's observation abilities, assuming they are visible when they might not be.[45] All these can lead the pedestrian to cross the road, believing that there is no hazard on their side or that the driver has enough time to stop before a collision.

For pedestrians, hazards are not limited to crossing the roads. Pavement obstacles such as potholes and uneven surfaces play a significant role in pedestrian safety. These obstacles may not be visually detected in sufficient time to adjust their gait, causing the pedestrian to fall.[7] Moreover, there is a risk of a pedestrian encountering another with aggressive intentions, which, due to insufficient light, may not be recognised in time to make a safe decision about whether to approach or avoid them.

1.9. Pedestrian casualties: Why should one expend effort

Globally, each year, more than 1.2 million people lose their lives on roads, with more than half of these deaths occurring among vulnerable road users such as pedestrians, cyclists and motorcyclists.[46] Pedestrians account for the highest number of fatalities among vulnerable road users.[47]

Pedestrian injuries and fatalities can stem from two causes: 1) traffic-related incidents, incidents involving a vehicle, like a pedestrian being struck by a vehicle in RTC,[41,48] and 2) non-traffic incidents, those that do not involve a vehicle, such as; tripping or slipping on an undetected pavement surface irregularity causing a fall.[49]

1.9.1. Traffic-related pedestrian fatalities

Traffic-related accidents are the leading cause of death among children and young adults aged 5 to 29 years.[50] In 2018, 311,614 pedestrians were killed in traffic incidents worldwide.[50] In the United Kingdom (UK), there were 385 pedestrian fatalities in 2022, comprising 24% of all road user fatalities, a higher percentage than cyclist fatalities (91 cyclists; 6%) and motorcyclist fatalities (342 motorcyclists; 20%) in the same year.[47]

This percentage of pedestrian fatalities has shown an increase over recent years, such as in the United States of America (USA), where the pedestrian fatalities as a percentage of all traffic fatalities rose from around 12% in 2005 to 17% in 2021, where the number increased by almost 2,500 deaths just in the last three years (from 6,205 in 2019 to 8,984

in 2021).[51,52] While the UK witnessed 415 pedestrian fatalities in 2022, the pedestrian fatalities were 317 in 2021.[47,53]

1.9.2. Traffic-related pedestrian injuries

In 2022, 18,942 pedestrians were injured in traffic-related incidents in the UK, accounting for approx. 14% of all road user injuries, with 5,908 pedestrians sustaining serious injuries. This percentage is higher than the proportion of cyclist injuries (15,602 cyclists; 11.5%) and motorcyclist injuries (16,083 motorcyclists; 12%) in the same year.[47] This means pedestrians are the most affected by traffic-related incidents among vulnerable road users.

The impact of traffic-related pedestrian casualties extends beyond the loss of lives and health. It also affects the financial well-being of individuals, their families and the government. These consequences include the costs of medical treatment, the loss of productivity for those who have been killed or disabled, and the need for family members to take time off work or school to care for the injured pedestrian.[50]

The average costs resulting from casualties in road accidents are £20,234 for each slightly injured, £262,480 for each seriously injured, and £2,335,815 for each fatality.[54] These costs have been adjusted to 2023 values using the Bank of England's inflation calculator.[55] Considering the number of traffic-related casualties in the UK in 2022, the estimated total national cost to the UK government for pedestrian accidents on the road is £2,705,344,781 (approx. £2.7 billion). This includes £255,679,166 for slightly injured pedestrians, £1,550,179,840 for seriously injured pedestrians and £899,485,775 for fatalities.

1.9.3. Non-traffic pedestrian fatalities

Pedestrian falls are the second leading cause of unintentional deaths globally, following RTCs,[56] resulting in over 684,000 fatalities annually.[57] A study using data from the Netherlands estimated that between 1996 and 2017, 46% (1610) of 3,526 pedestrian fatalities resulted from falls.[58]

Road safety is a key priority for the UK government, not only due to the economic costs but also because of the public health implications. The perceived danger of frequent road pedestrian casualties can discourage walking and act as a barrier to active travel.[59] Therefore, reducing pedestrian casualties on the road is both a direct and indirect benefit to public health.

Statistics on pedestrian falls in the UK and Europe (EU) do not include incidents where no vehicle is involved, making it challenging to determine the actual number and cost of these incidents. Nevertheless, a UK study estimated 5,835 deaths from falls in 2018,[60] encompassing pedestrian falls and falls in outdoor public spaces such as roads, sidewalks, public parks, squares, stairs and indoor falls. It is anticipated that at least half of this number occurs outdoors, on pavements, kerbs and streets,[48,61] equating to over 2900 deaths annually. The costs for pedestrian falls are individually comparable to those involved in cycle and motor vehicle collisions,[62] with each fatality amounting to £2,335,815. The annual estimated cost for outdoor falls in the UK totals approx. £6.8 billion. However, this estimate encompasses all fall fatalities outdoors.

1.9.4. Non-traffic pedestrian injuries

The exact number of pedestrian falls remains unclear due to limited available information from official statistics.[63] However, the World Health Organization has reported a global occurrence of approx. 37.3 million falls yearly that necessitate medical attention.[56] Within the EU, the annual tally of injuries resulting from pedestrian falls is estimated at around 1.6 million.[64] Various studies have proposed using hospital records to estimate the number of pedestrian falls.[49,63,65-67] For example, within the UK, approx. 76,000 pedestrian falls between 2007 and 2009 were estimated from such records.[49] Moreover, a recent study on pedestrian falls revealed that over 30,000 individuals were annually hospitalised in England due to pavement falls.[68] This figure accounts only for overnight hospital admissions resulting from footway fall injuries in England and does not encompass Accident and Emergency visits where patients were discharged home. The associated costs were reported to be as high as £500 million, covering expenses related to medical care, support services and injury claim settlements.[68]

While RTCs are the major well-documented cause of pedestrian deaths, it is essential to recognise the frequency of pedestrian fall injuries (see Table 1.3). For instance, in the UK, pedestrian falls caused nearly three times more injuries than RTCs between 2007 and 2009.[49] In Denmark, pedestrian falls accounted for 75% of all road injuries in 1995.[69] Similarly, within the Netherlands, Switzerland and Austria, the incidence of pedestrian fall injuries surpassed RTC injuries by a factor of four to nine.[63] Notably, the prevalence of pedestrian fall injuries was thirty times greater than that of RTC injuries in Oslo, Norway.[67] These statistics underscore the substantial burden of pedestrian falls contributing to pedestrian injuries compared to RTCs.

Table 1.3 Pedestrian injuries from falls and RTCs as estimated in different studies

Country	Injured pedestrian		Year	Context	Reference
	Falls	RTC			
England and Wales	20,000 To 190,000	8,631[a]	2002	Hospitalised pedestrians[b]	Bird, 2008[65]
Austria	32,500	4000	2009	Injured pedestrians	Furian *et al.* 2011[c]
The UK	76,000	26,000	2007-2009	Hospitalised pedestrians[d]	Mindell *et al.* 2012[49]
Canada, Montreal	960	-	2 months in 2009	Required ambulance	Morency, 2012[66]
Netherlands	43,000	5,000	2011	Injured pedestrians	Den Hertog *et al.* 2013[c]
Sweden	27,000	-	Per year	Injured pedestrians	Schyllander 2014[c]
Oslo	6,109	200	2016	Medical emergency[e]	Elvik, 2019[67]
Switzerland	47,850	6,270	2018	Injured pedestrians	Niemann *et al.* 2021[70]

[a] Reported killed or seriously injured pedestrians in the UK in 2002.[54]
[b] Based on interviews with patients at around 20 hospital accident and emergency.
[c] Cited in Elvik[67] and Methorst *et al.,*[63] the primary source of this information was not verified; the language of the primary source is not English or Arabic.
[d] Based on an analysis of the number of hospital admissions from Hospital Episodes Statistics data,
[e] Recorded by the medical emergency clinic in Oslo.

Not reporting pedestrian injuries resulting from falls in national statistics may lead to a disproportionate focus on addressing traffic-related pedestrian injuries (involving motor vehicles) and overlooking pedestrian injuries resulting from falls on minor roads—where no vehicles or only slow vehicles (speed ≤ 30 mph) are allowed. Reporting data on pedestrian falls is crucial, as it can influence the allocation of road maintenance funds and policy priorities. This thesis focuses on lighting on minor roads where pedestrian deaths and injuries can occur due to RTCs and falls.

1.10. Pedestrian casualties after dark: Should we blame the lack of light?

Knowing the number or percentage of pedestrian casualties during daylight versus after dark is critical for studies on outdoor lighting. The level of light is one of the key differentiating factors between the two conditions. When evaluating the ratio of casualties, it is important to account for the lower number of pedestrians after dark compared to during daylight. If this ratio of casualties in both conditions is similar, it suggests that the light conditions themselves may not significantly impact these casualties.

Several studies investigated the ratio of pedestrian casualties occurring after dark to daylight; pedestrian casualties are found to occur more likely after dark than during the day.[40,41,71-80] For example, Fotios *et al.*[80] analysed the data from 2005 to 2015 in the UK and

found that there was a 41% increase in pedestrian casualties after dark compared to daylight. In the USA, national data[74-77] from 1993 to 2019 showed that over 72% of pedestrian fatalities occurred after dark hours between 18:00 and 5:59. In addition, Sullivan and Flannagan[41] analysed 11 years of fatal collision data between 1987 and 1997, and they found that RTC involving pedestrians posed up to seven times more risk at night compared to daytime.

Pedestrian casualties after dark are associated with higher levels of injury severity and fatality.[78] In Singapore, between 2003 and 2008, the number of fatal injuries sustained by pedestrians was higher after dark than during daytime.[73] Similarly, in Florida, from 1999 to 2002, pedestrian casualties that occurred after-dark were found to result in greater injury severity.[39] In North Carolina, USA, after-dark was found to pose a two to four times higher risk of pedestrian fatalities compared to daylight.[79]

The differences in pedestrian casualties between daylight and after-dark highlight the significant impact of light conditions on pedestrian safety. Data from various studies, including those from the UK, USA, Singapore and Florida, consistently demonstrate that pedestrian casualties are more likely to occur and result in higher injury severity and fatality after dark. These findings underscore the critical role of the light as a key variable affecting pedestrian safety.

1.11. Pedestrian safety in road lighting: Previous research

Pedestrian's needs can be summarised as four items: "*to see, to be seen, to be safe, to feel safe*".[7] Pedestrian safety greatly depends on their ability to avoid various risks on the road, such as being hit by a vehicle, encountering threatening individuals, or tripping over unexpected obstacles on the pavement.[7]

Pedestrian safety after dark has been primarily investigated in terms of the visual effect of road lighting (which is relatively low-light environments) and if the road lighting conveys the pedestrian visual needs. Pedestrian visual needs are summarised as 1) identifying pavement obstacles, 2) assessing other pedestrians, 3) ensuring visibility to drivers and 4) feeling reassured.[7] Next, an overview of the crucial visual aspect essential for pedestrian safety, which can be influenced by road lighting conditions, is provided.

1.11.1. Obstacle detection

One of the pivotal factors that can be affected by road lighting conditions is obstacle detection.[48,81,82] Obstacle detection is "*the ability to visually detect pavement obstacles*

which, if not detected in sufficient time, could lead to a fall".[7] Obstacle detection, particularly in peripheral vision, can be enhanced by lighting with higher illuminance and Scotopic/Photopic (S/P) ratio.[48,81,82] This enhancement is significant only at the lower light levels (see Table 1.4). Obstacles detection ability can be affected by factors such as lighting conditions and the age of the observer, as shown in Table 1.4. For example, at low light levels (e.g. 0.2 lx), individuals over 60 years old have poorer detection ability compared to those under 45 years old.[81]

Table 1.4 Light-related variables that affect pedestrian obstacle detection ability

Study	Independent variable (IV)	Effect Found
Fotios and Cheal 2009[81]	Illuminance	Yes
	Observer's age	Yes[a]
	S/P ratio[b]	Yes[a]
Fotios And Cheal 2013[82]	Illuminance	Yes
Uttley *et al.* 2017[48]	Illuminance	Yes
	S/P ratio	Yes[a]
	Observer's age	Yes[a]
Rahm and Johansson 2018[83]	Lamp type	Yes
	Observer's age	Yes
Fotios *et al.* 2020[84]	Obstacle location	Yes[c]
	Obstacle size	Yes
	Luminaire position	Yes
	Obstacle configuration	No
Mao and Fotios 2022[85]	Illuminance	No
	Multi-Tasking	Yes[d]

[a] The experiment includes three illuminances (0.2 lx, 2 lx, 20 lx); this result occurs at the lowest illuminance.
[b] S/P ratio is the ratio of the luminous output of a source evaluated according to the CIE scotopic spectral luminous efficiency to the luminous output evaluated according to the CIE photopic spectral luminous efficiency.[23]
[c] This result occurs for some of the obstacle sizes.
[d] Multi-tasking impaired performance on the peripheral detection task but not the on-axis facial emotion recognition task.

1.11.2. Evaluating other people

Evaluating other people refers to the ability to visually judge the intentions of other pedestrians in time to make an appropriate response[86] or, as stated in the British Standards BS5489-1:2013,[87] "*at a distance sufficient to take avoiding action if necessary"*. Evaluating other people is considered the second key visual task for pedestrians after obstacle detection,[88,89] and described in the British standards as a key factor to provide the pedestrians a sense of security.[86]

The role of road lighting in judging the intentions of other people has been intensively investigated through evaluations seeking facial identification (Table 1.5) or facial emotion

recognition (Table 1.6). This helps the pedestrian decide whether it is safe to approach another person or avoid them.

Table 1.5 Light-related variables affect pedestrian's ability to evaluate other people in terms of facial identification using the Stop-Distance[a] method

Study	IV	Effect found
Caminada and van Bommel 1984[88]	Illuminance	Yes
Rombauts *et al.* 1989[90]	Illuminance	Yes
Boyce and Rea 1990[91]	Lamp type	No
	Lighting distributions	Yes
	Illuminance	Yes
Raynham and Saksvikrønning 2003[92]	Correlated colour temperature (CCT)[b]	Yes
Rea *et al.* 2009[93]	Lamp type	No
Yao *et al.* 2009[94]	Lamp type	Yes
Knight 2010[95]	Spectral power distribution (SPD)[c]	Yes
Alferdinck *et al.* 2010[96]	Illuminance	Yes
	SPD	No
	Observer's age	Yes
Iwata *et al.* 2015[97]	Illuminance	Yes
	CCT	Yes
Rahm and Johansson 2018[83]	Lamp Type	Yes
	Observer's Age	Yes

[a] Participants were asked to walk toward a real target person and stop at certain distances to evaluate the visibility of the face or vice versa.
[b] CCT refers to the colour of white light that correlates with the colour of light emitted by a black body at a specific temperature measured in Kelvin (K).
[c] SPD is a measure that describes the intensity of light at each wavelength across the visible spectrum.

Table 1.6 Light-related variables affect the pedestrian's ability to evaluate other people in terms of facial emotion recognition

Study	Method / Task	IV	Effect found
Fotios *et al.* 2015[98]	Forced-Choice judgements[a]	Lamp type (S/P ratio)	No
		Luminance	Yes
		Interpersonal distances	Yes
Yang and Fotios 2015[99]	Forced-Choice judgments[a]	Lamp type (S/P ratio)	No
		Luminance	Yes
Fotios *et al.* 2017[100]	Forced-Choice judgments[a]	Lamp type (SPD)	No
		Image colour	No
Li and Yang 2018[101]	Facial expressions identification[b]	Lamp type (SPD)	No
		Illuminance	Yes
		Target dimensions (2D, 3D)	No

[a] Participants must state whether the target (different facial expressions) would be considered. threatening or not if encountered alone after dark.
[b] Participants must identify the 3D facial expressions under different lighting conditions.

1.11.3. Being detected by drivers

Pedestrians must be recognised and identified as pedestrians by the driver in sufficient time, allowing the latter to take avoiding action if necessary. Pedestrian visibility has been evaluated under various road lighting conditions.[44,102,103]

Edwards and Gibbons[44] conducted field experiments to determine the minimum vertical illuminance needed for pedestrian visibility at crosswalks. They tested different light conditions (6 lx, 10 lx, 20 lx and 30 lx) and found that the vertical illuminance and the luminaire type had significant impacts on object detection distances. In addition, their research revealed that pedestrians wearing white clothes were detected faster than those wearing darker clothes.

Gibbons and Hankey[102] performed an experiment at a full-scale research facility to understand how different lighting levels, lamp types (MH versus HPS), and clothing colours (white, black and denim) impact pedestrian detection at crosswalks. Their findings suggested that vertical illuminance of 20 lx was sufficient for visibility, lamp type had minimal effect, and pedestrians in white clothing were detected the most.

Bhagavathula and Gibbons[103] evaluated the visual performance of five different lighting designs for midblock crosswalks, with and without pedestrian-crossing treatments (such as flashing signs and rectangular rapid flashing beacons), at three light levels on a realistic midblock crosswalk. The study found that optimal pedestrian visibility occurs at an average vertical illuminance of 10 lx. Bhagavathula and Gibbons[103] recommended the use of lighting designs that increase the positive contrast for pedestrians. This can be achieved by illuminating the area in front of the crosswalk. Pedestrian-crossing treatments should be used along with overhead or crosswalk illuminators that provide the necessary vertical illuminance to ensure optimal pedestrian visibility at midblock crosswalks.

1.11.4. Perceived safety

Perceived safety (also known as reassurance) is "*the confidence a pedestrian might gain from road lighting (and other factors) to walk along a footpath or road, in particular, if walking alone after dark*".[7] The pedestrian perceived safety has been investigated in several studies, as shown in Table 1.7.

Table 1.7 Light-related variables affect pedestrian perceived safety

Study	Method	IV	Effect found
Herbert & Davidson 1994[104]	Lamp replacement Survey: field	Lamp type	Yes
Knight 2010[95]	Questionnaire: field	SPD	Yes
Blobaum & Hunecke 2005[105]	Lamp replacement questionnaire: field	Illuminance	Yes
Haans and de Kort 2012[106]	A Forced-Choice and separate evaluations (rating scales): field	Spatial distribution	Yes
Kostic & Djokic 2014[107]	Questionnaire: field	Lamp type (SPD and spatial distribution)	Yes
Viliūnas *et al.* 2013[108]	Questionnaire: field	Spatial distribution	Yes
Boyce *et al.* 2000[109]	Questionnaire: field	Illuminance	Yes
Fotios *et al.* 2019[110]	Questionnaire: field	Illuminance	Yes

In addition, the impact of ambient light levels on pedestrian traffic flow has been investigated using an approach called "Odds ratio".[108-110] The odds ratio approach is a quantitative objective procedure to evaluate the shift in travel count between daylight and after-dark compared with simultaneous changes in control periods. This allows for an extensive examination of how light conditions may play a role in influencing one's initial decision to walk after dark. Using this approach it has been found that ambient light level affects pedestrian traffic flow.[110-112]

1.11.5. Limitations of previous studies: Why further research is needed

As described above, previous research on pedestrian lighting has primarily focused on the image-forming response to changes in lighting. NIF effects under adaptation and other conditions more closely pertinent to pedestrian activity in the evening have been considered in only two studies, Bhagavathula *et al.*[113] and Gibbons *et al.*[114], although the pedestrian context in those studies is somewhat limited. These studies are discussed in sub-section 2.6.4.

Assuming that light's NIF effects are significant for pedestrians, neglecting these effects will result in recommendations for road lighting design that are not sufficiently informed. Studies focused on the image-forming effect of light have considered variables such as light spectrum, light distribution, illuminance and observer age. These variables have been found to impact visual perception. However, they also affect the NIF responses (these are discussed in 2.6.1). This means that the results obtained might not solely reflect the impact of visual aspects on pedestrian safety but could also be influenced by the NIF effects of light. For example, experiments using different lighting conditions may lead to different levels of alertness, thus confounding the apparent image-forming component of detection.

Moreover, the specific timing of the experiments - such as the season and time of day - participants' sleep/wake cycle, the light exposure history, exposure duration and even the potential of coffee consumption on the experiment day are aspects that play a significant role in participant's alertness levels and the NIF responses to light. For example, experiments conducted at different times of day may, therefore, represent different levels of alertness and confound interpretation of lighting effects, which assume only an image-forming process.

1.12. Research aim

The aim of this study is to examine the influence of NIF effects of lighting on minor roads on pedestrian safety. The specific hypotheses being tested are defined in section 2.8.

1.13. Summary and thesis structure

To ensure pedestrian safety after dark, the standard guidelines documents for road lighting, such as CIE 115:2010[26] and BS EN 13201-2:2015,[28] provide recommended criteria for lighting on minor roads; these are known as the P-class. The P-class defines the amount of light using illuminance, with an average horizontal illuminance ranging from 2 to 15 lx on a surface. The recommended criteria do not appear to have a robust empirical basis[6] and do not account for the NIF effects of light. Previous research has focused on the visual aspect of road lighting and its effect on pedestrian safety, including its impact on several visual tasks, such as obstacle detection, evaluating other people, being detected by drivers and perceived safety. Until now, it is unknown to what extent the NIF effects of lighting on minor roads might impact pedestrian safety and whether this is a relevant consideration for them.

In Chapter 2, the literature review introduces the NIF effects of light through an argumentative literature review. It begins with a thorough background on NIF knowledge and then discusses specifically the two studies[113,114] that are more closely pertinent to the NIF effect of light on pedestrians in the evening. Chapter 2 reveals that the current knowledge of the alerting effects of light is insufficient for pedestrian activity in the evening. This is because the lighting conditions used in the adaptation and test phases do not represent typical pedestrian exposure to light, and the participants' physical activity does not reflect pedestrian activity, i.e. walking. Chapter 3 describes the method used in experiment 1, an experiment conducted to test the effect of light on pedestrian alertness using lighting conditions that better represent typical pedestrian activity than used in previous work. The results of experiment 1, reported in Chapter 4, do not reveal a significant effect of light on alertness. This null finding suggests either that light has no effect on alertness or that the experiment was insufficient to reveal an effect (Chapter 5). Experiment

2 was therefore repeated Experiment 1 but using an extreme light condition and faster walking speeds (Chapter 6). The results (Chapter 7) suggest that the extreme condition produced a significant effect. Chapter 8 discusses the experimental results in conjunction with previous studies. Finally, Chapter 9 summarises the key findings of the experiments and outlines the limitations that may be considered in potential future research.

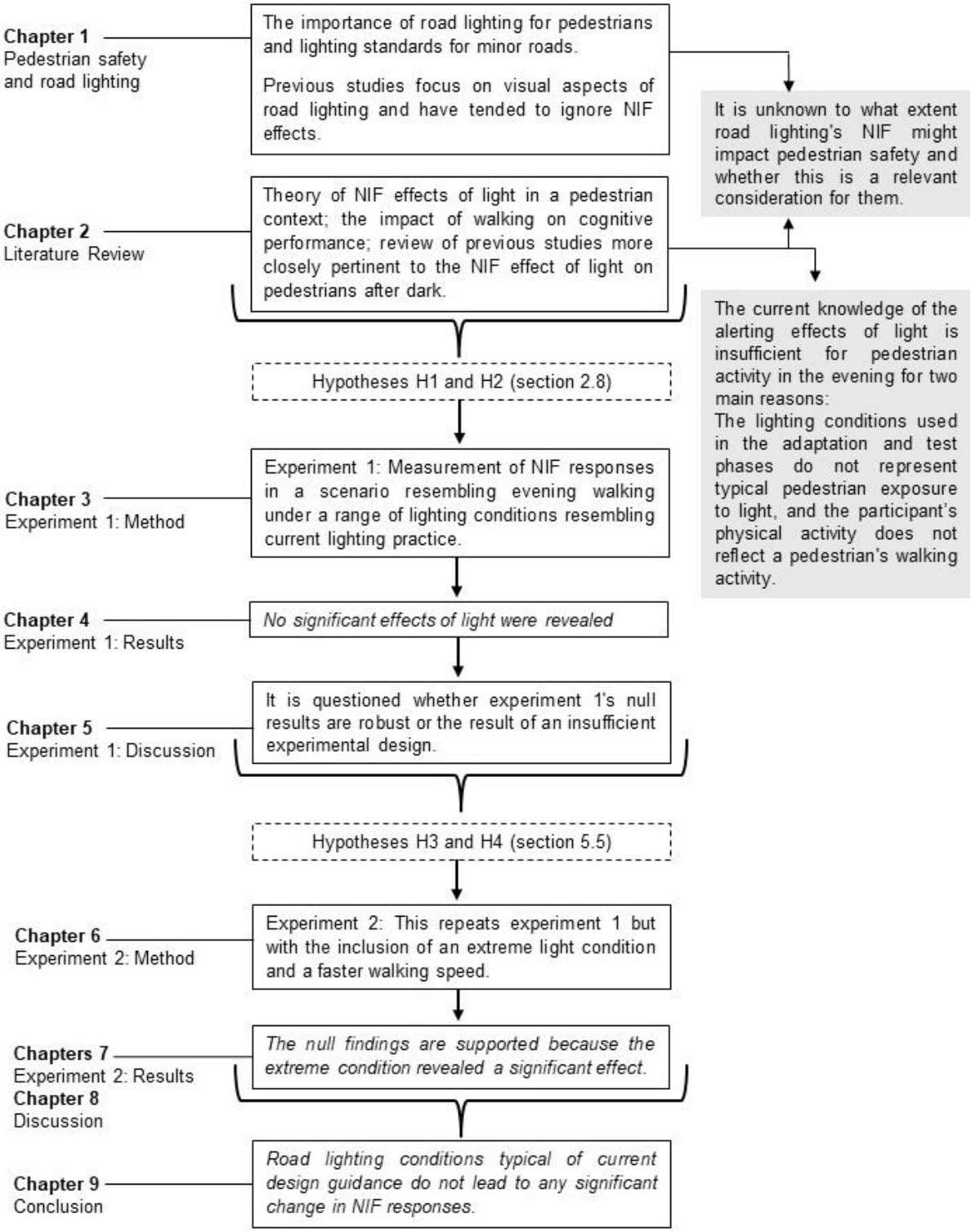

Figure 1.6 A summary of the thesis structure and the focus of each chapter

Chapter 2

Literature Review

2. Literature Review

2.1. Introduction

Chapter 1 provided insights into the visual aspect of road lighting and its relation to pedestrian safety after dark. It also presented the current lighting standard on minor roads in the UK and highlighted a significant gap in previous research on road lighting and pedestrian safety, namely that the NIF effects of light have yet to be investigated. This chapter introduces the NIF effects of light through an argumentative literature review, focusing specifically on the effect of light on alertness and melatonin levels and the degree to which this may affect pedestrian safety. Section 2.2 introduces the third photoreceptor of the eye and its role in the NIF effects of light. Section 2.3 describes the NIF responses to light, defines alertness, addresses how it can be assessed and articulates why pedestrian alertness is important. Section 2.4 explains the expected effect of walking, the main physical activity of pedestrians, on alertness, melatonin levels and skin temperature. Section 2.5 reviews the common light metrics and the new metric proposed to estimate NIF responses. Section 2.6 introduces the variables of the light stimulus through an argumentative literature review and discusses the two studies that are more closely related to the NIF effects of light on evening pedestrians. Section 2.7 highlights the limitations of previous research, explaining why no prior studies accurately reflect the pedestrian context. Section 2.8 summarises the chapter and sets out the research hypotheses.

2.2. The third photoreceptor: The beginning of a new understanding

Until recently, understanding of photoreceptors in the human retina was limited to rods and cones (discussed in sections 1.3 and 1.4). The electrical impulses generated in cones and rods are delivered to the visual cortex through a pathway known as the image-forming pathway, also referred to as the visual pathway of light.[115] In 1984, Takahashi *et al.*[116] suggested the existence of an additional photoreceptive system in the retina, supporting Keeler's[117] hypothesis from 1927. In the early 2000s, intrinsically photosensitive retinal ganglion cells (ipRGCs) were discovered,[118-120] expanding understanding of how the human eye and brain react to light (see Figure 1.2).

The ipRGCs are a unique class of retinal ganglion cells (RGCs). RGCs are neurons in the retina that transmit electrical impulses from the cones and rods to the brain via their axons through the optic nerve. ipRGCs are relatively rare, making up only 1–2% of all RGCs.[121] They are distributed evenly throughout the retina, except in the fovea, where cone photoreceptors are concentrated. Furthermore, ipRGCs are found on a different layer of the retina than rods and cones.[25] Compared to cone and rod photoreceptors, ipRGCs have

longer response times and are less sensitive.[123,124] They contain a pigment called melanopsin,[118,125-128] which has maximum absorption at a wavelength of 480 nm, making it most sensitive to short-wavelength light.[129-132]

The uniqueness of discovery of ipRGCs is not just related to the type of photoreceptor but particularly how it reacts to light. ipRGCs have been discovered to have the ability to transmit signals from the retina to the brain not only in sighted individuals but also, surprisingly, in blind individuals as well. Keeler[117] showed that mice without rod and cone cells still reacted to light as their pupils constricted. This means the signals transmitted to the brain by these newly identified photoreceptors may not directly affect vision but could be involved in other functions.

The theory of a new photoreceptor contributing to functions beyond vision is strongly supported.[133-137] ipRGCs project to various brain regions via the NIF pathway[138] (see Figure 2.1). The primary projections of ipRGCs are directed through the NIF tract to the suprachiasmatic nucleus (SCN), which acts as the human body's circadian clock located in the brain.[2] Research has investigated the specific wavelengths that most trigger NIF responses.[124,130,131-143] NIF responses have been found to demonstrate sensitivity to short-wavelength light, with a peak around 480 nm. This corresponds with the peak sensitivity of ipRGCs, further supporting their crucial role in the NIF response to light.[124,130-143]

In addition to ipRGCs, rods and cones have been suggested to play a role in NIF responses, particularly at lower light levels, by transmitting signals to the ipRGCs.[128,144-146] However, further research is needed to understand the synaptic connections between these receptors.

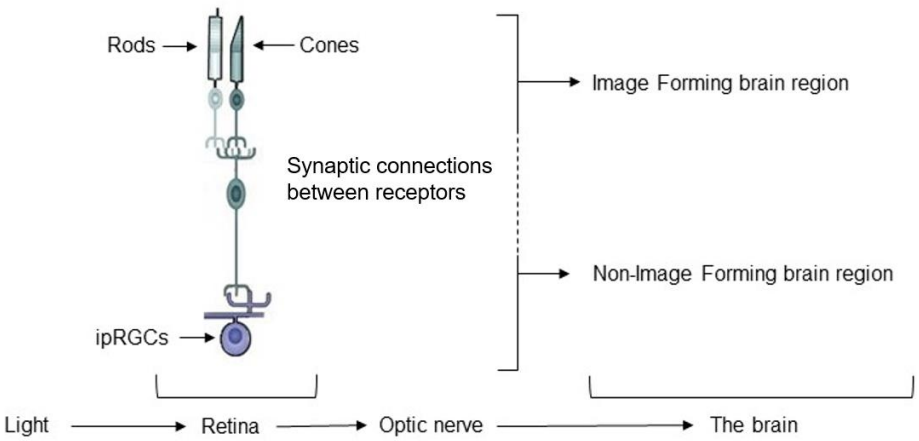

Figure 2.1 A schematic view of the three types of photoreceptors – cones, rods and ipRGCs – and their synaptic connections, together with the NIF and image-forming pathways. [Source: modified by the author after LeGates *et al.*[138]]

2.3. The NIF effect of light

Humans experience a 24-hour cycle known as the circadian rhythm, which is influenced by the environmental pattern of light and darkness. This cycle regulates various psychological, physiological and behavioural functions, including hormone secretion and the sleep-wake cycle.[25,124,147-150] The effects of light on humans can be divided into two main categories: 1) its long-term impact on circadian rhythms, leading to changes in the timing of the cycle,[134,138,151-154] and 2) its acute (short-term or immediate) effects on psychological, physiological and behavioural functions.

The behavioural effect includes the effect on cognitive performance, defined as how quickly and accurately an individual can perform tasks requiring mental processes. A change in cognitive performance can lead to a change in reaction times, assessed by cognitive tasks such as the Psychomotor Vigilance Test (PVT).[155] Subjective alertness, also called psychological alertness, pertains to self-perceived alertness. A change in subjective alertness can be assessed by having participants report their perceived alertness on a ranking scale, such as the Karolinska Sleepiness Scale (KSS).[156] Physiological effects refer to the influence of light on the body's physiological functions, encompassing changes in hormone secretion, brain activity and autonomic nervous activity. These physiological aspects can be assessed using appropriate methods for each aspect. For instance, brain activity can be assessed using an electroencephalogram (EEG).[157,158,159]

This thesis focuses on the acute effects of light on cognitive performance, subjective alertness and melatonin levels. The following sub-sections explain what alertness is and how it can be measured.

2.3.1. Defining alertness

Alertness is the state of being ready to see, understand and act in a particular situation.[31] It also refers to vigilance, arousal, or sustained attention, which is the ability to focus on an activity or stimulus over an extended period.[160] Alertness reflects the activation state of the cerebral cortex, which is associated with a person's highest mental capabilities.[161] States of alertness reflect both the degree of arousal on the sleep–wake axis and the level of cognitive performance. A decrement in alertness means a decline in the performance of daily life tasks.[162] The level of alertness, arousal, or wakefulness is subject to diurnal variations controlled by the circadian pacemaker and homeostatic sleep processes.[163,164]

In the field of study of the NIF effects of light, "alertness" is commonly described as the opposite of "sleep" and is essentially equated to "wakefulness".[162,165,166] Variations in

alertness are closely linked to the circadian clock (related to the 24-hour rhythm) and sleep homeostasis (related to the time spent awake), as shown in Figure 2.2. The circadian clock regulates physiological processes, which follow a 24-hour cycle, causing natural fluctuations in alertness, with peaks and dips throughout the day. Typically, the alerting signal from the circadian clock peaks around 20:00 in the evening and dips to its lowest point around 5:00 in the morning. This rhythm repeats every 24 hours and is distinct from the feeling of sleepiness that builds up the longer a person stays awake. Sleep homeostasis, in contrast, does not follow a 24-hour cycle. Sleep pressure builds continuously while a person is awake, regardless of the time of day or the circadian phase. Homeostatic sleep pressure increases with time awake due to a buildup of adenosine, which makes a person feel sleepier, reduces alertness, slows reaction times and impairs cognitive functions. This pressure dissipates once the person falls asleep. The two processes work together to regulate when a person feels alert or sleepy.[167,168]

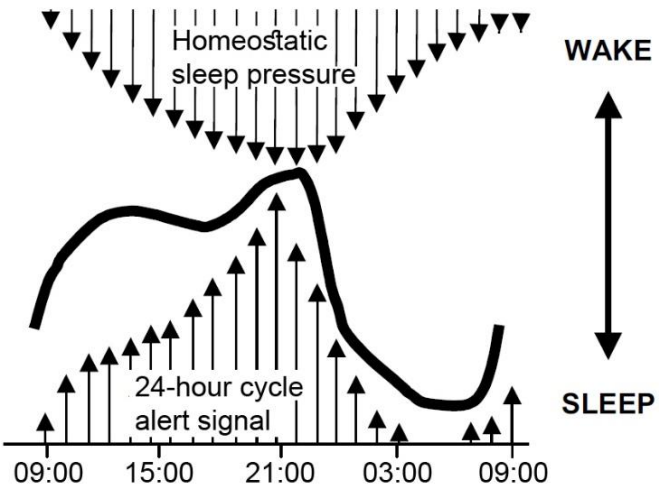

Figure 2.2 Schematic depicting the variations in alertness regulated by the circadian rhythm and homeostatic sleep pressure. The circadian rhythm modulates alertness in accordance with the time of day, while sleep pressure accumulates due to prolonged wakefulness. [Source: modified by the author after Cajochen *et al.*[167]]

The main factors that impair alertness are a rise in homeostatic sleep pressure due to staying awake for a long period, being in the sleep phase of the circadian sleep–wake cycle,[162] fatigue, monotony, distraction and the psycho-physiological effects of drugs, alcohol, or emotions.[169] Sleepiness, the opposite state of alertness, denotes a state of being tired and wanting to sleep.[31] It may stem from various sleep disorders or behavioural factors, such as sleep deprivation, which causes a rise in homeostatic sleep pressure, and shift

work, which disrupts the natural sleep–wake circadian rhythm.[170,171,172] Sleepiness can lead to difficulties in remaining awake and can hinder neuro-behavioural performance.[173] Table 2.1 delineates some of the impairments in performance associated with inhibited alertness.

Table 2.1 Performance decrement associated with alertness impairments

Performance decrement	Study
Delayed reaction time	Cajochen *et al.*1999[174] Phipps-Nelson, 2003[175] Anderson *et al.*2010[176]
Slowing cognitive processing	Durmer and Dinges, 2005[177] Ratcliff and Van Dongen, 2009[178]
Impaired visual perception	Russo *et al.* 2005[179] Anderson *et al.* 2010[176]
Increased distractibility	Anderson and Horne, 2006[180] Anderson *et al.* 2010[176]
Reduced ability to focus attention	Turner *et al.* 2007[181] Anderson *et al.* 2010[176]
Increased probability of eyelid closure with risk of-loss of situational awareness even with eyes open	Anderson *et al.* 2010[176]
Memory impairment	Turner *et al.* 2007[181]
Deterioration in vigilance with time-on-task Inattentional blindness – “looked but did not process”	Banks and Dinges, 2007[182] Avis *et al.* 2014[183] Lee *et al.* 2016[184]

2.3.2. Alertness assessment

Alertness can be assessed using physiological, behavioural and subjective indicators.[185-206] Assessing physiological indicators entails analysing biological responses, such as slow eye movements[159] and pupillary responses,[185] and conducting an EEG to measure brain electrical activity.[154] Behavioural indicators are evaluated through tests examining certain performance parameters, such as the PVT,[175] the Go-NoGo task and the N-back task.[186] Subjective indicators are evaluated as perceived alertness on a rating scale, such as the KSS, which rates subjective alertness–sleepiness on a scale from 1 to 9.[159]

The PVT is an objective measure of alertness, whereas the KSS is a subjective measure of alertness. Melatonin has been used in research, either alone or in combination with core body temperature (CBT), as a marker of the circadian phase.[207] The alerting effects of nocturnal light exposure are linked to melatonin suppression,[208] suggested to be the mechanism through which light enhances alertness.[141,209,210] However, the exact mechanism through which light enhances alertness is still largely unclear[150] (a more detailed explanation of these indicators is provided below).

The correlation between these indicators of alertness is not consistent in research; subjective alertness often exhibits a weak correlation with objective measures, such as task performance or physiological measurements,[207,211,212] although there are reports that physiological indicators can sometimes align with changes in subjective alertness and/or cognitive performance.[200,213]

2.3.2.1. Melatonin level

Melatonin, often referred to as the “sleep hormone”, plays a crucial role in regulating the sleep–wake cycle. This hormone is primarily produced by the pineal gland during the darker hours of the day and is closely tied to the body’s need for sleep. Lower levels of melatonin are associated with wakefulness.[214,215] The circadian rhythm of melatonin secretion from the pineal gland is controlled by the SCN in the brain.[189,216] Melatonin levels typically start to rise in the evening, peak around 3:00 and then gradually decline towards morning. By approx. 10:00, melatonin levels become minimal and are often undetectable. Around 21:00, melatonin levels begin to rise again[154,217] (see Figure 2.3). Melatonin is considered a reliable marker of the circadian phase in humans[151,217] and can be measured accurately by analysing saliva, urine, or blood samples.

The suppression of nocturnal melatonin secretion is a well-documented NIF response to light. Research on the NIF effects of light on humans is often conducted at night, when the impact of light on melatonin secretion is most noticeable. The suppression of melatonin can affect various physiological processes, including CBT, heart rate, EEG patterns and the promotion of sleep.[124,141,218,219]

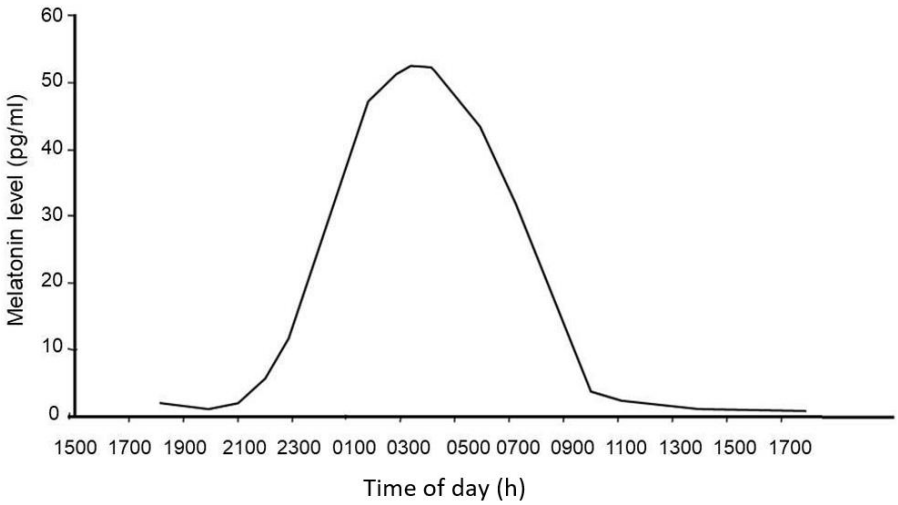

Figure 2.3 The 24-hour daily cycle profile of the melatonin hormone in the plasma of a normal, healthy human The unit used is picograms per millilitre (pg/ml), where a picogram is equivalent to one-trillionth of a gram. [Source: modified by the author after Arendt and Skene.[217]]

In several studies, melatonin suppression has been proposed as the mechanism through which light enhances alertness.[141,209,210] Phipps-Nelson *et al.*,[175,193] Lockley *et al.*[209] and Chellappa *et al.*[210] showed that melatonin suppression is associated with a faster reaction time and a similar association has been noted in studies measuring EEG rather than reaction time.[154,159,220-223] However, recent research shows that suppressing melatonin by light targeting the melanopic system does not automatically translate to acutely altered levels of alertness (vigilance or sleepiness).[224] This aligns with Ruger *et al.*'s[225] study, which suggested that melatonin suppression does not consistently affect subjective sleepiness or body temperature, despite the influence of light on melatonin. In this thesis, melatonin served as a marker of the circadian phase and any significant suppression in melatonin level was interpreted as a shift in circadian rhythm towards increased alertness rather than a direct increase in alertness.

2.3.2.2. Skin temperature

Skin temperature and CBT are linked through a network of blood vessels that enable heat transfer. [226] As CBT rises, the vessels near the surface of the skin expand, leading to heat dissipation and a decrease in skin temperature. CBT is regulated by the SCN and follows a daily rhythm. It peaks in the afternoon, gradually declines throughout the evening, and reaches its lowest point in the early morning (see Figure 2.4). This decrease in CBT in the evening is combined with a decrease in alertness. The proximal skin temperature (in the infraclavicular region, thigh and forehead) follows the same circadian rhythm as the CBT, while the distal skin temperature (hands and feet) exhibits an opposite pattern.[226]

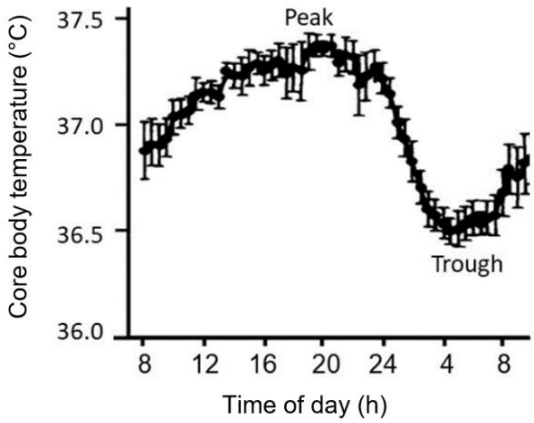

Figure 2.4 The 24-hour daily cycle profile of CBT in healthy individuals, CBT starts to rise in the morning, reaching its peak around 17:00 - 18:00, and then begins to decline towards bedtime, reaching its trough in the late night. [Source: modified by the author after Scales *et al.*[234]]

Exposure to light in the evening has been suggested to raise CBT, which in turn leads to a decrease in distal skin temperature.[159,227,228,229] Skin temperature has been proposed as a practical indicator of alertness[202] and a marker of the circadian phase.[230] Higher skin temperatures have been associated with lower cognitive performance [231] and linked to reduced subjective alertness.[232,233]

2.3.2.3. The Psychomotor Vigilance Test

The PVT is an objective tool used to measure changes in alertness by recording participants' reaction times to visual or auditory stimuli. During the test, participants press a response button as soon as the stimulus is detected.[155,187,195,235,236] The original PVT lasts 10 min, with stimuli presented at random intervals between 2 s and 10 s.[155] A modified version, the brief auditory PVT (PVT-B), shortens the test to 3 min.[236]

Exposure to light has been shown to enhance cognitive performance and improve the connectivity of brain networks related to working memory and attention.[175,192,237,238-240] A shorter reaction time on the PVT reflects improvements in cognitive function, indicating an enhancement in alertness.[159,175,195,198,203-205,242,243]

2.3.2.4. The Karolinska Sleepiness Scale

The KSS provides a quick and cost-effective method of evaluating subjective alertness.[156] Subjective measures in research address the participants' perspectives, feelings and general impressions. The KSS was originally developed by Åkerstedt and Gillberg[156] and comprised a nine-point scale with labels on every other step: 1 = extremely alert, 3 = alert, 5 = neither alert nor sleepy, 7 = sleepy – but no difficulty remaining awake, and 9 = extremely sleepy – fighting sleep. Another version, developed by Baulk *et al.*,[243] has labels for every step (see Table 2.2). Both versions are used to assess subjective alertness in various contexts and have been found to be highly correlated.[244]

Table 2.2 The nine-point KSS scale assessing alertness, developed by Baulk *et al.*[243]

Rating	Description
9	Very sleepy, great effort to keep awake (fighting sleep)
8	Sleepy, some effort to keep awake
7	Sleepy, no effort to keep awake
6	Some signs of sleepiness
5	Neither alert nor sleepy
4	Rather alert
3	Alert
2	Very alert
1	Extremely alert

2.3.3. Why does a pedestrian's alertness matter?

A person's level of alertness has a direct impact on his/her cognitive functions. Cognitive functions include mental processes that are required to be performed to ensure a person's safety on a daily life basis.[245] In a scenario involving a pedestrian crossing a road, Thomson *et al.*[37] detailed the processes and cognitive functions required to interact with traffic and cross safely, shown in the first and second columns of Table 2.3. The third column cites various studies conducted in different contexts, not specifically pedestrian, showing how changes in alertness can affect the performance of these cognitive tasks.

Table 2.3 According to Thomson *et al.*,[37] the first and second columns of the table outline the processes and cognitive functions necessary for interacting with traffic. The third column refers to previous studies that found these functions can be influenced by alertness levels.

Process	Cognitive function	Affected by alertness
Detecting the presence of traffic		
Look for traffic (pointing the head in the right direction)	Visual search	De Gennaro *et al.*2001[246] Vandewalle *et al.*2009[238]
Focus on the relevant signs	Attention	Lim and Dinges, 2008[235]
Ignore irrelevant objects or events	Minimising distractibility	Anderson *et al.*2006[180]
Additional factors	Auditory localisation Co-ordinate auditory and visual information	
Visual timing judgements		
Taking judgements concerning the vehicle's movement (moving or not, in what direction).	The pedestrian's sensitivity to a range of optical variables specifying time-to-contact, including distance and velocity information.	Bigica, 2023[247]
Co-ordinating information from different directions		
A crossing decision	Memory Divide attention between tasks Speed and accuracy of Information processing	Cajochen *et al.*1999[174] Turner *et al.*2007[181] Avis *et al.*2014[183] Lee *et al.*2016[184] Banks *et al.*2007[182] Chua *et al.*2017[248]
Co-ordinating perception and action		
Relate the time available to the time required to cross	Basic cognitive skills	-

A pedestrian wanting to cross a road needs to perform various perceptual and cognitive tasks simultaneously to proceed safely. The first step is to look in the direction of traffic and visually search for potential risks. It is important to focus on relevant signs, such as traffic lights, oncoming vehicles and road conditions, while ignoring any other distracting or irrelevant objects. This process is referred to as selective attention. It is also crucial to pay attention to relevant auditory stimuli, such as the sound of vehicles, in addition to visual input. This helps to make judgments about vehicle direction and speed, estimate stopping distance and define a proper gap in which to cross. These cognitive functions must be

performed while walking, which also requires the pedestrian to divide his/her attention between tasks. Walking itself may add an extra cognitive load in terms of maintaining balance and effectively regulating movement, both at the local level (step-by-step) and the global level (route planning).[36-38,249-252] (Further discussion on walking and cognitive performance is provided in 2.4.1).

A decrement in alertness leads to reduced cognitive performance, affecting the pedestrian's ability to carry out the perceptual and cognitive tasks required to proceed safely.[174,176,179-181,253,254] The effect of alertness on pedestrian safety has been addressed in the context of walking on or crossing a road, but it has not been investigated as a dependent variable (DV) of road lighting conditions.[255-260] However, the studies listed in Table 2.4 illustrate where an alerting benefit of lighting might be expected to be advantageous: while lighting may be able to enhance alertness, it is unlikely to mitigate the distraction of using a mobile phone.

Table 2.4 Studies investigating pedestrian alertness and its impact on safety

Context	Study
Attention as a skill associated with increased pedestrian safety	Foot *et al.*[261] Dunber[262]
Distraction lengthening perception time	Fugger *et al.*[263]
The effect of space perception on pedestrians' movement decisions	Willis *et al.*[264]
Enhancing alertness to potential hazards using a mobile phone app	Wen *et al.*[265]
Alertness as an essential factor in increasing pedestrian safety	Ding *et al.*[266]
The relation between an increment in alertness and the road crossing behaviours of pedestrians	Ravishankar and Nair[267]

The impact of impaired alertness has been studied among pedestrians but not with a focus on road lighting. A positive correlation has been found between impaired alertness (caused by distraction) and unsafe walking behaviour,[259,260] indicating that a lack of alertness can lead to pedestrian errors, such as forgetting to check the road before crossing. Impaired alertness can reduce situational awareness, which is essential for making effective decisions. Situational awareness is defined as the fundamental perception of elements in the environment over a certain period of time and space, understanding their significance and estimating their status in the near future.[268] Decreased alertness has also been associated with a higher risk of falling,[269,270,271] an increased likelihood of traffic-related injuries,[183,272,273,274] and a greater risk of being involved in RTCs.[275] Impaired alertness has also been found to increase unsafe behaviour and the risk of non-traffic accidents for pedestrians, as well as making them more susceptible to becoming victims of crime.[256,258] Moreover, impaired alertness has been linked to risky behaviours at crossings, such as making unsafe decisions when crossing the road.[255,257]

2.4. A deeper look into cognitive performance, melatonin level, skin temperature and subjective alertness in the pedestrian context

This thesis focuses on the NIF effects of light on four specific DVs in the pedestrian context. To simulate real-life conditions accurately, it is necessary to factor in the primary physical activity of pedestrians, i.e. walking, and its potential effects on the variables of alertness, melatonin levels and skin temperature. These elements are explored in this section.

2.4.1. Physical activity and cognitive performance

Some cognitive functions can easily be performed simultaneously, such as walking and talking. However, other tasks, such as driving and texting, interfere with each other, leading to a decrease in cognitive performance. Some tasks are almost impossible to perform at the same time, such as writing a thesis while engaging in a conversation. The level of interference between tasks depends on the overlap in their cognitive demands or structures. As the overlap increases, the difficulty of performing the tasks together also increases. For instance, writing a thesis and talking with a friend results in significant interference because both tasks rely heavily on language processing.[276]

The impact of walking, the primary pedestrian activity, on cognitive performance has been explored through two main theories: 1) the bottleneck theory and 2) the exercise-induced arousal effect. The bottleneck theory suggests that individuals have a limited capacity for processing resources. When pedestrians receive information from their surroundings, only a specific amount of this information is actually processed, with the rest being filtered out.[277] The act of maintaining balance while walking imposes a cognitive load on pedestrians, meaning it demands mental resources to perform the task.[249,250,251,252] As pedestrians must also process information from their surroundings to proceed safely, this creates a dual-tasking or multi-tasking situation, necessitating the performance of multiple cognitive tasks simultaneously. This can lead to a decline in cognitive performance, described as dual-task/multi-task cost.[278,279]

In contrast, the exercise-induced arousal effect refers to an expected improvement in cognitive performance driven by changes in brain neurotransmitter systems, specifically, the release of adrenaline and noradrenaline signals that cause a release of catecholamines in the brain. These catecholamines, a type of neurotransmitter and hormone produced in response to stress, may lead to improved stimulus encoding and decision-making processes and a reduction in reaction time.[280]

Cognitive performance while walking at a steady speed, as measured by simple reaction time tests, is expected to decrease in the first 20 min, with improvement occurring after 20 min or more.[280] The initial decline in cognitive performance during the first 20 min of walking has been linked to the dual-task cost. After 20 min of walking, cognitive performance is expected to improve due to the exercise-induced arousal effect. The impact of walking on cognitive performance can be influenced by various factors, including the timing of measurement, the specific cognitive tasks and the walking speed. Among these factors, walking speed has been a significant variable of focus in studies in relation to cognitive performance, with indications that different walking speeds may have varying effects on cognitive performance.

However, the research findings in this area have been somewhat inconsistent. For example, some studies have suggested that walking, as opposed to being seated, may increase cognitive load and potentially lead to a decrease in cognitive performance (i.e. longer reaction time). Nonnekes *et al.*[249] found that walking at a self-selected speed significantly increased reaction time in a simple auditory reaction time task compared to being seated. Similarly, Soga *et al.*[250] found that walking at a speed of 4.5 ± 0.4 $km.h^{-1}$ or 5.0 ± 0.6 $km.h^{-1}$ significantly prolonged reaction time on a visual N-back task compared to being seated. However, Kline *et al.*[281] and Alderman *et al.*[282] did not find significant differences in reaction time between being seated and walking at speeds ranging from 1.4 $km.h^{-1}$ to 5.8 $km.h^{-1}$. Alternatively, some studies have suggested that walking at different speeds could enhance cognitive performance.[283] Lajoie *et al.*[283] observed a significant reduction in reaction time when walking at a speed of 6.3 $km.h^{-1}$ compared to 4.6 $km.h^{-1}$, and at 4.6 $km.h^{-1}$ compared to 3.3 $km.h^{-1}$, indicating a shorter reaction time at faster walking speeds. In contrast, Richer *et al.*[284] did not find a significant change in auditory reaction time when walking at a speed of 4.5 ± 1.3 $km.h^{-1}$ compared to a slower speed of 3.5 ± 0.5 $km.h^{-1}$.

These previous studies have a major limitation in that they do not provide information on the environmental conditions during the experiments, such as light conditions, the specific time of day when the experiments were conducted and whether participants were instructed to avoid consuming caffeine on the day of the experiment. These factors can significantly influence the alertness levels of participants, potentially affecting their performance on cognitive tasks. This would likely affect the reliability of the findings in these studies, contributing to the conflicting and inconclusive results reported.

2.4.2. Physical activity and melatonin level

Physical activities, such as walking, cycling and aerobic exercise, have been investigated for their acute effects (i.e. within min) on melatonin secretion after dark. The intensity of physical activity is one of the key IVs in such research. It is classified into three categories related to the maximum heart rate (HRmax): high-intensity activities, where the heart rate reaches about 70–85% of HRmax, moderate-intensity activities, reaching about 50–70% of HRmax, and low-intensity activities, where the heart rate stays below 50% of HRmax.[285]

Some research has suggested that engaging in high-intensity physical activity after dark could increase melatonin levels by nearly 50%, whereas low- and moderate-intensity activities have not been found to have an immediate impact on melatonin levels.[286-288] In contrast, a study by Monteleone *et al.*[289] demonstrated that 10 min of moderate-intensity activity followed by 10 min of high-intensity activity resulted in a significant decrease in melatonin levels, although a subsequent repetition of their experiment did not find any melatonin suppression effect.[290] Notably, the initial experiment did not report light conditions, while the latter experiment was conducted under high light levels (2500 lx), which may have masked the impact of physical activity on melatonin levels. It is proposed that the increase in melatonin levels during high-intensity activities is related to the body's heightened oxygen consumption, leading to the production of reactive oxygen and nitrogen species in the muscles. Melatonin, which the body produces, functions as a strong antioxidant, potentially lowering oxidative damage and offering protection against inflammation.[291-294] In these previous studies, the effect of light on melatonin levels was not considered. Differences in lighting conditions between experiment sessions or conducting experiments under high light levels (e.g. 2500 lx) could lead to unreliable findings and potentially mask any impact of physical activity on melatonin levels.

In a different vein, studies have investigated changes in salivary melatonin concentrations between sitting and standing positions.[295,296] Kozaki *et al.*[295] examined the effect of posture (sitting vs. standing) at night between 0:25 and 1:00. The seated participants sat on a chair from 23:30 to 1:00, while the standing participants sat on a chair from 23:30 to 0:30 and stood on the floor from 0:30 to 1:00. Saliva samples were collected at 0:25 and 1:00. The experiment was conducted under low light conditions (less than 10 lx). The results suggested that melatonin concentrations in the standing condition were significantly higher than those in the sitting condition after 35 min of standing. This increase in saliva melatonin concentration in the standing position was attributed to the influence of gravity. Gravity leads to a decrease in plasma volume when standing, thereby causing an increase in melatonin concentration in saliva.[295,296]

In conclusion, changing position from sitting to standing is expected to increase a person's melatonin level due to a change in melatonin concentration, while walking at low and moderate intensity speeds might not have any effect on the melatonin level.

2.4.3. Physical activity and skin temperature

During physical activity, skin temperature varies according to several factors, including the type of physical activity, intensity and duration.[297,298] Ferreira *et al.*[299] investigated skin temperature while walking on a treadmill and reported a temperature increase up to 4 min into the exercise, followed by a reduction and stabilisation after 10 min. Neves *et al.*[300] and Tanda[301] investigated skin temperature during low constant-intensity exercise. They found a decrease in skin temperature up to 30–40 min of walking, followed by a gradual rise over time. The initial drop in skin temperature is thought to be linked to cutaneous vasoconstriction, during which blood vessels constrict to preserve core heat. Subsequently, the rise in temperature is associated with thermoregulatory vasodilation, where vessels dilate to enhance blood flow to the skin, allowing heat to dissipate and the skin temperature to increase.[300,301] In conclusion, a decrease in skin temperature followed by a gradual rise over time is an expected effect of pedestrians' physical activity regardless of the lighting conditions.

2.4.4. Physical activity and subjective alertness

Physical activity is generally expected to enhance subjective alertness, typically showing an increase of around one unit on the KSS.[302] In a study by Eriksen *et al.*,[303] a 20-min outdoor walk led to a 2-unit increase in subjective alertness (as measured by the KSS) compared to sitting indoors and reading at a computer. However, the study did not report light levels for either condition. An outdoor walk, which exposes participants to daylight, introduces a potential confounding variable – natural light exposure – which was not considered in the study but likely contributed to the observed increase in subjective alertness.

In another study by Matsumoto *et al.*,[304] the confounding variables were well-controlled, including the light conditions. The study investigated the effect of walking for 15 min at a moderate speed (4.2 $km.h^{-1}$) in the evening on subjective alertness. Subjective alertness was measured using the Visual Analogue Scale (VAS), a 100-mm line with endpoints anchored at "very alert" and "very sleepy". They found that physical activity led to a significant increase in subjective alertness. This indicates that an increase in subjective

alertness is an expected result of physical activity, regardless of lighting conditions, when walking at a moderate intensity.

2.5. Quantifying light

2.5.1. Common systems for quantifying light

There are three different systems for quantifying light: 1) the photon system, 2) the radiometric system and 3) the photometric system. In this thesis, the focus is on the last two, which are most commonly used in investigating the NIF effects of light. The radiometric system deals with the distribution of radiant power in space, while the photometric system deals with how light interacts with the human eye. The fundamental difference between these two systems is that the radiometric system accounts for the entire optical radiation spectrum, while the photometric system is limited to the visible spectrum[305] (See Figure 2.5).

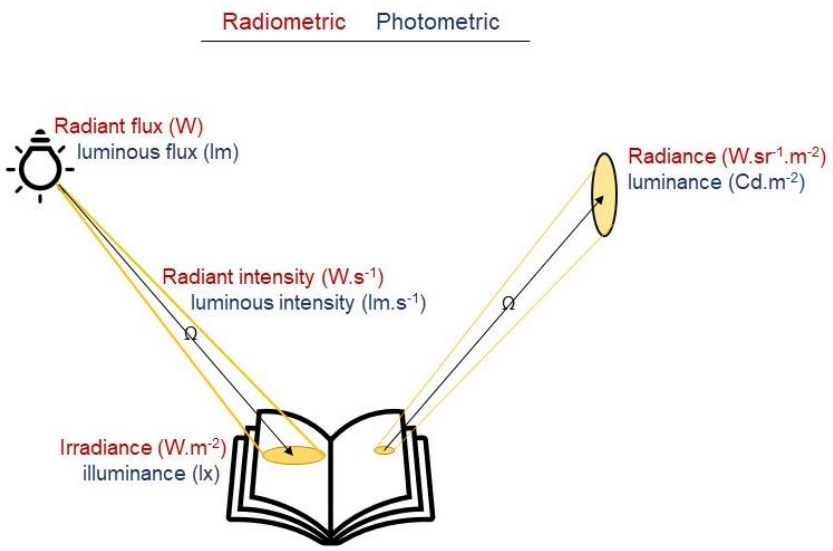

Figure 2.5 Radiometric and photometric system measurements and the associated quantities [Source: modified by the author, after Schlangen and Price.[305]]

In the radiometric system, the amount of light emitted, transferred, or received per unit of time is called “radiant flux” and is measured in Watts. The flux per unit solid angle (Ω) in a specified direction is known as “radiant intensity” and is measured in Watts per steradian. The luminous flux incident on a surface per unit area of that surface is termed “irradiance” and is measured in Watts per square meter. The flux per unit solid angle (Ω) in a specified direction emitted from the surface per unit area of that surface is called “radiance” and is measured in Watts per steradian per square meter. In the photometric system, these same parameters are referred to as luminous flux in lumens, luminous intensity in lumens per steradian, illuminance in lux, and luminance in candela per square meter, respectively.

These systems are commonly used to quantify light. However, with the increase in the scientific recognition of the light NIF effects, the need for a new metric to provide a better estimation of these influences has emerged. These new metrics are discussed in the following sub-section.

2.5.2. New metrics for quantifying NIF responses to light

In response to the emerging scientific understanding of the NIF effects of light, a novel approach to quantifying its effects has been introduced. This method involves estimating the effective irradiance perceived by the five types of photoreceptors, three of which are cone subtypes: S-cones, M-cones, L-cones, rods and ipRGCs. It recognises that each photoreceptor responds differentially, with their most intense reactions manifesting at the peak of their spectral sensitivity.[124,149] This novel approach respects these distinct sensitivities and categorises light stimuli into five classifications, each associated with different photoreceptor types: cyanopic (S-cones), chloropic (M-cones), erythropic (L-cones), rhodopic (rods) and melanopic (ipRGCs). These are collectively referred to as the five "α-opic" illuminances.[124] Figure 2.5 presents the relative sensitivity curves for the five photoreceptors as reported by the CIE.[1]

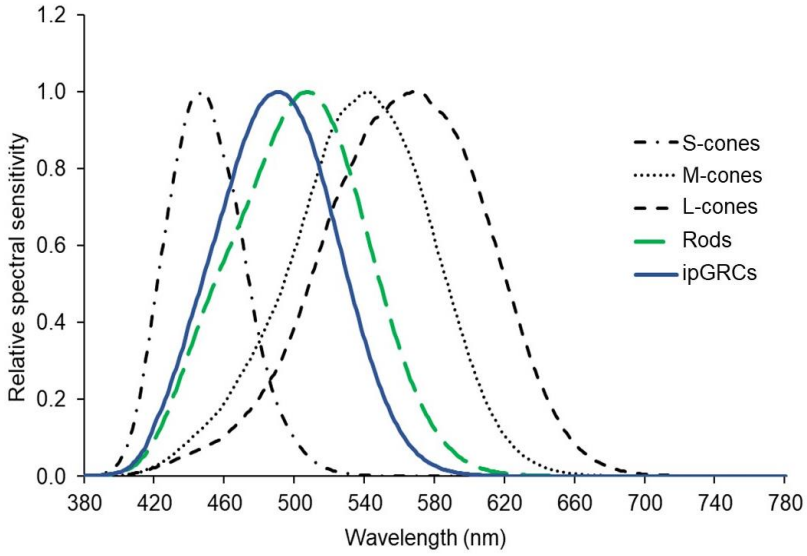

Figure 2.6 The five α-opic action spectra, plotted against wavelength, using a linear scale for the relative spectral sensitivity [Source: modified by the author, after the CIE.[1]]

In their study, Lucas *et al.*[124] provided a spreadsheet calculating five different types of illuminance (in lx) for any given light source based on its irradiances at different wavelengths (in $W.m^{-2}$). These irradiances can be captured using a device called a spectrometer (see Figure 3.4). The resulting values are then integrated with the International System of Units

(SI) and converted to five α-opic equivalent daylight illuminances (α-opic EDIs),[1] which are expressed in lx and correspond to the illuminance of equivalent daylight (D65) radiation that is required to provide an equal α-opic irradiance as the test light for a given α-opic photoreceptor.[305] CIE S 026/E:2018[1] introduces the term "melanopic equivalent daylight illuminance" (melanopic EDI) as one of the five α-opic EDIs. Melanopic EDI can be defined as "*the illuminance of standard daylight (D65), at a point, that provides equal melanopic irradiance as the test light. For example, a melanopic EDI of 100 lx means that the light source under evaluation produces the same amount of melanopsin-activating radiation as 100 lx of daylight at 6,500 K*".[306]

In assessing the NIF effects of light, the reference point for measuring light is the vertical plane at eye level, as shown in Figure 2.7. This is different from traditional methods that use horizontal planes or object surfaces as reference points. In this thesis, any measurements of the NIF effects of light mentioned below are in the vertical plane at eye level and the illuminance is reported in photopic lux (lx) unless stated otherwise.

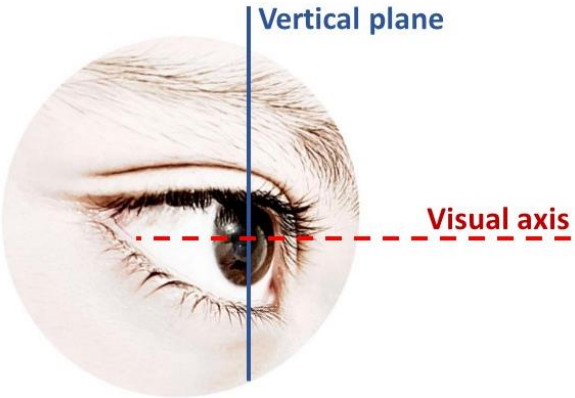

Figure 2.7 Vertical plane at the visual axis, where light should be measured for NIF effects.

2.6. The acute NIF effects of light

Before developing the α-opic EDI metrics, studies focused on NIF responses to light exposure used various light metrics to report light conditions, including those mentioned in Figure 2.5. The use of multiple methods and protocols, in addition to the varying methods used to report light conditions, made it challenging to replicate experiments and compare results across different studies.[154,159, 187,189,190,307-311] However, it is widely recognised that specific light stimulus variables affect acute NIF responses,[124] as discussed in the following section.

2.6.1. Light stimulus variables: Not-so-secret! The characteristic of light. What else?

It is well recognised that light plays a significant role as a potent synchroniser, resetting the internal circadian rhythm to align with the 24-hour day.[210] Under natural conditions, exposure to light occurs during the day, gradually increasing and then giving way to darkness at night. This synchronises with the human body's circadian rhythm. However, questions arise when light exposure occurs during the natural sleep phase, as light serves as a signal to the brain to awake. In certain situations, short-term NIF responses to light exposure during the sleep phase might be beneficial, reducing the risk of accidents, such as when driving or walking on the road. Research on the NIF effects of light on humans is primarily conducted at night, employing manipulations of light characteristics to explore its alerting effect. These manipulations are based on specific light variables, mainly including exposure timing, exposure duration, light intensity, prior light history and the light SPD. The following sub-sections provide a detailed discussion of these light stimulus variables.

2.6.1.1. The timing of exposure: When

Exposure timing refers to the specific time of day and session when an individual is exposed to light. Research suggests that the human body does not become unresponsive to light at any specific time during the day.[308] However, the alertness-enhancing effects of light are particularly noticeable at night or under conditions of sleep deprivation.[188,210,237]

Several studies have compared the impact of light exposure during the day versus at night. For example, Rüger *et al.*[237] conducted a study comparing the effects of exposure to bright light (5000 lx) for four hours during the daytime (12:00-16:00) versus nighttime (24:00-4:00) in two different groups of participants. They found that nighttime bright light exposure increased heart rate and reduced the circadian drop in CBT, indicating an enhancement in alertness (see Figures 2.8 and 2.9). In contrast, daytime bright light exposure did not affect heart rate or CBT. Interestingly, the effect of bright light on subjective alertness was similar regardless of the time of day, as both nighttime and daytime bright light exposure significantly enhanced subjective alertness to a similar degree, as measured by the KSS.

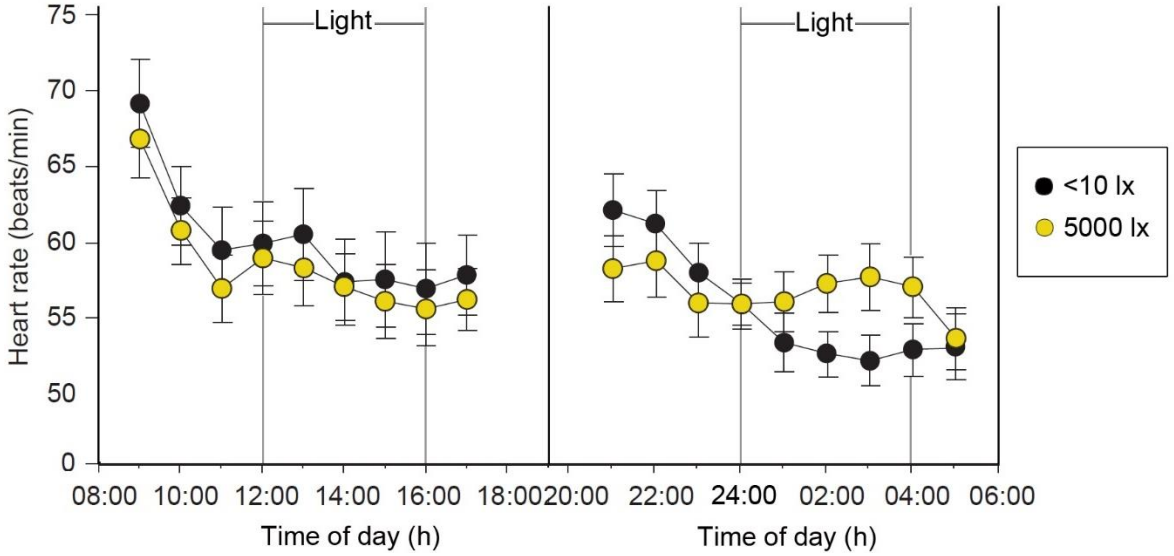

Figure 2.8 Mean heart rates under exposure to two illuminances (<10 lx and 5000 lx) at different times of day; vertical lines indicate the test phase. Error bars indicate standard deviation (SD). [Source: modified by the author, after Rüger *et al.*[237]]

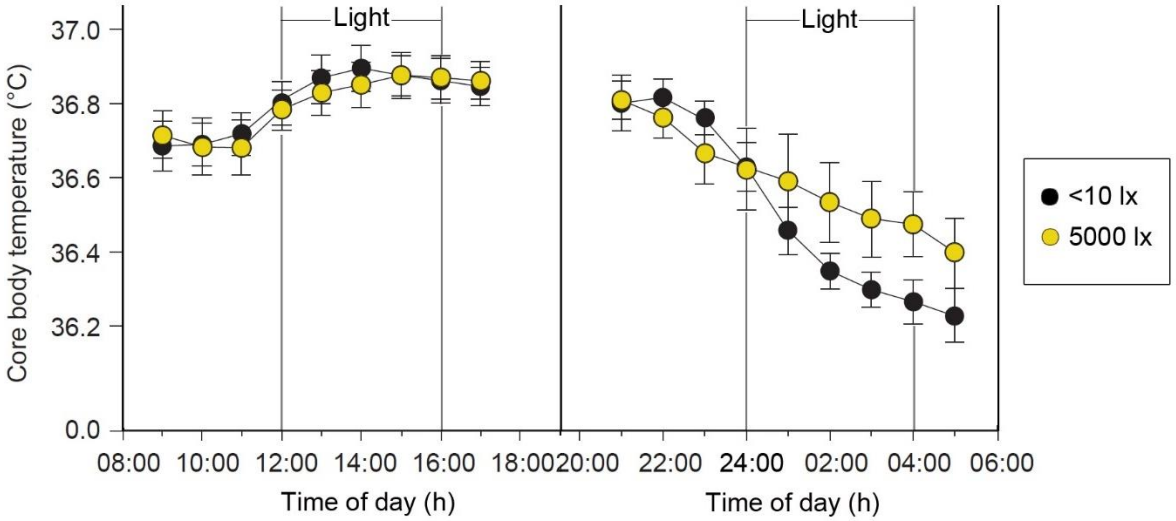

Figure 2.9 Courses of CBT under exposure to two illuminances (< 10 lx and 5000 lx) at different times of day; vertical lines indicate the test phase. Error bars indicate SD. [Source: modified by the author, after Rüger *et al.*[237]]

Scheer *et al.*[188] found that exposure to bright light for 20min during the nighttime led to an increase in heart rate. This effect was not observed during the daytime. The 20-min exposure included 10 min to100 lx and 10 min to 800 lx. However, the effect of light suggested to exist during the daytime but is generally more modest.[243]

In a study conducted by Smolders *et al.*[312], the NIF effects of light on subjective alertness, cognitive performance and physiological arousal were investigated during morning (09:00 or 11:00) and afternoon (13:00 or 15:00) sessions. It was suggested that reaction times, as measured by the PVT, were shorter under the 1000-lx condition than the 200-lx condition in the morning sessions, but not in the afternoon sessions. However, the effects on heart rate and subjective alertness were not found to be dependent on the time of day. Additionally, Huiberts *et al.*[313] found that the immediate effects of light on both subjective and objective alertness in the morning (09:00–10:30) were more pronounced for the 1700-lx condition compared to the 165-lx condition. This effect was observed only in autumn and winter, not in spring, suggesting that the alertness-enhancing effect of light can be influenced not only by the time of day but also by the season.

This thesis focuses on the effects of evening light exposure on NIF responses. However, it is important to consider that the timing of the experiment, in terms of both the time of day (in relation to the participants' circadian rhythm) and the time of year, is critical based on the findings of previous studies. Moreover, it must be noted that results obtained from studies conducted at different times of the day or year may not be directly comparable.

2.6.1.2. Exposure duration: How long

The exposure duration refers to the time between the start and end of light exposure.[23] Research has mostly focused on determining the necessary duration of exposure to induce NIF responses during the nighttime, when melatonin suppression is detectable. A positive correlation has been observed between NIF responses to light and exposure duration.[159] In a study undertaken by Lewy *et al.*,[157] participants were exposed to bright light (approx. 2500 lx of incandescent light) at 2:00. Their results suggested that exposure to this light level for 10 to 20 min caused a significant reduction in melatonin levels. Extending the exposure to one hour led to a further decline in melatonin levels, similar to those observed during the daytime.

The association between melatonin suppression and light exposure duration is non-linear, such that alterations in exposure time do not yield a commensurate change in melatonin suppression; shorter exposure durations show higher efficacy in per min melatonin suppression than longer exposure. For example, Chang *et al.*[307] found that exposure to intense light (around 10,000 lx) for 10 min and 60 min elicited more efficient melatonin suppression per min compared to longer exposure durations of 2.5 hours and 4 hours, respectively (see Figure 2.10).

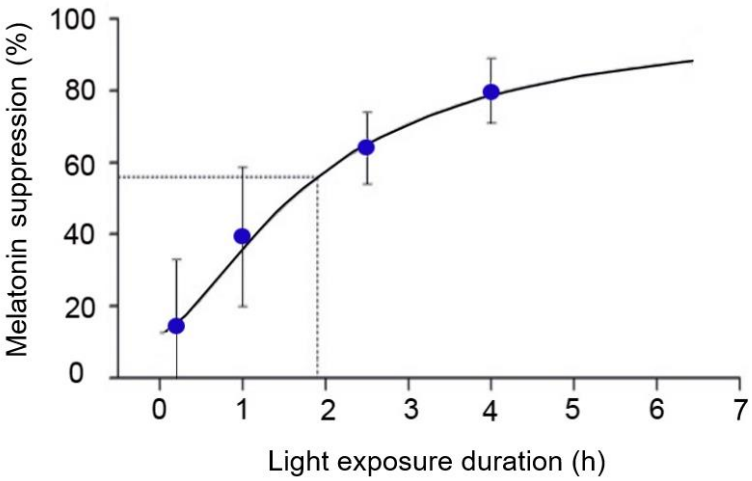

Figure 2.10 Exposure duration-response curve of melatonin suppression; the effects of different durations of exposure (0.2 h, 1.0 h, 2.5 h and 4.0 h) to a single high-intensity (~10,000 lx) light on melatonin suppression. Error bars indicate SD. [Source: modified by the author after Chang *et al.*[307]]

These findings suggest that prolonged exposure duration is not necessary to induce NIF responses. For instance, Thapan *et al.*[140] and Prayag *et al.*[218] demonstrated that an exposure duration of approx. 50 min was sufficient to trigger the majority of NIF responses, including changes in melatonin level, heart rate and EEG, with a melanopic illuminance of 90 lx (melanopic EDI of 81.5 lx‡). Moreover, shorter durations of around 30 min have been found to suppress melatonin, with a threshold illuminance of approx. 100 lx (melanopic EDI of 90.6 lx‡).[314]

The superscript symbol ‡ adjacent to the illuminance level (lx) is employed in this thesis to mark the values calculated by the author using the supplementary material from Lucas *et al.*[124] To convert the melanopic illuminance into melanopic EDI illuminance, the outcome melanopic illuminance from Lucas *et al.*'s supplementary material is multiplied by 0.9058.[315]

2.6.1.3. Light intensity: How much

Relatively low melanopic illuminance, as low as 1.5 lx, has been found to lead to melatonin suppression.[218] However, as the intensity of light increases, so does melatonin suppression[309] (see Figure 2.11), eventually reaching a saturation point, beyond which further increases in light intensity do not elicit further NIF responses.[159,194,209,307,316] According to Cajochen *et al.*,[159] this saturation point occurs at an illuminance of around 9100 lx, although Prayag *et al.*[218] suggested that a much lower melanopic illuminance of 305 lx (melanopic EDI of 274 lx‡) could also result in saturation.

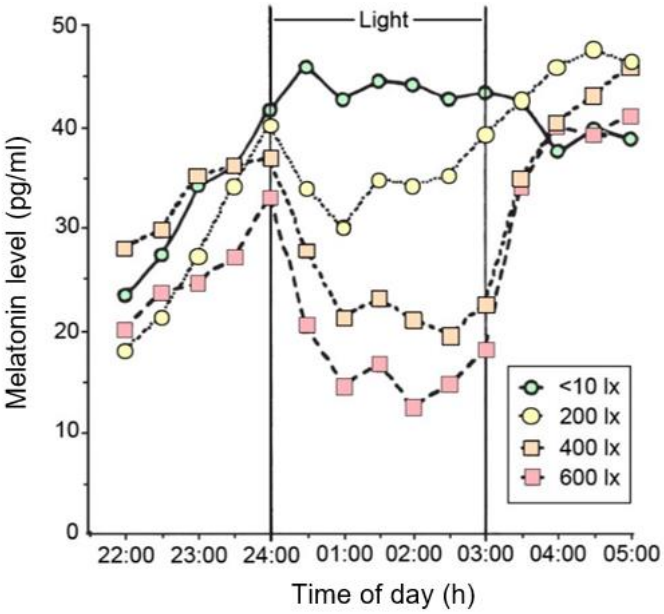

Figure 2.11 Melatonin suppuration under different illuminances: 200, 400, or 600 lx at the eye. The green circles represent the control condition; the illuminance was less than 10 lx between 22:00 and 00:00 and between 3:00 and 5:00. Vertical lines indicate the test phase. [Source: modified by the author after McIntyre *et al.*[309]]

The half-saturation constant (ED_{50}) is used to define the relationship between light intensity and NIF responses. The ED_{50} is the level of light needed to induce an NIF response that is half of the maximal possible response. It is often used as a relative metric to describe light sensitivity, with lower ED_{50} values indicating a higher light sensitivity.[149]

Zeitzer *et al.*[154] and Cajochen *et al.*[159] examined the effects of light on melatonin suppression, subjective alertness and the incidence of slow eye movements (SEMS) (see Figure 2.12). The participants were exposed to different light levels, ranging from 3 lx to 9100 lx, for 6.5 hours during the early biological night (3.5 hours before the minimum CBT). The results suggested that the NIF responses to changes in illuminance followed a logistic dose-response curve (i.e. an S-shaped curve), a finding also supported by studies conducted by Lockley *et al.*[209] and Figueiro *et al.*[316] The saturation point was observed at 9100 lx and ED_{50} was achieved with light at 100 lx. This means that exposure to 100 lx of light can produce half the levels of NIF responses compared to nearly 100 times brighter light. This explains why earlier studies investigating the alerting effects of light at night did not identify significant differences in subjective alertness across illuminance conditions ranging from 500 lx to 5000 lx, but did observe significant differences between low (50 lx) and high (> 500 lx) light levels.

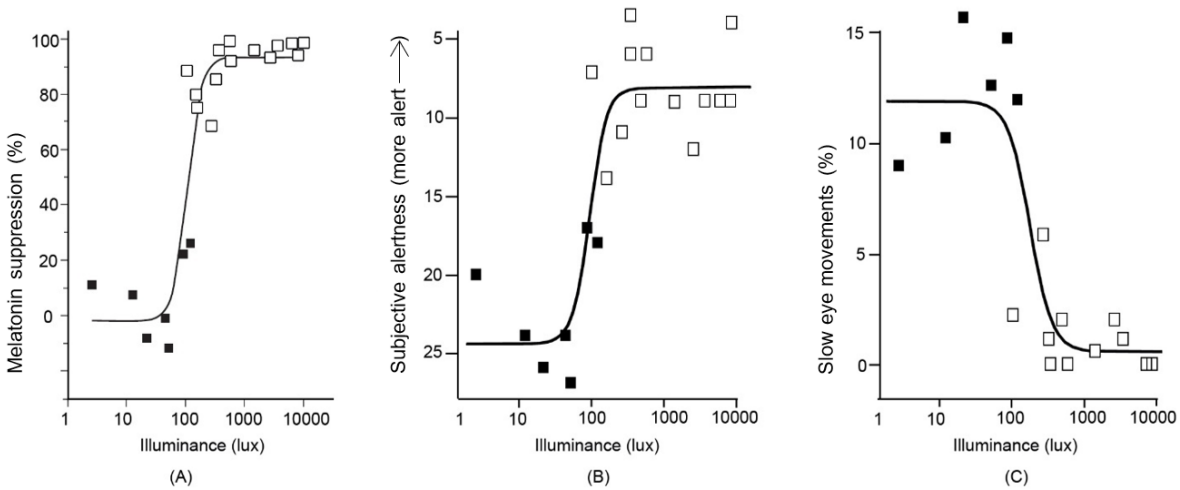

Figure 2.12 Illuminance-response curve; (A) the magnitude of melatonin suppression during light exposure for 6.5 h centred 3.5 h before the CBT minimum. [Source: modified by the author after Zeitzer *et al.*[154]] (B) subjective alertness and (C) the incidence of SEMS. [Source: modified by the author after Cajochen *et al.*[159]] Open symbols identify individuals with melatonin suppression of ED_{50} or more and closed symbols identify individuals with melatonin suppression of less than ED_{50}.

2.6.1.4. Prior light history

Prior light history refers to an individual's recent exposure to light, including the intensity, duration and timing of previous light exposure. This affects an individual's NIF responsiveness during subsequent exposures. To understand how prior light exposure affects subsequent NIF responses, it is important to consider the eye's adaptive mechanism. Exposure to illuminance induces light adaptation, which is a change in response to sustained light stimuli and acts as a protective mechanism against overstimulation of the eye's photoreceptors.[317,318] When the eye is consistently exposed to bright light (e.g. daylight), it becomes less responsive to changes in light intensity. This means that a specific amount of light can trigger more NIF responses in an individual who has previously experienced low light levels than in those who have experienced high light levels. In a study conducted by Huiberts *et al.*,[313] the alerting effect of light was significantly greater during morning sessions in autumn/winter compared to spring. This can be attributed to decreased responsiveness to light exposure due to the relatively high prior light exposure in spring compared to winter and autumn.

In another study, Hébert *et al.*[189] investigated the impact of prior light exposure on the sensitivity of the circadian system. Participants were exposed to two different light levels for four hours per day during the daytime for a week: bright light, ranging from 5000 lx to 7000 lx, and dim light, less than 200 lx. On the test night, the participants were exposed to 500 lx of light for three hours between 1:00 and 4:00; the results showed that those exposed to

higher light levels in the preceding week exhibited a significantly lower level of melatonin suppression compared to those exposed to the dim light levels (see Figure 2.13).

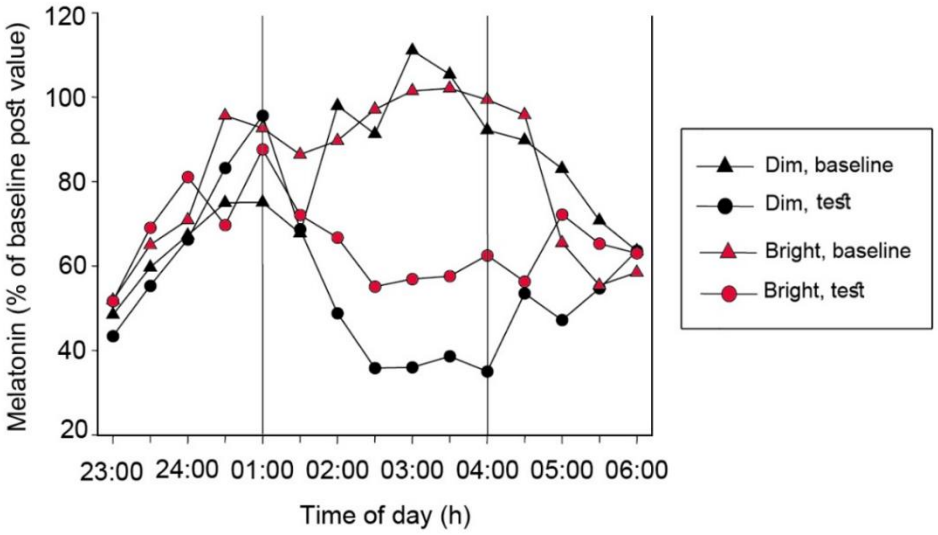

Figure 2.13 Melatonin profiles showing a higher level of melatonin suppression after a week of exposure to dim light compared to a week of exposure to bright light. The period of 500-lx light exposure on the test night is denoted by vertical lines; at all other times, the light intensity was less than 15 lx on the test day. [Source: modified by the author after Hébert *et al.*[189]]

Smith *et al.*[190] examined the impact of prior light exposure on melatonin suppression. On the test night, participants were exposed to 200 lx (50 µW.cm^{-2}) of light for 6.5 hours at night, following three days of exposure to light of either approx. 200 lx or 0.5 lx. The results indicated a significant increase in melatonin suppression during the test night after a prior light exposure of 0.5 lx compared to 200 lx, which supports the findings of Hébert *et al.*[189] In a separate study conducted by Jasser *et al.*,[191] participants were exposed to monochromatic light (460 nm wavelength) with irradiance of 3.1 µW.cm^{-2} (melanopic EDI of 16.5 lx‡) or 7.0 µW.cm^{-2} (melanopic EDI of 37 lx‡) for 1.5 hours at night, following 2 h of either darkness or illuminance of 18 lx. The results showed a significant increase in melatonin suppression during the stimulus after prior exposure to darkness compared to exposure to 18-lx illuminance.

In most studies investigating the NIF effects of light after dark, a period of dark adaptation is usually included in the study protocol just before the testing phase. This helps restore photoreceptor sensitivity, which in turn increases the sensitivity of the circadian system. However, it is important to note that this may not accurately represent real-life situations.

2.6.1.5. The spectral power distribution

The SPD of light provides a comprehensive description of the power of light based on individual wavelengths within the visible spectrum, each of which is linked to a distinct colour. SPD can be categorised as broadband (polychromatic), narrowband, or single wavelength (monochromatic). Broadband light covers a wide range of the visible light spectrum, while narrowband emissions are confined to a specific segment of the spectrum. Single-wavelength light emissions are restricted to a solitary wavelength. (See Figure 2.14).

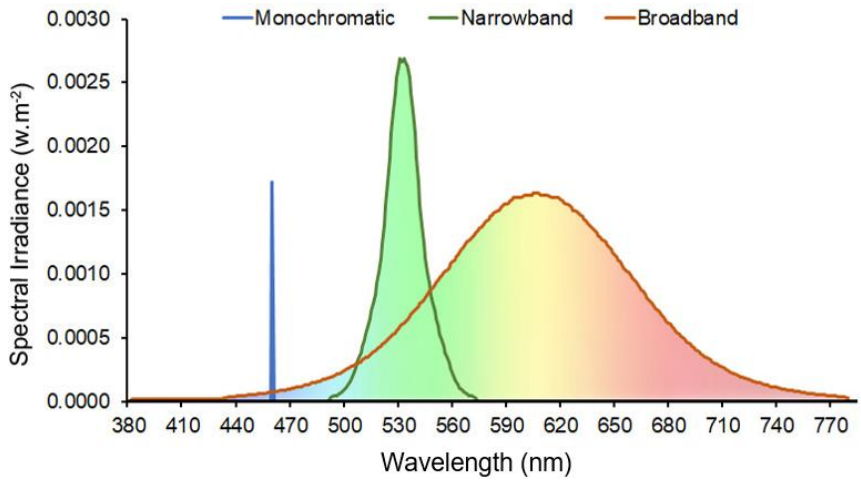

Figure 2.14 The SPDs of single wavelength, narrowband and broadband lights.

Research has shown that short wavelengths in the blue light range are more effective than other wavelengths in electing NIF responses, such as enhancing alertness and suppressing melatonin levels.[140,141,187,194,215,310,311] This has been explored by exposing research participants to single wavelength, narrowband or blue-enriched polychromatic light. The latter involves intensifying the power of blue wavelengths within polychromatic light. An example of blue-enriched light can be seen in Figure 2.15, which shows two SPDs of broadband light, both with the same photopic illuminance; one has a higher blue wavelength content, resulting in a higher melanopic EDI. This type of light, with higher blue content, is referred to as “blue-enriched light”.

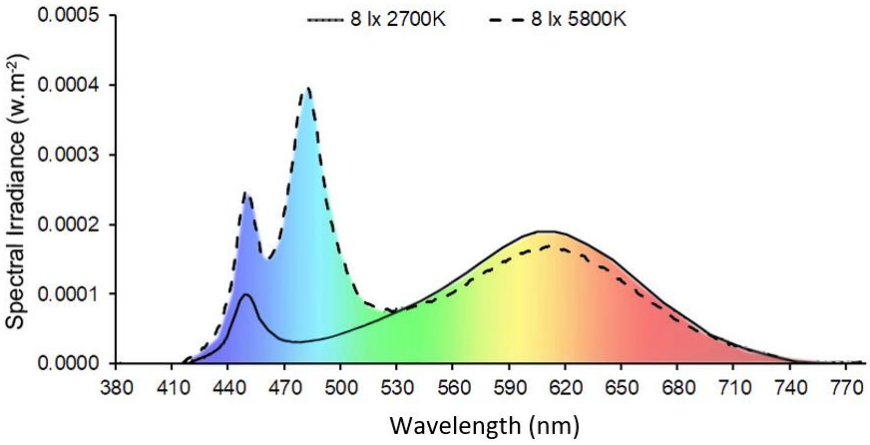

Figure 2.15 Two SPDs of LEDs with an illuminance of 8 lx and CCT of 2700 K and 5800 K. The SPD represented by a hatched line represents blue-enriched light.

Thapan *et al.*[140] investigated NIF responses at varying single wavelength irradiance levels, spanning from 0.70 µW.cm^{-2} to 65.0 µW.cm^{-2}. Their findings demonstrated that the blue wavelength at approx. 459 nm exhibited the highest efficacy in reducing melatonin levels. Similarly, Cajochen *et al.*[141] and Lockley *et al.*[209] conducted experiments involving exposure to blue light at 460 nm and green light at 550 nm. In Cajochen *et al.*'s[141] study, the participants were exposed to light in the test phase for 2 h between 21:30 and 23:30, following a 3.5-h adaptation phase under light of less than 2 lx. Conversely, Lockley *et al.*'s[209] study entailed a lengthier exposure period of 6.5 h during the night (between 23:00 and 05:30) with illuminance of 5 lx (12.1 µW.cm^{-2} for 460 nm and 10.05 µW.cm^{-2} for 550 nm). The results of both studies revealed that exposure to blue light resulted in greater suppression of melatonin, elevation of body temperature and heart rate than exposure to green light. Furthermore, Lockley *et al.*[209] reported that exposure to blue light enhanced subjective alertness, reduced reaction time, and minimised attentional lapses, whereas exposure to green light did not.

In Najjar *et al.*'s[187] study, participants were exposed to two types of broadband light: white light (CCT 4100 K) and blue-enriched light (CCT 17000 K), both at an equal illuminance of 175 lx. Their results suggested that blue-enriched white light significantly increased alertness compared to white light. Alertness was measured as subjective alertness (KSS) and objective alertness using a reaction time task (PVT).

West *et al.*[194] and Viola *et al.*[310] reported that blue light is still more effective at eliciting NIF responses even at lower illuminance levels compared to white light. In West *et al.*,[194] the participants attended the laboratory one night per week with at least a one-week interval

between test nights (within-subject design). The participants arrived at the laboratory by 23:45 and had blindfolds placed over their eyes at 24:00 A melatonin sample was collected at 02:00, after which the participants underwent a 90-min light exposure and a second sample was collected at 03:30. Each participant underwent light exposure at eight different irradiances, ranging from 0.09 lx to 562 lx (0.1 μW.cm^{-2} to 600 μW.cm^{-2}), with the narrowband blue LED light peaking at 469 nm, as well as one exposure of 85.4 lx, 40 μW.cm^{-2} with the 4,000 K white light. West *et al.*[194] found that increasing irradiances of narrowband blue light could increase melatonin suppression. In addition, 20 μW.cm^{-2} (18.7 lx) of narrowband blue light caused a significant suppression of melatonin, while double the energy from the 4,000 K white light (40 μW.cm^{-2}) did not result in a significant suppression of melatonin. Viola *et al.*[310] made comparisons between white light (421 lx, 4,000 K) and blue-enriched light (310 lx, 17,000 K). The results suggested that blue-enriched light improved subjective alertness and performance and reduced evening fatigue to a greater extent than white light; these were based solely on subjective expectation questionnaires.

Papamichael *et al.*[319] investigated whether red light could induce a similar alerting effect as blue light, which would suggest a significant role for L-cones in the NIF effects of light, similar to ipRGCs. The findings confirmed that melatonin suppression is predominantly influenced by the intensity of blue light and minimally affected by red light. The results also indicated that while blue light more effectively enhances alertness at low light intensities compared to red light, the difference becomes less pronounced as the irradiance increases. In Figueiro *et al.*,[215] 12 participants were exposed to 40 lx of either blue or red light periodically for 1 h while staying awake for 27 h. The results suggested that only the blue light decreased melatonin levels, in line with the expected outcome.

These studies show that short wavelengths in the blue light spectrum are more effective than other wavelengths in electing NIF responses, such as enhancing alertness and reducing melatonin levels.

2.6.2. Let's establish blue-enriched lighting in pedestrian roads: Wait a minute!

Despite the lack of consideration of pedestrian contexts in the studies mentioned earlier (discussed in detail in section 2.7), there are two main reasons for proceeding with caution before installing bluish lighting on pedestrian roads. First, other studies offer conflicting findings.[320-324] Second, there are unwanted effects associated with outdoor blue-enriched lighting. Each of these is discussed in turn.

2.6.2.1. Flip side studies: Are they reliable?

One group of studies offers the flip side, meaning that they did not find the expected alertness-enhancing effect of light. Campbell and Dawson[321] examined the impact of illuminance on alertness during two simulated night shifts from 23:00 to 07:00. The first night featured dim lighting at approx. 10 lx. On the second night, the participants were split into groups with lighting at approx. 10 lx, 100 lx, or 1000 lx. In each case, the lighting was white. One task was a 4-scale multiple-choice reaction test which required the participants to identify visual stimuli choosing from four response options, with reaction time as the DV: the results did not suggest a significant effect of illuminance. They also used manikin and logical reasoning tasks and found that performance increased when using 1000 lx. However, the nature of the tasks was not described sufficiently to be able to draw robust conclusions. A further limitation of these studies is that the results for the three levels of illuminance were not examined as *k* samples but only as pairs.

The lack of significant differences in the Wilkinson 4-choice reaction test across all lighting conditions may be attributed to the nature of the specific task used in the study. The Wilkinson 4-choice reaction test involves participants categorising stimuli using one of four responses. It is plausible that this task may not be sufficiently responsive to detect subtle variations in reaction time under different lighting conditions. Indeed, previous research has indicated that the Wilkinson 4-choice reaction test is less adept at assessing alertness than the simple reaction time test.[325]

In Dollins *et al.*'s[320] study, participants were studied over a 13.5-h period starting at 16:30 under different lighting levels (300 lx, 1500 lx, and 3000 lx). They found that light intensity significantly affected melatonin levels but did not affect task performance, including responses for simple auditory reaction time and the Wilkinson 4-choice reaction test. However, the baseline light level was 300 lx and the alertness-enhancing effect could already be obtained with such a high light level. Consequently, significant differences were not found under conditions of 1500 lx and 3000 lx. In addition, the study did not instruct participants to refrain from alcohol, caffeine, or napping on the day of the experiment or to adhere to a specific wake-sleep schedule in the 10 days between the experiment sessions. Furthermore, the participants had two snack breaks at 24:00 and 4:00; however, the study did not report the type of food consumed, which could have affected the alertness and melatonin measurements. For example, caffeine consumption can increase alertness regardless of light conditions.[326]

Whitmore *et al.*[327] compared the effects of exposure to different light levels for 60 min (between 02:00 and 03:00). Two full spectrum lights at intensities of 1000 lx and 500 lx, as well as two green light intensities at 1000 lx and 500 lx, were used. The impact of these light exposures on participants' oral temperature, salivary melatonin, cognitive performance and subjective mood was measured. The results showed that all lighting conditions significantly decreased melatonin levels immediately after exposure compared to the baseline condition (white light, 30 lx). However, there were no significant changes in oral temperature, cognitive performance, or mood, indicating that while the light could suppress melatonin, it did not improve cognitive performance or mood.

The cognitive task involved a tracking exercise in which the participants had to control an unstable cursor to avoid hitting boundaries. Two measures were used to assess performance: control losses (the number of times the cursor deviated significantly to the right or left) and root mean square error (indicating the average deviation of the cursor from the centre).

Although the participants' sleep-wake logs were reviewed by Whitmore *et al.*[327] prior to the experimental sessions (the sleep-wake schedule period is not reported), the participants were not instructed to refrain from consuming caffeine or alcohol, or to avoid napping on the day of the experiment, factors that can significantly affect alertness measurements. Napping and caffeine consumption can lead to decreased sleepiness and improved alertness-related performance.[328,329] It is also known that several cognitive functions are impaired by alcohol.[330] Furthermore, it is possible that the homeostatic sleep pressure at that time of night was high, i.e. to a point that masked any light enhancement in cognitive performance.

In Lavoie *et al.*,[322] sleep-deprived participants were subjected to bright white light (3000 lx) and dim red light (< 15 lx) overnight between 00:30 and 04:30 to test how light intensity influences inhibitory control (i.e. cognitive performance). The "Stopping Task" was used to measure impulse control. The participants engaged in a primary task but occasionally received a signal instructing them to stop responding. No differences in cognitive performance were found to be significant between light conditions. However, bright white light did suppress melatonin, raise CBT and alter specific EEG measures, suggesting an increase in alertness.[322] In their study, the known factors that could affect the measurements were well-controlled. However, the nature of the performance task could have resulted in varied outcomes. A review by Siraji *et al.*[331] indicated that the enhancement of cognitive performance by light could be influenced by the complexity of the cognitive task.

Revell *et al.*[324] conducted a study to investigate the impact of three different monochromatic light conditions on evening alertness. The lights used in the study had wavelengths of 437 nm, 479 nm and 532 nm, with corresponding melanopic EDI values of 46 lx, 76 lx and 94 lx, respectively. Each participant was exposed to each light condition for 30 min between 21:30 and 23:30 (no specific time for exposure was reported). The results indicated that the 479 nm light significantly reduced subjective alertness, as measured by the KSS, to a greater extent than the other two light conditions. No significant differences were observed in melatonin suppression or auditory reaction time, as measured by the PVT. However, an important limitation of the Revell *et al.*[324] study was that the participants were allowed to sleep before being exposed to light stimuli, which may have affected the results. This limitation was also noted in the experiment by Lerchl *et al.*'s[332], in which participants were allowed to nap until 5 min before the light exposure. It was found that napping on the day of the experiment decreased sleepiness and improved alertness-related performance.[328]

2.6.2.2. Unwanted effects of blue-enriched light: There are other living beings on the Earth besides us

The use of lighting on minor roads should be carefully considered, taking into account various factors that affect pedestrians, other road users, and the built environment. These factors include road safety, energy conservation, the impact on health, sky glow and the effects on the surrounding ecology.

Figure 2.16 displays the glow in the sky over a European city at night, illustrating the impact of nocturnal light on the environment and the resulting light pollution that negatively affects wildlife. This issue has a long history, dating back to documented bird impacts into lighthouses in 1912[333] and studies showing migrating birds attracted to offshore facilities, raising concerns about nesting sea turtles and other habitats.[334] The impact of different light conditions on specific species has been investigated; blue light can disrupt the natural behaviours of nocturnal animals, interfere with their mating patterns, and disorient migrating birds, causing significant ecological consequences and disrupting the natural balance of ecosystems.[24] Birds are attracted to longer wavelengths, such as red and amber,[335] while sea turtles are less drawn to these colours.[334]

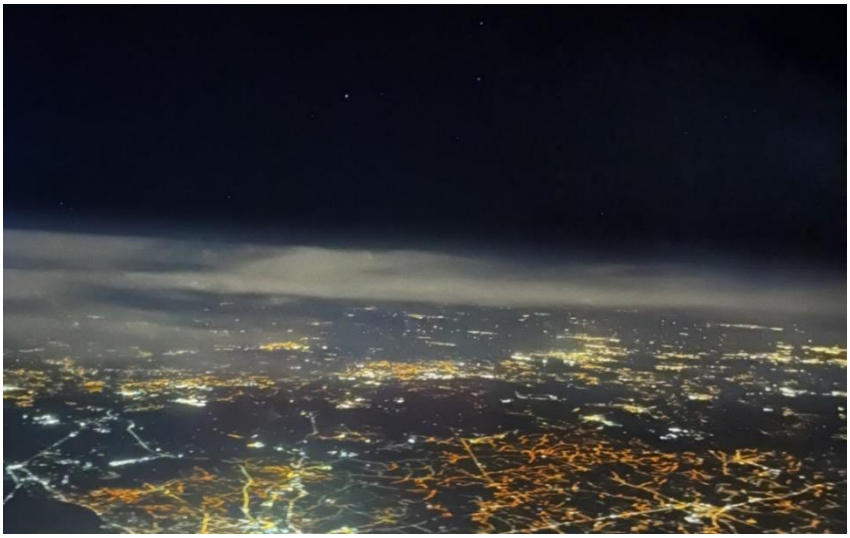

Figure 2.16 A nighttime sky over a European city, showing light pollution. The image was captured by the author in June 2023.

Blue light has also implications for the eyes of older individuals; as people age, the natural yellowing of the lens, combined with reduced pupil size and changes in the eye's vitreous body, can lead to reduced visual acuity, particularly under conditions with intense blue light.[336,337] While yellowing may reduce the transmission of blue light,[338] it can also affect colour perception, contrast sensitivity and the ability to see and distinguish objects in low light conditions for older individuals.[81]

2.6.3. The NIF effect at relatively low light intensity

Many studies have shown that exposure to polychromatic light during the evening or nighttime increases alertness and suppresses melatonin levels.[140,152,159,175,194,220,227,299, 311,322] The light intensities used in these studies were higher than those typically used in road lighting. This section presents studies that have explored the NIF effects of low illuminances similar to those used in road lighting.

Thapan *et al.*[140] investigated the impact of different monochromatic light peaks at 456 nm, 472 nm and 496 nm on melatonin levels. The study was carried out over three consecutive nights from 19:00 to 07:00. The first night served as a baseline, with no light exposure, followed by two nights of test light exposure. During the baseline night, various factors, such as posture, pupil dilation, season and circadian phase, were carefully controlled to eliminate their potential influence on melatonin levels.[339] Throughout the study period, light levels were maintained at less than 10 lx between 21:00 and 23:00, followed by complete darkness from 23:00 to 07:00, with the participants wearing eye masks. On the light exposure nights, the participants were exposed to monochromatic light for 30 min at specific

circadian times falling between 23:30 and 02:30. In addition, a pupil dilator was administered 90 min before light exposure. Blood samples were collected at various intervals ranging from -90 min to +120 min after the lights were on. The results indicated significant melatonin suppression effects from light peaks at 424 nm (1.9 µW.cm^{-2}, < 0.1 lx‡, melanopic EDI of 2.5 lx‡), light peaks at 456 nm (2 µW.cm^{-2}, 0.6 lx‡, melanopic EDI of 9.5 lx‡), and the light peak at 472 nm (1.8 µW.cm^{-2}, 1.1 lx‡, melanopic EDI of ~ 12 lx‡).

Phipps-Nelson *et al.*[175] compared the alerting effect of a narrowband blue light (peaks at 460 nm, ~1 lx, melanopic EDI ~11 lx‡) at the horizontal angle of gaze and a broad spectrum ambient white light of 0.2 lx. Eight participants underwent a prolonged nighttime performance test, with light exposure between 23:30 and 05:30. The results suggested that the method of measurement matters; measurement of driving performance using a driving simulator did not show any effect of lighting. However, other measurements showed that the blue light led to shorter reaction times, tested using a PVT, reduced sleepiness and decreased EEG delta and theta activity (indicating enhanced alertness). The results also confirmed that the timing of exposure matters.

Figueiro *et al.*[323] examined the effects of different lighting conditions over 2-h periods, from 24:00 to 01:00 and from 02:00 to 03:00. The study involved four different light conditions, including high (40 lx) and low (10 lx) intensities of narrowband blue light (peaking at 470 nm) and narrowband red light (peaking at 630 nm). The results suggested that both low and high intensities of red and blue light decreased alpha power and increased beta power levels in EEG, indicating increased alertness compared to the adaptation phase (less than 1 lx for 1 h). High intensities of red and blue light, but not low intensities, were associated with a significant increase in heart rate. Only the higher intensity of blue light was found to reduce melatonin levels. None of the lighting conditions had a significant impact on reaction time, as measured by the PVT, or subjective alertness, as measured by the KSS.

Plitnick *et al.*[311] studied NIF effects under the same lighting conditions as in Figueiro *et al.*,[323] but with a modified experimental protocol. The test phase took place from 01:00 to 02:30, with an adaptation phase that lasted for nearly an hour under less than 1 lx of red light. The results showed that compared to the adaptation phase, both red and blue lights at an illuminance of 10 lx (peaks at 555 or 630 nm) enhanced alertness as measured by EEG and KSS. The four light conditions studied in both Figueiro *et al.*[323] and Plitnick *et al.*[311] were as follows: melanopic EDI of 65 lx‡ and 1 lx‡ for the blue and red lights at an illuminance of 10 lx and melanopic EDI of 260 lx‡ and 1 lx‡ for the blue and red lights at an illuminance of 40 lx.

West *et al.*[194] discovered that exposure to light at an intensity of 9.4 lx and 10 μW/cm^{-2}, with peak wavelength at 469 nm for 90 min, led to significant suppression of plasma melatonin compared to a light condition of 0.09 lx (0.1 μW/cm^{-2}). Brainard *et al.*[219] investigated eight monochromatic lights with peak wavelengths ranging from 420 nm to 600 nm. The testing phase took place between 02:00 and 03:30, following a 2-h dark adaptation phase with dilated pupils. The results suggested that exposure to monochromatic light at 460 nm with an irradiance of 2.3 μW/cm^{-2} (melanopic EDI of 12.3 lx‡) did not lead to a significant change in melatonin levels. However, at 3.1 μW/cm^{-2} (melanopic EDI of 16.5 lx‡), significant suppression in plasma melatonin was indicated. In contrast, Lerchl *et al.*[332] found that low light intensity did not suppress melatonin after a short period of exposure (i.e. 10 min). During the test phase, the participants were exposed to blue narrowband light peaks at 465 nm for only 10 min at two different intensities: 0.22 lx (melanopic EDI of about 2.5 lx‡) or 1.25 lx (melanopic EDI of about 13.5 lx‡), following a 2.5-h adaptation phase between 21:00 and 01:30, under illuminance of less than 0.1 lx of red light. The results suggested that under these light conditions, there was no suppression of salivary melatonin.

In conclusion, while the above studies do not specifically relate to the pedestrian context, the light intensities used were low enough to be compared to those typically found in conventional outdoor lighting. Their results imply that these light intensities can elicit NIF responses. The only two studies that better represent the pedestrian context are discussed in the next sub-section.

2.6.4. The NIF effect of road lighting on alertness and melatonin levels

In two experimental studies, Gibbons *et al.*[114] and Bhagavathula *et al.*[113] examined the impact of outdoor lighting on alertness and melatonin levels. Their studies better represent the pedestrian context. Bhagavathula *et al.*[113] asked 10 participants (males and females, aged between 18 and 30 years) to drive for 2 h (01:00 to 03:00) on a closed loop road under five lighting conditions resembling those typical of road lighting (Table 2.5). This was done after 2 h of adaptation (23:00 to 01:00) to lighting representing indoor home lighting (incandescent). Their findings did not indicate a statistically significant impact of lighting condition on their DVs – melatonin levels derived from saliva samples, subjective alertness, or response to a visual reaction time test. In the reaction time test, the participants were asked to detect objects appearing on the roadway ahead: the distance ahead at which the objects and their colour were recognised was used to estimate reaction times.

Table 2.5 Lighting conditions reported by Bhagavathula *et al.*[113]

Represented situation	Light source	Luminance (cd.m^{-2})	Illuminance (lx)	CCT (K)	M-EDI (lx)
Road lighting (Test phase)	HPS	1.5	1.8	2100	0.3
	LED	1.5	1.9	4000	0.8
		1.0	1.4	4000	0.6
		0.7	1.1	4000	0.5
	None	< 0.05	0.8	-	-
Home lighting (Adaptation phase)	LED	(Not reported)	200	4000	87.1

A null finding, such as that from Bhagavathula *et al.*,[113] does not reveal whether there is no effect or whether the experiment failed to reveal a real effect. Bhagavathula *et al.*[113] used road lighting conditions typical of current practice. It may be that their highest melanopic EDI (0.8 lx) was insufficient to stimulate greater alertness or suppress melatonin levels. During the test, the participants were driving, a task with a significant cognitive load.[324,325] It may be that the demands of driving during this experiment outweighed any effect of lighting on alertness measurements.

In Gibbons *et al.*'s[114] experiment targeting pedestrian application, the 9 participants (5 males, 4 females, aged between 18 and 30 years) were seated on chairs on a closed road for 4 h (22:00 to 02:00) after a 2-h adaptation phase (20:00 to 22:00) to lighting under the same condition as also used for adaptation in Bhagavathula *et al.*[113] This study used six lighting conditions during the test phase, including a luminance of 1,0 cd.m^{-2}, illuminance of 10 lx and CCTs ranging from 2100 K to 5000 K, giving melanopic EDIs in the range of around 1.5 lx to 5.7 lx.

The results of the experiments conducted by Gibbons *et al.*[114] and Bhagavathula *et al.*[113] did not indicate a significant effect of lighting on reaction time, KSS, or melatonin levels. Their results are surprising given the evidence from other studies,[140,175,194,311] namely that lighting influences alertness and melatonin levels. One possible reason why Gibbons *et al.*[114] and Bhagavathula *et al.*[113] did not reveal an effect is that their melanopic EDI was not sufficient, being a maximum of 5.7 lx, a result of their decision to use light sources typical of current road lighting practice. A second reason is that the experimental design was insufficient to reveal an effect. In addition, they used seated participants, assuming these results would be relevant to pedestrians, but the level of physical activity may affect alertness and melatonin measurements.

2.7. Limitations of previous research

A specific real-life scenario that underpins the context of this study is a typical pedestrian's evening, which usually involves spending time indoors under domestic lighting conditions before transitioning to outdoor walking under road lighting. To assess the influence of road lighting on alertness and melatonin levels when walking, this scenario was replicated in an experimental setting: the indoor period corresponded to the adaptation phase of the experiment (between 21:00 and 23:00), while the outdoor period corresponded to the test phase (between 23:00 and 00:00).

The existing literature does not adequately represent the pedestrian context during the evening. First, during the adaptation phase, most controlled laboratory studies used low light conditions (between darkness and 7 lx), in contrast to the relatively high light levels of indoor domestic lighting. Dark adaptation helps eyes regain sensitivity after exposure to bright light, thereby increasing the sensitivity of the circadian system to light.[140,194,342-344] Second, some studies utilised the pupil dilation technique, applying eye drops to widen the participants' pupils,[140,144,187, 219,319,324,345,346] which affects light sensitivity and the amount of light entering the eye.[347] This is not a typical condition experienced by pedestrians. Furthermore, during the test phase, the focus was mainly on the effects of high light levels relative to road lighting.[140,154,209,227,307,316,320,348] Moreover, the participants in some studies were allowed to sleep and were only awakened 5 to 30 min before being exposed to the test lighting.[324,332] Napping would have reduced their sleepiness and improved alertness-related performance.[328]

Also, the types of light examined were often monochromatic (or narrowband) rather than polychromatic.[140,141,175,209,219,311,319,323,324] Polychromatic light is more commonly found on pedestrian roads. In addition, the durations of test light exposure in the studies were often very long, lasting for hours or even days,[140,144,154,159,195,199,201,209] which does not reflect typical pedestrian contexts. Lastly, the timing of light exposure in several studies was late at night, often after midnight,[219,327,349] which correlates with heightened circadian and homeostatic sleepiness. This increased sleepiness at that time of night may have masked any potential alertness-enhancing effects of the light conditions utilised in the studies. In conclusion, the experimental designs used in the existing literature do not represent the pedestrian context during evening hours.

Even in Gibbons *et al.*'s[114] study (see 2.6.4), which directly targeted the pedestrian context, the participants were seated, a condition that does not accurately reflect the real-life scenario of pedestrians walking. In this thesis, both seated and walking participants were

included in the test phase to investigate whether physical activity would affect alertness and melatonin levels by comparing the results for the seated participants with those for the walking participants. In addition, this was a joint experiment, in which a colleague's research focused on the NIF effects of road lighting on drivers. Seated participants more accurately represent the driving situation, thus serving both research objectives.

Table 2.6 Context desirable in an experiment to represent the typical pedestrian situation

Study	Adaptation level	Pupil dilation used	Napping before	Walking during
Ideal for pedestrian context	Bright [a]	No	No	Yes
Cajochen *et al.* 2000[159] Zeitzer *et al.* 2000[154] Cajochen *et al.*2005[141] Rüger *et al.* 2006[237] Figueiro *et al.* 2009[323] Phipps-Nelson *et al.* 2009[175] Figueiro and Rea, 2010[215] West *et al.* 2011[194]	Dark	No	No	No
Brainard *et al.* 2001[219] Thapan *et al.* 2001[140] Lockley *et al.* 2006[209] Revell and Skene 2007[345] Brainard *et al.* 2008[346] Gooley *et al.* 2010[144] Papamichael *et al.* 2012[319] Rahman *et al.* 2014[199]	Dark	Yes	No	No
Lerchl *et al.* 2009[332]	Dark	No	Yes	No
Revell *et al.* 2010[324]	Dark	Yes	Yes	No
Bhagavathula *et al.* 2021[113] Gibbons *et al.* 2022[114]	Bright	No	No	No

[a] Relative to road lighting level.

2.8. Summary and research hypotheses

The ipRGCs are a third photoreceptor in the eye that was recently discovered. They contain a pigment called melanopsin, which absorbs light and transmits electromagnetic signals through the NIF pathway to various brain regions, primarily the SCN, which regulates several body functions. The NIF responses to light include changes in various psychological, physiological and behavioural functions, such as hormone secretion, the sleep-wake cycle, mood and alertness status. Alertness can be measured using objective and subjective methods, such as the PVT and the KSS, respectively. Melatonin levels and skin temperature are reliable markers of the circadian rhythm. Melatonin suppression has been thought to be the mechanism through which light can influence circadian rhythms, the sleep-wake cycle and alertness. However, a recent study has shown that suppressing

melatonin by light targeting the melanopic system does not automatically translate to acutely altered levels of alertness.[224]

The NIF effects of light have a non-linear and dose-dependent relation with light intensity and exposure duration. Blue light has been scientifically substantiated to be particularly efficacious in stimulating NIF effects due to the heightened sensitivity of the ipRGCs to the blue spectrum range. This newfound understanding of NIF effects has instigated the formulation of the melanopic EDI metric, which is typically measured vertically at eye level. The NIF effects of light are contingent upon several factors, encompassing exposure timing, duration, adaptation, intensity and the SPD of light. While numerous studies have corroborated the affirmative influence of light on alertness and melatonin levels, it is necessary to acknowledge that these findings do not extend to pedestrian scenarios.

Pedestrian safety depends on various perceptual and cognitive tasks, which can be influenced by the pedestrian's alertness level. Reduced alertness has been associated with a higher risk of pedestrian casualties related to traffic and non-traffic incidents. Enhancing road lighting may help elevate pedestrian alertness, thereby decreasing these risks. When investigating the NIF effects of light in a pedestrian context, it is important to take into account the potential effect of physical activity on subjective alertness, cognitive performance, skin temperature and melatonin levels.

The impact of road lighting on minor roads on pedestrian alertness and melatonin levels is not yet known. Two studies, Gibbons *et al.*[114] and Bhagavathula *et al.*,[113] which better represent the pedestrian context, did not find any significant impact of road lighting on alertness or melatonin levels. Various factors potentially explain the null finding. One plausible explanation is that the melanopic EDI level used in these studies was insufficient, being a maximum of 5.7 lx. Furthermore, the use of seated participants, presumed to be representative of pedestrians, disregards the potential influence of physical activity on measures of alertness and melatonin level. These limitations underscore the importance of further research to understand fully the NIF effects of road lighting in a pedestrian context.

The aim of this thesis is to examine the influence of different lighting conditions on NIF responses under conditions representing pedestrians' experience on minor roads in the evening. This objective is pursued by examining two hypotheses. The first hypothesis concerns the impact of road lighting on pedestrians' alertness when walking outdoors in the evening. Based on previous research (see 2.6.4), it is anticipated that variations in road lighting characteristics, within the range of those typical of conventional outdoor lighting practice, will not significantly affect alertness or melatonin levels. Typical conditions mean

up to 15 lx photopic illuminance, equivalent to a maximum melanopic EDI of approx. 10 lx. This would result in a failure to support H1:

H1 Variations in the illuminance and SPD of road lighting within the range of conditions typical of lighting on minor roads will affect alertness, melatonin levels and skin temperature.

In the two previous studies that best resembled the pedestrian context,[114,113] the participants were seated. Transitioning from sitting to standing is expected to increase melatonin concentrations due to reduced blood volume and the effects of gravity[295,296] (see 2.4.2). Walking at a self-selected speed compared to being seated may lead to a change in cognitive performance (see 2.4.1),[249] and it is anticipated that this will increase subjective alertness by one unit in the KSS (see 2.4.4).[302] In addition, it is expected to decrease skin temperature until approximately 30 to 40 min of walking,[301] followed by a gradual rise over time (see 2.4.3).[300,301] This is tested through the second hypothesis:

H2 Walking at a self-selected speed, compared with remaining seated, will affect alertness, melatonin level, and skin temperature.

Chapter 3

Experiment 1: Method

3. Experiment 1: Method

3.1. Introduction

Extensive research has been conducted on the impact of road lighting for pedestrian safety. The literature review (Chapter 2) highlighted, however, that this has focussed mainly on the effects of light on vision: NIF effects, such as changes in alertness and melatonin levels, have received very little attention. In addition, past studies on the NIF effects of light have not adequately reflected the typical pedestrian context. To fill this research gap, an experiment was carried out to investigate how changes in lighting impact alertness and melatonin levels in a context that better simulates pedestrians exposed to road lighting after dark. The experiment aimed to test hypotheses H1 and H2 regarding the effects of light and participant physical activity on the DVs (see section 2.8). The current chapter describes the method used in the experiment.

3.2. Apparatus

The experiment was conducted in a laboratory, during which participants' responses to various lighting conditions were recorded over three hours in the evening. A screen divided the laboratory into two parts, separating participants from the researcher. The test area in which participants were located was 3.45 m in length (limited by the placement of a door), 2.43 m in width and 2.8 m in height (see Figure 3.1). Electric lighting, other than the experimental lighting, was switched off during trials.

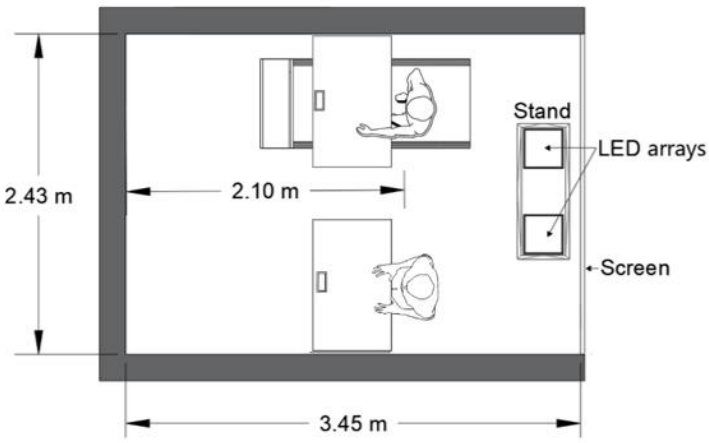

Figure 3.1 Plan layout of the laboratory.

The test area was illuminated using two sets of LED arrays (THOUSLITE LEDCube-I14 R27), as shown in Figure 3.2. Each LED array has 14 different primary sources (LEDs with different SPDs), allowing for precise adjustment of the overall SPD. The LED arrays ensure

light stability with a variation in CCT of less than ±20 K and a variation in luminance of less than ±1% over a 24-hour period.[350] The LEDNavigator-LV software was used to control the LED settings (see Figure 3.3).

Figure 3.2 LED arrays (THOUSLITE LEDCube-I14 (R27)), dimensions 0.3×0.3×0.21 m, emitting area dimensions are 0.27×0.27 m.[348]

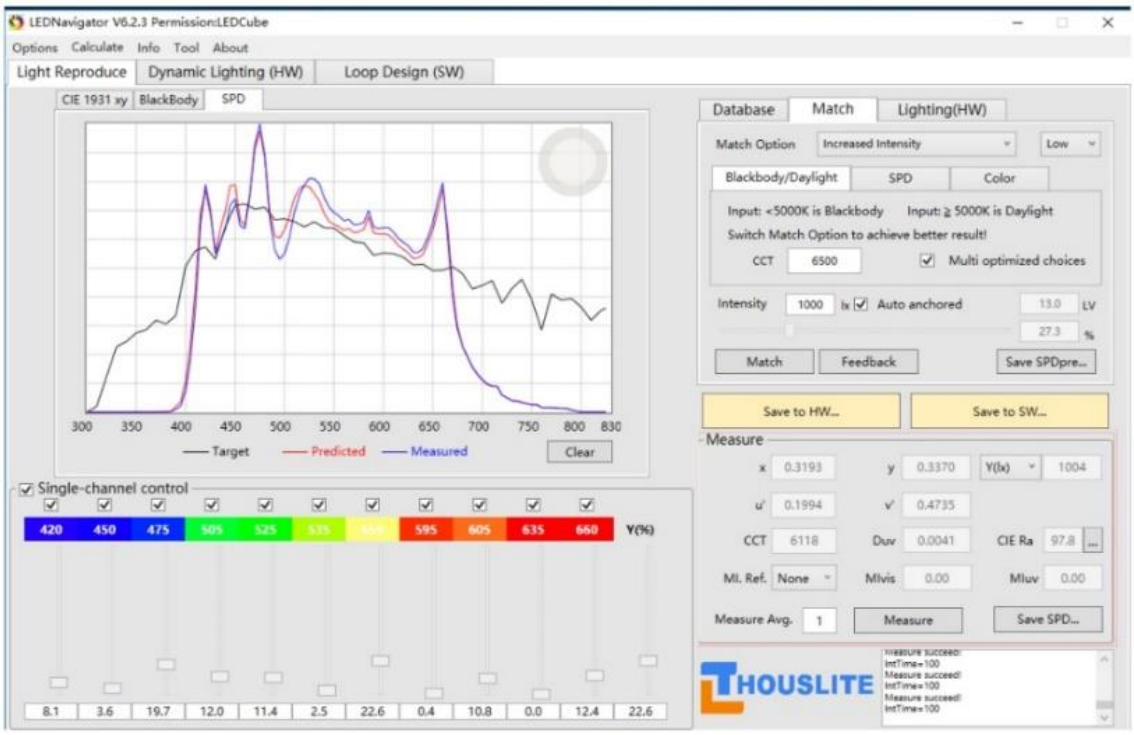

Figure 3.3 The Thouslite LEDNavigator-LV software panel[350]

The LED arrays were positioned on stands behind the two participants and faced upwards, illuminating the room indirectly by reflection from the white ceiling. This ensured that each participant received indirect light only. Illuminance, luminance, and SPD measurements of the light conditions were taken in the vertical plane at 1.5 m above the floor. The height of participant seats was adjustable so that eye heights remained at approx. 1.5 m above the floor level when seated or when walking. These measurements covered the participants'

line of sight at angles of -30°, -15°, 0°, 15° and 30° relative to the horizontal sight line while facing the wall in front [see the measurement points in Appendix A]. Measurements were taken at both participant locations. Based on this data, a ratio of the light levels at participant 1 to participant 2 was calculated to ensure that the two participants were exposed to similar light levels within a range of ±5%.

The light measurements were conducted using an illuminance meter (Konica Minolta illuminance meter T-10), a luminance meter (Konica Minolta luminance meter LS-150), and a spectroradiometer (JETI spectroradiometer model no 1511) (see Figure 3.4). Each measurement was repeated three times, and the average of these three measurements was the value then recorded. This process minimises the impact of random errors thereby enhancing the accuracy and reliability of the collected data.

Figure 3.4 The illuminance meter, luminance meter and spectroradiometer used in this study (left to right)

The context of the experiment was a person seated at home for 2 h followed by a 1 h under the road lighting as if they had gone out for a walk. In the first two hours, here labelled as the adaptation phase, all participants were exposed to the same lighting condition. For the final hour, the test phase, participants were exposed to one of four different lighting conditions.

In each test session, there were two test participants. For the adaptation phase, both remained seated. For the test phase, this was varied: one participant remained seated, and the other walked upon a treadmill (LifeSpan TR1200-DT3-BT). The treadmill is shown in Figure 3.5.

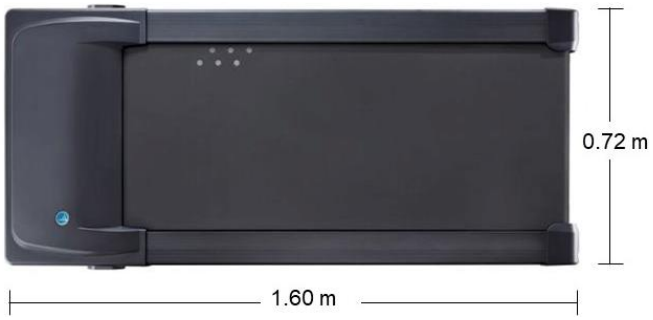

Figure 3.5 Plan view of the treadmill (LifeSpan TR1200-DT3-BT)[351]

3.3. Independent variables

There were two IVs: the lighting condition (four combinations of illuminance and SPD) and the participant's physical activity during the test phase (seated or walking). The lighting conditions used in the experiment are shown in Table 3.1.

For the adaptation phase, the lighting condition was chosen to match the illuminance conditions typically found in residential settings. This decision was based on the use of warm-white residential lighting at 2700 K, which is commonly used in the UK and Europe,[352] (the SPD of typical warm white lighting is shown in Figure 3.6). The level of melanopic illuminance selected aimed to replicate typical evening home lighting, with median values ranging from approx. 11.0 lx (melanopic EDI of 9.9 lx) and 13.4 lx (melanopic EDI of 12.0 lx)[353] (see Figure 3.7). Additional illuminance measurements taken in two British dwellings further support the representation of residential lighting condition: the illuminances ranged from 20 lx to 70 lx (horizontal illuminances at 1.5 m above the floor). The vertical-to-horizontal illuminance ratio for artificial light at a given point in space is approx. 0.5 at most.[354] This implies vertical illuminances of 10 lx to 35 lx, which brackets the 25 lx used in the adaptation phase.

Table 3.1 Light conditions (illuminance and SPD-derived metrics) used in the adaptation and test phases of the experiment

Lighting condition	Illuminance (lx)	CCT (K)	Alpha-opic equivalent daylight illuminance (lx)[a]				
			S-cone-opic	M-cone-opic	L-cone-opic	Rhodopic	Melanopic
Adaptation Condition							
	25	2700	8.2	19.5	25.6	12.7	10.7
Test Conditions							
C1	< 0.5	2700	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5
C2	8	2700	2.6	6.1	8.0	4.0	3.4
C3	8	5800	9.2	8.2	8.6	9.4	10.4
C4	25	2700	8.2	19.5	25.6	12.7	10.7

[a] alpha-opic and melanopic equivalent daylight (D65) illuminances calculated using luox from Spitschan *et al.*[355]

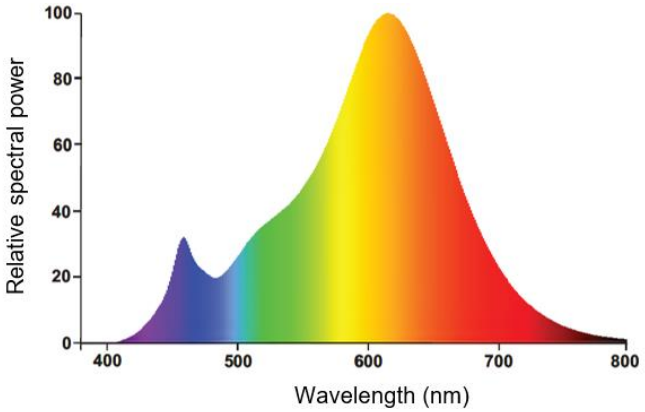

Figure 3.6 The SPD of typical warm white lighting (2700 K) as might be used in a dwelling.[352]

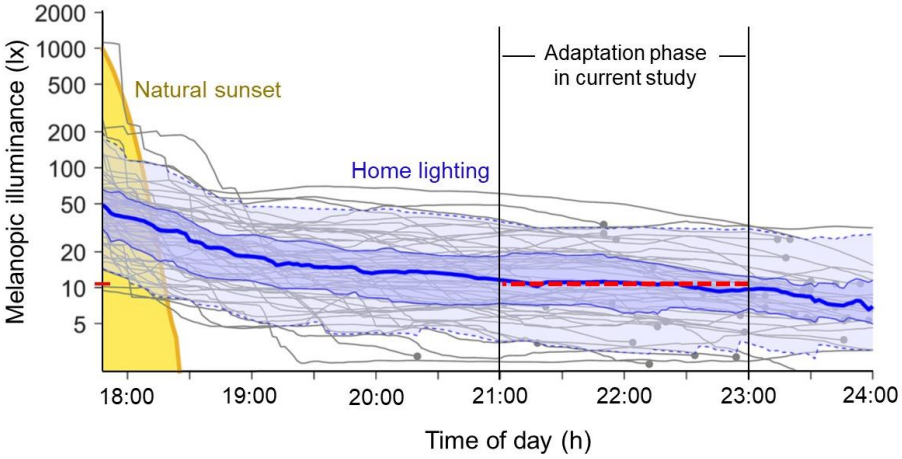

Figure 3.7 Changes in evening melanopic illuminance are compared between natural sunset conditions (yellow line) and home lighting. The grey curves represent individual homes, with data averaged across nights and smoothed using a 3-hour moving average. Each curve ends with a grey dot indicating the individual's average bedtime. The blue lines are the median (thick solid line), interquartile range (thin solid lines), and the 10th and 90th percentiles (dashed lines) for homes before bedtime. [Source: modified by the author after Cain *et al.*[353]] The red line shows the melanopic illuminance for the adaptation phase in the current study (11.9 lx; melanopic EDI of 10.7 lx).

In the test phase, participants were exposed for one hour to one of four test conditions. These are labelled as C1 to C4 in Table 3.1. The first test condition (C1) was a benchmark condition representing an outdoor setting with no road lighting. The second condition (C2) used an illuminance within the range of the P-classes for pedestrian environments[26] and subsidiary roads[27], a lower illuminance but the same SPD as that for the adaptation phase. This was a vertical illuminance of 8.0 lx at 1.5 m above the floor, facing the participants' direction of view. For outdoor environments, the CIE[356] suggest that adaptation illuminances are estimated as the average horizontal illuminance, which for P-class roads ranges from 2.0 lx to 15.0 lx. Informal measurements were conducted by the researcher to assess the

vertical illuminance on minor roads in Sheffield, the UK. About 100 measurements were recorded. These revealed a range of 0.5 lx to 20.0 lx which confirmed that 8.0 lx was within the range of likely experience. The third test condition (C3) used the same illuminance as C1, but with the SPD changed to increase the melanopic content from melanopic EDI of 3.4 lx to 10.4 lx. This value was chosen because a melanopic EDI of 10.0 lx is the maximum recommended for unavoidable activities for(at least) three hours before bedtime to avoid melatonin suppression, which would affect sleep quality.[357] The fourth test condition (C4) used the same SPD as C1 and C2 but with the illuminance increased to offer similar melanopic EDI as C3. C4 is the same lighting condition as used in the adaptation phase. Figures 3.8 and 3.9 show the SPDs of the four light conditions in the test phases.

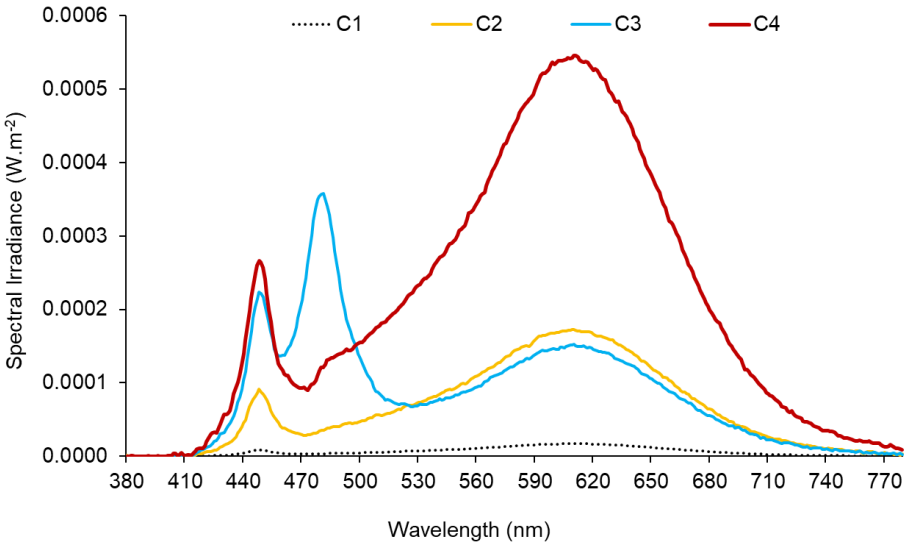

Figure 3.8 SPDs of the four light conditions in the test phases shown in absolute units

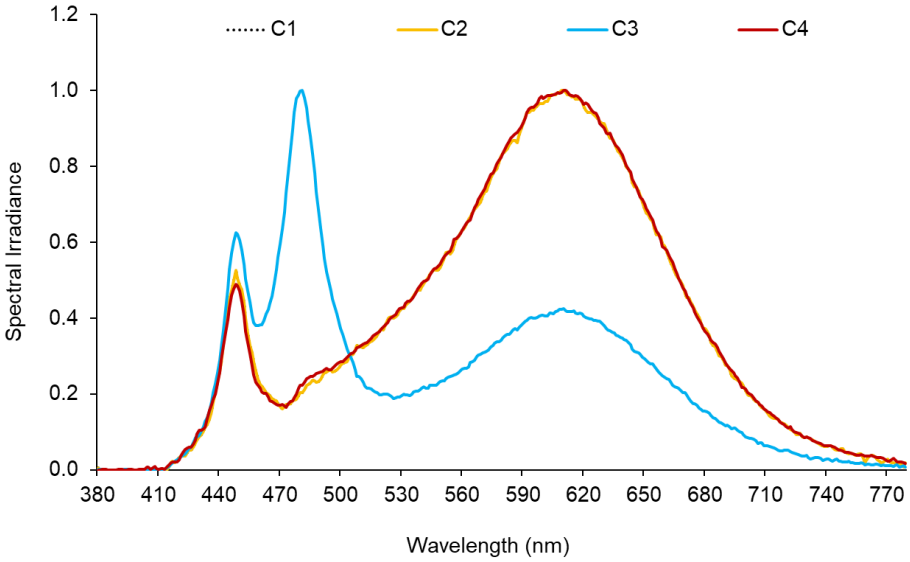

Figure 3.9 SPDs of the four light conditions in the test phases normalised to a peak response of unity (Note that the curves for light conditions C1, C2, and C4 overlap)

3.4. Dependent variables

The effect of changes in lighting and physical activity were measured using four DVs: melatonin level, auditory reaction time, subjective alertness and skin temperature.

Melatonin levels were determined from saliva samples captured using Salivette tubes (Sarstedt) at intervals of approx. 30 min during the adaptation and test phases (Figure 3.10). Participants were required to chew a cotton bud for one to two min and then place it into a tube. The tubes were labelled and stored in a freezer set to -20°C. Upon completion of all trials, the samples were packaged in dry ice to reduce degradation and transported to the Chorono@work laboratory at the University of Groningen (the Netherlands) for analysis using radioimmunoassay.[358,359]

Figure 3.10 Salivette tube-into which a cotton bud was inserted as used for saliva sample collection

Alertness was assessed through an auditory PVT, which measures the time taken to react to the onset of an auditory stimulus by pressing a response button placed upon the desk (see Figure 3.11). The specific version used was that known as PVT-B, as developed by Basner *et al.*[236] The stimulus was a 1000 Hz tone delivered through headphones. The stimulus was played for 0.5 s at inter-stimulus intervals randomly chosen from the range of 2 s to 6 s.

In order to maximise differences in reaction times between the various experimental conditions, the loudness of the tone was set to be near the audibility threshold of each participant, as established in the preparation phase (discussed in detail in section 3.5). Test participants attended in pairs, and each participant received a personally randomised stimulus pattern to prevent his/her reaction (pressing the button) from serving as a cue for the other participant.

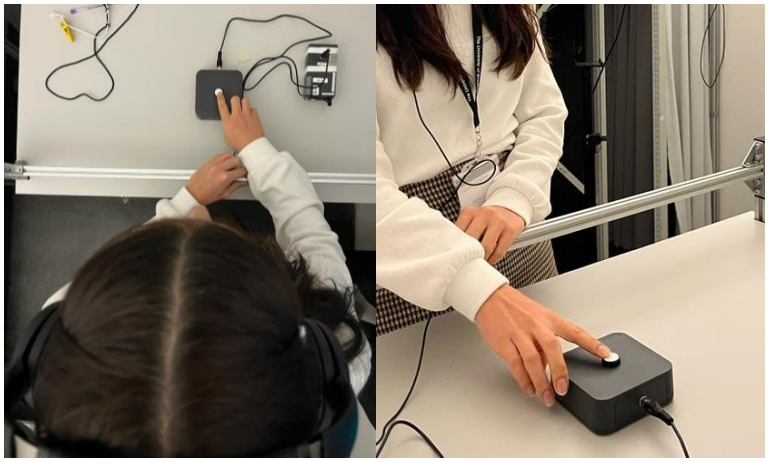

Figure 3.11 For the PVT task, test participant wore a headphone and pressed a response button

Subjective alertness was captured using the KSS.[156] In the original 9-point scale, the endpoints are labelled 1 (extremely alert) to 9 (very sleepy). For the current thesis, the scale direction was reversed so that the categories were labelled from 1 (very sleepy) to 9 (extremely alert), meaning that a higher rating described a greater level of perceived alertness (see Figure 3.12). Participants were asked to state their alertness level at 30 min intervals throughout the adaptation and test phases.

Rate	Description
1	Very sleepy, great effort to keep awake
2	Sleepy, some effort to keep awake
3	Sleepy, but no effort to keep awake
4	Some signs of sleepiness
5	Neither alert nor sleepy
6	Rather alert
7	Alert
8	Very alert
9	Extremely alert

Figure 3.12 The 9-point category response scale used in the experiment

Skin temperature was measured using temperature sensors (iButtons, DS1922L) attached to each participant at four locations (Figure 3.13): the neck, both wrists, and the shin; these locations are feasible for sensor attachment and also allow for capturing the distal skin temperatures. After being attached before the start of the adaptation phase, these sensors subsequently measured temperatures at three-second intervals throughout the

three-hour experiment. To estimate the representative skin temperature at a specific interval, first, the arithmetic mean temperature for the 60 s period before and after that interval at each location has been established, and subsequently, the mean across the four locations. As in previous work,[202] room temperature was also measured using an iButton. The iButton was suspended at a height above floor level of approx. 1 m, beside the test participants.

Figure 3.13 Temperature sensors (iButtons, DS1922L)

3.5. Procedure

The participants arrived at the laboratory at least 45 min before the start of the adaptation phase to allow for preparation. The preparation phase was carried out under the same lighting as that used in the adaptation phase. The adaptation phase started at 21:00; this time was chosen to commence around three hours prior to the habitual bedtime of the recruited participants. The participants wore their normal clothing and were advised to bring paper-based reading material to occupy themselves in the time between the measurements of the DVs.

Two examinations were conducted to confirm normal vision. A Landolt C chart was used to check visual acuity (Figure 3.14); two C chart versions with different random gap locations were used, ensuring an acuity of not less than 6/12 with their normal corrective lenses, which is the minimum visual acuity required for driving in the UK.[360] Colour vision was evaluated using the Ishihara colour plates illuminated by a D65-simulating source.

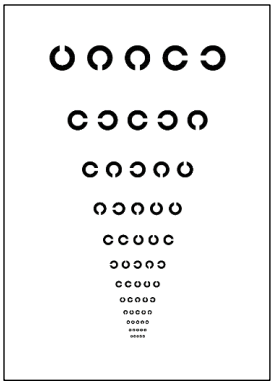

Figure 3.14 A version of a Landolt C acuity test chart printed on A4 paper and used at a distance of 2.10 m

The iButton four temperature sensors were fixed onto the skin with adhesive tape. The participants were seated in their chairs for the adaptation phase. The choice of seated or walking for the test phase was initially assigned at random by drawing lots from a sealed bag, but towards the end of the experiment, this was assigned by the experimenter to assure a gender-balanced participant assignment across all lighting-condition groups.

During the test phase, one of the participants walked on the treadmill at a speed that felt comfortable to them (described here as their self-selected speed); this speed was determined during the preparation phase, where participants walked for five min and selected a comfortable speed for the hour in the test phase. These self-selected speeds ranged between 1.2 $km.h^{-2}$ and 2 $km.h^{-2}$ (low-intensity exercise, see 2.4.2).

Hearing thresholds were measured to set the loudness of the tone used in the auditory PVT test. To determine the hearing threshold - the lowest level of sound that a participant can detect - of each participant, a range of tones of different loudness were played in random order through headphones, to which participants were instructed to press a button when they heard a tone. The threshold level for hearing was determined by identifying the loudness level that corresponded with a 50% detection rate. The tone volume for the PVT test was set to that individual's estimated hearing threshold plus an additional 10 dB, resulting in a perceived loudness twice as loud as the original tone.[361] The hearing threshold was determined both while the participants were seated and while one of them was walking on the treadmill at the determined walking speed. The initial threshold was employed during the adaptation phase, whereas the latter threshold was utilised during the test phase. The hearing thresholds were tested twice due to the anticipated variations in thresholds; this is because the noise from the treadmill while walking could potentially mask the lowest tones detected when the participants were seated. As a result, it was consistently observed that the thresholds while participants were walking were higher than when they were seated.

The adaptation and test phases of the experiment lasted for 3 h. During this period, the DVs (Saliva samples, PVT and KSS) were recorded at intervals of approx. 30 min, with measurements centred on min 5, 30, 60, 90 and 110 in the adaptation phase and min 130, 150 and 180 in the test phase. For min 30 and 90 in the adaptation phase, only the KSS and melatonin were recorded and collected (Figure 3.15).

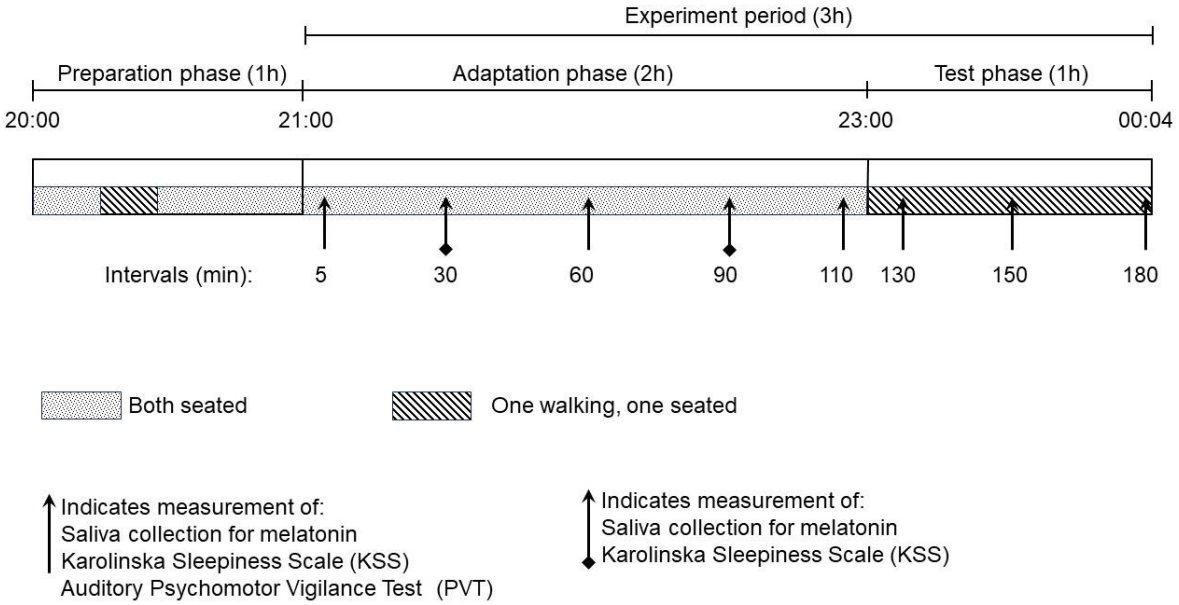

Figure 3.15 Overview of the test protocol for the experiment (note: skin temperature was measured at three-second intervals throughout the three-hour experiment)

The measurement intervals used in the test phase were selected based on the analysis of typical journey times for walking after dark [see full details in Appendix B]. This analysis revealed two journey categories based on trip durations: 1) short trips, with a median duration of 10 min and 2) long trips, with a median duration of 45 min.

The PVT test at each interval consisted of two blocks of 3 min each. The first block was conducted immediately prior to, and the second immediately after, the interval point at which KSS and saliva samples were taken. The combined results from both PVT tests were analysed as one block of 6 min, having responses to approx. 60 stimuli. The PVT data were cleaned by omitting assumed errors of omission (reaction time greater than twice the participant's median reaction time) and errors of assumed commission (reaction time < 100 ms). These data displayed a non-normal distribution thus the reaction time for each test interval was characterised using the median. This reduced the reaction time data to 40 responses (one per participant) at each of the six test intervals.

The test phase started two hours after the adaptation phase. At this point, the light setting changed to one of the four test conditions (shown in Table 3.1), and one participant changed from being seated to walking. The treadmill was set to the walking speed that was established in the preparation phase.

3.6. Sample size

An experiment requires a suitable sample size to ensure it is able to detect an effect if one exists.[362] In this case, the objective is to investigate whether changes in lighting (the IV) lead to changes in melatonin levels, reaction times, skin temperature, and subjective alertness (the DVs). The sample size was determined using G*Power,[363] which requires three main inputs: the alpha level (α), the desired statistical power,[364] and the effect size.[362,365]

The alpha level (α) sets the level for statistical significance in hypothesis testing. It represents the probability of a Type I error, which is the risk of incorrectly rejecting a true null hypothesis. A significance level of 0.05 is commonly employed,[366] indicating a 5% chance of rejecting the null hypothesis when it is true.

Statistical power denotes the probability of correctly rejecting a false null hypothesis in a statistical test.[364,367] This indicates the likelihood of detecting significant changes in melatonin levels, reaction times, skin temperature, and subjective alertness over time or between different lighting conditions. Statistical power was set at 0.8, the standard value.[362,364,368]

The effect size quantifies the magnitude of the phenomenon under study. Different fields accept various effect sizes due to differences in measurement noise.[369] Estimating the effect size usually relies on previous literature. However, determining the effect size for the NIF effect of light is challenging because many studies do not report effect sizes or provide the detailed results necessary for their calculation. For example, in the two studies most relevant to the current work,[113,114] the effect size is not reported.

Two main tests were planned based on the experimental design:

1. *Within-Subject Design*: This test compares data from the adaptation phase with data from the test phase within the same lighting group. According to G*Power, detecting an effect size of 0.5 with a power of 0.8 and α = 0.05 requires a sample size of 8 (see Figure 3.16).

2. *Between-Subject Design*: This test compares data from the test phases across different lighting groups. G*Power indicates that detecting an effect size of 0.5 with 0.8 power and α = 0.05 requires a sample size of at least 36 (see Figure 3.17).

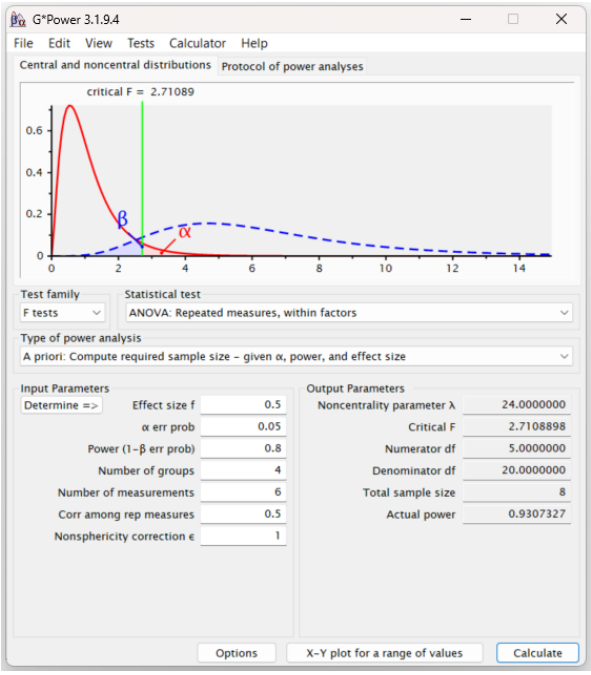

Figure 3.16 Sample size calculation for a within-subject design using G*Power 3.1.9.4

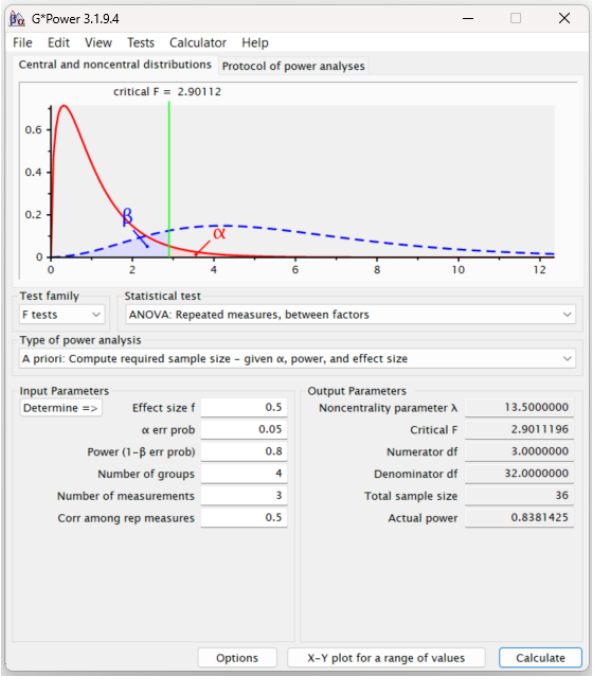

Figure 3.17 Sample size calculation for a between-subject design using G*Power 3.1.9.4

The experiment was conducted with a total of 40 participants, distributing 10 individuals across each light condition, thereby slightly surpassing the sample sizes recommended by G*power for detecting an effect size of 0.5. In previous work investigating the NIF effect, the samples have ranged from 3 to 14 participants (independent samples) - see Table 8.4 in Chapter 8 - so this sample is consistent with previous work.

The selection of this sample was also influenced by practical limitations and feasibility considerations. For instance, the size of the lighting laboratory allowed for only two participants per night, necessitating that the experiment was conducted over 20 nights, which demanded notable effort. Furthermore, this decision was informed by the potential for unexpected and sudden building closures due to future COVID-19 outbreaks.

After the completion of the two experiments reported in this study, it was realised that the initial plan to target a medium effect size was not fully accurate. Originally, a medium effect size was defined as 0.5 using Cohen's d.[370] However, because G*Power uses Cohen's f to specify effect sizes for repeated measures ANOVA, a medium effect size in this context is represented as 0.25. Therefore, a post-hoc sensitivity analysis was carried out to identify the smallest effect size that could be reliably detected with a sample of 40 participants (see section 8.5).

3.7. Sample recruitment

This study recruited participants through emails posted to volunteer recruitment lists of university staff and students, with the following inclusion criteria: age (18-30 years), have normal vision (wearing glasses or lenses if normally worn), healthy (assessed using self-report of no short or long-term medication, non-smoking, and no history of health issues), a habitual bedtime before/at midnight, no recent overnight work (for one year), or travel over a time zone in the last three months. Forty participants were recruited for the experiment with 10 participants (five males and five females) allocated to each of the four test conditions. Their median age was 20.5 years and ranged from 18 to 30 years.

Participants were asked to keep a steady sleep-wake schedule for the seven days prior to the experiment. A daily email was sent to remind participants to maintain the sleep-wake schedule [Appendix C], and this was confirmed through a self-reported sleep-wake diary for that period. On the day of their experiment, participants were asked not to eat bananas or chocolate during the day, nor take any medication, to avoid consuming substances after midday, which contain alcohol or caffeine, to prevent contamination of the saliva samples with any compounds likely to interfere with the assay and minimise light suppression of melatonin,[371] and to refrain from napping: otherwise, these might influence the alertness-related performance.[328] During the experiment, orange juice, nuts, and water were provided for participants as refreshments. Upon finishing the experiment, each participant received a remuneration of £40.

Ethical approval for this experiment was received from the University of Sheffield Research Ethics Committee on 29 August 2021 (Reference Number 042711). In accordance with this, informed consent was obtained from all participants for the experiment [Appendix D], and all collected data were anonymised to ensure privacy and confidentiality.

3.8. Analysis

The analysis of this experiment was designed to evaluate the effects of various lighting conditions on melatonin level, reaction time, skin temperature and subjective alertness. Data obtained during the three-hour duration of the experiment underwent thorough analysis to discern significant differences. The initial two hours represented the adaptation phase, during which all 40 participants were exposed to the same lighting condition. In the final hour, participants were distributed into four groups, each subjected to a distinct light condition (C1 to C4). Data were gathered at consistent intervals of six to eight to ensure uniformity across all groups. The subsequent sections provide an elaborate overview of the planned tests, methods employed for assessing data normality, and the procedures for interpreting significance.

3.8.1. Planned statistical tests

The data of the four DVs were analysed using two main tests:

1. Repeated Measures ANOVA (Within-Subject Analysis): This test compares data collected from the same group of participants at different intervals during the adaptation and test phases. Its purpose is to identify trends or significant changes in alertness, melatonin level, or skin temperature over time and between the two phases within the same group.
2. Repeated Measures ANOVA (Between-Subject Analysis): This test compares data from different groups of participants, each exposed to different light conditions, at the same intervals during the test phase (the last hour of the experiment). The goal is to identify significant differences between groups exposed to different lighting conditions.

These tests are parametric, assuming a normal distribution of the data. If the data do not exhibit a normal distribution, non-parametric alternative tests were utilised instead; Freidman for within-subject analysis and the Kruskal-Wallis test for between-subject analysis.

3.8.2. Data normality checking method

After collecting data for each DV (melatonin level, reaction time, skin temperature, and subjective alertness), the next step was to assess whether they followed a normal distribution pattern. This normality assessment involved several analytical tests:

1. Statistical tests: The Shapiro-Wilk and Kolmogorov-Smirnov tests were used, and data was considered non-normal if the p-value was less than 0.05.[372]
2. Graphical tests: Histograms and box plots: Normality was evaluated based on the visual shape and spread of the data distribution. Histograms display data frequency within specific intervals, while box plots illustrate quartiles, outliers, and overall dispersion.[373]
3. Measures of central tendency: Normality was indicated if the median of the data fell within the 95% confidence interval for the mean.[374]
4. Measures of dispersion: Kurtosis was considered normal if it fell within ±1.0, indicating the distribution's peak. Skewness was deemed normal if it fell within ±0.5, reflecting the data distribution's symmetry.[375]

These tests collectively aim to assess the normality of the data in preparation for applying appropriate statistical tests.

3.8.3. Interpretation of significance

If a primary test, such as ANOVA, reveals a significant difference, it is important to conduct pairwise comparisons multiple times to identify which intervals or groups exhibit significant differences. However, performing multiple comparisons increases the risk of Type I errors (erroneously rejecting a null hypothesis). This phenomenon is referred to as capitalising on chance, as with a p-value threshold of 0.05, there is a 1 in 20 chance of making a Type I error. One way to mitigate this risk is to employ a Bonferroni correction. This correction method aims to control the family-wise error rate, addressing the concern that the probability of committing a Type I error rises with the number of comparisons.

The Bonferroni correction is a method used to adjust the significance threshold by dividing the fixed alpha level (e.g., 0.05) by the number of all possible pairwise comparisons. For instance, in this current thesis, if the main test suggests a significant difference in melatonin levels over the three-hour experiment (among 6 intervals), the pairwise comparisons would be conducted 15 times (15 different possible pairs), adjusting the significance level for each individual comparison to 0.003 (0.05/15). This method is simple but can be overly conservative, especially with many comparisons, potentially increasing the risk of Type II errors (false negatives; failing to reject a false null hypothesis).

The Holm-Bonferroni correction is an improved version of the Bonferroni correction and is performed in a step-wise fashion. It starts by sorting the p-values from smallest to largest. The smallest p-value is compared to the most stringent adjusted significance level (e.g., 0.003 (0.05/15)), the second smallest *p*-value to a slightly less stringent level (e.g., 0.004 (0.05/14)), and so on, until the largest *p*-value is compared to the least stringent level (0.05/1). This approach provides a compromise between controlling the family-wise error rate (as effectively as the one-step Bonferroni) and reducing Type II errors, as it becomes less conservative for larger p-values compared to the Bonferroni correction. (see Holm,[376] Ludbrook,[377] and Groppe.[378]) In this thesis, the Holm-Bonferroni correction method was used to adjust significance levels in multiple comparisons.

3.9 Summary

The experimental design aimed to investigate hypotheses H1 and H2, as described in section 2.8. The main goal was to explore how the NIF effects of lighting on minor roads impact pedestrian safety in the evening. The experiment comprised three phases: preparation, adaptation, and test. During the preparation phase, participants' visual acuity, colour vision and hearing thresholds were assessed. Additionally, iButtons were used to measure skin temperature, and treadmill speed was set to participants' comfort levels.

Following the preparation phase, the adaptation phase began, during which all 40 participants were exposed to the same light level for two hours while seated, mimicking typical residential indoor lighting. In the subsequent test phase, participants were divided into four groups, each exposed to one of four lighting conditions (C1 to C4). Half of the participants remained seated, while the other half walked on a treadmill at their preferred speed to assess the impact of physical activity on DVs. The experiment had four DVs: reaction time (measured via PVT), subjective alertness (assessed via KSS), melatonin levels (collected via saliva samples), and skin temperature (measured via iButtons). Data for these variables were collected at six to eight intervals throughout the experiment.

The appropriate sample size was determined using G*Power software. Data normality was assessed using statistical tests, graphs and measures of central tendency and dispersion. Analyses of the four DVs were conducted using two main approaches: within-subject and between-subject analyses, using repeated measures ANOVA, or their non-parametric alternative in cases of non-normality. For multiple comparisons, the Holm-Bonferroni correction method was used to adjust the significance levels.

Chapter 4

Experiment 1: Results

4. Experiment 1: Results

4.1. Introduction

Chapter 4 presents the results of the experiment described in Chapter 3, in which NIF responses to different lighting conditions were measured after a period of adaptation. It was first examined whether the results were drawn from a normally distributed population, as that defines which statistical tests should be applied to examine the significance of differences. The results from each of the NIF DVs are then analysed in turn. These analyses first look for differences between all levels of the variable, and where that suggests a statistically significant effect, further pairwise tests are conducted with significance values adjusted using the Holm-Bonferroni correction to account for multiple comparisons.[378]

As recommended by Ellis,[379] effect sizes are reported for all results regardless of whether or not the differences are suggested to be statistically significant, as doing so helps to provide a better understanding of the data and makes the results meta-analytically friendly; meaning they can be easily included in a comprehensive analysis that combines findings from multiple studies.

4.2. Data normality

The data recorded for each DV were initially checked to see if they were drawn from a normally distributed population. As explained in 3.8.2, this was done by four methods of analysis: comparing measures of central tendency, statistical tests (Shapiro-Wilks and Kolmogorov-Smirnov), measures of dispersion (skewness and kurtosis) and graphical representations (histogram and box plot). The results of these analyses are shown in Appendix E. It was concluded that skin temperatures followed a normal distribution; an example of box plots illustrating the distribution of the skin temperature dataset at the eight intervals is shown in Figure 4.1. The results for reaction times, melatonin levels, and KSS ratings did not exhibit a normal distribution; Figure 4.2 shows, as an example, the non-normal distribution of the melatonin level dataset at eight intervals.

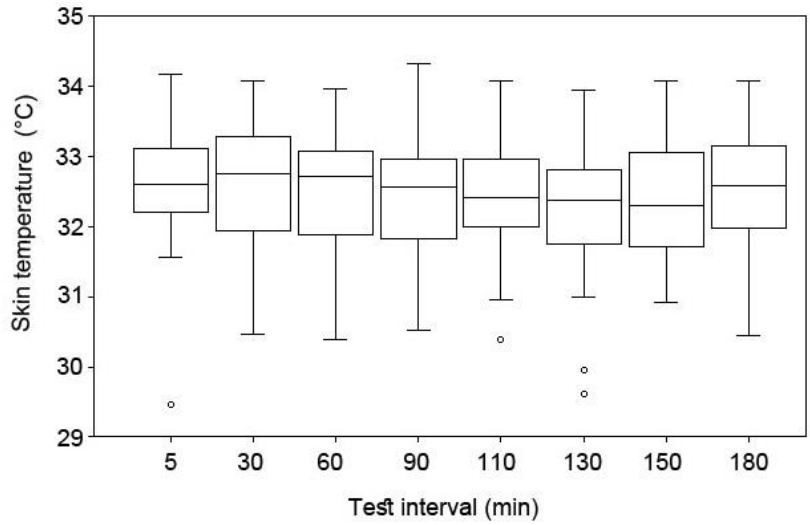

Figure 4.1 Box plots of skin temperature at eight intervals. These data are suggested to be normally distributed at each interval because the median lines tend to be central within each box, and the whiskers tend to be of similar length above and below each box.

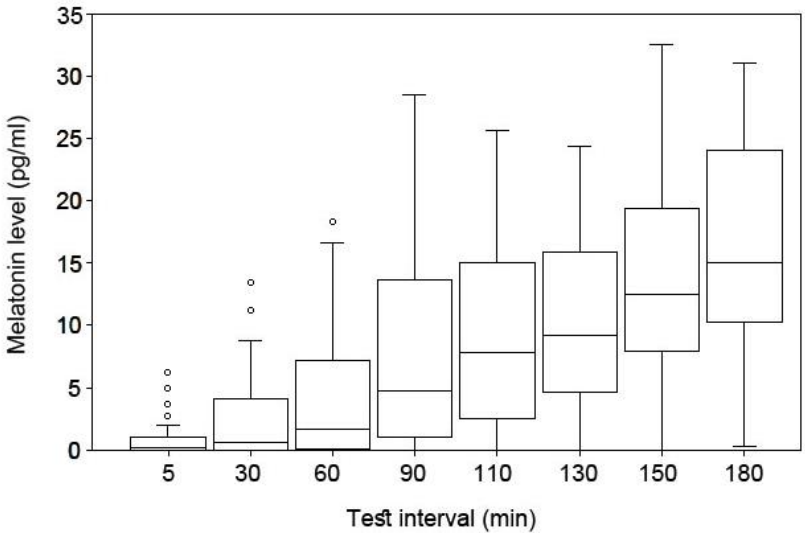

Figure 4.2 Box plots of melatonin level at eight intervals. These data are not suggested to be drawn from a normally distributed population because the median lines do not tend to be central within each box, and the whiskers do not tend to be of similar length above and below each box.

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4.3. Psychomotor Vigilance Test

Figure 4.3 displays the median reaction times at the six test intervals. Analysis of these data over the three-hour duration indicates a slower reaction time at the first interval (5 min) than at the other intervals. The Friedman test suggested a significant change across the intervals ($\chi^2(5) = 17.851$, $p < 0.01$, Kendall's $W = 0.09$). Kendall's W value indicates a small effect size.

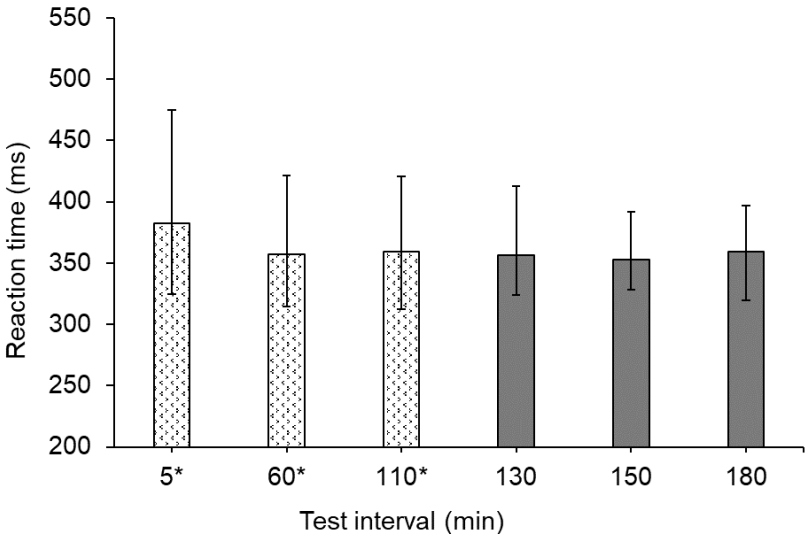

Figure 4.3 Median reaction times (in milliseconds) measured using the auditory PVT at each test interval. Error bars show the Inter Quartile Range (IQR): *shading distinguishes between the adaptation and test phases of the experiment

Since the Friedman test suggested a significant change with test interval, a series of pairwise comparisons was conducted using *post-hoc* Wilcoxon tests. These results, shown in Table 4.1, indicated a longer reaction time at the first measurement interval (5 min; median reaction time = 382.5 ms) in comparison to the subsequent test intervals ($p < 0.05$ for each comparison).

Table 4.1 Statistical values for interval comparisons using the Wilcoxon signed-rank test for reaction time data

No.	Intervals	*Z* statistics (*Z*)	Correlation coefficient (*r*)	Effect size	Adjusted Significance (Adj.Sig.)[a]
1	60 – 5	-2.97	0.77	L	-
2	110 – 5	-2.08	0.54	L	-
3	130 – 5	-3.27	0.84	L	-
4	150 – 5	-3.50	0.90	L	-
5	180 – 5	-3.37	0.87	L	-
6	110 – 60	-0.11	0.03	S	+
7	130 – 60	-1.64	0.42	M	+
8	150 – 60	-1.47	0.38	M	+
9	180 – 60	-1.59	0.41	M	+
10	130 – 110	-1.20	0.31	M	+
11	150 – 110	-1.22	0.32	M	+
12	180 – 110	-1.17	0.30	M	+
13	150 – 130	-0.46	0.19	S	+
14	180 – 130	-0.84	0.22	S	+
15	180 – 150	-0.78	0.20	S	+

[a] Significance values have been adjusted using the Holm-Bonferroni correction for multiple tests.[378]
Note: for Adj.Sig., (+) indicates $p \geq 0.05$, and (-) indicates $p < 0.05$, for effect sizes: L = large, M = medium, S = small.

For the adaptation phase, all participants were exposed to the same lighting condition, and thus, no differences were expected between the groups subsequently allocated to the four test lighting conditions. Comparing the differences in reaction time between the groups at each interval in the adaptation phase (5 min, 60 min and 110 min) therefore test whether participants were fairly assigned to each group. The results from the Kruskal-Wallis tests did not suggest significant differences at the 5 min, 60 min and 110 min intervals ($H(3) = 4.843$, $p = 0.18$, $\eta^2 = 0.05$; $H(3) = 5.999$, $p = 0.11$, $\eta^2 = 0.08$; $H(3) = 7.217$, $p = 0.07$, $\eta^2 = 0.12$). The eta squared (η^2) values for these intervals indicate small, medium and medium effect sizes, respectively.

To compare differences between lighting conditions, the results from the three measurement intervals in the test phase, as well as the final measurement interval of the adaptation phase, were included. Specifically, for the melatonin and KSS data, only the final measurement interval was used to represent the adaptation phase if the values in the adaptation phase varied significantly between intervals. The average of the final two adaptation intervals (60 min and 110 min) was used for the reaction time data as they were not suggested to be significantly different. For skin temperature, data from all adaptation phase intervals were used for the same reason.

For each light condition, the change in reaction times over successive intervals was tested using the Friedman test (Figure 4.4). For light conditions, C1, C2, C3 and C4, the Friedman test did not suggest any differences in reaction time between the measurement intervals to be significant ($p \geq 0.190$; in each case). In other words, the change in lighting from the adaptation phase to the test phase did not significantly affect reaction time under any of the four light conditions (C1: $\chi^2(3) = 4.333$, $p = 0.23$, Kendall's $W = 0.14$; C2: $\chi^2(3) = 4.758$, $p = 0.19$, Kendall's $W = 0.16$; C3: $\chi^2(3) = 1.800$, $p = 0.62$, Kendall's $W = 0.06$; C4: $\chi^2(3) = 3.960$, $p = 0.27$, Kendall's $W = 0.13$). The Kendall's W values for the four light conditions indicate small effect sizes.

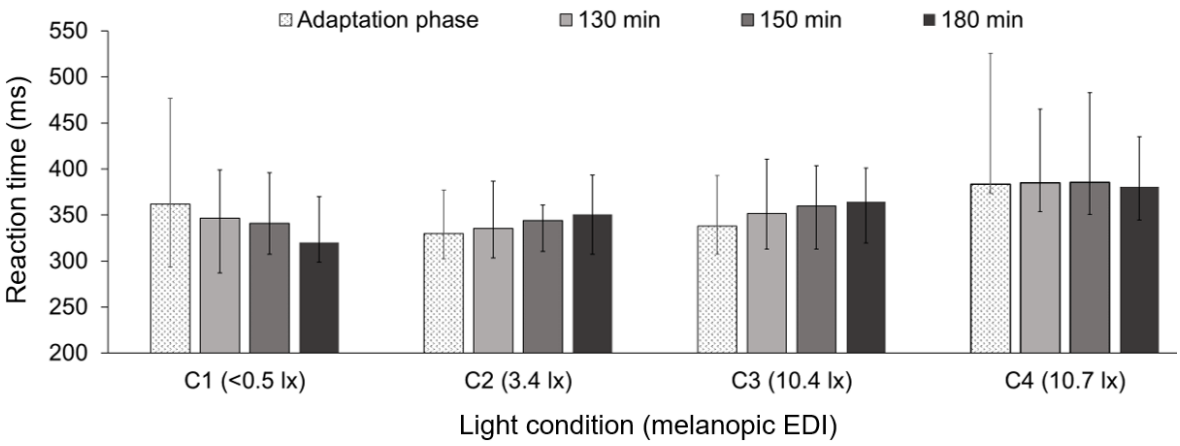

Figure 4.4 Median reaction times during the adaptation phase (average of reaction times at 60 min and 110 min) and at each test interval during the test phase according to the light condition during the test phase. Error bars show the IQR.

The Friedman test compares changes in responses within each light condition group across the measurement intervals in the test phase, a within-subjects analysis. An alternative approach is to compare responses among the different groups (i.e. different lighting conditions) at the same measurement interval. A between-subjects analysis using the Kruskal-Wallis test did not suggest significant differences at the 130 min, 150 min, or 180 min intervals ($H(3) = 5.258$, $p = 0.15$, $\eta^2 = 0.06$; $H(3) = 6.182$, $p = 0.10$, $\eta^2 = 0.09$; $H(3) = 4.910$, $p = 0.18$, $\eta^2 = 0.05$). The η^2 values for these intervals suggest small, medium and small effect sizes, respectively.

To investigate the effect of physical activity, a between-subjects analysis using the Mann-Whitney U Test was used to compare responses between the different physical activity groups at the same measurement interval in the test phase (see Figure 4.5). This did not suggest any differences to be significant ($U = 168.000$, $p > 0.05$, PS = 0.42; $U = 199.000$, $p > 0.05$, PS = 0.50; $U = 190.500$, $p > 0.05$, PS = 0.48) at 130 min, 150 min and 180 min intervals, respectively. The Probability of Superiority (PS) values for these intervals indicate small effect sizes.

The Friedman test, a within-subjects analysis, was used to compare changes in responses within each physical activity group across the measurement intervals in the test phase and the adaptation phase (average of reaction times at 60 min and 110 min). The results did not suggest any significant changes across the measurement intervals for the two physical activity groups (seated: $\chi^2(3) = 2.700$, $p = 0.44$, Kendall's $W = 0.05$) and (self-selected speed: $\chi^2(3) = 5.515$, $p = 0.14$, Kendall's $W = 0.09$). The Kendall's W values for both groups indicate small effect sizes.

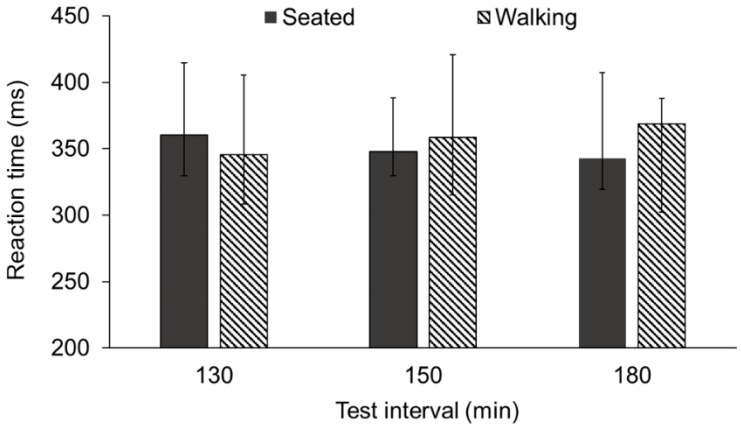

Figure 4.5 Median reaction times at each test interval during the test phase according to the physical activity. Error bars show the IQR.

4.4. Melatonin levels

Melatonin, the hormone that helps to regulate the diurnal sleep-wake cycle: high levels of melatonin are secreted by the pineal gland during the dark phase of the day and low levels during the light phase.[214,215]

The median melatonin levels of the 40 participants at each interval are shown in Figure 4.6. As expected, the melatonin levels progressively increased as the measurement interval approached habitual bedtimes. The Friedman test suggested a significant change across the measurement intervals ($\chi^2(7) = 221.213$, $p < 0.01$; Kendall's $W = 0.79$; indicating a large effect size).

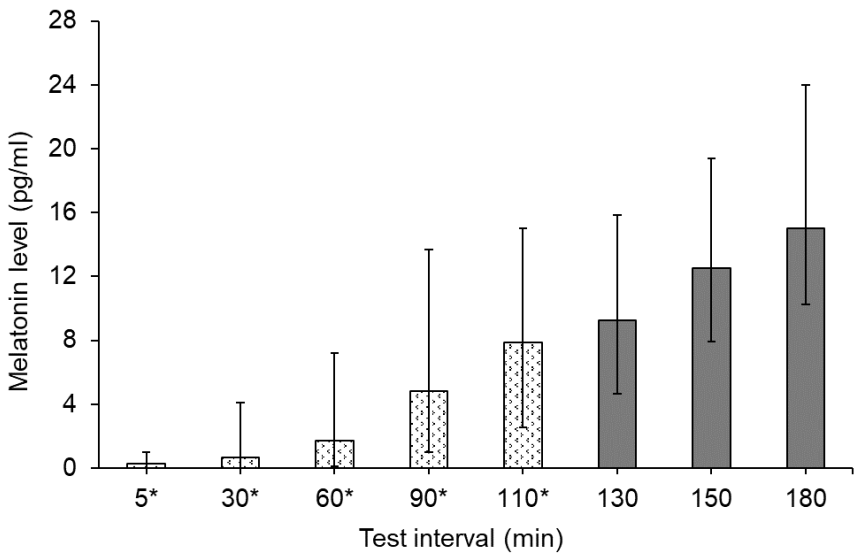

Figure 4.6 Median melatonin levels derived from saliva samples collected at each test interval. Error bars show the IQR: *shading distinguishes between the adaptation and test phases of the experiment

Since the Friedman test suggested a significant change with test interval, a series of pairwise comparisons was conducted using *post-hoc* Wilcoxon tests. These results, shown in Table 4.2, suggested that differences in melatonin levels between all the intervals were significant; where the melatonin level was suggested to increase significantly at any given interval compared to the preceding intervals.

Table 4.2 Statistical values for interval comparisons using the Wilcoxon signed-rank test for melatonin levels data

No.	Intervals	*Z*	*r*
1	30 – 5	-4.26	0.81
2	60 – 5	-4.57	0.87
3	90 – 5	-5.19	0.98
4	110 – 5	-5.28	1.00
5	130 – 5	-5.42	1.03
6	150 – 5	-5.44	1.03
7	180 – 5	-5.51	1.04
8	60 – 30	-4.56	0.86
9	90 – 30	-5.07	0.96
10	110 – 30	-5.27	1.00
11	130 – 30	-5.42	1.02
12	150 – 30	-5.50	1.04
13	180 – 30	-5.44	1.03
14	90 – 60	-5.04	0.95
15	110 – 60	-5.29	1.00
16	130 – 60	-5.44	1.03
17	150 – 60	-5.43	1.03
18	180 – 60	-5.50	1.04
19	110 – 90	-3.13	0.59
20	130 – 90	-4.71	0.89
21	150 – 90	-5.46	1.03
22	180 – 90	-5.07	0.96
23	130 – 110	-4.17	0.79
24	150 – 110	-5.01	0.95
25	180 – 110	-5.25	0.99
26	150 – 130	-4.41	0.83
27	180 – 130	-4.96	0.94
28	180 – 150	-2.76	0.52

Note: For each interval comparison, Adj.Sig. < 0.05 indicates significant differences, with r values representing large effect sizes.

To test whether participants were fairly assigned to each group in the adaptation phase, the Kruskal-Wallis test was used to compare group differences at the same interval. The results did not suggest significant differences across the groups at the 5 min, 30 min, 60 min, 90 min and 110 min intervals ($H(3) = 1.930$, $p = 0.587$, $\eta^2 < 0.01$; $H(3) = 2.856$, $p = 0.41$, $\eta^2 < 0.01$; $H(3) = 1.237$, $p = 0.74$, $\eta^2 < 0.01$; $H(3) = 0.543$, $p = 0.91$, $\eta^2 < 0.01$; $H(3) = 0.919$, $p = 0.82$, $\eta^2 < 0.01$), respectively. The η^2 values indicate that there was no effect across all five intervals. This suggests a fair distribution of participants across the four lighting conditions.

To investigate the effect of light conditions on melatonin levels, the results from the three measurement intervals in the test phase, as well as the final measurement interval of the adaptation phase (i.e. 110 min), were included. For each light condition, the change in melatonin level over successive intervals was tested using the Friedman test (Figure 4.7). For light conditions, C1, C2, C3 and C4, the Friedman test suggested significant differences among the measurement intervals: C1 ($\chi^2(3) = 20.758$, $p < 0.01$, Kendall's $W = 0.69$), C2 ($\chi^2(3) = 20.937$, $p < 0.01$, Kendall's $W = 0.70$), C3 ($\chi^2(3) = 17.182$, $p < 0.01$, Kendall's $W = 0.57$) and C4 ($\chi^2(3) = 20.160$, $p < 0.01$, Kendall's $W = 0.67$). The Kendall's W values for all four light conditions suggest large effect sizes.

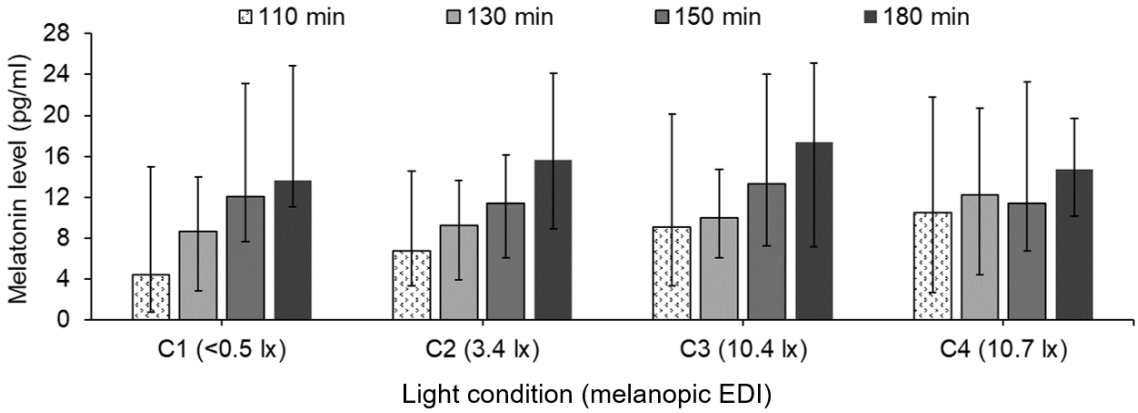

Figure 4.7 Median melatonin level at the last interval in the adaptation phase (110 min) and at each test interval during the test phase according to the light condition during the test phase. Error bars show the IQR

Since the Friedman tests suggested significant changes with test interval, a series of pairwise comparisons was conducted using *post-hoc* Wilcoxon tests. These results are shown in Table 4.3. This suggested a significant increase in melatonin levels under light conditions C1, C2 and C4 at the final interval (180 min) compared to the adaptation phase ($p < 0.05$ in each case). For light condition C3, the test did not indicate a significant increase in melatonin levels at 180 min compared to the adaptation phase ($p > 0.05$). Additionally, the test suggested significant increases in melatonin levels under light conditions C1 and C2 at 180 min compared to 130 min ($p < 0.05$), but not under light conditions C3 and C4.

Table 4.3 Statistical values for interval comparisons using the Wilcoxon signed-rank test for melatonin levels data under four light conditions C1 to C4

		Light Condition							
		C1		**C2**		**C3**		**C4**	
No.	**Intervals**	*Z*	*r*/effect size (Adj.Sig.)	*Z*	*r*/effect size (Adj.Sig.)	*Z*	*r*/effect size (Adj.Sig.)	*Z*	*r*/effect size (Adj.Sig.)
1	130–110	-2.30	0.94 / L (-)	-0.59	0.24 / S (+)	-1.78	0.73 / L (+)	-2.81	1.15 / L (-)
2	150–110	-2.80	1.15 / L (-)	-1.72	0.70 / L (+)	-2.81	1.15 / L (-)	-2.80	1.15 / L (-)
3	180–110	-2.70	1.10 / L (-)	-2.80	1.15 / L (-)	-2.43	0.99 / L (+)	-2.70	1.10 / L (-)
4	150–130	-2.60	1.06 / L (-)	-1.47	0.60 / L (+)	-2.80	1.15 / L (-)	-2.19	0.90 / L (+)
5	180–130	-2.67	1.09 / L (-)	-2.80	1.15 / L (-)	-2.29	0.94 / L (+)	-1.99	0.81 / L (+)
6	180–150	-0.97	0.40 / M (+)	-2.81	1.15 / L (-)	-0.46	0.19 / S (+)	-1.38	0.56 / L (+)

Note: for Adj.Sig., (+) indicates $p \geq 0.05$, and (-) indicates $p < 0.05$, for effect sizes: L = large, M = medium, S = small.

To compare melatonin levels among the different lighting conditions at the same measurement interval in the test phase, a between-subjects analysis using the Kruskal-Wallis test was conducted. The results did not suggest significant differences at either the 130 min, 150 min or 180 min intervals ($H(3) = 0.852$, $p = 0.84$, $\eta^2 < 0.01$; $H(3) = 0.670$, $p = 0.88$, $\eta^2 < 0.01$; $H(3) = 0.119$, $p = 0.99$, $\eta^2 < 0.01$). The values of η^2 indicate that there was no significant effect at any of the intervals.

To investigate the effect of physical activity, a between-subjects analysis using the Mann-Whitney U Test was conducted to compare the melatonin level between the different physical activity groups at the same measurement interval in the test phase (Figure 4.8). This did not suggest any differences to be significant ($U = 171.000$, $p > 0.05$, PS = 0.43; $U = 185.000$, $p > 0.05$, PS = 0.46; $U = 177.500$, $p > 0.05$, PS = 0.44) at 130 min, 150 min and 180 min intervals, respectively. The PS values indicate small effect sizes for all of them.

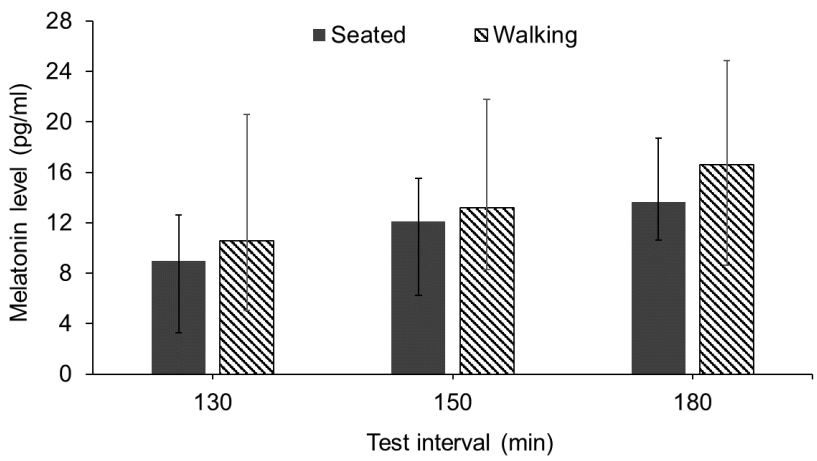

Figure 4.8 Median melatonin level at each test interval according to whether the test participant was seated or walking during the test phase. Error bars show the IQR.

The Friedman test, a within-subjects analysis, was used to compare changes in melatonin levels within each physical activity group across the measurement intervals in the test phase and the adaptation phase (i.e. 110 min) (see Figure 4.9). The results suggested significant changes across the measurement intervals for the two physical activity groups (seated: $\chi^2(3) = 40.809$, $p < 0.01$, Kendall's $W = 0.68$; indicating a large effect size and self-selected speed: $\chi^2(3) = 34.036$, $p < 0.01$, Kendall's $W = 0.57$, indicating a large effect size). Pairwise comparisons using the Wilcoxon test, shown in Table 4.4, suggested a significant increase in melatonin level at any given interval compared to the preceding ones for the seated group and the self-selected walking speed group; except between the 150 min and 180 min intervals in the seated group, where the test did not suggest any difference to be significant.

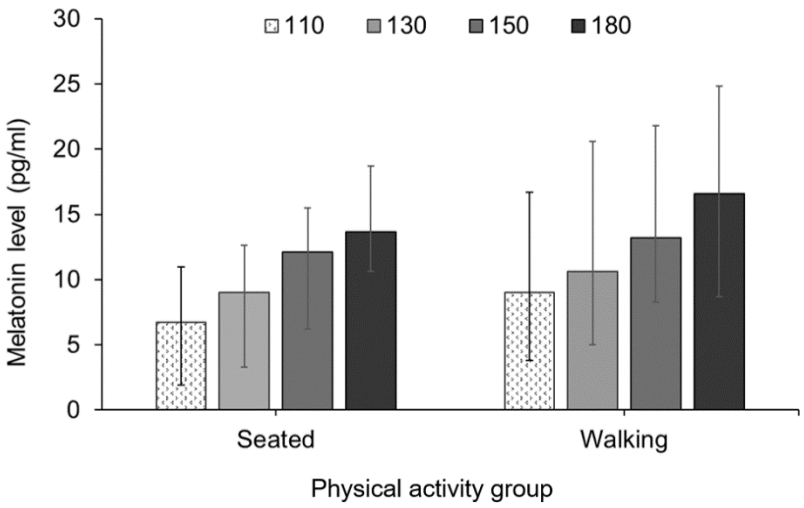

Figure 4.9 Median melatonin level reported at the last interval in the adaptation phase (110 min) and at each test interval during the test phase according to the physical activity during the test phase. Error bars show the IQR.

Table 4.4 Statistical values for interval comparisons using the Wilcoxon signed-rank test for melatonin levels of the two physical activity groups.

		Physical activity group					
		Seated			**Self-selected speed**		
No.	**Intervals**	***Z***	***r***	**Adj.Sig.**	***Z***	***r***	**Adj.Sig.**
1	130 – 110	-3.81	1.55	-	-1.99	0.81	-
2	150 – 110	-3.77	1.54	-	-3.38	1.38	-
3	180 – 110	-3.81	1.55	-	-3.62	1.48	-
4	150 – 130	-3.38	1.38	-	-2.90	1.18	-
5	180 – 130	-3.42	1.40	-	-3.64	1.49	-
6	180 – 150	-1.35	0.55	+	-2.46	1.01	-

Note: for Adj.Sig. (+) indicates $p \geq 0.05$ and (-) indicates $p < 0.05$.
The r values indicate large effect sizes for each interval comparison.

4.5. The Karolinska Sleepiness Scale

The median KSS scores of the 40 participants at each interval are shown in Figure 4.10. The KSS scores progressively decreased as the measurement interval approached habitual bedtimes. The Friedman test suggested a significant change in KSS scores across the measurement intervals ($\chi^2(7) = 179.548$, $p < 0.01$, Kendall's W=0.64; indicating a large effect size).

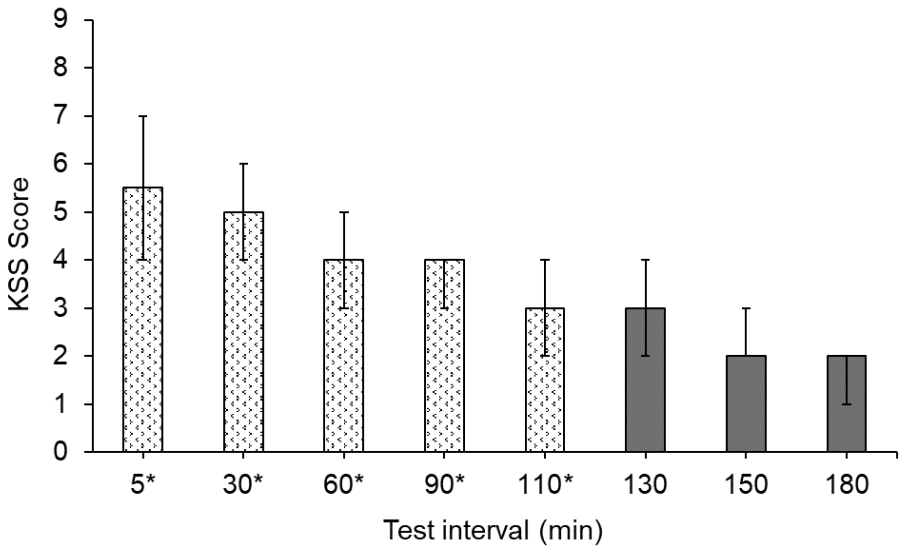

Figure 4.10 Median KSS scores reported at each test interval. Error bars show the IQR. For KSS score: 1 = very sleepy, 9 = extremely alert: *shading distinguishes between the adaptation and test phases of the experiment

Since the Friedman test suggested a significant change with test interval, a series of pairwise comparisons was conducted using *post-hoc* Wilcoxon tests. These results, shown in Table 4.5, suggested that the differences in KSS scores between all intervals were significant, except between the 110 min and the 130 min intervals, where the test did not suggest a difference to be significant.

Table 4.5 Statistical values for interval comparisons using the Wilcoxon signed-rank test for KSS data

No.	Intervals	*Z*	*r*	Effect size	Adj.Sig.
1	30 – 5	-3.64	0.69	L	-
2	60 – 5	-4.77	0.90	L	-
3	90 – 5	-4.82	0.91	L	-
4	110 – 5	-5.29	1.00	L	-
5	130 – 5	-5.02	0.95	L	-
6	150 – 5	-5.36	1.01	L	-
7	180 – 5	-5.38	1.02	L	-
8	60 – 30	-3.55	0.67	L	-
9	90 – 30	-4.29	0.81	L	-
10	110 – 30	-4.99	0.95	L	-
11	130 – 30	-4.85	0.92	L	-
12	150 – 30	-5.28	1.00	L	-
13	180 – 30	-5.42	1.03	L	-
14	90 – 60	-2.87	0.54	L	-
15	110 – 60	-4.58	0.87	L	-
16	130 – 60	-4.02	0.76	L	-
17	150 – 60	-4.87	0.92	L	-
18	180 – 60	-5.07	0.96	L	-
19	110 – 90	-4.32	0.82	L	-
20	130 – 90	-3.19	0.60	L	-
21	150 – 90	-4.64	0.88	L	-
22	180 – 90	-5.20	0.98	L	-
23	130 – 110	-0.42	0.08	S	+
24	150 – 110	-3.17	0.60	L	-
25	180 – 110	-4.36	0.82	L	-
26	150 – 130	-4.22	0.80	L	-
27	180 – 130	-4.46	0.84	L	-
28	180 – 150	-3.40	0.64	L	-

Note: for Adj.Sig., (+) indicates $p \geq 0.05$, and (-) indicates $p < 0.05$, for effect sizes: L = large, M = medium, S = small.

To test whether participants were fairly assigned to each group in the adaptation phase, the Kruskal-Wallis test was used to compare group differences at the same interval. The results did not suggest significant differences across the groups at the 5 min, 30 min, 60 min, 90 min and 110 min intervals ($H(3)= 1.567$, $p= 0.67$, $\eta^2 < 0.01$; $H(3)= 0.677$, $p= 0.88$, $\eta^2 < 0.01$; $H(3)= 0.070$, $p= 0.99$, $\eta^2 < 0.01$; $H(3)= 2.615$, $p= 0.46$, $\eta^2 < 0.01$; $H(3)= 0.698$, $p= 0.87$, $\eta^2 < 0.01$), respectively. The η^2 values indicate no effect for all five intervals. This suggests a fair distribution of participants across the four lighting conditions

To investigate the effect of light conditions on KSS scores, the results from the three measurement intervals in the test phase, as well as the final measurement interval of the adaptation phase (i.e. 110 min), were included. For each light condition, the change in KSS scores over successive intervals was tested using the Friedman test (Figure 4.11). For light conditions, C1, C2, C3 and C4, the Friedman test did not suggest significant differences among the intervals ($\chi^2(3) = 10.329$, $p = 0.02$, Kendall's $W = 0.34$; $\chi^2(3) = 20.111$, $p < 0.01$,

Kendall's W = 0.67; $\chi^2(3) = 10.273$, $p = 0.02$, Kendall's W = 0.34; $\chi^2(3) = 12.689$, $p < 0.01$, Kendall's W=0.42), respectively. The Kendall's W values indicate Medium effect sizes for C1, C3 and C4 and a large effect size for light condition C2.

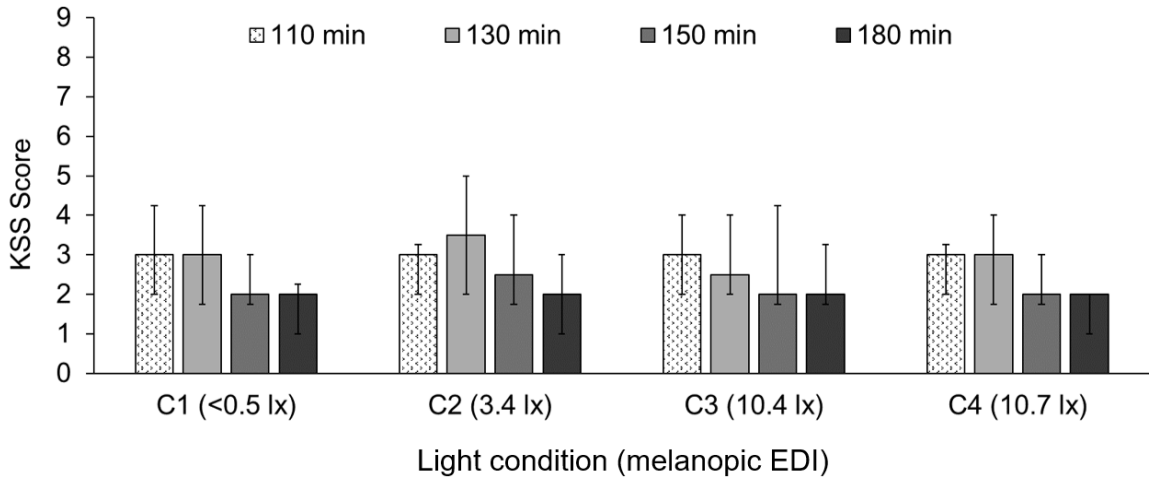

Figure 4.11 Median KSS scores reported at the last interval in the adaptation phase (110 min) and at each test interval during the test phase according to the light condition during the test phase. Error bars show the IQR and KSS score: 1 = very sleepy, 9 = extremely alert

Since the Friedman tests suggested significant changes with test interval, a series of pairwise comparisons was conducted using *post-hoc* Wilcoxon tests. These results, shown in Table 4.6, did not suggest significant changes in KSS scores at any intervals under light conditions (C1, C3 and C4). For light condition C2, a significant decrease in KSS score (feeling less alert) was suggested at the 180 min interval compared to the 130 min interval ($p < 0.05$) and compared to the 110 min interval ($p < 0.05$), as well as at the 150 min interval compared to the 130 min interval ($p < 0.05$).

Table 4.6 Statistical values for interval comparisons using the Wilcoxon signed-rank test for KSS scores under four light conditions C1 to C4

		Light Condition							
		C1		**C2**		**C3**		**C4**	
No.	**Intervals**	*Z*	*r*/effect size (Adj.Sig.)	*Z*	*r*/effect size (Adj.Sig.)	*Z*	*r*/effect size (Adj.Sig.)	*Z*	*r*/effect size (Adj.Sig.)
1	130–110	-0.80	0.32/ M (+)	-0.71	0.29/ M (+)	-0.11	0.04/ S (+)	-1.13	0.46/ M (+)
2	150–110	-1.65	0.68/ L (+)	-1.93	0.79/ L (-)	-1.35	0.55/ L (+)	-1.67	0.68/ L (+)
3	180–110	-1.72	0.70/ L (+)	-2.81	1.15/ L (-)	-2.06	0.84/ L (+)	-2.46	1.00/ L (+)
4	150–130	-2.24	0.91/ L (+)	-2.71	1.11/ L (+)	-2.12	0.87/ L (+)	-1.41	0.58/ L (+)
5	180–130	-1.73	0.71/ L (+)	-2.74	1.12/ L (-)	-2.23	0.91/ L (+)	-2.27	0.93/ L (+)
6	180–150	-0.82	0.33/ M (+)	-2.24	0.91/ L (+)	-1.89	0.77/ L (+)	-2.00	0.82/ L (+)

Note: for Adj.Sig., (+) indicates $p \geq 0.05$, and (-) indicates $p < 0.05$, for effect sizes: L = large, M = medium, S = small.

To compare the KSS scores among the different lighting conditions at the same measurement interval in the test phase, a between-subjects analysis using the Kruskal-Wallis test was conducted. The results did not suggest significant differences between the light conditions ($H(3) = 1.590$, $p = 0.66$, $\eta^2 < 0.01$; $H(3) = 0.972$, $p = 0.81$, $\eta^2 < 0.01$; $H(3) = 1.057$, $p = 0.79$, $\eta^2 < 0.01$) at 130 min, 150 min and 180 min intervals, respectively. The η^2 values indicate no effect for all five intervals.

To investigate the effect of physical activity, a between-subjects analysis using the Mann-Whitney U Test, was used to compare KSS scores between the different physical activity groups at the same measurement interval in the test phase (Figure 4.12). The results suggested a near-significant difference between the two groups at the 130 min interval ($U = 131.000$, $p > 0.05$, PS = 0.33) and the 150 min interval ($U = 140.500$, $p > 0.05$, PS = 0.35), but not at the 180 min interval ($U = 157.000$, $p > 0.05$, PS = 0.39). The PS values indicate small effect sizes at all intervals. However, there was a tendency for seated participants to report feeling less alert than walking participants at the first and second intervals in the test phase.

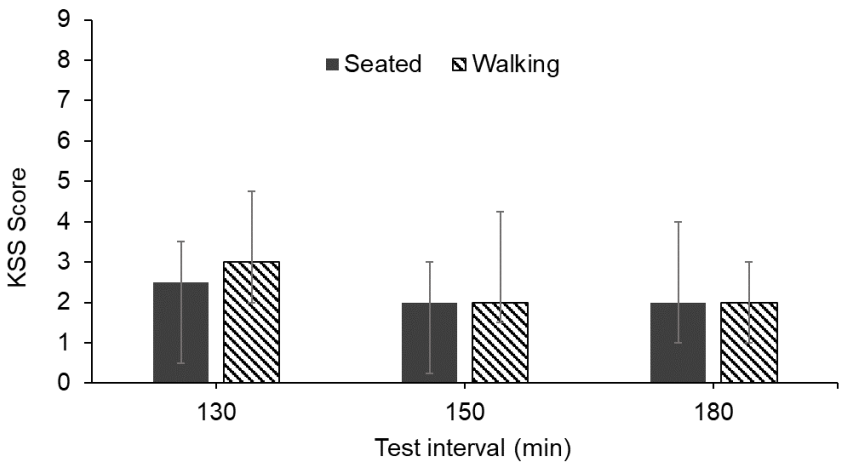

Figure 4.12 Median KSS scores reported at each test interval according to physical activity during the test phase. Error bars show the IQR. Note for KSS score: 1 = very sleepy, 9 = extremely alert

The Friedman test, a within-subjects analysis, was used to compare changes in KSS scores within each physical activity group across the measurement intervals in the test phase and the adaptation phase (i.e. 110 min). The test suggested significant changes across the measurement intervals for both groups (seated: $\chi^2(3) = 35.932$, $p < 0.001$, Kendall's $W = 0.60$, indicating a large effect size; and self-selected speed group: $\chi^2(3) = 25.593$, $p < 0.01$, Kendall's $W = 0.43$, indicating a medium effect size).

A series of pairwise comparisons was conducted using *post-hoc* Wilcoxon tests. These results, shown in Table 4.7, suggested a significant decrease in KSS score (indicating feeling less alert) for the seated group at any given interval compared to the preceding ones ($p < 0.05$ in each case), except between the 150 min and 180 min intervals, where the test did not suggest the difference to be significant. For the self-selected walking speed group, the test suggested a significant decrease in KSS score at any given interval compared to the preceding ones ($p < 0.05$ in each case), except between the adaptation phase and the 130 min interval, as well as between the adaptation phase and the 150 min interval, where no significant changes between them were suggested to be significant.

Table 4.7 Statistical values for interval comparisons using the Wilcoxon signed-rank test for KSS of the two physical activity groups

		Physical activity group							
		Seated				**Self-selected speed**			
No.	**Intervals**	*Z*	*r*	Effect size	Adj.Sig.	*Z*	*r*	Effect size	Adj.Sig.
1	130 – 110	-2.81	1.15	L	-	-1.73	0.71	L	+
2	150 – 110	-3.60	1.47	L	-	-0.44	0.18	S	+
3	180 – 110	-3.58	1.46	L	-	-2.45	1.00	L	-
4	150 – 130	-2.81	1.15	L	-	-3.15	1.29	L	-
5	180 – 130	-2.80	1.14	L	-	-3.49	1.42	L	-
6	180 – 150	-1.67	0.68	L	+	-3.05	1.25	L	-

Note: for Adj.Sig., (+) indicates $p \geq 0.05$, and (-) indicates $p < 0.05$, for effect sizes: L = large, M = medium, S = small

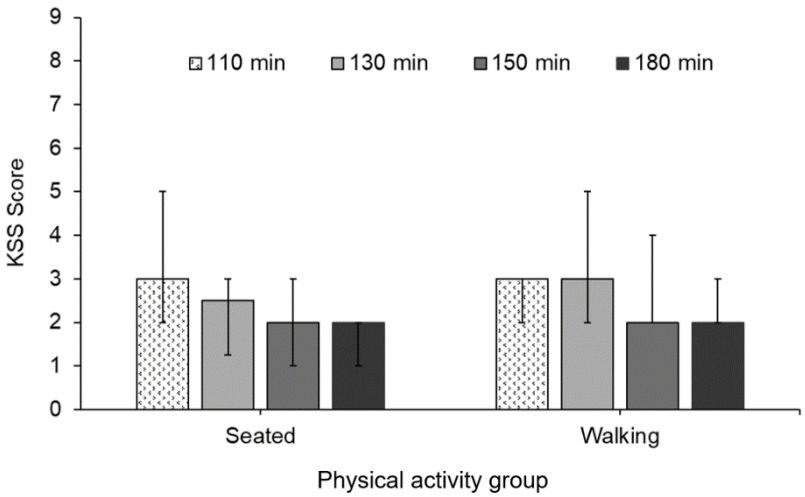

Figure 4.13 Median KSS scores reported at the last interval in the adaptation phase (110 min) and at each test interval during the test phase according to the physical activity during the test phase. Error bars show the IQR and KSS score: 1 = very sleepy, 9 = extremely alert

4.6. Skin temperature

The mean skin temperatures of the 40 participants at each interval are shown in Figure 4.14. The skin temperatures decreased in the first two hours of the experiment and progressively increased in the last hour. A repeated measures ANOVA suggested significant changes across the measurement intervals ($F(3.924, 125.553) = 4.427$, $p < 0.01$, $\eta_p^2 = 0.12$, with Greenhouse-Geisser correction). The partial eta squared (η_p^2) value indicates a medium effect size.

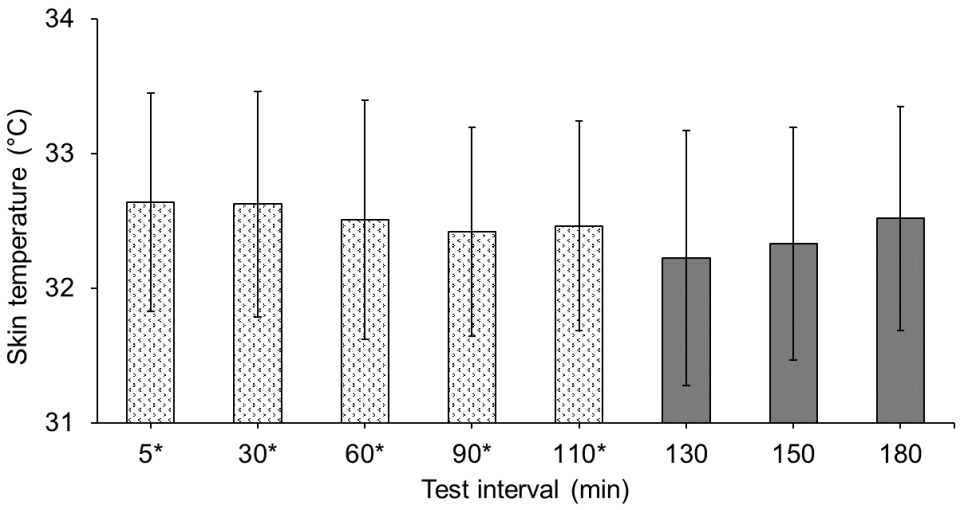

Figure 4.14 Mean skin temperature at each test interval. Error bars show one SD above and below the mean: *shading distinguishes between the adaptation and test phases of the experiment

A series of pairwise comparisons was conducted using t-tests (with Holm-Bonferroni correction for multiple comparisons). These results, shown in Table 4.8, suggested significant differences in skin temperature between the 130 min and 30 min intervals and between the 130 min and 110 min intervals.

Table 4.8 Statistical values for interval comparisons using paired sample t-test for skin temperature data

No.	Intervals	Mean Difference (MD)	Cohen's *d*	Adj.Sig.
1	5 – 30	0.01	0.01	+
2	5 – 60	0.13	0.15	+
3	5 – 90	0.22	0.27	+
4	5 – 110	0.18	0.22	+
5	5 – 130	0.41	0.47	+
6	5 – 150	0.31	0.37	+
7	5 – 180	0.12	0.15	+
8	30 – 60	0.12	0.14	+
9	30 – 90	0.21	0.25	+
10	30 – 110	0.16	0.20	+
11	30 – 130	0.40	0.46	-
12	30 – 150	0.30	0.35	+
13	30 – 180	0.11	0.13	+
14	60 – 90	0.09	0.11	+
15	60 – 110	0.05	0.06	+
16	60 – 130	0.28	0.32	+
17	60 – 150	0.18	0.20	+
18	60 – 180	-0.01	0.01	+
19	90 – 110	-0.04	0.06	+
20	90 – 130	0.20	0.22	+
21	90 – 150	0.09	0.11	+
22	90 – 180	-0.10	0.12	+
23	110 – 130	0.24	0.27	-
24	110 – 150	0.13	0.16	+
25	110 – 180	-0.05	0.07	+
26	130 – 150	-0.11	0.12	+
27	130 – 180	-0.29	0.33	+
28	150 – 180	-0.19	0.22	+

Note: for Adj.Sig., (+) indicates $p \geq 0.05$, and (-) indicates $p < 0.05$. Positive values of the MD indicate that the interval listed first in the comparison has a higher mean than the interval listed second, while negative values indicate the opposite. Cohen's *d* values indicate small effect sizes for each interval comparison

To investigate the effect of light conditions and physical activity on skin temperatures, the results from the three measurement intervals in the test phase and the average of the five measurement intervals of the adaptation phase (i.e. an average of 5 min, 30 min, 60 min, 90 min and 110 min intervals) were included (Figure 4.15). A repeated measures ANOVA was conducted with the intervals as a within-subjects variable and light condition and physical activity as between-subjects factors. The test suggested differences in skin temperature over the intervals to be statistically significant between at least two intervals ($F(3,96) = 6.012$, $p < 0.01$, $\eta_p^2 = 0.16$; indicating a large effect size). Pairwise comparisons using a paired sample t-test (with Holm-Bonferroni correction for multiple comparisons) suggested significant differences in skin temperature between the adaptation phase and 130 min interval and the 130 min and 180 min intervals; these results are shown in Table 4.9.

The effect of light conditions C1, C2, C3 and C4 on skin temperature across the measurement intervals was not suggested to be significant (F(9,96) = 0.931, p = 0.50, η_p^2 = 0.08, indicating a medium effect size) (Figure 4.16). While the effect of physical activity on skin temperature across the measurement intervals was suggested to be significant (F(3, 96) = 2.976, p = 0.04, η_p^2 = 0.085, indicating a medium effect size) (Figure 4.15). A series of pairwise comparisons was conducted using t-tests (with Holm-Bonferroni correction for multiple comparisons); these are shown in Table 4.9. For the seated group, the tests did not suggest any differences in skin temperature between the measurement intervals to be significant. For the self-selected speed group, the results suggested a significant decrease in skin temperature at the 130 min and 150 min intervals compared to the adaptation phase (p < 0.05 in each case) and a significant increase at the 180 min interval compared to the 130 min interval (p < 0.05).

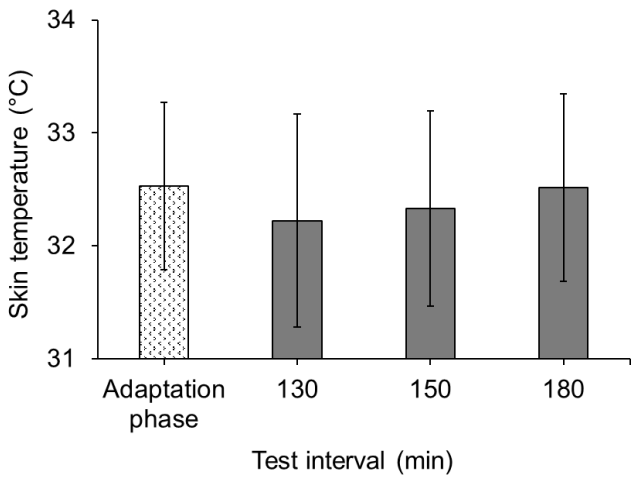

Figure 4.15 Mean skin temperature during the adaptation phase (average of skin temperature at 5 min, 30 min, 60 min, 90 min and 110 min) and at each test interval during the test phase for the 40 participants. Error bars show one standard deviation above and below the mean.

Table 4.9 Statistical values for interval comparisons using paired sample t-test for skin temperature data

No.	Intervals	MD	Cohen's *d*	Adj.Sig.
1	Adaptation phase – 130	0.31	0.37	-
2	Adaptation phase – 150	0.20	0.25	+
3	Adaptation phase – 180	0.01	0.02	+
4	130 – 150	-0.11	0.12	+
5	130 – 180	-0.29	0.32	-
6	150 – 180	-0.19	0.22	+

Note: for Adj.Sig., (+) indicates $p \geq 0.05$, and (-) indicates $p < 0.05$. Positive values of the MD indicate that the interval listed first in the comparison has a higher mean than the interval listed second, while negative values indicate the opposite. Cohen's *d* values indicate small effect sizes for each interval comparison

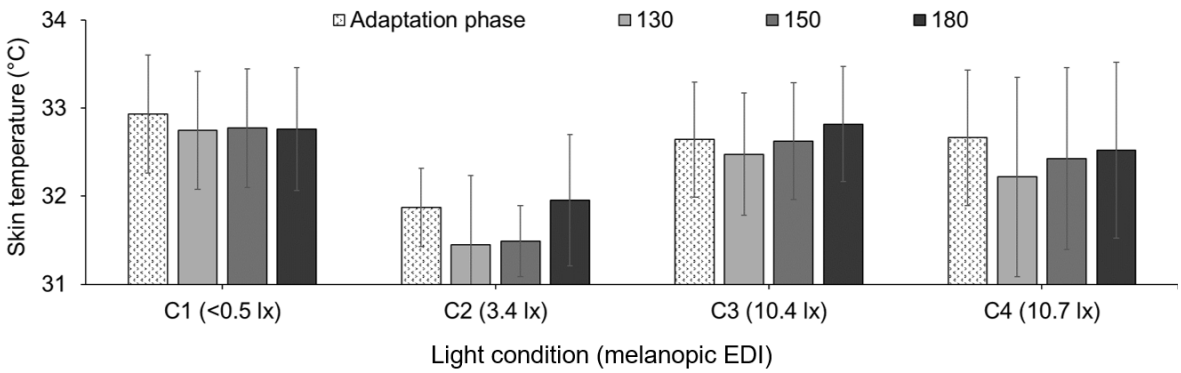

Figure 4.16 Mean skin temperature during the adaptation phase (average of skin temperature at 5 min, 30 min, 60 min, 90 min and 110 min) and at each test interval during the test phase according to the light condition in the test phase. Error bars show one SD above and below the mean

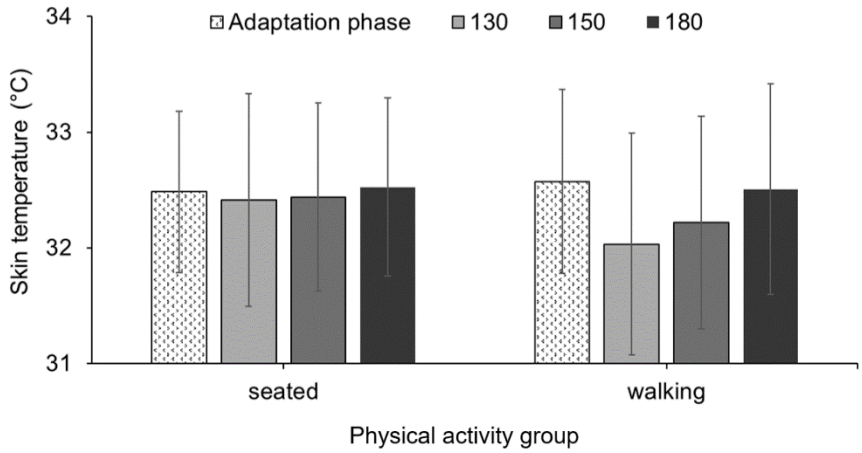

Figure 4.17 Mean skin temperature during the adaptation phase (average of skin temperature at 5 min, 30 min, 60 min, 90 min and 110 min) and at each test interval during the test phase according to the physical activity in the test phase. Error bars show one SD above and below the mean

Table 4.9 Statistical values for interval comparisons using paired sample t-test for skin temperature of the two physical activity groups

		Physical activity group					
		Seated			**Self-Selected Speed**		
No.	**Intervals**	MD	Cohen's *d*	Adj.Sig	MD	Cohen's *d*	Adj.Sig
1	Adaptation phase – 130	0.072	0.09 / S	+	0.54	0.62 / M	-
2	Adaptation phase – 150	0.045	0.06 / S	+	0.36	0.41 / S	-
3	Adaptation phase – 180	-0.040	0.06 / S	+	0.07	0.08 / S	+
4	130 – 150	-0.027	0.03 / S	+	-0.19	0.20 / S	+
5	130 – 180	-0.112	0.13 / S	+	-0.47	0.51 / M	-
6	150 – 180	-0.085	0.11 / S	+	-0.29	0.31 / S	+

Note: for Adj.Sig., (+) indicates $p \geq 0.05$, and (-) indicates $p < 0.05$. Positive values of the MD indicate that the interval listed first in the comparison has a higher mean than the interval listed second, while negative values indicate the opposite.

The effect of physical activity on skin temperature was also assessed using independent sample t-tests, a between-subjects analysis, to compare skin temperatures between the two physical activity groups at the same measurement interval during the test phase. The results of the t-tests did not suggest a significant difference in the skin temperature between the physical activity groups at any of the intervals: 130 min (t(38) = 1.286, *p* = 0.21, Cohen's *d* = 0.62; indicating a medium effect size, MD = 0.381), 150 min (t(38) = 0.807, *p* = 0.43, Cohen's *d* = 0.41; indicating a small effect size, MD = 0.222) and 180 min (t(38) = 0.071, *p* = 0.94, Cohen's *d* = 0.08; indicating a small effect size, MD = 0.019) (see Figure 4.16).

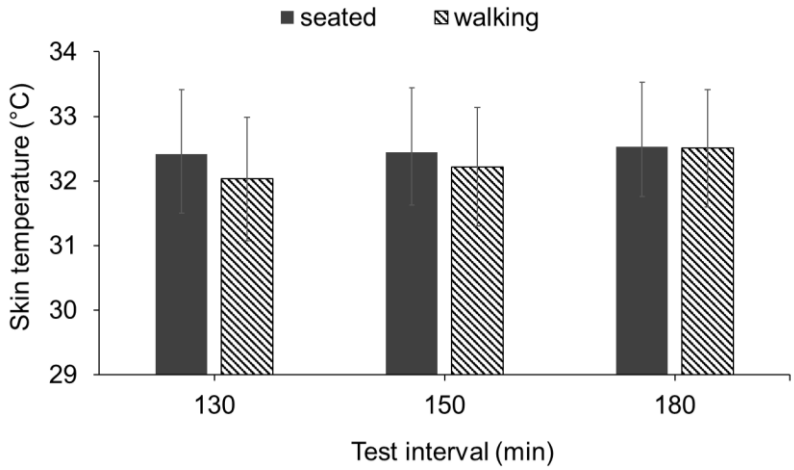

Figure 4.16 Mean skin temperature at each test interval according to whether the test participant was seated or walking during the test phase. Error bars show one SD above and below the mean

The average temperature across all sessions was 23°C, with a range of 20.9°C to 24.1°C in specific test sessions. Within any one test session, the air temperature varied by an amount ranging from almost zero to 1°C, with an average variation of 0.6°C.

4.7. Summary

This chapter presented the results of an experiment where four measures were recorded to investigate the impact on NIF responses of changes to lighting and physical activity. The PVT results indicated that the reaction time at the first interval (5 min) was longer than at most subsequent intervals over the three-hour period of the experiment. Neither lighting conditions nor physical activity were suggested to affect reaction time significantly.

Melatonin levels progressively increased over the three-hour period of the experiment. The tests across the four light conditions indicated inconsistent patterns of change in melatonin levels, suggesting no significant effect of light conditions on melatonin levels. Regards

physical activity, the melatonin level was suggested to significantly increase in both groups at any given interval compared to the preceding intervals, except at the 180 min interval compared to the 150 min interval for the seated group, where the test did not suggest the difference in melatonin level to be significant.

The KSS scores decreased over the three-hour period of the experiment, indicating reduced subjective alertness. Light conditions were not suggested to have a significant effect on KSS scores. Regarding physical activity, seated participants reported lower KSS scores and felt less alert than those who were walking.

The skin temperature results indicated significant variations over the three-hour experimental period. Light conditions were not suggested to have a significant effect on skin temperature. Regarding physical activity, for the self-selected speed group, the tests suggested a significant decrease in skin temperature at the first intervals of the test phase, followed by a significant increase after 30 min of walking. While, the tests did not suggest any significant differences in skin temperature across the measurement intervals in the test phase for the seated group.

In conclusion, these data do not suggest that lighting conditions have a significant impact on reaction time, melatonin levels, subjective alertness or skin temperature. However, physical activity suggests to influence melatonin levels, subjective alertness and skin temperature, with differences observed between seated and walking participants.

Chapter 5

Experiment 1: Discussion

5. Experiment 1: Discussion

5.1. Introduction

Experiment 1 aimed to examine the influence of different lighting conditions on NIF responses under conditions representing pedestrians' experience on minor roads in the evening. Specifically, the experiment targeted hypotheses H1 and H2 (see section 2.8), which asked whether changes in lighting and physical activity would affect the measures of alertness, melatonin level and skin temperature.

Experiment 1 was a laboratory experiment that represented the pedestrian context through the choice of lighting conditions, physical activity and timing. There were four DVs: reaction time to an auditory stimulus (PVT), melatonin levels derived from saliva samples, skin temperature (measured via iButtons) and subjective alertness (KSS). Four lighting conditions were examined, which varied in illuminance at the eye and SPD to achieve different melanopic EDI values (from near zero to 10.7 lx). A test session started three hours before participants' habitual bedtime and lasted for three hours (21:00 - 00:00) to represent walking in the evening, in the hour between 23:00 and 00:00. The first two hours were the adaptation phase (21:00 - 23:00), during which the participants were seated and exposed to lighting representing a domestic interior. For the final hour, intended to represent an outdoor walk, they were exposed to one of the four test lighting conditions shown in Table 3.1. During the test phase, one participant walked on a treadmill at a self-selected speed while the other remained seated.

5.2. The effect of light

As participants approach their habitual bedtime, reaction time to an auditory stimulus (PVT), skin temperature and melatonin level are anticipated to rise, while subjective alertness (KSS score) is expected to fall (i.e., to indicate a lower degree of perceived alertness).[156,217,226,234,380] Consider first the changes in the DVs with time. Throughout the three-hour duration of experiment 1, four trends were observed:

1. Melatonin levels increased. This aligns with the expected trend as participants approach their habitual bedtime.[214]
2. KSS scores decreased. This decrease in KSS score is consistent with the expected trend as participants become less alert approaching their habitual bedtime.[381]

3. Reaction time significantly reduced from the first to subsequent intervals. This can be attributed to a learning effect, where participants become more familiar with the task over time.[382]
4. Skin temperature increased as participants approached their habitual bedtime, aligning with expectations [226,234]. Specifically, during the final hour of the experiment, an increase in skin temperature was noted among the intervals leading up to the habitual bedtime. However, skin temperature changes were inconsistent across intervals during the adaptation phase. This variability in skin temperature could be potentially attributed to room temperature differences between the sessions.

Next, consider the impact of changes in lighting. Based on previous research,[113,114] changes in road lighting characteristics within the typical range of conventional outdoor lighting practice were not expected to affect alertness significantly. This is what was found. Two approaches were used to analyse the results of experiment 1. The first was to compare the results for different lighting conditions (C1, C2, C3 and C4) at a given interval. This did not suggest any significant differences in melatonin levels, reaction time, skin temperature or subjective alertness. The second approach was to compare changes in each DV with time for each lighting condition. Results from the PVT tests did not suggest that transitioning from the lighting in the adaptation phase to the lighting in the test phase significantly affected reaction time under light conditions C1, C2, C3 or C4.

The melatonin levels in the last interval of the test phase (180 min), as compared to the adaptation phase (i.e.110 min interval), showed a significant increase under three light conditions (C1, C2 and C4). However, under light condition C3, the melatonin level showed a non-significant increase (see Table 4.3). This implies that light condition C3 could potentially suppress melatonin secretion between 30 min and one hour of exposure. Nonetheless, the inconsistent patterns of change in melatonin levels across the four light conditions until the 150 min interval (30 min of exposure) make it difficult to draw a definite conclusion; there was a significant increase in melatonin levels at the 150 min interval (after 30 min of exposure) under light conditions C1, C3 and C4, but not under light condition C2. Similarly, there was a significant increase in melatonin levels at the 130 min interval (after 10 min of exposure) under light conditions C1 and C4 but not under light conditions C2 and C3. This inconsistency might suggest that the level of melanopic EDI used in the experiment might not have been sufficient to produce a noticeable effect on melatonin levels. This is further supported by the fact that the other three variables (reaction time, skin temperature and KSS) showed no significant changes under light condition C3 at any of the test intervals.

To account for random changes in melatonin levels, further investigation under extreme light conditions could be beneficial (more details are provided in section 5.4).

The KSS results suggested that participants under the four different light conditions experienced decreased subjective alertness over time. Participants under light condition C2 reported feeling significantly less alert during the test phase (at 150 min and 180 min intervals) than during the adaptation phase (i.e. 110 min interval).In contrast, Figure 4.11 shows an increase in subjective alertness at 130 min interval compared to 110 min interval; this increase was not suggested to be significant ($p > 0.05$) and it is unexpected that the NIF effect of light may be related to this result — condition C2 provided lower illuminance than C3 and C4, as measured by any of the five alpha-opic EDI illuminances (see Table 3.1). Moreover, responses to rating scale data are notoriously noisy.[383]

Skin temperature results suggested no significant differences among the four light conditions. Research by Te Kulve *et al.*[202] found a correlation between skin temperature, subjective alertness and reaction time in PVT. However, their data revealed no significant variances in skin temperature between the light conditions. According to Cajochen *et al.*,[141] skin temperature is not sensitive to variations in light wavelengths. Combining their findings with the null results in our current experiment, it appears that skin temperature may not reliably indicate changes in lighting conditions.

To conclude, the four test light conditions were insufficient to reveal significant differences in reaction time to an auditory stimulus, melatonin levels derived from saliva samples, subjective alertness (scored using KSS) and skin temperature. This is consistent with previous research by Bhagavathula *et al.*[113] and Gibbons *et al.*,[114] who also found no significant effects of road lighting conditions on melatonin levels and alertness, measured through subjective alertness and cognitive performance on a visual reaction time task.

The highest melanopic EDI used in Bhagavathula *et al.*[113], Gibbons *et al.*[114] and this current experiment was approx. 10 lx. Being the recommended maximum threshold for the 3 hours before bedtime to avoid melatonin suppression,[357] it may not be surprising that no effects on alertness and melatonin level were found. Instead of using conditions suitable for road lighting applications, using an extreme light level sufficient to reveal an effect would be useful,[384] thereby demonstrating the experiment's ability to reveal an effect if such an effect exists (discussed in section 5.4).

In summary, this experiment did not support hypothesis H1.

5.3. The effect of physical activity

In the experiment by Gibbons *et al.*[114] targeting a pedestrian application, the participants were seated on chairs for the whole experiment. In experiment 1, the 40 participants were seated during the adaptation phase but then either seated or walking at a self-selected speed during the test phase. The effect of physical activity on alertness, skin temperature and saliva melatonin was tested through two methods:

(1) In the test phase, a between-subjects analysis was used to compare the responses of two physical activity groups at the same measurement interval. The Mann-Whitney U Test was used to compare PVT, melatonin level and KSS data because their distributions were not normal. For skin temperature data, which showed a normal distribution, an independent sample t-test was used.

The results indicate that the seated participants exhibited lower subjective alertness compared to the walking participants. The differences between the physical activity groups reached near statistical significance at the 130 min and 150 min intervals but not at the 180 min interval (Figure 4.10). Neither reaction time in the PVT test (Figure 4.3), melatonin level (Figure 4.6), nor skin temperature (Figure 4.16) suggested a statistically significant effect of physical activity.

(2) A within-subjects analysis was used to compare response changes within each physical activity group across the measurement intervals in the test phase and the representative value for the adaptation phase. The Friedman test was used to analyse the PVT, melatonin level and KSS data. A repeated measures ANOVA was used for skin temperature.

The results for melatonin levels indicated a significant increase in both physical activity groups up to the second interval in the test phase (150 min). At this interval, the melatonin level for the self-selected walking speed group showed a significant increase, while there was no significant increase in melatonin level for the seated group. These changes in melatonin levels are likely associated with the difference in posture between the two groups (sitting versus standing) rather than the physical activity itself.[295,296] Further investigation is needed to explore this conclusion.

The results of the KSS test indicated that for the seated group, there was a significant decrease in subjective alertness between all intervals, except between the 150 min and 180 min intervals. For the self-selected walking speed group, there was a significant decrease in KSS scores in all intervals, except for between the adaptation phase and the first and

second intervals in the test phase, which was an expected outcome due to the physical activity undertaken.[302]

The skin temperature result indicated that, for the seated group, there were no significant changes between the intervals. For the self-selected walking speed group, there was a significant decrease in skin temperature during the first (130 min) and second (150 min) intervals in the test phase (up to 30 min of walking) compared to the adaptation phase. Conversely, there was a significant increase in skin temperature during the final interval in the test phase (180 min) compared to the adaptation phase. This pattern aligns with the expected trend of skin temperature during constant low-intensity exercise, where the skin temperature is expected to decrease initially and then gradually increase over time.[300,301] The initial decrease is believed to be associated with cutaneous vasoconstriction, narrowing of blood vessels at the skin surface — because the body sends more blood to the working muscles and away from the skin. The subsequent increase is related to thermoregulatory vasodilation, which dilates the blood vessels near the skin. This helps the body release the produced heat.[300,301,385]

In summary, this experiment supported hypothesis H2.

5.4. Further work

Similar to the studies of Bhagavathula *et al.*[113] and Gibbons *et al.*,[114] the findings of experiment 1 did not reveal any significant differences among the four lighting conditions. There could be two reasons why neither of these studies showed an effect of lighting on the DVs. First, it is possible that the melanopic EDI levels used were insufficient to reveal an effect. In experiment 1, the melanopic EDI levels ranged from < 0.5 lx to 10.7 lx, while in Bhagavathula *et al.*[113] they ranged from 0.3 lx to 0.8 lx and in Gibbons *et al.*[114] they ranged from 1.5 lx to 5.7 lx. These melanopic EDI levels were chosen to use conditions representative of the application.

Instead of using conditions suitable for real-world application, it would be useful to use an extreme value sufficient to reveal an effect, thereby demonstrating the ability of the experiment to reveal an effect if such an effect exists. This approach follows the advice from Veitch *et al.*[384] that "*if the experiment concludes no significant effect with extreme level, then this suggests an error in either the current experiment or the previous studies.*" According to Veitch *et al.*,[384] for the null conclusion of a study to be robust, a relatively extreme condition needs to be added to the experimental conditions. In this study, essentially, there

is a need to include an extreme level of melanopic EDI illuminance, which, according to previous studies, is expected to lead to a significant difference in the DVs.

For the current context, a melanopic EDI of about 100 lx might be considered extreme. There are two reasons for this: 1) it offers an increase in melanopic EDI of one log unit above that provided under C3 (i.e. 10 lx), 2) previous research by Nowozin *et al.*[314] has shown that melanopic EDI of about 90 lx‡ is the threshold at which melatonin secretion becomes suppressed after 30 min of light exposure in the evening, regardless of the differential effects from prior light history and physical activity before starting the adaptation phase in the experiment day.

The second possible reason for the null findings of experiment 1 and Gibbons *et al.*[114] is related to physical activity level. Higher activity levels could induce a dual-task detriment, placing additional demands on attentional resources than lower activity levels.[249] Therefore, Different physical activity levels might affect participants' responses in the reaction time task. In experiment 1 and the pedestrian-focussed study of Gibbons *et al.,*[114] test participants were either seated or walking slowly. The walking speed in experiment 1 was self-selected by participants and these speeds, ranging from 1.2 $km.h^{-1}$ to 2 $km.h^{-1}$ (i.e. low-intensity physical activity), were slower than the typical walking speed of 4.5 $km.h^{-1}$.[386,387] Walking instead at a normal speed could demand greater cognitive attention to maintain balance.[251,252] and this demand may lead to an effect on alertness measurements. The typical walking speed for adults aged 20 to 29 years is around 4.5 $km.h^{-1}$ to 5.2 $km.h^{-1}$,[387] while the median walking speed for individuals aged 17 to 65 years is around 4.5 $km.h^{-1}$.[386] A walking speed in the range of 4.0 $km.h^{-1}$ to 6.8 $km.h^{-1}$ is considered moderate-intensity exercise according to the Compendium of Physical Activities (activity code 1717).[388] Moderate-intensity exercise is defined as physical activity that raises the heart rate to 50–70% of the HRmax,[285] where HRmax is defined as the participant's age in years subtracted from 220.[389]

In order to verify the null finding of experiment 1, a second experiment was conducted. The experimental design was modified to include an extreme light condition (melanopic EDI of 100 lx) and a faster walking speed during the test phase to better reflect typical walking conditions (walking that raises the heart rate to 50–70% of the HRmax; this required participants to wear a smartwatch to record their heart rates). Additionally, three light conditions (C1, C2 and C3) with a maximum melanopic EDI of 10.4 lx were included to replicate the conditions used in experiment 1. This offered the dual purpose of verification by replication and an analysis of the effect of a higher level of physical activity.

5.5. Summary and additional hypotheses

The results of experiment 1 did not suggest a significant effect of lighting on alertness, melatonin and skin temperature in the context of evening walking, in agreement with the results of previous studies.[113,114] It is recommended[384] that such null findings found when using lighting conditions relevant to practice are tested by extending the range of conditions employed to force a significant effect if one exists. Doing so provides more confidence that the null findings gained under practically relevant conditions are valid. A second experiment was therefore conducted. Chapters 6 and 7 describe the method and results for this further experiment.

Experiment 2 was designed to test two additional hypotheses:

H3. Melanopic EDI levels significantly greater than those typical of conventional road lighting will affect alertness and melatonin levels when walking in the evening.

The findings from experiment 1 indicated that physical activity had no significant impact on reaction time in PVT. Participants who were walking, as opposed to those who were seated, reported similar levels of subjective alertness in the first 30 min of walking as they did during the adaptation phase. In contrast, the seated participants experienced a decrease in subjective alertness. There was a higher increase in melatonin levels after 30 min of walking compared to sitting, possibly due to changes in melatonin concentration in saliva. Additionally, there was a decrease in skin temperature only in the first 30 min of walking, likely attributable to changes in blood flow to regulate heat loss in the body.

The effect of walking at a speed that better reflects typical walking conditions will be further assessed in experiment 2, in conjunction with data from experiment 1, through the introduction of an additional hypothesis (H4):

H4. Walking at a moderate speed, compared to sitting and walking at a self-selected speed, will affect alertness and melatonin levels.

Chapter 6

Experiment 2: Method

6. Experiment 2: Method

6.1. Introduction

A second experiment was conducted to test the null findings of experiment 1 by extending the range of conditions. This second experiment replicated the procedure of experiment 1 but with two main changes: 1) an extreme lighting condition was included, i.e. one having a much higher melanopic EDI than was used in experiment 1 and 2) a faster walking speed was used during the test phase to better represent typical walking speed. This second change required participants to wear a smartwatch during trials to record their heart rates. The method for experiment 2 is the same as outlined in Chapter 3 for experiment 1, with the exceptions detailed below.

6.2. Apparatus

In each test session, there were two test participants. As in experiment 1, they remained seated for the adaptation phase, but for the test phase, both participants walked on a treadmill; in experiment 1, only one participant walked during the test phase while the other remained seated. The apparatus used was, therefore, identical to that for experiment 1, except for the addition of a second treadmill to enable both participants to walk during the test phase (Figure 6.1).

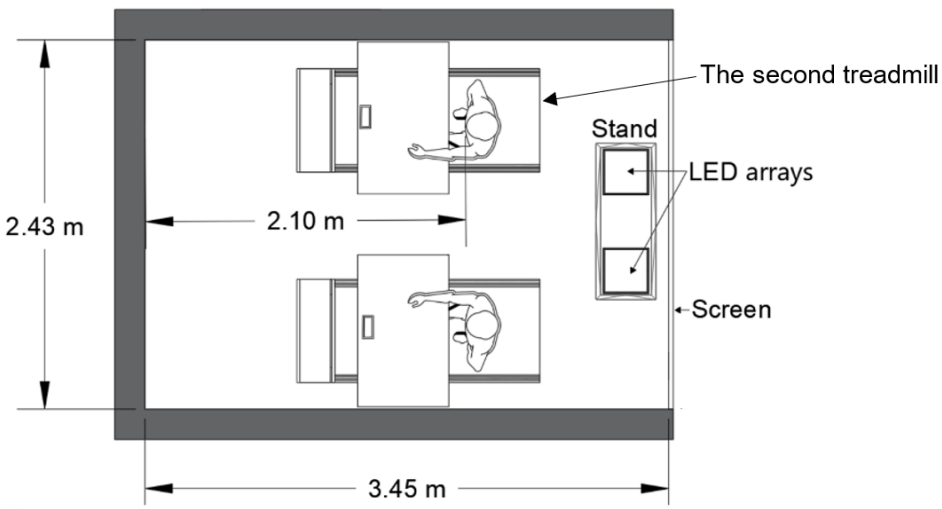

Figure 6.1 The laboratory plan for experiment 2. This is identical to experiment 1 (see Figure 3.1) except for adding the second treadmill

6.3. Independent variables

The experiment involved one IV, which was the lighting condition. This variable had four levels, defined by variations in illuminance and SPD, as indicated in Table 6.1. The illuminances reported here are vertical illuminance at 1.5 m above the floor, in the participants' direction of view.

Participants were exposed for one hour to one of four test conditions in the test phase. These are labelled as L1 to L4 in Table 6.1. Lighting conditions L1, L2 and L3 were identical to conditions C1, C2 and C3 in experiment 1. The fourth lighting condition (L4) used the same SPD as L3, but with the intensity changed to increase the melanopic content from melanopic EDI 10.4 lx to 98.8 lx (photopic illuminance = 83.0 lx). Figure 6.2 shows the SPDs of the four light conditions in the test phases in experiment 2.

Table 6.1 Light conditions (illuminance and SPD-derived metrics) used in the adaptation and test phases of experiment 2

Lighting condition	Illuminance (lx)	CCT (K)	Alpha-opic equivalent daylight illuminance (lx)[a]				
			S-cone-opic	M-cone-opic	L-cone-opic	Rhodopic	Melanopic
Adaptation condition							
	25	2700	8.2	19.5	25.6	12.7	10.7
Test Conditions							
L1	<0.5	2700	<0.5	<0.5	<0.5	<0.5	<0.5
L2	8	2700	2.6	6.1	8.0	4.0	3.4
L3	8	5800	9.2	8.2	8.6	9.4	10.4
L4	83	5800	110.1	81.8	89.7	89.9	98.8

[a] alpha-opic and melanopic equivalent daylight (D65) illuminances calculated using luox from Spitschan *et al.*[355]

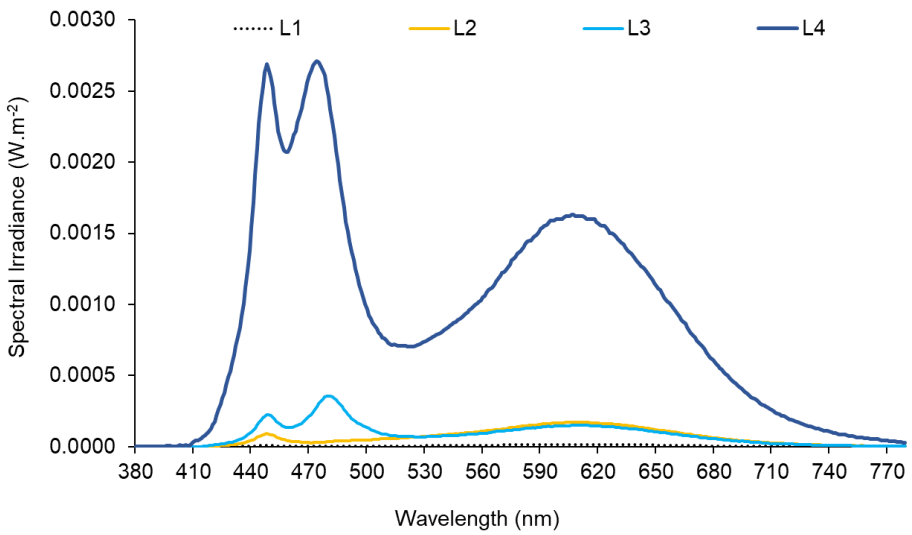

Figure 6.2 SPDs of the four light conditions in the test phases shown in absolute units

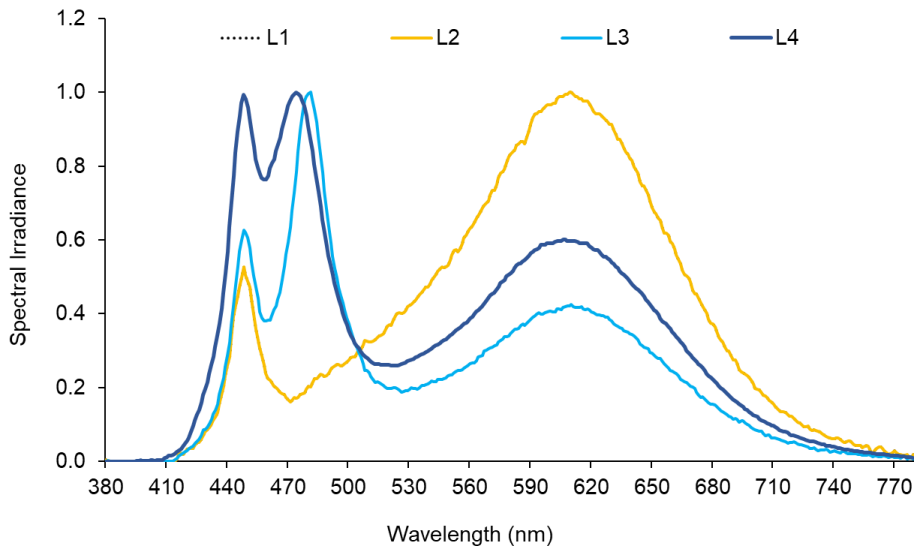

Figure 6.3 SPDs of the four light conditions in experiment 2 normalised to a peak response of unity (Note that the curves for light conditions L1 and L2 overlap)

6.4. Dependent variables

The experiment involved three DVs, assessing the influence of changes in lighting on melatonin levels and alertness. Alertness was evaluated through an auditory PVT task and subjective alertness using the KSS. These tasks replicated their usage in experiment 1.

As in experiment 1, melatonin levels were determined from saliva samples collected using Salivette tubes (Sarstedt) at approx. 30 to 50 min intervals during the adaptation and test phases. The tubes were labelled and stored in a freezer set to -20°C. Following a change in University of Sheffield guidance subsequent to experiment 1, the saliva samples were transferred at weekly intervals to the University's biorepository, where they were stored at -80 °C. Upon completion of all trials, the samples were packaged in dry ice to reduce degradation and transported to the Chorono@work laboratory at the University of Groningen (the Netherlands) for analysis using radioimmunoassay.[358,359] In experiment 1, skin temperature was also included as a DV. This was omitted from experiment 2 (see section 5.2 for explanation).

6.5. Procedure

Similar to experiment 1, the participants arrived at the laboratory at least 45 min before the start of the adaptation phase to allow for preparation. Two examinations were conducted to confirm normal visual acuity and colour vision (see section 3.5).

For experiment 2, participants wore a Polar Vantage M2 smartwatch (see Figure 6.3) to record their heart rates. This was worn throughout the experiment but used specifically to

ensure that during the test phase, participants walked on the treadmill at a speed that maintained their heart rate between 50% and 70% of their HRmax. Previous work by Ruiz-Malagón *et al.*[390] and Shumate *et al.*[391] shows that the Polar Vantage smartwatch measures heart rate with sufficient precision.

Figure 6.4 Front (left) and rear (right) views of the Polar Vantage M2 Smartwatch.

Heart rate was recorded continuously throughout the experiment session at 1s intervals. The speed of the treadmill was adjusted so that the heart rate reached the lower bound of the target range (50% ± 5% of HRmax).[250] The treadmill speed was set at 2.5 km.h^{-1} for the first two min, a period sufficient to reach the target exercise intensity.[392] Following the protocol of Soga *et al.*[250] when the heart rate of the participant did not reach the target range, the treadmill speed was increased each min in intervals of 0.5 km.h^{-1}. If the heart rate exceeded the target range, the speed of the treadmill was decreased by 0.1 km.h^{-1} each min. Participants tended to reach the target heart rate range after about 6 min of walking. After doing so, participants were seated for at least 20 min before the adaptation phase started to allow enough time to rest.[393] The treadmill gradient was set to 0%, representing a horizontal surface.

Participants' hearing thresholds were determined twice; while the participants were seated and while both participants were walking at the determined walking speed. Figure 6.4 shows the time schedule of experiment 2. Identical to experiment 1, experiment 2 lasted for 3 h. During this period, the DVs (Saliva samples, PVT and KSS) were recorded at intervals of approx. 30 min, with measurements centred on min 5, 30, 60, 90 and 110 in the adaptation phase and min 130, 150 and 180 in the test phase. For min 30 and 90 in the adaptation

phase, only the KSS was recorded. Two hours after the start of the adaptation phase, the light setting changed to one of the four test conditions shown in Table 6.1 and both participants changed from being seated to walking on the treadmill. The treadmill was set to the walking speed that was established for that participant in the preparation phase.

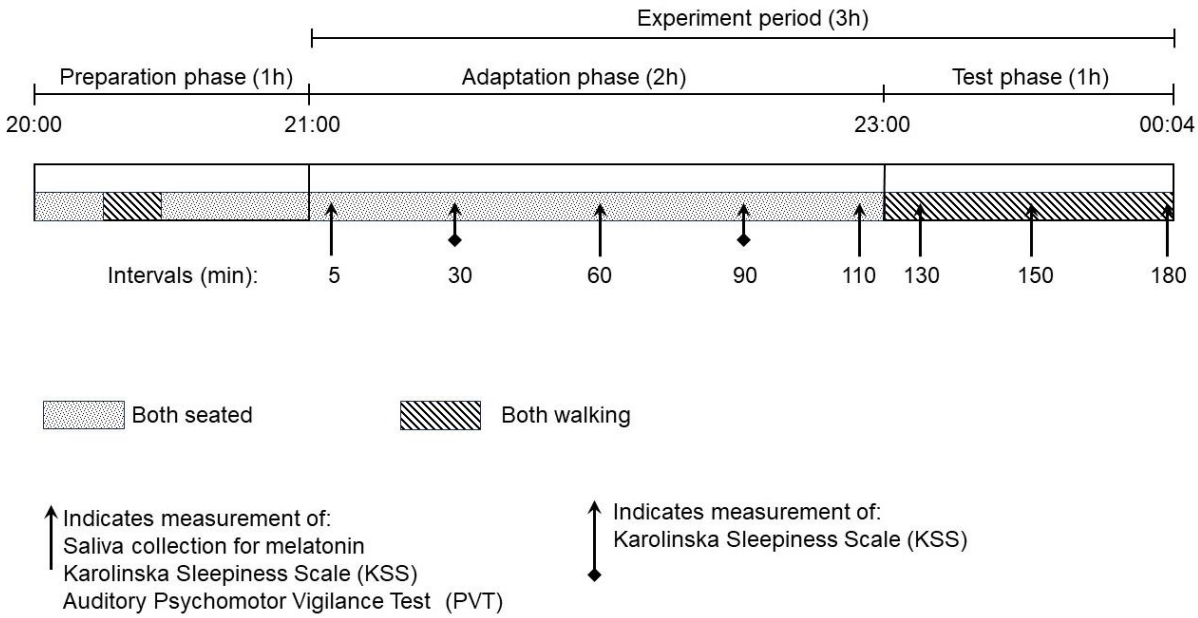

Figure 6.5 Overview of the test protocol for experiment 2

6.6. Sample recruitment

The recruitment criteria used in experiment 1 (see section 3.7) were also followed for experiment 2. A total of 40 participants, 20 females and 20 males, were recruited. The median age of the participants was 21 years, ranging from 18 to 30 years. Experiment 2 followed the same procedures as experiment 1 regarding participants' sleep-wake schedule for seven days prior to the experiment, food instructions for the experiment day and refreshments during the experiment (see section 3.7).

Ethical approval for experiment 2 was received from the University of Sheffield Research Ethics Committee on 21 September 2022 (Reference Number 042711). In accordance with this, informed consent was obtained from all participants for the experiment, and all collected data were anonymised to ensure privacy and confidentiality. The participant consent form can be found in Appendix F.

6.7. Summary

The main goal of experiment 2 was to verify the null finding of experiment 1. The experimental design was modified to include an extreme light condition (melanopic EDI of 100 lx) and a faster walking speed during the test phase to better reflect typical walking conditions. The experiment comprised three phases: preparation, adaptation and test. Participants' visual acuity, colour vision and hearing thresholds were assessed during the preparation phase. Additionally, participants wore a smartwatch to record their heart rates, and the treadmill was set to a speed that increased the participant's heart rate to 50–70% of the HRmax.

Following the preparation phase, the adaptation phase began, during which all 40 participants were exposed to the same light level for two hours while seated, mimicking typical residential indoor lighting. In the subsequent test phase, participants were divided into four groups, each exposed to one of four lighting conditions (L1 to L4). All of the participants walked on a treadmill at a moderate intensity speed. The experiment had three DVs: reaction time (measured via PVT), subjective alertness (assessed via KSS) and melatonin levels (collected via saliva samples). Data for these variables were collected at six to eight intervals throughout the experiment. The data collected from experiment 2 was analysed using the same analysis plan that was used in experiment 1 (see section 3.8). The results of experiment 2 are presented in the next chapter (Chapter 7).

Chapter 7

Experiment 2: Results

7. Experiment 2: Results

7.1. Introduction

Chapter 7 presents the findings from the experiment outlined in Chapter 6. This experiment measured NIF responses under various lighting conditions, extending experiment 1 by including a relatively extreme lighting condition and a faster walking speed. Initially, whether these results originated from a normally distributed population was verified, as this determination informs the selection of appropriate statistical tests for assessing the significance of observed differences. Following this, the results of each NIF test were analysed sequentially. This involved examining differences across all variable levels and, when indicative of a statistically significant effect, conducting further pairwise tests with significance values adjusted using the Holm-Bonferroni correction to account for multiple comparisons.[378] As Ellis[379] recommends, effect sizes are reported for all results regardless of whether or not the differences are suggested to be statistically significant (see section 4.1).

7.2. Data normality

The data recorded for each DV were initially checked to see if they were drawn from a normally distributed population. As explained in 3.8.2, this was done by four methods of analysis: comparing measures of central tendency, statistical tests (Shapiro-Wilks and Kolmogorov-Smirnov), measures of dispersion (skewness and kurtosis) and graphical representations (histogram and box plot). The results of these analyses are shown in Appendix G.

It was concluded that reaction times, melatonin levels and KSS ratings did not exhibit a normal distribution; Figure 7.1 shows, as an example, the non-normal distribution of the melatonin dataset at six intervals. As a result, non-parametric tests were used for the analyses. First, Friedman tests were used to compare changes in responses within each lighting group across the measurement intervals. Second, Kruskal-Wallis tests were employed to compare responses between the different lighting groups at the same measurement interval.

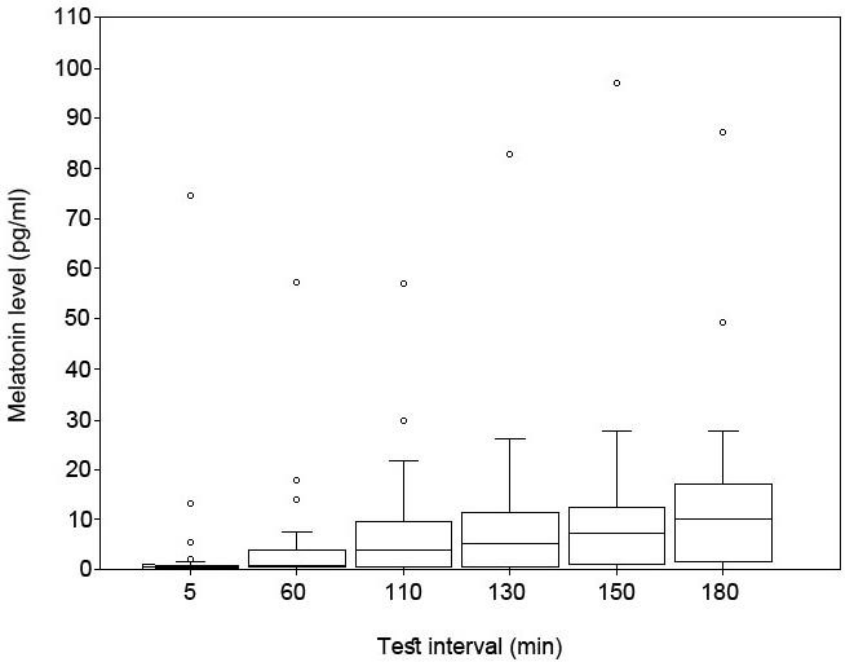

Figure 7.1 Box plots of melatonin level at six intervals. These data are not suggested to be drawn from a normally distributed population because the median lines do not tend to be central within each box, and the whiskers do not tend to be of similar length above and below each box.

7.3. Psychomotor Vigilance Test

Figure 7.2 shows the median reaction times at the six test intervals. Analysis of these data over the three-hour duration indicates a longer reaction time at the first interval (5 min) and a shorter reaction time at the final interval (180 min) than at the other intervals. The Friedman test suggested a significant change across the intervals ($\chi^2(5) = 23.474$, $p < 0.01$, Kendall's $W = 0.117$). Kendall's W value indicates a small effect size.

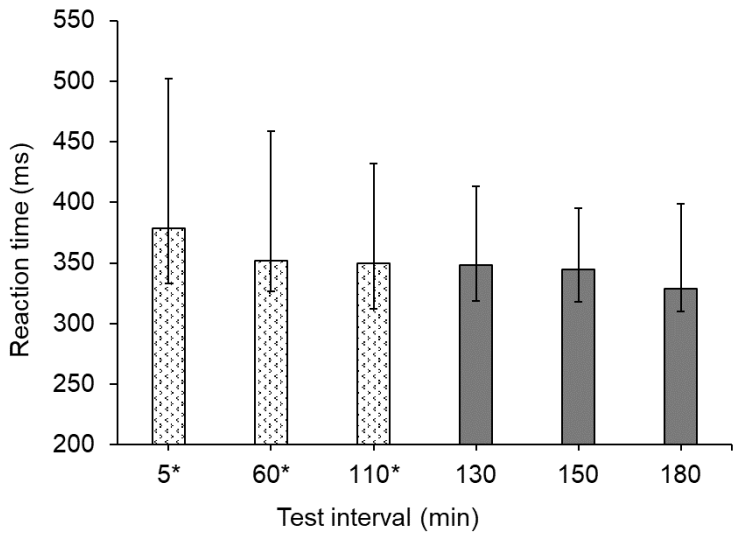

Figure 7.2 Median reaction times measured using the auditory PVT at each test interval. Error bars show the IQR: *shading distinguishes between the adaptation and test phases of the experiment.

Since the Friedman test suggested a significant change with test interval, a series of pairwise comparisons was conducted using *post-hoc* Wilcoxon tests. These results, shown in Table 7.1, indicated a longer reaction time at the first measurement interval (5 min; median reaction time = 379 ms) in comparison to the subsequent test intervals ($p < 0.05$ for each comparison), and a shorter reaction time at the final test interval (180 min; median reaction time = 329 ms) than at 150 min and 130 min intervals.

Table 7.1 Statistical values for interval comparisons using the Wilcoxon signed-rank test for reaction time data

No.	Intervals	*Z*	*r*	Effect size	Adj.Sig.
1	60–5	-2.816	0.73	L	-
2	110–5	-2.964	0.77	L	-
3	130–5	-3.193	0.82	L	-
4	150–5	-3.031	0.78	L	-
5	180–5	-4.424	1.14	L	-
6	110–60	-0.249	0.06	S	-
7	130–60	-1.143	0.30	M	+
8	150–60	-1.290	0.33	M	+
9	180–60	-2.635	0.68	L	+
10	130–110	-0.780	0.20	S	+
11	150–110	-0.807	0.21	S	+
12	180–110	-2.107	0.54	L	+
13	150–130	-0.652	0.17	S	+
14	180–130	-2.987	0.77	L	-
15	180–150	-3.671	0.95	L	-

Note: for Adj.Sig., (+) indicates $p \geq 0.05$, and (-) indicates $p < 0.05$, for effect sizes: L = large, M = medium, S = small.

For the adaptation phase, all participants were exposed to the same lighting condition, and thus, no differences were expected between the groups subsequently allocated to the four test lighting conditions. Comparing the differences in reaction time between the groups at each interval in the adaptation phase (5 min, 60 min and 110 min) therefore test whether participants were fairly assigned to each group. The results from the Kruskal-Wallis tests did not suggest significant differences at the 5 min, 60 min and 110 min intervals ($H(3) = 3.165$, $p = 0.37$, $\eta^2 = 0.08$; $H(3) = 3.266$, $p = 0.35$, $\eta^2 = 0.08$; $H(3) = 2.146$, $p = 0.54$, $\eta^2 = 0.06$). The η^2 values for these intervals indicate a medium effect size.

To compare differences between lighting conditions, the results from the three measurement intervals in the test phase, as well as the final measurement interval of the adaptation phase, were included. Specifically, for the melatonin and KSS data, only the final measurement interval was used to represent the adaptation phase if the values in the adaptation phase varied significantly between intervals. The average of the final two

adaptation intervals (60 min and 110 min) was used for the reaction time data as they were not suggested to be significantly different.

For each light condition, the change in reaction times over successive intervals was tested using the Friedman test (Figure 7.3). For light conditions L1, L2 and L3, the Friedman test did not suggest any differences in reaction time between the measurement intervals to be significant ($\chi^2(3) = 2.091$, $p = 0.55$, Kendall's $W = 0.07$; $\chi^2(3) = 1.727$, $p = 0.63$, Kendall's $W = 0.06$; $\chi^2(3) = 2.727$, $p = 0.13$, Kendall's $W = 0.191$), respectively. The Kendall's W values for the three light conditions indicate small effect sizes. In other words, the change in lighting from the adaptation phase to the test phase did not significantly affect reaction time under any of these three light conditions L1, L2 and L3. For lighting condition L4, the Friedman test suggested significant differences among the measurement intervals ($\chi^2(3) = 16.440$, $p < 0.01$, Kendall's $W = 0.55$, indicating a large effect size).

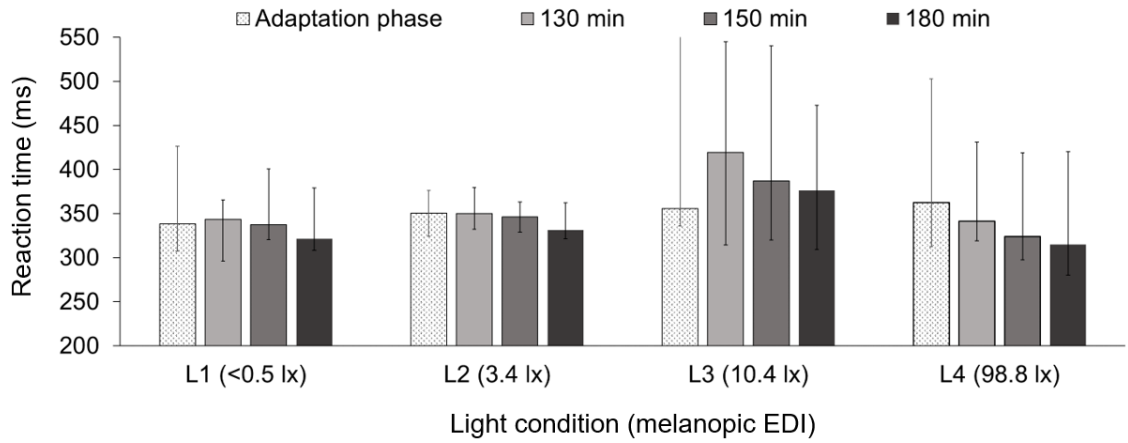

Figure 7.3 Median reaction times during the adaptation phase (average of reaction times at 60 min and 110 min) and at each test interval during the test phase according to the light condition during the test phase. Error bars show the IQR.

Since the Friedman test suggested significant changes with test interval under light condition L4, a series of pairwise comparisons was conducted using *post-hoc* Wilcoxon tests. These results are shown in Table 7.2. The results suggested that the reaction time at the final interval of the test phase (180 min) was significantly shorter compared to the reaction times at the adaptation phase, as well as at the 130 min and 150 min intervals. Additionally, reaction time at the 150 min interval was significantly shorter than that at the 130 min interval, showing a progressive improvement in reaction time over the test intervals in the test phase.

Table 7.2 Statistical values for interval comparisons using the Wilcoxon signed-rank test for reaction time under light condition L4.

No.	Intervals	*Z*	*r*	Adj.Sig.
1	Adaptation phase – 130	-1.478	0.60	+
2	Adaptation phase – 150	-2.191	0.89	+
3	Adaptation phase – 180	-2.599	1.06	-
4	130 – 150	-2.655	1.09	-
5	130 – 180	-2.499	1.02	-
6	150 – 180	-2.449	1.00	-

Note: for Adj.Sig., (+) indicates $p \geq 0.05$, and (-) indicates $p < 0.05$.
The *r* values indicate large effect sizes for each interval comparison

To compare reaction time over the different lighting conditions at the same measurement interval in the test phase, a between-subjects analysis using the Kruskal-Wallis test was conducted. The results did not suggest significant differences at either the 130 min, 150 min or 180 min intervals ($H(3) = 3.597$, $p = 0.31$, $\eta^2 = 0.09$; $H(3) = 2.548$, $p = 0.47$, $\eta^2 = 0.07$; $H(3) = 2.915$, $p = 0.41$, $\eta^2 = 0.07$). The η^2 values indicate medium effect sizes at the three test intervals.

7.4. Melatonin levels

The median melatonin levels of the 40 participants at each interval are shown in Figure 7.4. As expected, the melatonin levels progressively increased as the measurement interval approached habitual bedtimes. The Friedman test suggested a significant change across the measurement intervals ($\chi^2(5) = 83.786$, $p < 0.01$, Kendall's $W = 1.02$; indicating a large effect size).

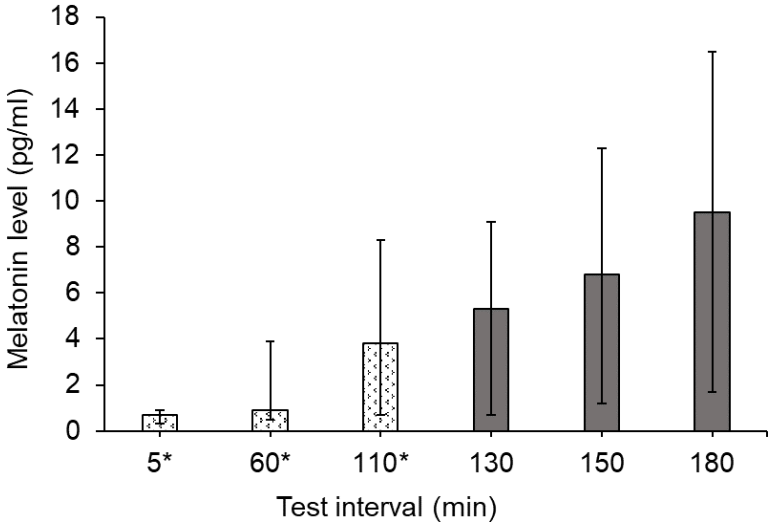

Figure 7.4 Median melatonin levels derived from saliva samples collected at each test interval. Error bars show the IQR: *shading distinguishes between the adaptation and test phases.

Since the Friedman test suggested a significant change with test interval, a series of pairwise comparisons was conducted using *post-hoc* Wilcoxon tests. These results, shown in Table 7.3, suggested that differences in melatonin levels between all the intervals were significant; where the melatonin level was suggested to increase significantly at any given interval compared to the preceding intervals.

Table 7.3 Statistical values for interval comparisons of melatonin levels using the Wilcoxon signed-rank test

No.	Intervals	*Z*	*r*
1	60 – 5	-3.381	0.87
2	110 – 5	-4.222	1.09
3	130 – 5	-5.066	1.31
4	150 – 5	-5.189	1.34
5	180 – 5	-5.162	1.34
6	110 – 60	-4.343	1.12
7	130 – 60	-4.885	1.26
8	150 – 60	-5.162	1.34
9	180 – 60	-4.982	1.29
10	130 – 110	-3.419	0.88
11	150 – 110	-4.090	1.06
12	180 – 110	-3.901	1.01
13	150 – 130	-3.749	0.97
14	180 – 130	-3.959	1.02
15	180 – 150	-3.213	0.83

Note: for each interval comparison, Adj.Sig. < 0.05, indicating significant differences, with *r* values indicating large effect sizes

To test whether participants were fairly assigned to each group in the adaptation phase, the Kruskal-Wallis test was used to compare group differences at the same interval. The results did not suggest significant differences across the groups at the 5 min, 60 min and 110 min intervals ($H(3) = 1.307$, $p = 0.73$, $\eta^2 = 0.03$; $H(3) = 1.178$, $p = 0.76$, $\eta^2 = 0.03$; $H(3) = 0.552$, $p = 0.91$, $\eta^2 = 0.01$), respectively. The η^2 values indicate small effect sizes at these intervals. This suggests a fair distribution of participants across the four lighting conditions.

To investigate the effect of light conditions on melatonin levels, the results from the three measurement intervals in the test phase, as well as the final measurement interval of the adaptation phase (i.e. 110 min), were included. For each light condition, the change in melatonin level over successive intervals was tested using the Friedman test (Figure 7.5). For light conditions, L1, L2, L3 and L4 the Friedman test suggested significant differences among the measurement intervals ($\chi^2(3) = 18.840$, $p < 0.01$, Kendall's $W = 0.63$; $\chi^2(3) = 12.765$, $p < 0.01$, Kendall's $W = 0.43$; $\chi^2(3) = 22.898$, $p < 0.01$, Kendall's $W = 0.76$; $\chi^2(3) = 7.800$, $p = 0.05$, Kendall's $W = 0.26$), respectively. Kendall's *W* values indicate large effect sizes for the three light conditions L1, L2 and L3, and a small effect size for light condition L4.

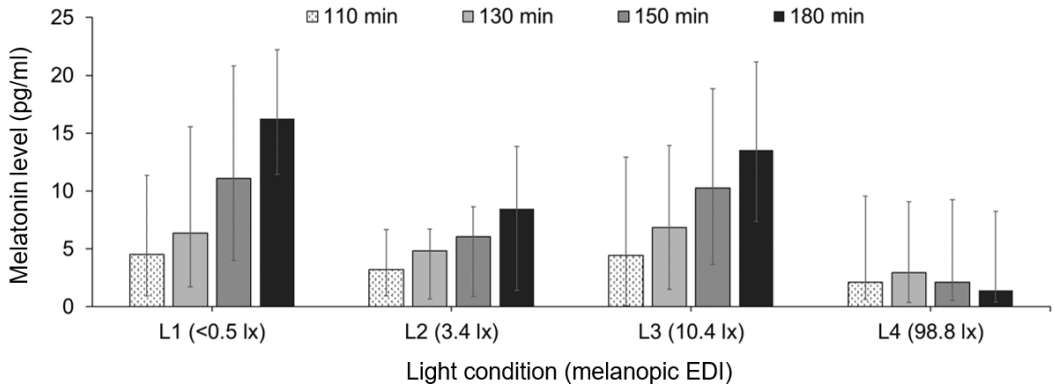

Figure 7.5 Median melatonin level at the last interval in the adaptation phase (110 min) and at each interval during the test phase for each light condition during the test phase. Error bars show the IQR.

Since the Friedman tests suggested significant changes with test interval, a series of pairwise comparisons was conducted using *post-hoc* Wilcoxon tests. These results are shown in Table 7.4. This suggested significant increases in melatonin levels under lighting conditions L1, L2 and L3, with the highest melatonin levels reached at 180 min interval. For light condition L4, the results suggested a near-significant decrease in melatonin level at 180 min compared to the 150 min interval, as well as at 180 min compared to 130 min. In other words, exposure to light condition L4 resulted in the suppression of melatonin but only after an exposure of 30 min to one hour.

Table 7.4 Statistical values for interval comparisons using the Wilcoxon signed-rank test for melatonin levels under four light conditions L1 to L4

		Light Condition							
		L1		**L2**		**L3**		**L4**	
No.	**Intervals**	*Z*	*r* (Adj.Sig.)	*Z*	*r* (Adj.Sig.)	*Z*	*r* (Adj.Sig.)	*Z*	*r*/effect size (Adj.Sig.)
1	130 – 110	-1.784	0.73 (+)	-2.675	1.09 (-)	-2.527	1.03 (-)	-0.255	0.10/S (+)
2	150 – 110	-2.191	0.90 (+)	-2.501	1.02 (+)	-2.805	1.15 (-)	-0.415	0.17/S (+)
3	180 – 110	-2.599	1.06 (-)	-2.497	1.02 (+)	-2.701	1.10 (-)	-2.134	0.87/L (+)
4	150 – 130	-2.497	1.02 (-)	-1.956	0.80 (+)	-2.803	1.15 (-)	-0.357	0.15/S (+)
5	180 – 130	-2.803	1.14 (+)	-2.395	0.98 (+)	-2.703	1.10 (-)	-2.402	0.98/L (+)
6	180 – 150	-2.599	1.06 (-)	-1.275	0.52 (+)	-2.703	1.10 (-)	-2.524	1.03/L (+)

Note: for Adj.Sig., (+) indicates $p \geq 0.05$, and (-) indicates $p < 0.05$, for effect sizes: L = large, M = medium, S = small.The *r* values indicate large effect sizes for each interval comparison under light conditions L1, L2 and L3

To compare melatonin levels among the different lighting conditions at the same measurement interval in the test phase, a between-subjects analysis using the Kruskal-Wallis test was conducted. The results did not suggest significant differences at either the 130 min or 150 min intervals ($H(3) = 2.691$, $p = 0.44$, $\eta^2 = 0.07$; indicating a medium effect size; $H(3) = 6.321$, $p = 0.10$, $\eta^2 = 0.16$; indicating a large effect size). For the 180 min interval,

the Kruskal-Wallis test indicated a significant difference between the groups (H(3) = 11.622, $p = 0.009$, $\eta^2 = 0.30$, indicating a large effect size). Since the Kruskal-Wallis test suggested significant differences between the groups at 180 min interval, a series of pairwise comparisons was conducted using the Mann-Whitney U test with Holm-Bonferroni correction applied; a significant difference was suggested only between light conditions L1 and L4 (U = 8.000, $p < 0.05$, PS = 0.08; indicating a small effect size).

7.5. The Karolinska Sleepiness Scale

The median KSS scores of the 40 participants at each interval are shown in Figure 7.6. The KSS scores progressively decreased as the measurement interval nears habitual bedtimes during the adaptation phase. At the first interval in the test phase (i.e. 130 min), there was an initial increase, followed by a decrease and then stability in the KSS scores. The Friedman test suggested a significant change in KSS scores over the eight measurement intervals ($\chi^2(7) = 94.489$, $p < 0.01$, Kendall's $W = 0.337$; indicating a large effect size).

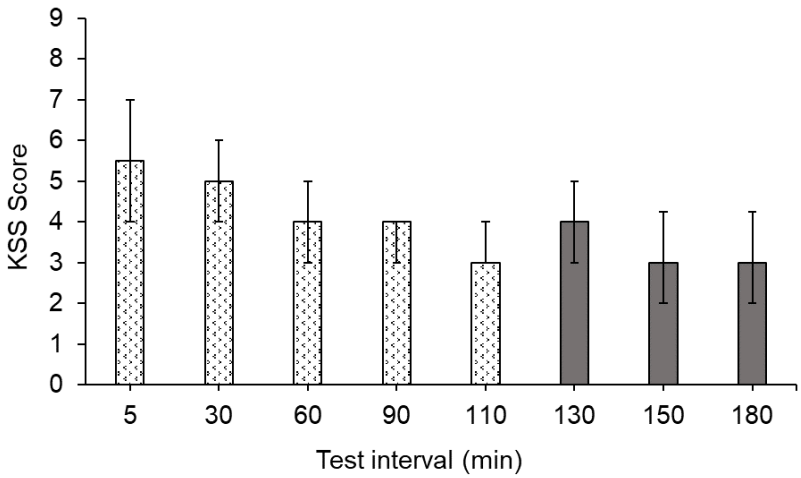

Figure 7.6 Median KSS scores reported at each test interval. Error bars show the IQR. Note for KSS score: 1 = very sleepy, 9 = extremely alert: *shading distinguishes between the adaptation and test phases of the experiment

Since the Friedman test suggested a significant change with test interval, a series of pairwise comparisons was conducted using *post-hoc* Wilcoxon tests. These results, shown in Table 7.5, suggested that the KSS scores at 5 min and 30 min intervals were significantly higher than all other intervals; the KSS score at the 5 min interval was significantly higher than at 30 min interval, and the KSS score at the 60 min interval was significantly higher than at 110 min. It also suggested that there was a significant increase of about one unit in the KSS score at 130 min interval compared to 110 min interval, which coincides with the

participants' transition from being seated to walking on the treadmill. This increase in perceived alertness is an expected result of the physical activity undertaken.[302]

Table 7.5 Statistical values for interval comparisons using the Wilcoxon signed-rank test for KSS Data

No.	Intervals	*Z*	r	Effect size	Adj.Sig.
1	30–5	-3.695	0.70	L	-
2	60–5	-4.855	0.92	L	-
3	90–5	-4.871	0.92	L	-
4	110–5	-5.027	0.95	L	-
5	130–5	-3.889	0.73	L	-
6	150–5	-4.149	0.78	L	-
7	180–5	-4.756	0.90	L	-
8	60–30	-4.257	0.80	L	-
9	90–30	-3.932	0.74	L	-
10	110–30	-4.392	0.83	L	-
11	130–30	-2.139	0.40	M	+
12	150–30	-2.863	0.54	L	-
13	180–30	-4.023	0.76	L	-
14	90–60	-1.235	0.23	S	+
15	110–60	-2.952	0.56	L	-
16	130–60	-1.08	0.20	S	+
17	150–60	-0.1	0.02	S	+
18	180–60	-1.893	0.36	M	+
19	110–90	-3.283	0.62	L	-
20	130–90	-1.528	0.29	S	+
21	150–90	-0.123	0.02	S	+
22	180–90	-1.275	0.24	S	+
23	130–110	-3.136	0.59	L	-
24	150–110	-1.874	0.35	M	+
25	180–110	-0.352	0.07	S	+
26	150–130	-1.647	0.31	M	+
27	180–130	-2.843	0.54	L	+
28	180–150	-2.078	0.39	M	+

Note: for Adj.Sig., (+) indicates $p \geq 0.05$, and (-) indicates $p < 0.05$, for effect sizes: L = large, M = medium, S = small.

To test whether participants were fairly assigned to each group in the adaptation phase, the Kruskal-Wallis test was used to compare group differences at the same interval. The results did not suggest significant differences across the groups at the 5 min, 30 min, 60 min, 90 min and 110 min intervals ($H(3) = 2.111$, $p = 0.55$, $\eta^2 = 0.05$; $H(3) = 2.656$, $p = 0.49$, $\eta^2 = 0.067$; $H(3) = 1.818$, $p = 0.61$, $\eta^2 = 0.05$; $H(3) = 1.506$, $p = 0.68$, $\eta^2 = 0.04$; $H(3) = 1.833$, $p = 0.61$, $\eta^2 = 0.05$), respectively. The η^2 values indicated a small effect size at all intervals. This suggests a fair distribution of participants across the four lighting conditions

To investigate the effect of light conditions on KSS scores, the results from the three measurement intervals in the test phase, as well as the final measurement interval of the adaptation phase (i.e. 110 min), were included. For each light condition, the change in KSS

scores over successive intervals was tested using the Friedman test (Figure 7.7). For light conditions, L1 and L4, the Friedman test suggested significant changes across the measurement interval ($\chi^2(3) = 8.094$, $p < 0.04$, Kendall's $W = 0.27$, indicating a small effect size; $\chi^2(3) = 10.162$, $p < 0.02$, Kendall's $W = 0.34$, indicating a medium effect size), respectively. However, for lighting condition L2, the Friedman test did not suggest any significant differences ($\chi^2(3) = 1.779$, $p = 0.62$, Kendall's $W = 0.06$, indicating a small effect size). In addition, for lighting condition L3, the changes were suggested to be nearly significant ($\chi^2(3) = 7.147$, $p = 0.07$, Kendall's $W = 0.24$, indicating a small effect size).

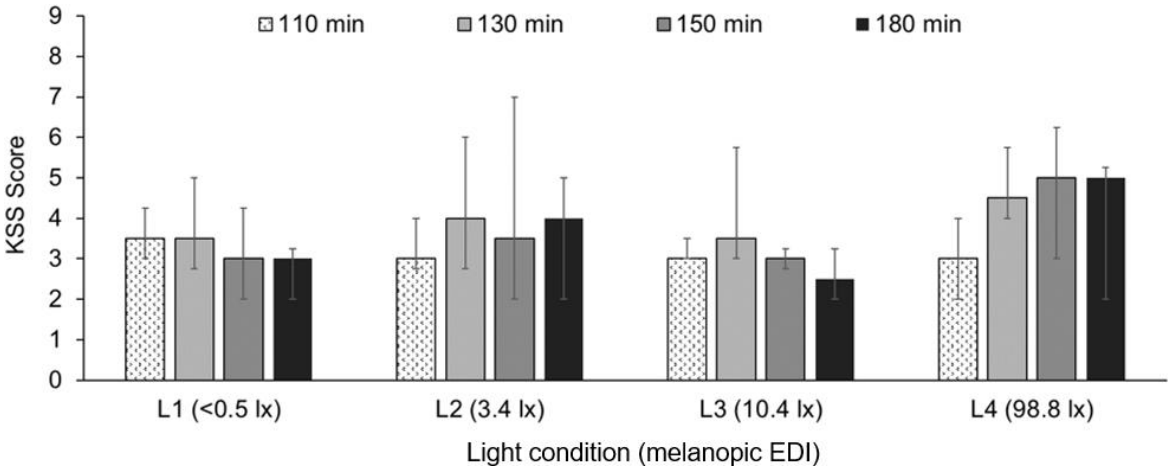

Figure 7.7 Median KSS scores reported at the last interval in the adaptation phase (110 min) and at each test interval during the test phase according to the light condition during the test phase. Error bars show the IQR, KSS score: 1 = very sleepy, 9 = extremely alert.

Since the Friedman tests suggested significant changes with test interval under light conditions L1 and L4, a series of pairwise comparisons was conducted using *post-hoc* Wilcoxon tests. These results, shown in Table 7.6, did not suggest significant changes in KSS scores at any intervals under light condition L1. For light condition L4, the results suggested a significant increase in KSS score (i.e. feeling more alert) at the 180 min interval compared to the 110 min interval.

To compare the KSS scores among the different lighting conditions at the same measurement interval in the test phase, a between-subjects analysis using the Kruskal-Wallis test was conducted. The results did not suggest significant differences between the light conditions ($H(3) = 3.241$, $p = 0.36$, $\eta^2 = 0.08$; $H(3) = 4.872$, $p = 0.18$, $\eta^2 = 0.12$; $H(3) = 3.424$, $p = 0.33$, $\eta^2 = 0.09$) at 130 min, 150 min and 180 min intervals, respectively. The η^2 values indicated medium effect sizes for each interval.

Table 7.6 Statistical values for interval comparisons using the Wilcoxon signed-rank test for Melatonin levels of the two physical activity groups

		Light condition							
		L1				**L4**			
No.	**Intervals**	*Z*	*r*	Effect size	Adj.Sig.	*Z*	*r*	Effect size	Adj.Sig.
1	130 – 110	<0.01	<0.01	S	+	-2.585	0.49	M	+
2	150 – 110	-1.134	0.21	S	+	-2.384	0.45	M	+
3	180 – 110	-2.07	0.39	M	+	-1.845	0.35	M	-
4	150 – 130	-1.732	0.33	M	+	-0.378	0.07	S	+
5	180 – 130	-1.933	0.37	M	+	-1.121	0.21	M	+
6	180 – 150	-1.414	0.27	S	+	-1.265	0.24	M	+

Note: for Adj.Sig., (+) indicates $p \geq 0.05$, and (-) indicates $p < 0.05$, for effect sizes: L = large, M = medium, S = small

The KSS data, therefore, again shows that the lighting condition of the highest melanopic EDI (L4) led to an effect on an alertness measure, subjective alertness, but only after an exposure of somewhere between 30 min and 60 min. Responses to rating scale data are notoriously noisy,[383] and this may explain why differences between measurement intervals revealed within the overall data set were less prominent when analysing the smaller samples of the individual lighting condition groups.

7.6. Summary

This chapter presented the results of an experiment where three measures were recorded to investigate the impact on NIF responses of changes to lighting.

The PVT results indicated a significant reduction in reaction time over a three-hour period. The initial reaction time at 5 min interval was significantly longer than at most subsequent intervals. The reaction time at the final test interval (180 min) was significantly shorter than at the 150 min and 130 min intervals. Lighting conditions L1, L2 and L3 did not affect reaction time; however, lighting condition L4 significantly shortened the reaction time during the test phase.

Melatonin levels increased significantly throughout the measurement intervals over the three hours. Significant increases were suggested under lighting conditions L1, L2 and L3 during the test phase. Under lighting condition L4, the melatonin level started to decrease after 30 min of exposure.

The KSS results showed a progressive decrease in subjective alertness as participants approached their habitual bedtimes over the adaptation phase. A significant increase in subjective alertness was suggested at 130 min interval compared to 110 min interval as the

participants started walking at moderate speed. Lighting conditions L1, L2 and L3 did not affect subjective alertness. However, under lighting condition L4, an increase in KSS scores (i.e., participants feeling more alert) was suggested to be significant at 180 min interval compared to 110 min interval.

In summary, the results do not indicate that lighting conditions L1, L2 and L3 have a significant impact on reaction time, melatonin levels and subjective alertness. However, Light condition L4 appears to suppress melatonin levels, increase subjective alertness and improve cognitive performance between 30 min and 60 min of exposure.

Chapter 8

Discussion

8. Discussion

8.1. Introduction

This thesis investigates the impact of light on the alertness and melatonin level of pedestrians walking after dark. Two experiments were conducted; the first experiment used four lighting conditions close to those experienced by pedestrians, and the second experiment aimed to verify the null finding through repetition with the inclusion of an extreme lighting condition. Experiment 2 was, therefore, similar to experiment 1 but with two changes. First, it included a lighting condition that provided a much higher level of melanopic EDI (approx. 100 lx compared with approx. 10 lx in experiment 1). Second, the walking speed during the test phase of experiment 2 was increased to be more in line with typical walking speed (moderate-intensity walking compared to low-intensity walking in experiment 1).

In this chapter, the results of experiments 1 and 2 are discussed to respond to hypotheses 1 and 2 from section 2.8, as well as hypotheses 3 and 4 from section 5.5. The focus of section 8.2 is on the NIF effect of light, while section 8.3 presents the analysis and discusses the effects of physical activity on alertness and melatonin levels. Section 8.4 provides an overview of the sample sizes used in previous studies.

8.2. The effect of light on NIF responses

As participants approach their habitual bedtime reaction time to an auditory stimulus (measured by PVT), skin temperature and melatonin levels are expected to increase, while subjective alertness (measured by KSS) is expected to decrease (indicating a lower degree of alertness).[156,217,226,380] If lighting of sufficient melanopic EDI can enhance alertness, this would be revealed as a shorter reaction time and higher subjective alertness, potentially combined with lower melatonin levels and lower skin temperature (i.e., indicating a shift in circadian rhythm towards increased alertness). Both experiments revealed the expected trends over their three-hour duration as participants approached their habitual bedtime:

1. Melatonin levels increased (see Figures 4.6 and 5.3).[214]
2. KSS scores decreased (see Figures 4.10 and 5.5).[381]
3. Reaction time reduced after the first interval, reflecting participants' increased familiarity with the task over time (see Figures 4.3 and 5.1).[382]
4. Skin temperature increased over the last hour of the experiment (included only in experiment 1),[234] (see Figure 4.14).

Lighting conditions of melanopic EDI up to 10.7 lx (conditions C1 to C4 in experiment 1 and L1 to L3 in experiment 2) were not suggested to significantly affect melatonin levels, reaction time, KSS and skin temperature (the latter included only in experiment 1). The lighting condition L4 in experiment 2 (melanopic EDI of 98.8 lx) was suggested to have a significant effect on melatonin levels, reaction time and KSS. These effects were a reduction in reaction time, an increase in subjective alertness and suppression of the increase in melatonin level after more than 30 min of exposure to the test lighting (i.e. when measured at the 180 min interval).

In the context of this thesis, the results suggest that exposure to polychromatic light with a melanopic EDI of 98.8 lx for more than 30 min in the evening shortens reaction times, increases subjective alertness and prevents the increase in saliva melatonin levels. These results are consistent with the findings of Nowozin *et al.*[314]. In their study, Nowozin *et al.*[314] started the test phase one hour before participants' habitual bedtime, similar to this thesis. However, they included a three-hour adaptation phase under dim illuminance (less than 7 lx), while the adaptation phase in this thesis lasted for 2 h under illuminance of 25 lx. The dimmer adaptation illuminance in the study by Nowozin *et al.*[314] likely increases the participants' circadian sensitivity. Although Nowozin *et al.*[314] found a decrease in melatonin levels after 30 min of exposure to light with a melanopic EDI of around 90 lx, Nowozin *et al.*[314] did not find a significant change in subjective alertness.

In conclusion, the findings from experiment 2 supported Hypothesis H3, they confirmed the null finding obtained in experiment 1, and the use of an extreme condition validated the experimental design employed in both experiments (see Veitch *et al.*[384]). The next section presents the combined datasets from both experiments to discuss the effect of physical activity.

8.3. Analysis of physical activity effects

8.3.1. Introduction

To investigate whether walking at a moderate speed, which better represents typical walking speed, affects the DVs (melatonin level, reaction time and KSS) compared to walking at a self-selected speed and being seated, data was collected from 60 participants. These participants were exposed to three different light conditions (C1, C2 and C3) in experiment 1 and (L1, L2 and L3) in experiment 2. These specific light conditions were chosen to be included in the analysis for two reasons. First, they were not found to be significantly different. Second, each lighting condition encompassed three different physical

activity groups: seated, walking at a self-selected speed and walking at a moderate speed. This allows for a valid comparison among the three physical activity groups. The results of each DV were analysed sequentially. This involved examining differences across all levels of the variable and, when suggesting a statistically significant effect, conducting further pairwise tests with significance values adjusted using the Holm-Bonferroni correction to account for multiple comparisons.[378]

8.3.2. Data normality

The data recorded for each DV were initially checked to see if they were drawn from a normally distributed population. As explained in sub-section 3.8.2, this was done by four methods of analysis: comparing measures of central tendency, statistical tests (Shapiro-Wilks and Kolmogorov-Smirnov), measures of dispersion (skewness and kurtosis) and graphical representations (histogram and box plot). The results of these analyses are shown in Appendix H. None of the DVs was suggested to be normally distributed; Figure 8.1 shows, as an example, the non-normal distribution of the melatonin dataset at six intervals. As a result, non-parametric tests were used for the analyses. First, Friedman tests were used to compare changes in responses within each physical activity group across the measurement intervals in the test phase. Second, Kruskal-Wallis tests were employed to compare responses between the different physical activity groups at the same measurement interval in the test phase.

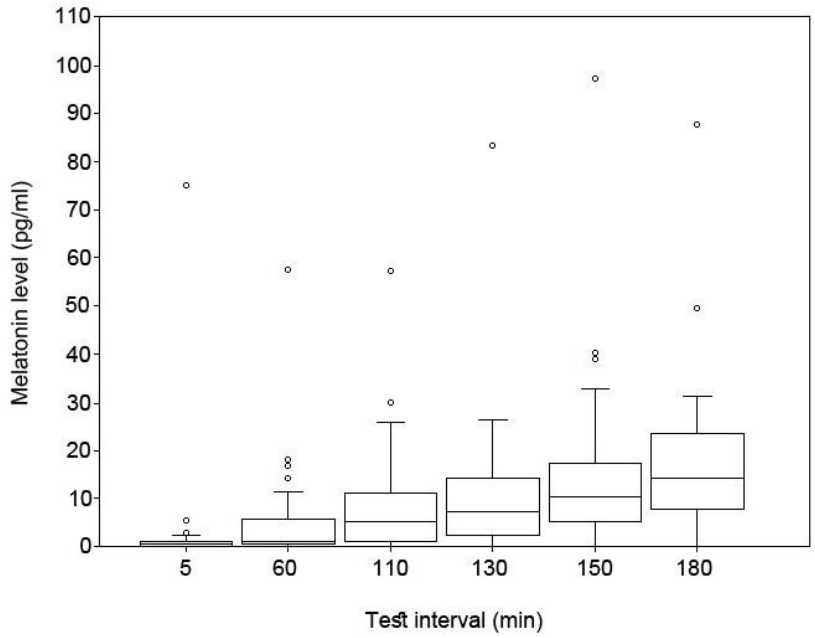

Figure 8.1 Box plots of melatonin level at six intervals. These data are not suggested to be drawn from a normally distributed population because the median lines do not tend to be central within each box, and the whiskers do not tend to be of similar length above and below each box.

8.3.3. Psychomotor Vigilance Test

Figure 8.2 shows the median reaction times at the three measurement intervals in the test phase for the three physical activity groups. The Friedman test suggested no significant changes across the measurement interval for the seated group ($\chi^2(2) = 2.533$, $p = 0.28$, Kendall's $W = 0.08$; indicating a small effect size) and the self-selected speed group ($\chi^2(2) = 0.552$, $p = 0.76$, Kendall's $W = 0.02$; indicating a small effect size)). For the moderate speed group, the Friedman test suggested a significant change across the intervals ($\chi^2(2) = 0.552$, $p = 0.02$, Kendall's $W = 8.153$; indicating a large effect size).

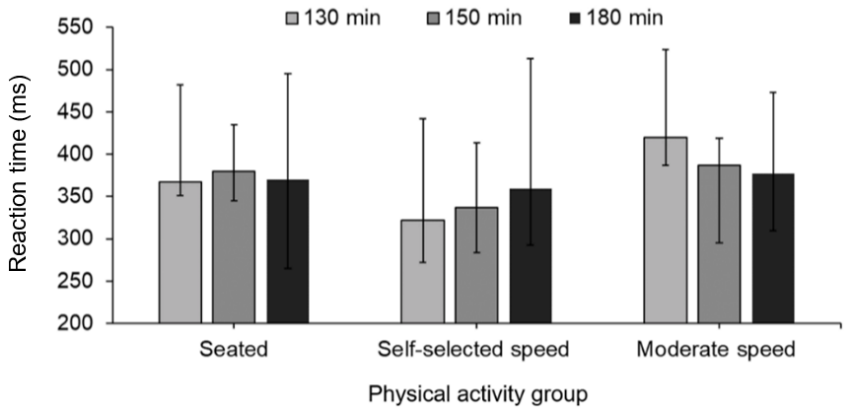

Figure 8.2 Median reaction times at each test interval during the test phase according to the physical activity group. Error bars show the IQR.

Since the Friedman test suggested a significant change with the test interval for the moderate speed group, a series of pairwise comparisons were conducted using *post-hoc* Wilcoxon tests. These results, shown in Table 8.1, suggested a significant decrease in reaction times at 180 min interval (median reaction time = 331 ms) compared to 150 min interval (median reaction time = 346 ms).

Table 8.1 Statistical values for interval comparisons using the Wilcoxon signed-rank test for moderate speed group reaction time

No.	Intervals	*Z*	*r*	Effect size	Adj.Sig.
1	150 – 130	-0.802	0.15	S	+
2	180 – 130	-1.893	0.35	M	+
3	180 – 150	-2.920	0.53	L	-

Note: for Adj.Sig., (+) indicates $p \geq 0.05$, and (-) indicates $p < 0.05$.
For effect sizes: L = large, M = medium, S = small.

To compare responses among the different physical activity groups at the same measurement interval. A between-subjects analysis using the Kruskal-Wallis was used. The test did not suggest significant differences at the 130 min, 150 min, or 180 min intervals ($H(2) = 1.252$, $p = 0.54$, $\eta^2 < 0.01$; $H(2) = 0.667$, $p = 0.72$, $\eta^2 < 0.01$; $H(2) = 0.007$, $p = 0.99$, $\eta^2 < 0.01$). The η^2 values indicated no effect at the three intervals.

8.3.4. Melatonin levels

The median melatonin levels of the 60 participants at each interval in the test phase are shown in Figure 8.3. The melatonin levels progressively increased as the measurement interval approached habitual bedtimes. The Friedman test suggested a significant change across the measurement intervals within the three physical activity groups ($\chi^2(2) = 12.600$, $p < 0.01$, Kendall's W=0.63; indicating a large effect size); $\chi^2(2) = 9.282$, $p = 0.01$, Kendall's $W = 0.46$; indicating a medium effect size); $\chi^2(2) = 15.936$, $p < 0.01$, Kendall's $W = 0.20$; indicating a small effect size) for seated, self-selected speed group and moderate speed group, respectively.

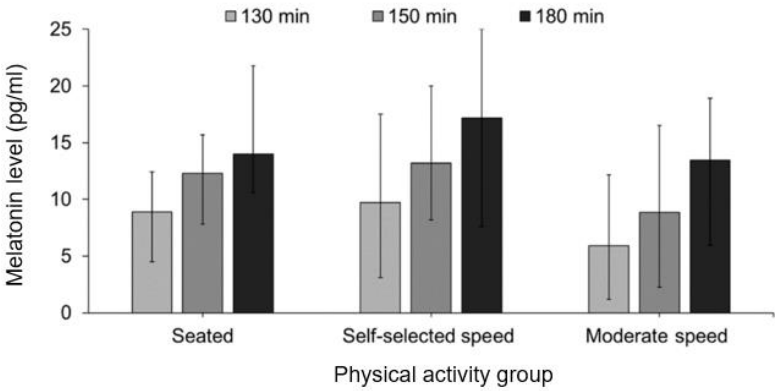

Figure 8.3 Median melatonin level at each interval during the test phase for each physical activity group. Error bars show the IQR

Since the Friedman test suggested a significant change with test interval, a series of pairwise comparisons was conducted using *post-hoc* Wilcoxon tests. These results, shown in Table 8.2, suggested that differences in melatonin levels between all the intervals were significant; where the melatonin level was suggested to increase significantly at any given interval compared to the preceding intervals. Except for one non-significant increase suggested in the seated group between 150 min and 180 intervals.

Table 8.2 Statistical values for interval comparisons using the Wilcoxon signed-rank test for melatonin levels of seated, self-selected, and moderate speed groups.

		Physical activity					
		Seated		**Self-selected speed**		**Moderate-speed**	
No.	**Intervals**	*Z*	*r* / effect Size (Adj.Sig.)	*Z*	*r* / effect Size (Adj.Sig.)	*Z*	*r* / effect Size (Adj.Sig.)
1	150 – 130	-3.108	0.80 / L (-)	-2.356	0.61 / L (-)	-4.240	0.77 / L (-)
2	180 – 130	-3.324	0.86 / L (-)	-3.109	0.80 / L (-)	-4.639	0.85 / L (-)
3	180 – 150	-1.165	0.30 / M (+)	-2.045	0.53 / L (-)	-3.826	0.70 / L (-)

Note: for Adj.Sig., (+) indicates $p \geq 0.05$, and (-) indicates $p < 0.05$, for effect sizes: L = large, M = medium, S = small.

To compare melatonin levels among the different physical activity groups at the same measurement interval in the test phase, a between-subjects analysis using the Kruskal-Wallis test was conducted. The results did not suggest significant differences at the 130 min, 150 min or 180 min intervals ($H(2) = 2.282$, $p = 0.32$, $\eta^2 = 0.005$; $H(2) = 2.251$, $p = 0.31$, $\eta^2 = 0.005$; $H(2) = 1.305$, $p = 0.52$, $\eta^2 < 0.01$). The η^2 values indicated small to no effect sizes.

8.3.5. The Karolinska Sleepiness Scale

The median KSS scores of the 60 participants at each interval in the test phase are shown in Figure 8.4. The subjective alertness decreased after the first interval in the three physical activity groups. The Friedman test suggested a significant change in KSS scores across the measurement intervals of the three physical activity groups ($\chi^2(2) = 11.400$, $p < 0.01$, Kendall's $W = 0.38$, indicating a medium effect size; $\chi^2(2) = 21.143$, $p < 0.01$, Kendall's W = 0.71, indicating a large effect size; $\chi^2(2) = 10.756$, $p < 0.01$, Kendall's W = 0.18, indicating a small effect size) for seated, self-selected speed and moderate speed groups, respectively.

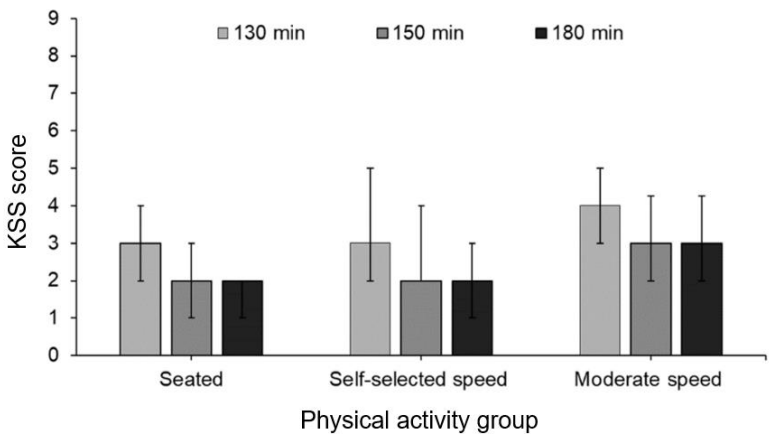

Figure 8.4 Median KSS scores reported at each test interval during the test phase according to the physical activity group. Error bars show the IQR, KSS score: 1 = very sleepy, 9 = extremely alert.

Since the Friedman test suggested a significant change with test interval, a series of pairwise comparisons was conducted using *post-hoc* Wilcoxon tests. The results, shown in Table 8.3, indicated significant decreases in KSS scores (feeling less alert) over time. Specifically, the results suggested a significant decrease in KSS scores at 180 min compared to 130 min intervals in all three physical activity groups ($p < 0.05$ in each case), a significant decrease in KSS scores at 150 min compared to 130 min intervals in the seated and self-selected speed groups ($p < 0.05$ in each case), but not in the moderate speed

group ($p > 0.05$). This indicates that the moderate speed group feels more alert after 30 min of walking than the seated and self-selected speed groups.

Table 8.3 Statistical values for interval comparisons using the Wilcoxon signed-rank test for KSS scores of seated, self-selected speed group and moderate speed group

		Physical activity					
		Seated		**Self-selected speed**		**Moderate speed**	
No.	**Intervals**	*Z*	*r* / effect Size (Adj.Sig.)	*Z*	*r* / effect Size (Adj.Sig.)	*Z*	*r* / effect Size (Adj.Sig.)
1	150 – 130	-2.636	0.68 / L (-)	-3.162	0.82 / L (-)	-1.641	0.30 / M (+)
2	180 – 130	-2.354	0.61 / L (-)	-3.126	0.81 / L (-)	-2.613	0.48 / M (-)
3	180 – 150	-1.134	0.29 / S (+)	-2.714	0.70 / L (-)	-1.667	0.30 / M (+)

Note: for Adj.Sig., (+) indicates $p \geq 0.05$, and (-) indicates $p < 0.05$, for effect sizes: L = large, M = medium, S = small.

To compare KSS scores among the different physical activity groups at the same measurement interval in the test phase, a between-subjects analysis using the Kruskal-Wallis test was conducted. The Kruskal-Wallis test suggested significant differences among the three physical activity groups at 150 min interval ($H(2) = 8.342$, $p = 0.02$, $\eta^2 = 0.11$, indicating a medium effect size) and at 180 min interval ($H(2) = 10.742$, $p < 0.01$, $\eta^2 = 0.15$, indicating a large effect size), but not at 130 min interval ($H(2) = 5.269$, $p = 0.07$, $\eta^2 = 0.06$, indicating a medium effect size).

A series of pairwise comparisons using Wilcoxon Rank-Sum test was conducted; these results suggested that at the second measurement interval (150 min), the moderate speed group significantly reported a higher KSS score, indicating they felt more alert, compared to the seated group ($U = 109.500$, $p < 0.05$, PS = 0.24, indicating small effect size). Similarly, at the third measurement interval (180 min), the moderate speed group reported a higher KSS score compared to both; the seated group ($U = 108.500$, $p < 0.05$, PS = 0.24, indicating a small effect size) and the self-selected speed group ($U = 133.000$, $p < 0.05$, PS = 0.30, indicating a small effect size).

8.3.6. The effect of physical activity

The findings from experiment 1 indicated that physical activity impacted subjective alertness, melatonin levels and skin temperature but not reaction time. The experiment involved 40 participants who were divided into two groups during the test phase: one group remained seated while the other walked at a self-selected speed. The data analysis involved within-subjects and between-subjects methods. The within-subjects analysis compared the change in the DV across the measurement intervals in the adaptation phase and the test phase; the results suggested a significant increase in melatonin levels in both groups,

particularly for those who were walking. The walking group reported a similar level of alertness in the first 30 min of the test phase, while the seated group reported feeling significantly less alert during the same period compared to the adaptation phase. Skin temperature significantly changed in the walking group, following expected trends during low-intensity exercise, while for the seated group, the results did not suggest any change in skin temperature to be significant. The between-subjects analysis compared responses between seated participants and those walking at a self-selected speed at the same test intervals. This analysis suggested that subjective alertness was higher for walking participants, nearing statistical significance at some intervals. No changes in melatonin levels, reaction time and skin temperature were suggested to be significant between the groups (see Chapter 4 and section 5.3).

In the combined data from experiments 1 and 2, with a total of 60 participants, data involving three physical activity groups: seated, walking at a self-selected speed and walking at a moderate speed. Analysis was conducted using; First, the Friedman test to compare changes in responses within each physical activity group across the measurement intervals in the test phase. Second, the Kruskal-Wallis test to compare changes across the independent physical activity groups at the same interval in the test phase.

The PVT results did not suggest any change in reaction time to be significant among the test intervals for the seated and self-selected speed groups. However, in the moderate speed group, the results suggested a significant decrease in reaction time at the 180 min interval compared to the 150 min interval (see Figure 8.2). These findings suggest that walking at a moderate speed in the evening (23:00) for over than 30 min can reduce reaction time, regardless of light conditions. This improvement might be related to the "end-spurt effect", where participants knowing that the experiment is about to conclude, initially show a decline in performance that later improves as the task nears completion.[399,400] However, if this were the case, the same effect would be expected in experiment 1, which involved forty participants (as shown in Figure 4.3) who were also aware of the experiment's end time; yet, no such effect was observed. This suggests that the improvement in cognitive performance (shorter reaction time) is more likely due to an increase in walking speed rather than the end-spurt effect. In experiment 2, where the analysis for each set of 10 participants under each light condition was done separately, the improvement in reaction time was only suggested to be significant under the light condition with a melanopic EDI of ~100 lx. It is expected that the interaction between light and physical activity resulted in enhanced cognitive performance through 1) the NIF effects of light and 2) the exercise-induced arousal effect; this explanation aligns with a meta-analysis by Lambourne and

Tomporowski,[280] which suggested an improvement in cognitive performance in a simple reaction time test following 20 min of steady walking.

Melatonin level results suggested a significant increase in all three physical activity groups during the test phase between the 130 min and 150 min intervals. However, between the 150 min and 180 min intervals, the increase in melatonin level was suggested to be significant for the walking groups (self-selected speed and moderate speed) but not for the seated group. This difference is unlikely to be linked to the physical activity itself; previous studies have associated increases in melatonin levels with high-intensity exercise but not moderate-intensity exercise.[286,291,394] Rather, the observed increase in melatonin in both self-selected speed and moderate speed walking groups can be attributed to the influence of gravity, which leads to a decrease in plasma volume when standing, thereby causing an increase in melatonin concentration in saliva.[295,296] Kozaki *et al.*[295] compared salivary melatonin concentrations between sitting and standing positions in the evening and found that melatonin concentrations in the standing position were significantly higher compared to those in the sitting position.

The subjective alertness was suggested to be significantly lower in the seated and self-selected speed groups at the 150 min interval compared to the 130 min interval. However, the moderate speed group reported a consistent level of alertness that did not significantly differ between the 130 min and 150 min intervals. When comparing the physical activity groups to each other at the same interval, the subjective alertness was suggested to be significantly higher in the moderate speed group compared to the seated and self-selected speed groups after an hour of walking (180 min interval). While subjective alertness was not suggested to be significantly different between the walking groups (low and moderate speeds) at 150 min interval (30 min after walking), the moderate speed group reported a significantly higher level of subjective alertness than the seated group.

8.4. Sample size

Prior to experiment 1, the required sample size was estimated using G*Power.[363] The parameters were to detect an effect size of 0.5 (Cohen's f) with a power of 0.8 and an alpha level of 0.05 (see section 3.6). This analysis suggested a total sample size of at least 36 participants for a between-subjects design and more than 8 participants per condition for a within-subjects design. While this is an objective assessment, the sample size sounds small.[162]

In previous studies, researchers have investigated the NIF effects of light using sample sizes ranging from 3 to 14 participants per light condition. Specifically, Table 8.4 details the sample sizes in studies with independent sample designs, with examples like Higuchi *et al.*[395] and Cajochen *et al.*[159] using samples of 3 to 7 participants per condition. On the other hand, Table 8.5 presents sample sizes from studies employing repeated measures designs, such as Thapan *et al.*[140] and Phipps-Nelson *et al.*,[193] with participant numbers ranging from 3 to 10 per condition. In this thesis, given the capacity of the laboratory to accommodate only two participants per night, a sample size of 40 participants has been deemed both reasonable and feasible. This aligns with the sample sizes typically employed in similar NIF research, ensuring robustness within the constraints of available resources.

Table 8.4 Sample sizes in studies using an independent samples design

Study	Total sample	Sample per condition
Higuchi *et al.* 2011[395]	11	3 to 4
Cajochen *et al.* 2000[159]	23	5 to 7
Zeitzer *et al.* 2000[154]	23	5 to 7
Rüger *et al.* 2005[225]	12	4 to 6
Phipps-Nelson *et al.* 2003[175]	15	7 to 8
Lockley *et al* 2006[209]	15	7 to 8
Rahman *et al.* 2014[199]	16	8
Papamichael *et al.* 2012[319,a]	20	10
Appleman *et al.* 2013[396]	21	10
Sasseville *et al.* 2015[397]	20	10
Crowley and Carskadon 2010[398]	28	14

[a] Repeated measures design using data of 3 to 5 participants

Table 8.5 Sample sizes in studies using a repeated measures design

Study	Number of conditions	Sample per condition
Thapan *et al.* 2001[140]	6 wavelengths 5 to 8 irradiances	3 to 7 per condition (Total 22 participants)
Phipps-Nelson *et al.* 2009 [193]	3	8
Revell and Skene, 2007[345]	3	9
Cajochen *et al* 2005[141]	3	10
Najjar *et al.* 2014[187]	2	6 to 10
Bhagavathula *et al.* 2021[113]	5	10
Zeitzer *et al* 2018[185]	2	10
Rüger *et al.* 2006[237]	2	12
Rahman *et al.* 2011[401]	5	12
Cajochen *et al* 2011[402]	2	13
Van der Lely *et al.*2015[403]	2	13
Lavoie *et al.* 2003[322]	3	14
Chellappa *et al.* 2011[210]	3	16
Van de Werken *et al.* 2013 experiment 1[404]	3	17
Van de Werken *et al.* 2013 experiment 2[404]	3	16

As mentioned in Section 3.6, after completing the two experiments in this study, it became clear that the initial approach to targeting a medium effect size was not fully accurate. In

response, a sensitivity analysis was conducted to identify the smallest effect size that could be reliably detected with a sample of 40 participants. The details of this analysis are presented in the following section.

8.5. Sensitivity analysis

Sensitivity analysis is a method used to determine the smallest effect size that can be reliably detected in a study.[363] When conducting sensitivity analysis using G*Power for repeated measures ANOVA, the parameters depend on the study's design: for a within-subject design, the key parameters include: (1) alpha level (see section 3.6), (2) statistical power (see section 3.6), (3) total sample size (N), (4) number of groups (N_g), (5) number of measurements (N_m), (6) nonsphericity correction (i.e. ε), and (7) the correlation among repeated measures (rmcorr). For a between-subject design, these parameters are similar, except that nonsphericity correction value is not required.

Sphericity refers to the assumption that the variability of changes in the DV across intervals or experimental conditions is equal. The nonsphericity correction is a factor that quantifies the degree to which this assumption is violated.[405] When sphericity holds true, the nonsphericity correction equals 1.0. However, when this assumption is violated, the value falls below 1.0, with the minimum possible value being 1 / (t - 1), where t represents the number of measurements.[406] In G*Power, using higher nonsphericity correction values leads to the estimation of smaller detectable effect sizes.

The rmcorr value in a within-subject design reflects the consistency of the DV when measured in the same participants across different intervals. These measurements are typically correlated since they come from the same individuals, though this correlation can vary over time. Measurements taken at closer (consecutive) intervals generally show stronger correlations than those taken farther apart.[407] The correlation coefficient ranges from -1 (perfect negative correlation) to 1 (perfect positive correlation). A value of 0 represents no correlation. In a within-subject design sensitivity analysis, using higher rmcorr values in G*Power indicate a reduction in variability between intervals, which leads to the estimation of smaller detectable effect sizes. In contrast, in a between-subject design sensitivity analysis, using higher rmcorr values result in the estimation of larger detectable effect sizes. This is because higher rmcorr indicates greater similarity in responses between groups, making it more difficult to detect differences unless the effect size is larger.

The parameters used for the sensitivity analysis in this study were set to reflect the study's analysis methods as detailed in Table 8.6:

1. Alpha level: set at 0.05.
2. Statistical power: set at 0.80.
3. N: either 40 (representing data from one experiment) or 60 (reflecting the combined dataset from two experiments).
4. N_g: set to 2, 3, or 4 depending on the data processed in the analysis.
5. N_m: In the within-subject design sensitivity analysis, this was set to 4 measurements (one interval representing the adaptation phase and three intervals in the test phase). In the between-subject sensitivity analysis, it was set to 3 measurements (three intervals in the test phase). Although data were collected at 6 to 8 intervals, only three to four data points were processed in the analysis.
6. Nonsphericity correction: set conservatively to the lowest possible value (i.e., 1 / (4 - 1) or 1 / (3-1)).
7. rmcorr: set at 0.5, which is a common estimate in social and behavioural research, indicating moderate correlation typical of repeated measures designs.[408-410]

To account for variability in the rmcorr parameter, the correlation matrices between intervals were analysed for each dependent variable, including melatonin, reaction time, skin temperature and subjective alertness. The rmcorr values for each possible pair of intervals in any matrix ranged from approximately 0.3 to 0.9. To model different scenarios, G*Power was used to conduct sensitivity analyses with rmcorr values starting at 0.3 and increasing by 0.1 up to 0.9. In the between-subject sensitivity analysis, rmcorr values ranging from 0.0 to 0.9 were assigned to represent the potential correlation between the groups. Negative values observed in the correlation matrices between the groups were not used in the sensitivity analysis to maintain a conservative approach. In contrast to the within-subject design, increasing rmcorr values in the between-subject design indicate greater similarity in responses between groups, resulting in larger detectable effect sizes (see sensitivity plots in Figures 8.5, 8.6, 8.7, and 8.8).

Table 8.6 Smallest detectable effect sizes (Cohen's f) based on experimental parameters in sensitivity analysis using g*power

IV	**N**	**N_g**	**N_m**	**ε**	***Smallest detectable Cohen's f*** [a]							**Effect size**[b]
ANOVA: repeated measure, within-subject												
Light condition	40	4	4	0.34	0.33	0.30	0.28	0.25	0.21	0.18	0.12	S to M
Physical activity	60	3	3	0.5	0.25	0.23	0.21	0.19	0.16	0.13	0.09	S to M
ANOVA: repeated measure, between-subject												
Light condition	40	4	3	NA	0.40	0.43	0.45	0.47	0.49	0.51	0.53	L
Physical activity	60	3	3	NA	0.30	0.32	0.34	0.35	0.37	0.38	0.39	M to L

[a] The first to seventh columns under Cohen's f correspond to rmcorr values of 0.3, 0.4, 0.5, 0.6, 0.7, 0.8 and 0.9, respectively. [b] For effect size: L = large, M = medium, S = small.

As shown in Table 8.6, the sensitivity analysis conducted using G*Power explored the smallest detectable effect sizes (Cohen's f) for repeated measures ANOVA in both within-subject and between-subject designs - repeated with various rmcorr values. In the within-subject design, two main scenarios were analysed:

- For the analysis of the effect of light condition with 40 participants, 4 groups, 4 measurements and nonsphericity correction = 0.34, the smallest detectable effect size (Cohen's f) ranged from 0.12 to 0.33, corresponding to small to medium effect sizes (see Figure 8.5)
- For the analysis of the physical activity, with 60 participants, 3 groups, 3 measurements and nonsphericity correction = 0.5, the smallest detectable effect size (Cohen's f) ranged from 0.09 to 0.25, also indicating small to medium effect sizes (see Figure 8.6).

In the between-subject design, two scenarios were also examined:

- For the analysis of the effect of light condition with 40 participants, 4 groups and 3 measurements, the smallest detectable effect size (Cohen's f) ranged from 0.32 to 0.53, indicating medium to large effect sizes (see Figure 8.7).
- For the analysis of the Physical activity, with 60 participants, 3 groups and 3 measurements, the smallest detectable effect size (Cohen's f) ranged from 0.30 to 0.39, indicating medium to large effect sizes (see Figure 8.8).

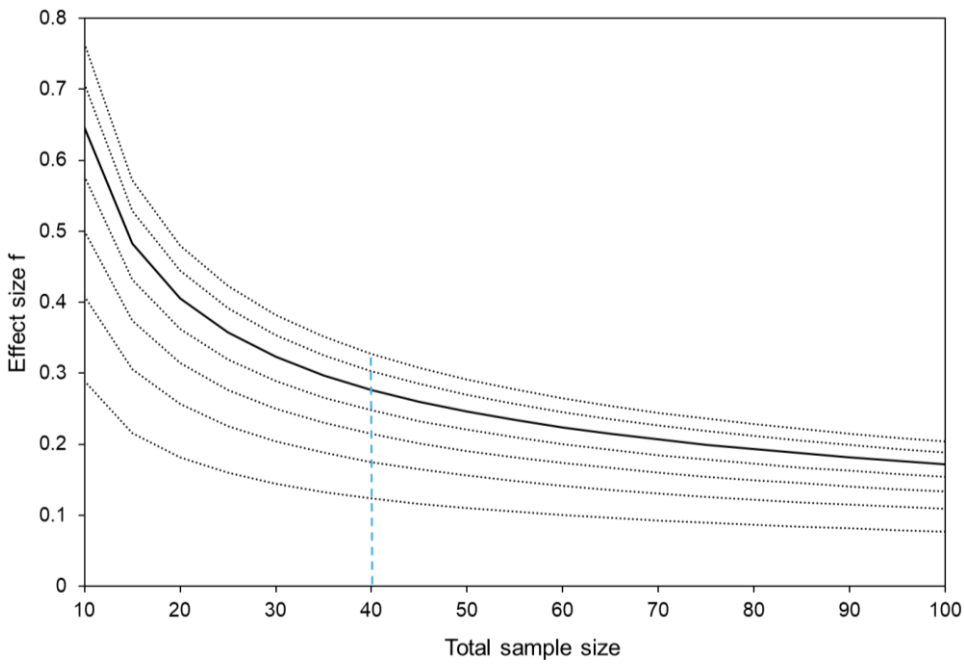

Figure 8.5 Effect size as a function of sample size for repeated measures ANOVA (within-subject test, $N_g = 4$, $N_m = 4$) across different rmcorr values: The curves, ordered from top to bottom, represent the rmcorr values of 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, and 0.9, respectively. The continuous line indicates an rmcorr of 0.5. The alpha level for all curves is set at 0.05, with a nonsphericity correction of 0.34 and a statistical power of 0.8. The dashed vertical line highlights the specific case of the study with total sample size of 40.

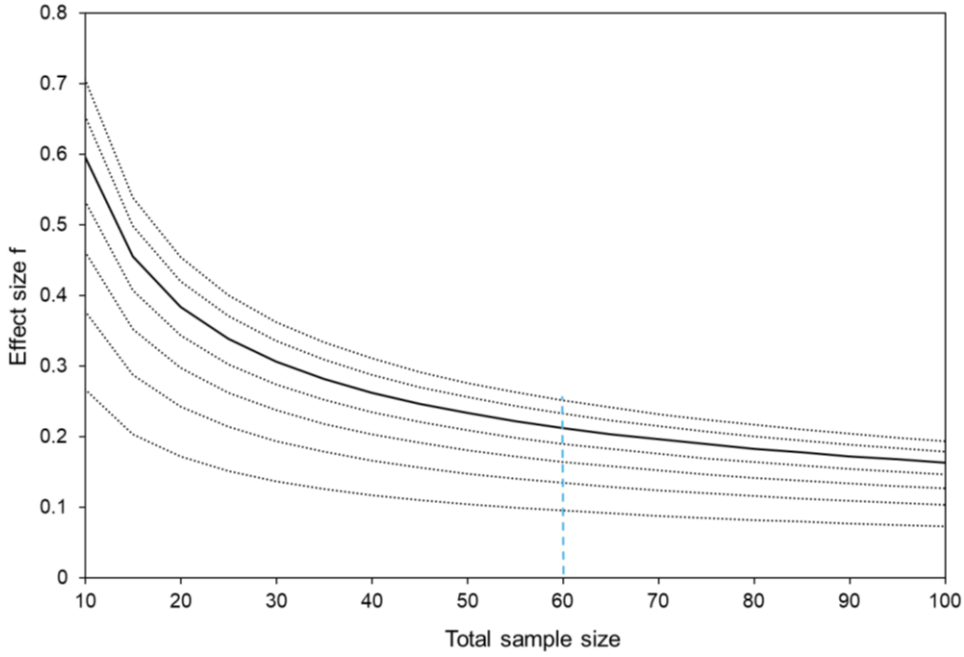

Figure 8.6 Effect size as a function of sample size for repeated measures ANOVA (within-subject test, $N_g = 3$, $N_m = 3$) across different rmcorr values: The curves, ordered from top to bottom, represent the rmcorr values of 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, and 0.9, respectively. The continuous line indicates an rmcorr of 0.5. The alpha level for all curves is set at 0.05, with a nonsphericity correction of 0.34 and a statistical power of 0.8. The dashed vertical line highlights the specific case of the study with total sample size of 60.

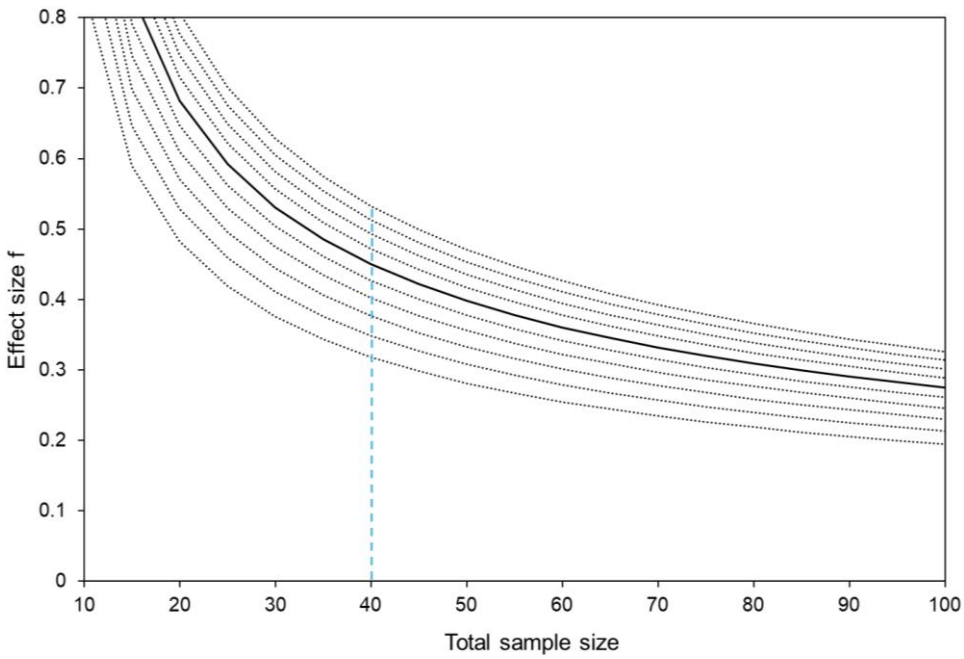

Figure 8.7 Effect size as a function of sample size for repeated measures ANOVA (between-subject test, $N_g = 4$, $N_m = 3$) across different rmcorr values: The curves, ordered from bottom to top, represent the rmcorr values of 0.0, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, and 0.9, respectively. The continuous line indicates an rmcorr of 0.5. The alpha level for all curves is set at 0.05, with a statistical power of 0.8. The dashed vertical line highlights the specific case of the study with total sample size of 40.

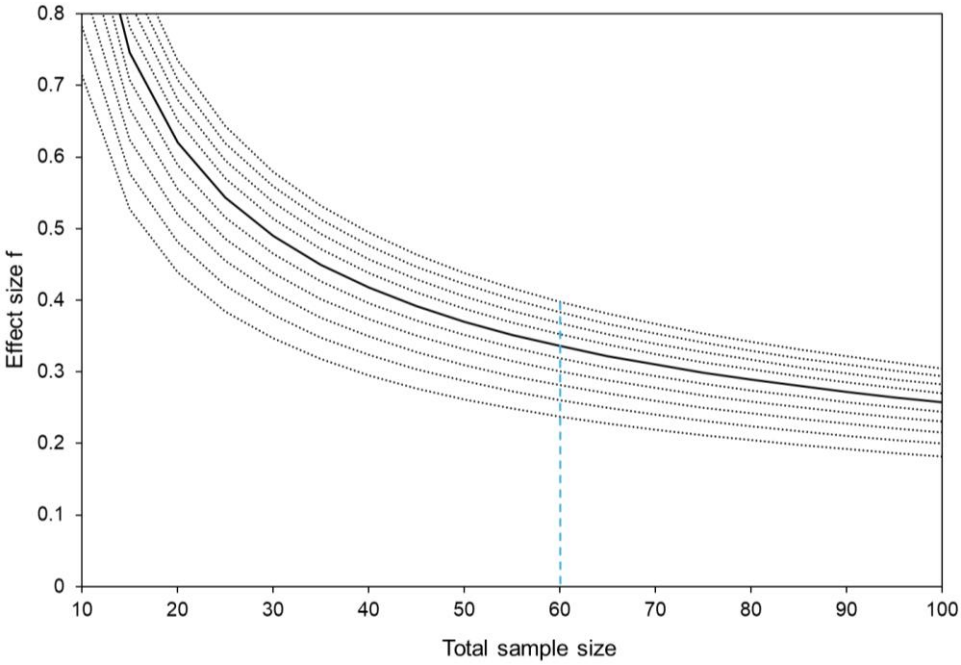

Figure 8.8 Effect size as a function of sample size for repeated measures ANOVA (between-subject test, $N_g = 3$, $N_m = 3$) across different rmcorr values: The curves, ordered from bottom to top, represent the rmcorr values of 0.0, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, and 0.9, respectively. The continuous line indicates an rmcorr of 0.5. The alpha level for all curves is set at 0.05, with a statistical power of 0.8. The dashed vertical line highlights the specific case of the study with total sample size of 60.

G*Power assumes normally distributed data and is typically used when parametric tests are applied. In this study, while parametric tests were used to analyse skin temperature data, non-parametric alternatives to repeated measures ANOVA were employed for reaction time, melatonin levels, and KSS scores. As a solution when conducting an analysis using tools like G*Power under the assumption of normality, Lehmann[411] suggested adjusting the sample size by approximately 15%. Accordingly, although the experiment involved 40 participants, a conservative adjustment to the sensitivity analysis assumed a reduced sample size—34 participants instead of 40, and 51 instead of 60 (reflecting a 15% reduction). As shown in the sensitivity analysis plots (Figures 8.5, 8.6, 8.7 and 8.8), this adjustment in total sample size does not alter the conclusions regarding the smallest detectable effect sizes; these remain within the small to medium range for within-subject designs and medium to large for between-subject designs.

8.6. Summary

This chapter presented and discussed the results of experiments 1 and 2, in which measures were recorded to examine the influence of different lighting conditions on NIF responses under conditions representing pedestrians' experience on minor roads in the evening.

Experiment 1 aimed to examine two hypotheses; *H1*. Variations in the illuminance and SPD of road lighting within the range of conditions typical of lighting on minor roads will affect alertness, melatonin level and skin temperature, and *H2*. Walking at a self-selected speed, compared with remaining seated, will affect alertness, melatonin level and skin temperature.

Experiment 1 involved two IVs: four lighting conditions (as mentioned in Table 3.1) and two physical activity groups (seated and walking at a self-selected speed). It also involved four DVs: melatonin level, reaction time, subjective alertness and skin temperature. The findings of experiment 1 suggested that lighting conditions within the range of those typical of conventional outdoor lighting practice (up to a melanopic EDI of 10.7 lx) did not have an impact on melatonin levels, skin temperature and alertness measured by reaction time and subjective alertness. Regarding physical activity, the results did not suggest any differences in reaction time between the seated and walking groups to be significant. Melatonin levels were suggested to be significantly higher at the final interval compared to the 150 min interval in the walking group, but not in the seated group, possibly due to changes in melatonin concentration in saliva. The walking group reported feeling more alert than those who were seated. The skin temperature was observed to be significantly lower during the first 30 min of walking compared to the adaptation phase, and it was significantly higher at the final interval (180 min) compared to the 150 min interval. This variation in skin temperature was only observed in the walking group. This pattern corresponds with the anticipated trend of skin temperature during low-intensity constant exercise[301,300].

In conclusion, *the findings from experiment 1 did not support Hypothesis H1, but they did provide support for Hypothesis H2.*

A second experiment was conducted to test the null findings of experiment 1 by extending the range of conditions. This second experiment replicated the procedure of experiment 1 but with two main changes: 1) an extreme lighting condition was included (melanopic EDI of ~ 100 lx) and 2) a moderate-intensity walking speed was used during the test phase to better represent typical walking speed. Two additional hypotheses were introduced; *H3*. Melanopic EDI levels significantly greater than those typical of conventional road lighting

will affect alertness and melatonin levels when walking in the evening and *H4*. Walking at a moderate speed, compared to sitting and walking at a self-selected speed, will affect alertness and melatonin levels. The findings of experiment 2 confirm the null finding obtained in experiment 1 and validate the experimental design employed in both experiments (see Veitch *et al.*[384]). The results suggested that exposure to relatively extreme light condition (melanopic EDI of 98.8 lx) significantly shortened reaction time, enhanced subjective alertness and suppressed melatonin level after 30 min of exposure in the evening.

In conclusion, *the findings from experiment 2 supported Hypothesis H3.*

The combined data from experiments 1 and 2 included three physical activity groups: seated, walking at a self-selected speed and walking at a moderate speed. These data were used to investigate the effect of physical activity on DVs. The results indicated a significant improvement in cognitive performance, as measured by reaction time, in the group walking at a moderate speed compared to the self-selected speed and seated groups. This improvement is likely linked to the exercise-induced arousal effect. Subjective alertness was reported to be significantly higher at the 150 min interval for both walking groups compared to the seated group, and it was significantly higher for the moderate speed walking group at the 180 min interval compared to the seated group. Melatonin levels were shown to be significantly higher in both walking groups compared to the seated group, possibly due to the effects of gravity on plasma volume.

In conclusion, *the findings from the combined analysis of experiments 1 and 2 supported Hypothesis H4.*

The following table (Table 8.7) outlines the decisions made regarding the thesis's hypotheses using data from experiments 1 and 2. It details whether each null hypothesis was retained or rejected and provides a concise explanation of these outcomes.

Table 8.7 Hypothesis decisions reached using the datasets from experiments 1 and 2

Hypothesis	Decision	Interpretation
H1	Null hypothesis retained	Variations in the illuminance and SPD of road lighting within the range of conditions typical of lighting on minor roads (up to melanopic EDI of 10.7 lx) did not affect melatonin level, skin temperature, reaction time and subjective alertness.
H2	Null hypothesis rejected	Walking at a self-selected speed, compared with remaining seated, affected subjective alertness, melatonin level and skin temperature: Neither walking nor sitting affected reaction time. Walking maintained a similar level of subjective alertness over the first 30 min of walking compared to the adaptation phase. Sitting led to feeling less alert at all intervals in the test phase compared to the adaptation phase. Walking, unlike sitting, was suggested to result in a significant increase in saliva melatonin levels at the final test interval compared to the 150 min interval. This is likely due to a change in melatonin concentration in saliva. Walking, unlike sitting, was suggested to cause a significant decrease in skin temperature in the first 30 min of walking, followed by an increase at the last interval - likely due to changes in blood flow to regulate heat loss in the body.
H3	Null hypothesis rejected	Melanopic EDI levels significantly greater than those typical of conventional road lighting affected alertness and melatonin levels when walking in the evening: Light level with melanopic EDI of 98.8 lx enhances alertness as measured by reaction time and subjective alertness, and suppressed melatonin level after 30 min of exposure while walking in the evening.
H4	Null hypothesis rejected	Walking at a moderate speed, compared to sitting and walking at a self-selected speed, affected alertness and melatonin levels: Walking at a moderate speed Shortened reaction time after 30 min of walking (probably due to the exercise-induced arousal effect). Walking at a moderate speed enhanced subjective alertness (feeling more alert after 30 min of walking). Walking at moderate and self-selected speeds, unlike sitting, was suggested to result in a significant increase in saliva melatonin levels at the final test interval compared to the 150 min interval. This is likely due to a change in melatonin concentration in saliva.

Chapter 9

Conclusion

9. Conclusion

9.1. Summary of results and implications

The implementation of lighting on minor roads should be carefully considered, taking into account various factors that affect pedestrians, other road users and the built environment. These factors include road safety, energy conservation, impacts on health, sky glow and effects on the surrounding ecology. This thesis focused on investigating the influence of different lighting conditions on NIF responses under conditions representing pedestrians' experience on minor roads in the evening between 23:00 and 00:00. Two experiments examined the effects of lighting on four DVs: reaction time to an auditory stimulus, melatonin levels derived from saliva samples, skin temperature and subjective alertness.

For melanopic EDI of up to 10.7 lx, the data did not indicate any statistically significant changes in the DVs, confirming the findings of previous studies by Bhagavathula *et al.*[113] and Gibbons *et al.*[114] The light condition L4, with a melanopic EDI of 98.8 lx, shortened reaction time, increased subjective alertness and decreased melatonin levels after 30 min of exposure. The recommended average horizontal photopic illuminance for road lighting for pedestrians ranges from 2 lx to 15 lx.[26] Lighting condition L4 had a photopic illuminance at the eye of 83 lx, with a CCT of 5800 K. To reach the same melanopic EDI with a CCT of 2700 K, it would require a photopic illuminance at the eye of 230 lx. Therefore, while this lighting can affect the alertness and melatonin levels of pedestrians, the results of this thesis suggest that the conditions required are unlikely to be found in road lighting applications.

Regarding physical activity, a significant increase in melatonin levels was observed in the self-selected speed and moderate-speed groups compared to the seated group. This change in melatonin level is linked to posture-induced changes in melatonin concentration rather than the intensity of physical activity. There were higher salivary melatonin concentrations in a standing position compared to a sitting position.

While walking at a moderate speed did not decrease melatonin levels, it significantly shortened the reaction time after 30 min of walking and enhanced subjective alertness compared to the other groups. This enhancement was linked to the exercise-induced arousal effect.

Skin temperature decreased significantly in the first 30 min of walking at a self-selected walking speed, followed by an increase in skin temperature in the last interval of the test phase. This pattern aligns with the expected trend of skin temperature during low constant-

intensity exercise. The initial decrease is believed to be associated with cutaneous vasoconstriction, with the body sending more blood to the working muscles and away from the skin. The subsequent increase is related to thermoregulatory vasodilation, which helps the body release the heat produced.

9.2. Limitations and future research

This study has some limitations that can be taken into consideration in future studies:

1. Melatonin levels were measured solely through saliva samples due to safety concerns about collecting blood samples in a poorly illuminated laboratory while walking on a treadmill. Previous research found that blood sampling is more sensitive than saliva for accurately quantifying melatonin levels.

2. The laboratory environment was free from traffic or other lighting sources, such as light from shops or passing vehicles. This was done to isolate the effects of road lighting on NIF responses. However, future studies could consider these additional light sources.

3. The participants were exposed to steady light during the test phase. In reality, the light levels will fluctuate as pedestrians move along the road, diminishing as they move away from a light post and increasing as they approach the next light post. Another limitation is the use of road lighting data from an industrial lamp catalogue rather than measuring actual road lighting in the field.

4. Age limitation: only a young sample was included, those aged between 18 and 30 years. Older people are expected to have different responses to light. With increasing age, there are changes in the central visual pathways,[412,413] which can influence NIF responses: older people may have different sleep patterns and circadian rhythms than younger people.[414] In addition, there is an age-related decline in cognitive performance, with older individuals tending to experience reduced cognitive performance compared to younger individuals.[415] Future research should consider incorporating a more diverse age range to gain a better understanding of the potential variations in the NIF effects of road lighting on NIF responses across different age groups.

5. The indoor light level chosen for the adaptation phase assumed only one source in the room, which is likely to occur in small rooms found in residential buildings but

not in offices or manufacturing spaces. This factor should be considered in future research.

6. The study only considered the immediate effects of exposure to road lighting between 23:00 and 24:00. Future research should explore various evening times to develop a better grasp of the impact of road lighting on alertness and melatonin levels. It is also necessary to examine how daily exposure to road lighting affects alertness and melatonin levels over the long term rather than just the immediate effects.

Appendices

Appendices

Appendix A. Laboratory sections

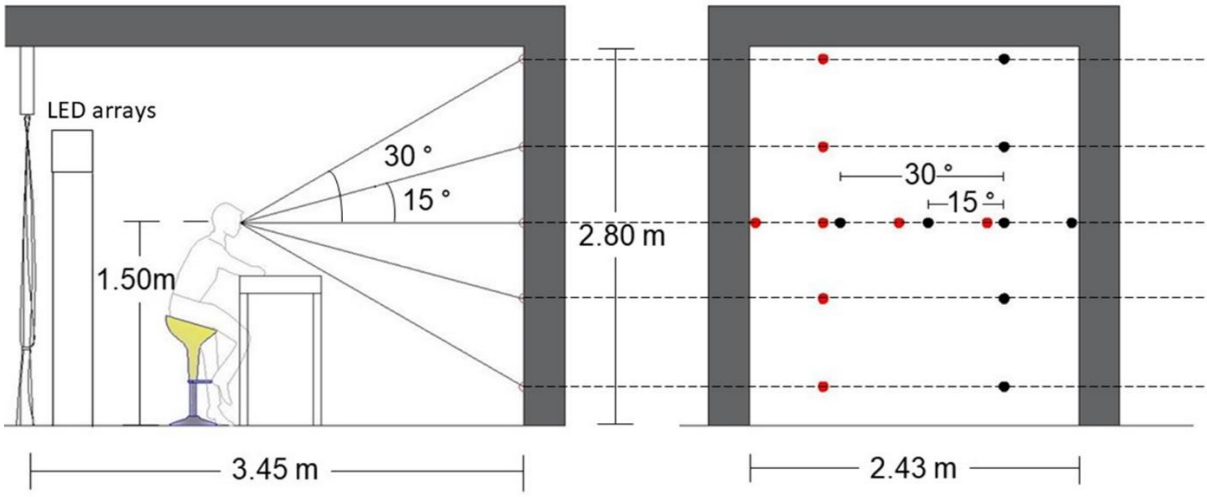

Figure A.1. Laboratory sections show the measuring points for illuminance and luminance within participants' "angle of view". Measuring points in the wall facing the participants: Left-Red points for participant 1 and Right-Black points for participant 2.

Appendix B. Estimating the typical duration of a pedestrian trip

B.1. Introduction

The aim of this thesis is to investigate how changes in lighting impact alertness and melatonin levels in a context that better simulates pedestrians exposed to road lighting after dark. One important factor influencing the significance of the NIF effects of light is the duration of exposure. For pedestrians, the duration of exposure is determined by the time they spend walking outdoors under road lighting (i.e., walk trip duration after dark). A trip is defined as "*a journey in which you go somewhere, usually for a short time, and come back again: a trip from somewhere to somewhere*".[31]

An estimation of walk trip duration after dark was necessary to plan an experimental protocol representing a real-life pedestrian context. This estimation helped decide the DVs' measurement intervals during the test phase.

A main source of walk trip duration data is the countries' National Travel Surveys (NTS), household surveys designed to provide consistent information on personal travel behaviour. For the UK, this is called the UK NTS and is accessible through the Department for Transport.[416] The most recent dataset available at the time of this analysis was the 2019 dataset. The survey was conducted between January 2019 and December 2019, involving

15,953 individuals providing information through seven-day diaries and face-to-face interviews with 6,789 households. The available data included details about demographics, trip specifics, and travel choices but did not provide detailed data on disruptions; this means that further investigation into trips conducted after dark was not possible.

The UK NTS reported that the average walking trip duration in 2019 was 17 min.[416] However, it is unclear whether this reported average represents the mean or another measure of central tendency. If the data is not normally distributed, using the median would be more suitable for estimating the average duration. Additionally, the reported average includes walking trips conducted at all times of day, not specifically after-dark walking trips. Therefore, it was necessary to explore datasets from other countries that provide access to original data to evaluate walking trip duration after-dark while considering various factors:

1. Variations based on trip purposes, origins, or destinations: the duration of a walking trip can be influenced by the purpose of the trip and its specific starting and ending points. For example, leisurely walks may take different amounts of time compared to trips to specific destinations.
2. Variations over time: the duration of walking trips may change from year to year due to differences in infrastructure, urban development, and societal habits.
3. Variations between countries: different countries may show differences in walking trip duration due to variations in urban design and individual preferences for walking as a mode of transportation.
4. Variations in data collection and analysis methods: differences in how data is collected and analysed across different studies or surveys can also lead to variations in reported walking trip durations.

The next section presents the estimated duration of walking trips based on NTS and previous studies and discusses the variables affecting trip duration.

B.2. Data sources of walk trip durations

B.2.1. National statistics

This section provides data on the duration of walking trips from various National Statistics sources, including those from the UK,[416] US, [418-420] and Australia.[421] In the UK, the average duration of walking trips ranged from approx. 15 to 18 min from 2002 to 2019, as illustrated in Figure B.1. In the US, the average duration was 10 min in 1990, and in 2017 it was similar to the UK's walking trip duration, at an average of 15 min (Table B.1). In Australia, the

average duration was reported as around 13 min for Sydney and Hunter, and 14:42 min for Illawarra in 2018/2019 (Table B.2).

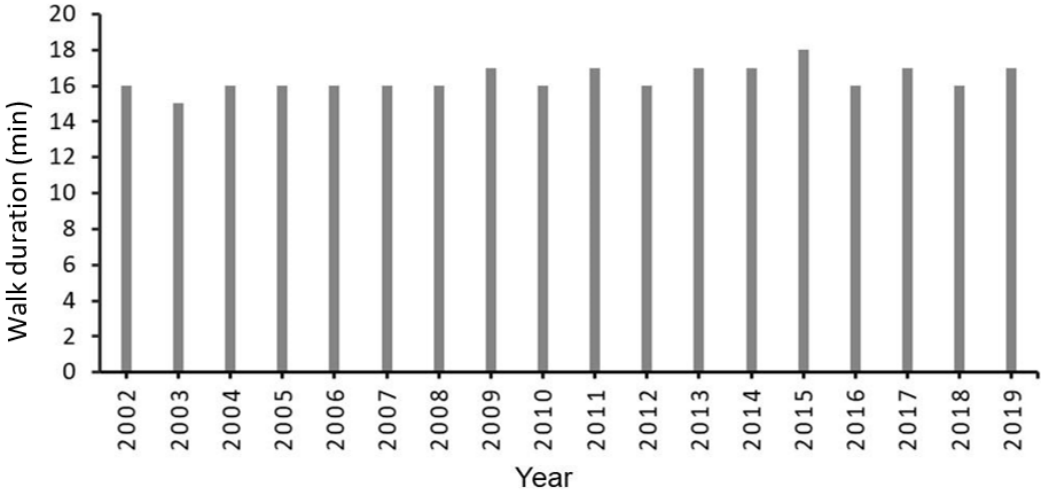

Figure B.1 The average walking durations reported in the UK NTS[416] from 2002 to 2019. The data illustrates that there is minimal variation in walking durations throughout this period.

Table B.1. Average walk trip durations as reported in The US NHTS [418-420]

	Year				
	1990	**1995**	**2001**	**2009**	**2017**
Survey period	-	-	March 2000 to May 2001	March 2008 to April 2009	April 2016 through April 2017
Average Commute Travel Time (min)	**9:47**	**10:51**	**14:04**	**16:09**	**15:16**
All Samples*	93,347	98,990	107,365	113,101	118,208
Sample size**	22,317 [18,000 national and 4,300 add-ons]	42,031 [21,000 national and 21,031 add-ons]	26,038 national and approx. 40,000 add-ons	150,147 [25,510 national and 124,637 add-ons]	129,696 [26,099 national and 103,597 add-ons]
Travel day data	From memory	Travel diary	Travel diary	Travel diary	Travel log used
Interview method(s)	Tel. interview	Tel. interview	Tel. interview	Tel. interview	Tel. interview Mail-back and web

*Number of occupants of households aged 5 years or older
**Number of Households

Table B.2 Average walk trip duration in min as reported in Household Travel Survey (HTS) for Australia regions, Sydney (GMA)[421]

Period	2008/2009	2010/2011	2012/2013	2014/2015	2016/2017	2018/2019
City	Average walk-only* trip duration (min)					
Sydney	10:36	10:24	10:42	10:48	11:42	12:30
Illawarra	11:24	11:36	10:24	12:18	12:06	14:42
Hunter	12:12	11:36	10:18	10:18	13:00	12:54

* Trips that are solely made by walking, with no change of mode involved; the sample included approx. 4,000 randomly selected households.

The duration of walking trips in the UK was 1 to 2 min longer than those in the US and Australia, as shown in Tables B.1 and B.2. In 2009, the average walking trip duration was 17 min in the UK and 16 min in the US. The longest reported duration in Australia was 14:42 min in 2018/2019.[418] These small variations in walk trip duration between countries do not necessarily need to be precise; one potential reason for this difference is the method of data collection. For example, the UK data was collected through seven-day diaries and face-to-face interviews, while the Australian survey involves face-to-face interviews with participants reporting activities over a designated 24-hour period. Additionally, the Australian HTS uses pooled data from three consecutive years to generate annual estimates—the estimates for 2015/16 are based on data pooled from 2013/14, 2014/15, and 2015/16, which are then weighted to reflect the population distribution of 2015/16. [421] These different methods rely on varying resources, which could potentially affect the reported duration — for example, maintaining a detailed written diary of walking trips over a seven-day period may capture more detailed trips than brief face-to-face interviews.

However, if the average reported in these national statistics represents the mean, it could be skewed by outlier trips — such as very long durations that make up a small proportion of the total trips. This potential bias has been examined in previous research.

B.2.2. Previous studies reanalysed the NTS dataset

Table B.3 presents previous research that estimated both the median and mean durations of walking trips across several countries. The median is generally considered a more reliable measure than the mean when dealing with data that is not normally distributed. [417]

In the US, Sydney, and Canada, the median walking duration was found to be 3 to 7 min shorter than the mean. This emphasises the need to test the normality of the data reported in the NTS, as the average reported may not accurately reflect the typical duration of walking trips if the data is not normally distributed.

Table B.3 Walk trip duration; average and median as reported in previous studies

Reference	Data source	Country and period	Sample	walk trip duration (min)		Comments
				Mean	Median	
Agrawal and Schimek 2007[423]	2001 NHTS	USA, 2001	26,000 households	16:24	10:00	All day; Walk-only, excluded walk trips - to and from public transport.
Yang and Diez-Roux, 2012[423]	2009 NHTS	USA, 2009	80,222 walk trips [43,724 respondents].	14:54	10:00	All day: 20,183 walking trips were excluded from the 2009 NHTS
Millward *et al*, 2013[424]	The 2007–8 [STAR]	Canada, 2007-2008	1887 walking trips	9:24	6:18	All day (weighted mean, median)
Merom *et al.* 2010[425]	2004-2006 HTS	Sydney	3250 households	9:30	6:36	All day (weighted mean, median)
Stopher, 2007[426]	2003–2004 HTS	Sydney	70 households	8:36	-	HTS method
Stopher, 2007[426]	2003-2004 GPS device	Sydney	70 households	8:06	-	Optional; telephone or the postal for the prompted recall survey/face-to-face

In addition, the average duration of walking trips in the USA in 2001 was reported as 14:04 minutes by the NHTS,[418-420] and 16:24 minutes by Agrawal and Schimek.[422] By 2009, the NHTS reported an average of 16:09 minutes, while Yang and Diez-Roux[423] reported it as 14:54 minutes.

These discrepancies in the reported averages are primarily due to the different data analysis approaches used in these studies compared to the NTS. Many studies exclude certain outlier trips, which can significantly affect the mean but not the median. Notably, both Agrawal and Schimek[422], as well as Yang and Diez-Roux[423], reported a consistent median of around 10 minutes, despite variations in the mean.

B.2.3. Variables affect the duration of walk trips

Various factors can influence the duration of a walking trip, such as the purpose, starting point, destination and walking speed. The purpose of the trip refers to walking with a specific objective in mind. Generally, individuals are willing to walk for up to 10 min to reach transportation facilities and local amenities, whereas they are willing to walk up to 30 min for urban services, such as workplaces.[427,428] In the USA, the average walking duration for recreational activities and exercise was reported as 25:18 min, while it was only 11:54 min for shopping (see Table B.4).[423]

Table B.4 Mean and median walk trip durations by trip purpose in the Sydney Greater Metropolitan Area, 2004 -2006 [source: modified by author after Merom *et al.*[425]]

Trip purpose	Mean (min)	Median (min)
Change of mode	7:12	5
Commuting	9:30	7
work-related trip	7:18	5
shopping	8:00	5
personal business	8:42	5
Social visits	9:36	5
Entertainment	9:06	5
Accompany/pick up	9.:06	6
Recreation	18:42	15
Sport	9:36	10

The mean durations reported for different trip purposes varied significantly, ranging from 7 to 18 min. For instance, recreational walk trips averaged 17:18 min, while commuting to work or school was reported at 9 min.[424] Change-of-mode trips, such as walking to a bus station, averaged 7:12 min, whereas recreational walks were reported at 18:42 min.[425] (See Table B.4 for details). The median duration was more consistent across different trip purposes compared to the mean. A similar conclusion can be drawn regarding the starting and ending points of walking trips, where the reported mean varies significantly, ranging from as short as 3:48 min to as long as 27:18 min, depending on the trip's origin and destination[424] (see Table B.5).

Table B.5 The average walking trip durations in min, categorised by origin and destination, in Canada during 2007-2008 [modified by the author after Millward *et al.*[424]]

	Destinations						
Origins	Home	Workplace	Other's home	School	Outdoors	Other places	Total
Home	-	14:36	7:24	15:00	7:24	13:30	11:06
Workplace	14:48	8:30	-	-	6:36	7:48	8:42
Other's home	6:18	27:18	8:24	18:00	5:48	9:42	7:36
School	19:48	-	21:00	3:48	10:18	7:18	9:42
Outdoors	6:54	5:30	5:00	5:00	3:18	6:42	6:18
Other places	12:54	6:24	8:30	7:18	6:54	6:54	8:18
Total	11:12	8:18	7:42	7:36	7:00	8:54	9:00

Walking speed indicates how quickly a pedestrian is moving, usually measured in meters per second or kilometres per hour. "Walk trip distance" refers to the distance covered by a pedestrian in a single trip, typically measured in meters or kilometres. To calculate the duration of a walk trip, simply divide the walking distance by the walking speed.

Several factors can affect walking speed, including gender, age, weather conditions, road slope and the size of the pedestrian group. Studies have estimated the walking speed for pedestrians to range from 2.4 $km.h^{-1}$ to 6.9 $km.h^{-1}$, with an average of around 4.5 $km.h^{-1}$. [423-

[425,428-434] An individual's assumed walking speed directly affects the estimated walk duration; for example, a 30-year-old male with a walking speed of around 5.4 km.h^{-1} would take approx. 11 min to walk 1 km,[435] while a 70-year-old male with a walking speed of around 4.3 km.h^{-1} would require 13 min and 54 s to cover the same distance.[435] Studies have also shown that the typical walking speed for adults aged 20 to 29 years ranges from 4.5 km.h^{-1} to 5.2 km.h^{-1}. The average walking distance in the UK in 2017 was approx. 0.7 miles (1.13 km), which, based on the estimated typical walking speed of 4.5 km.h^{-1}, translates to a walking duration of around 15:04 min. This suggests the need for further examination of the data reported in the UK NTS.

Some studies have reported distances walked rather than duration.[436,437] From these studies, the trip duration can be estimated by assuming a walking speed of 4.5 km.h^{-1}. Burke & Brown[436] reported a median distance of 0.78 km for walks from home to other places in Australia. This would equate to a duration of approx. 10:24 min (based on the estimated typical walking speed). Another study from the Netherlands found that the median distance that people tend to walk is between 1.1 and 1.3 km,[437] translating to durations of 14:40 min to 17:19 min. The mode distance in the same study was reported as 0.8 km, which would result in a duration of 10:40 min. The mode is the value that appears most frequently in a data set.

A limitation of all these previous studies is that they focused on walking trip duration throughout the day. In our present thesis, our focus is specifically on walk trip duration after dark.

B.3. California database analyses

Previous studies and the NTS have reported walking trip durations during the day, but there is uncertainty regarding the average durations reported. This study specifically focuses on walking durations after dark. To investigate this further, access to raw data was required. Although raw data for the England NTS is not available, the 2017 California NTS raw data is accessible to the public online.

In 2017, California was one of the 13 partners involved in the US NHTS. The survey was conducted by the Federal Highway Administration (FHA) from April 19, 2016, to April 25, 2017. The sample included 26,095 households, with a total of 55,793 participants. Each participating household recorded all the travel conducted by household members during a randomly assigned 24-hour period, including trips taken between 4:00 am and 3:59 am the following day.

In order to determine if the dataset from California can be considered representative of the dataset in the UK, a comparison of the reported walking trip durations for each national statistic in 2017 was conducted (see Figure B.2). The average walking trip duration for the UK was 17 minutes, compared to 17:18 minutes for California. This slight difference indicates that the original dataset from California can be considered a valid representation of walking trips in the UK.

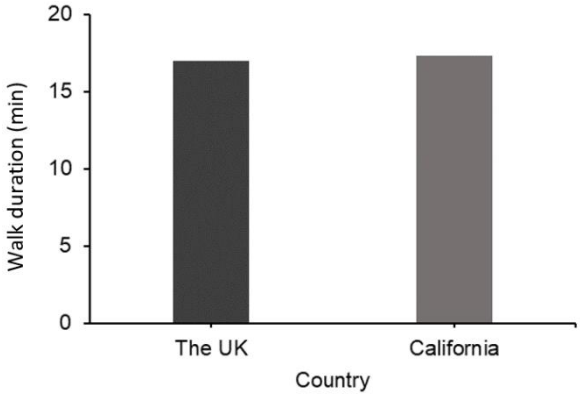

Figure B.2 Comparison of walk trip duration in the UK and California, 2017

B.3.1. Method

An analysis was conducted using both SPSS Statistics and Microsoft Excel to examine walking trip data extracted from a comprehensive California dataset. Initially, the dataset enumerated a total of 21,891 walk trips. Following a meticulous cleaning process, 110 trips were deemed unfit for inclusion in the analysis for the following reasons:

1. There were 26 trips reported as [Not ascertained] in the trip durations column, which means that no value exists.

2. In the trip distance column,77 trips were reported as [Not ascertained].

3. 7 trips were reported as [Regular home activities: chores, sleep], while these, along with 13 other trips, were the longest trips in the dataset. The duration of these trips ranged between 305 and 810 min, representing less than 0.1% of the total trips. The category suggesting that these trips should be captured in this long duration may have been an error.

To explore the impact of ambient light conditions on walk trip durations, the data was stratified into two predominant categories based on ambient light levels: after-dark and daylight. The categorisation criteria were established according to the annual mean morning

twilight time (5:57) and the annual mean evening twilight time (19:06) specific to California in the year 2017.[439]

There were 552 trips, representing 2.5% of total walk trips, including partially light and dark trips; these being a trip starting in daylight and ending in darkness, or vice versa, were also excluded from the analyses.

Upon completing the exclusion criteria, a total of 662 trips were removed from consideration, resulting in a dataset comprising 21,229 trips. Within this refined dataset, daylight trips numbered 18,685, and after-dark trips totalled 2,544. These figures correspond to 88% and 12% of the compiled walk trips, respectively, providing a substantive basis for further statistical investigation into the variance in trip duration across differing ambient light conditions. In Figure B.4, the mean and median trip durations for each trip group are shown. The mean duration for trips taken during daylight was 16:48 min, with a median duration of 10:00 min. For after-dark trips, the mean duration was 15:39 min, with a median duration of 10:00 min.

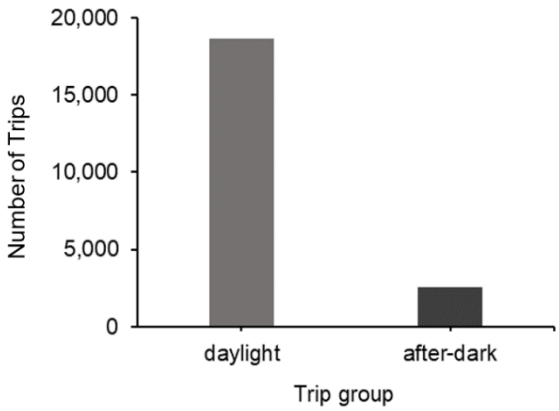

Figure B.3 The walk trips in daylight and after-dark for California NHTS 2017

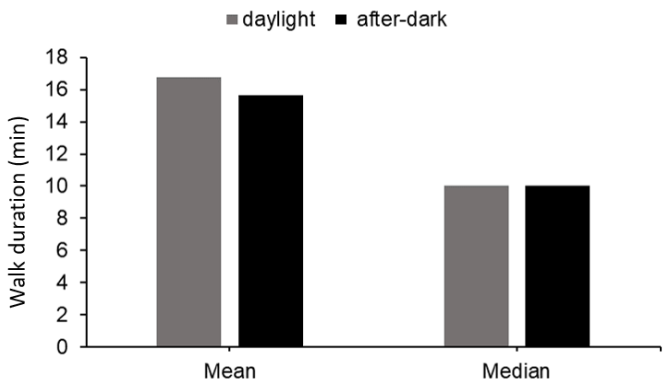

Figure B.4 Overview of the duration of walk trips for California NHTS 2017

B.3.2. Daylight and after-dark trips

The data of daylight and after-dark trips were checked to see if they were drawn from a normally distributed population. This was done by four methods of analysis: comparing measures of central tendency, statistical tests (Shapiro-Wilks and Kolmogorov-Smirnov), measures of dispersion (skewness and kurtosis) and graphical representations (histogram and box plot). The results of these analyses revealed that the durations of walking trips for both groups were not normally distributed (see Tables B.6 and B.7).

Table B.6 The Kolmogorov-Smirnov test of normality for the daylight and after-dark groups

Group	Statistic	Degrees of freedom (df)	Sig.
Daylight	.235	18685	.000
After-dark	.214	2544	.000

Table B.7 The descriptive statistics for the daylight and after-dark groups

Statistics	Daylight	After-dark
N	18,685	2544
Mean	16.78	15.65
Median	10.00	10.00
Std. Deviation	21.815	15.751
Skewness	7.772	2.859
Kurtosis	145.902	15.444

The skewness values for both groups showed that the distribution was not symmetrical and fell outside the normal range of ± 0.5. Furthermore, the kurtosis results indicated a highly peaked distribution, especially for the daylight trip duration, which had a kurtosis value of 145.9. The significantly positive kurtosis values for both types of trips suggested the presence of major outliers, indicating that most trip durations were located in the tails of the distribution rather than around the mean (Figure B.5).

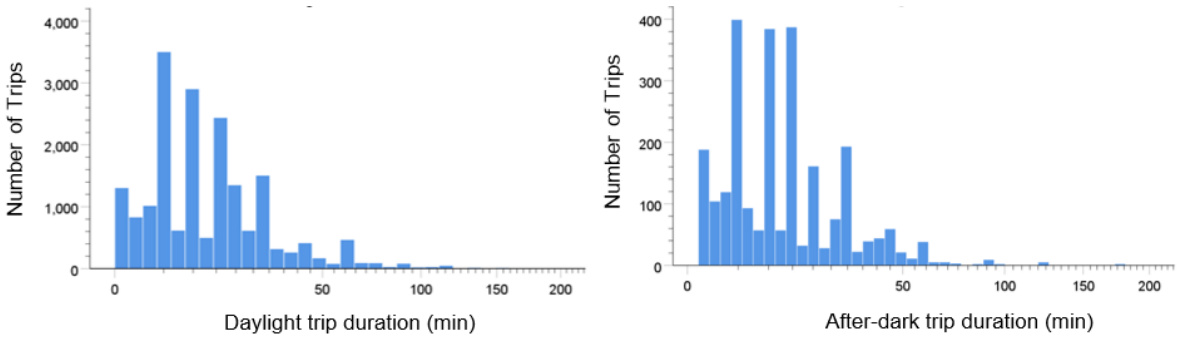

Figure B.5 Normality profiles for daylight (left) and after-dark (right) groups.

As a result, a non-parametric test, the Mann-Whitney U test, was used to compare the two groups. The results revealed that the difference between the groups was not statistically

significant. This suggests that the duration of daylight walking trips can serve as a reliable indicator of after-dark trip durations when using the median rather than the mean.

Table B.8 The nonparametric test results conducted to compare the daylight and after-dark trip groups

Group	N	Mean rank	Sum of ranks	Mann-Whitney U	23588613
Daylight	18685	10605	198162568	Wilcoxon W	190287560.5
After-dark	2544	10685	27183267	Z	-.620
				Asymptotic Significance (Asymp.Sig.) (2-tailed)	**.536**

B.3.3. Short And Long Walk Trips

The duration of walking trips varies based on their purpose, origin, or destination, ranging from short to long durations. The distribution of walking trip durations in the California dataset suggests the presence of two types of walking trips: short (S) trips and long (L) trips. To establish the threshold for short walk trips, outliers were filtered out to obtain a normally distributed dataset of walking trips conducted separately for both daylight and after-dark trips. For daylight trips, the filtering process resulted in a dataset without outliers (N=16,551 trips) and suggested that a maximum duration of 30 min is appropriate for defining short walking trips. Trips exceeding this duration were classified as long trips. Short trips accounted for 88.6% of the total number of trips, with long trips comprising 11.4% of the dataset. The number of short trips in both categories is significantly higher than that of long trips. Almost 90% of the after-dark trips were classified as short trips, indicating that the study should focus on the duration of short trips (see Tables B.9 and B10).

Table B.9 Excluding the outliers to define daylight short walk trip duration

		Remove outliers	
Short trip	**Original data set**	**First**	**Second**
N	18,685	17,150	16,551
Median (min)	10	10	10
Mean (min)	16.:47	12:12	11:18
Outliers (min)	>=43	>=31	No outliers
Range (min)	1 – 750	1 - 42	1 – 30

Table B.10 Daylight long walk trip duration

Long trips	
N	2134
Median	50
Mean	59:12
Outliers	>=93
Range	31 - 750

A similar method to differentiate between short and long after-dark trips was used. This involved three rounds of filtering the dataset to remove outliers (see Tables B.11 and B.12 and Figure B.6). A short trip was classified as lasting 30 minutes or less. These short trips comprised 89.3% of all after-dark walking trips, while long trips accounted for the remaining 10.7% of the dataset.

Table B.11 Excluding the outliers to define after-dark short walk trip duration

		Remove outliers		
Short trip	**Original data set**	**First**	**Second**	**Third**
N	2544	2382	2285	2274
Median (min)	10	10	10	10
Mean (min)	15:36	12:42	11:36	11:30
Outliers (min)	>=43	>=33	>=31	No outliers
Range (min)	1-180	1-42	1-32	1-30

Table B.12 After-dark long walk trips duration

Long trip	
N	270
Median	45
Mean	50:18
Outliers	>= 90
Range	31-180

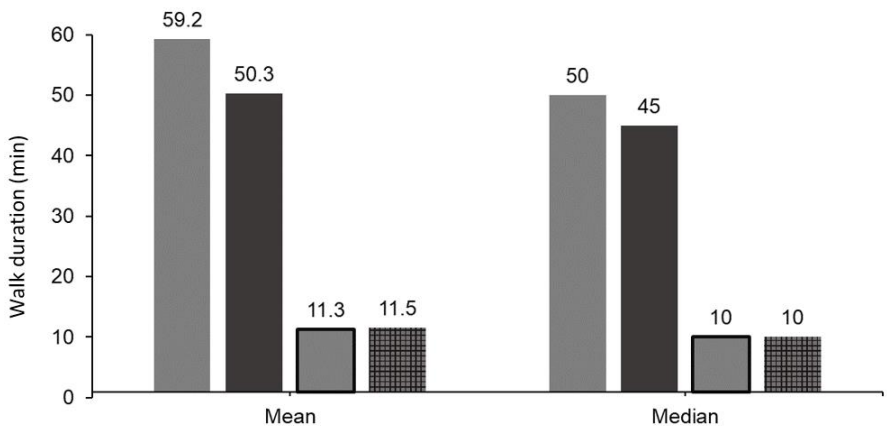

Figure B.6 Summary for mean and median of Long and Short walk trips in daylight and after-dark

The normality of each of the four groups was tested separately, and it was found that all groups had distributions that were not normal (see Tables B.13 and B.14). Long walk trips had heavy tails and high skewness, while short walk trips had moderate skewness and light tails without outliers. Since the statistical tests showed non-normal distributions, the median is a better measure than the mean for representing both short and long walk trips in this dataset.[41]

Table B.13 The normality test (Kolmogorov-Smirnov) results for all walk trip groups

Normality test [N]	p-value	Skewness	Kurtosis	95% CIM
Normality range	> .05	± 0.5	± 1	-
After-dark (S) [2274]	.000 Not normal	0.78 moderately skewed	-0.25 light-tailed	11.53 to 11.87
After-dark (L) [270]	.000 Not normal	3.04 highly skewed	13.39 heavy-tailed	47.8 to 52.71
Daylight (S) [16551]	.000 Not normal	0.83 moderately skewed	-0.23 light-tailed	11.18 to 11.44
Daylight (L) [2134]	.000 Not normal	6.89 highly skewed	77.20 heavy-tailed	57.51 to 60.89

Table B.14 The distribution of short and long walk trip durations in daylight and after-dark

Normality test	Daytime		After-dark	
	Short	Long	Short	Long
Median lies in a 95% confidence interval of the mean	No Not normal	No Not normal	No Not normal	No Not normal
Skewness and kurtosis are within acceptable limits	Yes Acceptable	No highly skewed heavy-tailed	Yes Acceptable	No highly skewed heavy-tailed
Statistic tests suggest data follows a normal distribution (Kolmogorov-Smirnov)	Not normal	Not normal	Not normal	Not normal

The Mann-Whitney U test was used to compare the duration of short trips during daylight and after-dark conditions. The results for the short trip groups, as displayed in Table B.15, indicated that there was no statistically significant difference between the groups. The test was also performed for long trips, and the results revealed a statistically significant difference in trip duration between daylight and after-dark conditions (see Table B.16).

Table B.15 Wilcoxon test results for short trip groups in daylight and after-dark

Group [short trips]	N	Mean Rank	Sum of Ranks	Mann-Whitney U	18392710.5
Daylight	16551	9387.27	155368786.5	Wilcoxon W	155368786.5
After-dark	2274	9600.24	21830938.5	Z	-1.766
Asymp. Sig. (2-tailed)					.077

Table B.16 Wilcoxon test results for long trip groups in daylight and after-dark

Group [long trips]	N	Mean Rank	Sum of Ranks	Mann-Whitney U	232993.5
Before dark	2134	1228.3	2621231.5	Wilcoxon W	269578
After dark	270	998.44	269578.5	Z	-5.162
Asymp. Sig. (2-tailed)					.000

B.3.4. Summary of California NTS 2017 analysis

The analysis of California's NTS 2017 data reveals that walking trips can be categorised into two groups based on their duration: short and long trips. The proportion of short walk trips was much higher than long walking trips (around 90%). The duration of short walk trips was similar during daylight and after-dark hours. The median duration for both daylight and after-dark short trips is 10 minutes per trip, while the median duration for long walk trips after dark is 45 minutes per trip (refer to Table B.17). These estimations of walk trip duration helped determine the measurement interval during the test phase in the experiment protocol (see Figures 3.15 and 6.5).

Table B.17 Average walking trip duration based on the 2017 NHTS California dataset analysis

Trip time	Sample (N)	Walk trip duration (Min)		Group
		Mean	Median	
All day	21781	17:18	10	All
Daylight	18685	16:47	10	All
	16551	11:18	10	Short
	2134	59:12	50	Long
After-dark	2544	15:38	10	All
	2274	11:30	10	Short
	270	50:18	45	Long

B.4. Limitations

The categorisation of walking trips according to the mean twilight times in the morning and evening might not adequately consider the seasonal fluctuations over the course of the year.

Appendix C. Daily email for one week to remind participants to maintain their self-selected sleep-wake schedule.

Email subject: **Sleep-wake schedule - Participants for lighting research - £40 payment offered**

Dear participant,

This is a kind reminder of keeping the similar self-selected sleep-wake schedule.

Regards,

Aysheh Alshdaifat

a.alshdaifat@sheffield.ac.uk

Appendix D. Participant consent form for experiment 1

The University Of Sheffield.

Participant Consent Form
[Using road lighting to enhance pedestrian's and driver's alertness]
Consent Form

Please tick the appropriate boxes	Yes	No
Taking Part in the Project		
I have read and understood the project information sheet, or the project has been fully explained to me. (If you will answer No to this question, please do not proceed with this consent form until you are fully aware of what your participation in the project will mean.)	☐	☐
I have been given the opportunity to ask questions about the project.	☐	☐
I agree to take part in the project. I understand that taking part in the project will include two phases. In the adaptation phase I will sit under normal room lighting conditions wearing headphones and will have thermal sensors taped to my skin; at intervals I will take saliva samples and participate in a series of tasks. During the test period I will sit or walk for 1 hour under a lower light level and repeat the same tests.	☐	☐
I understand that my taking part is voluntary and that I can withdraw from the study at any time; I do not have to give any reasons for why I no longer want to take part and there will be no adverse consequences if I choose to withdraw.	☐	☐
I have completed the online training course for working out-of-hours in the Arts Tower	☐	☐
How my information will be used during and after the project		
I understand my personal details such as name, phone number, address and email address etc. will not be revealed to people outside the project.	☐	☐
I understand and agree that my result might be used in publications, reports, web pages, and other research outputs anonymously. Your name will only be reported if you specifically request for it.	☐	☐
I understand and agree that other authorised researchers will have access to this data only if they agree to preserve the confidentiality of the information as requested in this form.	☐	☐
I understand and agree that other authorised researchers may use my data in publications, reports, web pages, and other research outputs, only if they agree to preserve the confidentiality of the information as requested in this form.	☐	☐
I give permission for the test results that I provide to be deposited with the researchers (Nima Hafezparast Moadab, Aysheh Alshdaifat) and the project supervisor (Professor Steve Fotios), so it can be used for future research and learning.	☐	☐
So that the information you provide can be used legally by the researchers		
I agree to assign the copyright I hold in any materials generated as part of this project to The University of Sheffield.	☐	☐

Name of participant [printed] Signature Date

Name of Researcher [printed] Signature Date

Appendix E. Normality check for DVs, experiment 1

Statistical normality: (not normal if p<0.05). Central Tendency: Normal if the median is in 95% CI for the mean. Graphical: Include histogram and box blot. Measures of dispersion: Kurtosis: normal if (within ±1.0), Skewness: normal if (within ±0.5)

Table E.1 Normality check for Melatonin level at each interval; 40 participants

Tests of Normality													
	Statistical			***Graphical***	***Measures of Dispersion***			***Central Tendency***					**Overall Normality**
Interval (min)	Kolmogorov-Smirnov	Shapiro-Wilk	Normal	Normal	Kurtosis	Skewness	Normal	Mean	95% CI of mean		Median	Normal	
	Sig.	Sig.							lower	upper			
5	.000	.000	No	No	4.405	2.238	No	0.92	0.41	1.42	0.25	No	No
30	.000	.000	No	No	3.126	1.850	No	2.28	1.22	3.34	0.65	No	No
60	.000	.000	No	No	0.509	1.195	Near	4.30	2.63	5.98	1.70	No	No
90	.006	.000	No	Near	0.203	1.040	Near	7.42	4.94	9.89	4.80	No	No
110	.200*	.016	Near	Near	-0.617	0.589	Near	8.77	6.46	11.07	7.85	Yes	No
130	.105	.032	Near	Near	-0.949	0.333	Yes	10.66	8.31	13.00	9.25	Yes	Yes
150	.038	.017	No	Yes	0.760	0.936	Near	13.95	10.81	17.08	12.50	Yes	No
180	.099	.212	Yes	Near	-0.952	.009	Yes	15.86	13.21	18.51	15.00	Yes	Yes

Table E.2 Normality check for PVT at each interval; 40 participants

Tests of Normality													
	Statistical			***Graphical***	***Measures of Dispersion***			***Central Tendency***					**Overall Normality**
Interval (min)	Kolmogorov-Smirnov	Shapiro-Wilk	Normal	Normal	Kurtosis	Skewness	Normal	Mean	95% CI of mean		Median	Normal	
	Sig.	Sig.							lower	upper			
5	0.075	0.001	yes	no	5.236	1.782	No	415	377	452	382	Yes	No
60	0.016	0.002	no	no	0.658	1.063	Near	378	350	407	357	Yes	No
110	0.022	0.005	no	no	0.426	1.01	Near	380	351	409	359	Yes	No
130	0.200	0.391	yes	yes	-0.091	0.416	Yes	366	343	389	356	Yes	Yes
150	0.200	0.409	yes	yes	0.087	0.241	Yes	364	342	385	353	Yes	Yes
180	0.200	0.296	yes	yes	1.075	0.666	No	362	339	385	359	Yes	Yes

Table E.3 Normality check for skin temperature at each interval; 40 participants.

Tests of Normality													
	Statistical			***Graphical***	***Measures of Dispersion***			***Central Tendency***					**Overall Normality**
Interval (min)	Kolmogorov-Smirnov	Shapiro-Wilk	Normal	Normal	Kurtosis	Skewness	Normal	Mean	95% CI of mean		Median	Normal	
	Sig.	Sig.							lower	upper			
5	.189	.003	Near	Yes	4.81	-1.32	No	32.64	32.38	32.90	32.60	Yes	Yes
30	.200	.488	Yes	Yes	-0.19	-0.47	Yes	32.63	32.36	32.89	32.76	Yes	Yes
60	.014	.180	Near	Yes	-0.16	-0.57	Yes	32.51	32.23	32.79	32.72	Yes	Yes
90	.200	.902	Yes	Yes	0.33	-0.20	Yes	32.42	32.17	32.68	32.56	Yes	Yes
110	.200	.942	Yes	Yes	0.29	-0.34	Yes	32.46	32.21	32.71	32.41	Yes	Yes
130	.200	.253	Yes	Yes	0.79	-0.61	Near	32.22	31.92	32.52	32.37	Yes	Yes
150	.200	.229	Yes	Yes	-0.77	0.25	Yes	32.33	32.05	32.60	32.29	Yes	Yes
180	.200	.898	Yes	Yes	-0.09	-0.18	Yes	32.52	32.25	32.78	32.58	Yes	Yes

Table E.4 Normality check for KSS scores at each interval; 40 participants

Tests of Normality													
	Statistical			***Graphical***	***Measures of Dispersion***			***Central Tendency***					**Overall Normality**
Interval (min)	Kolmogorov-Smirnov	Shapiro-Wilk	Normal	Normal	Kurtosis	Skewness	Normal	Mean	95% CI of mean		Median	Normal	
	Sig.	Sig.							lower	upper			
5	0.010	0.086	No	Yes	-0.653	0.027	Yes	5.43	4.91	5.94	6	No	No
30	0.000	0.028	No	No	-0.13	0.41	Yes	4.9	4.42	5.38	5	Yes	No
60	0.006	0.055	No	Yes	0.96	0.595	Near	4.18	3.67	4.68	4	Yes	No
90	0.000	0.000	No	No	1.731	1.134	No	3.75	3.32	4.18	4	Yes	No
110	0.000	0.001	No	No	0.493	0.912	Near	3.2	2.76	3.64	3	Yes	No
130	0.000	0.003	No	No	1.127	0.914	No	3.1	2.6	3.6	3	Yes	No
150	0.000	0.000	No	No	-0.435	0.674	Near	2.48	2.09	2.86	2	No	No
180	0.000	0.000	No	No	1.22	1.082	No	2.08	1.76	2.39	2	Yes	No

Appendix F. Participant consent form for experiment 2

The University Of Sheffield.

Participant Consent Form

[Using road lighting to enhance pedestrian's and driver's alertness]
Consent Form

Please tick the appropriate boxes	Yes	No
Taking Part in the Project		
I have read and understood the project information sheet, or the project has been fully explained to me. (If you will answer No to this question, please do not proceed with this consent form until you are fully aware of what your participation in the project will mean).	☐	☐
I have been given the opportunity to ask questions about the project.	☐	☐
I agree to take part in the project. I understand that taking part in the project will include two phases. In the adaptation phase I will sit under normal room lighting conditions wearing headphones; at intervals I will take saliva samples and participate in a series of tasks. During the test period I will walk for 1 hour under a lower light level and repeat the same tests. I will wear a smartwatch to track my walking intensity.	☐	☐
I understand that my taking part is voluntary and that I can withdraw from the study at any time; I do not have to give any reasons for why I no longer want to take part and there will be no adverse consequences if I choose to withdraw.	☐	☐
I have completed the online training course for working out-of-hours in the Arts Tower	☐	☐
How my information will be used during and after the project		
I understand my personal details such as name, phone number, address and email address etc. will not be revealed to people outside the project.	☐	☐
I understand and agree that my result might be used in publications, reports, web pages, and other research outputs anonymously. Your name will only be reported if you specifically request for it.	☐	☐
I understand and agree that other authorised researchers will have access to this data only if they agree to preserve the confidentiality of the information as requested in this form.	☐	☐
I understand and agree that other authorised researchers may use my data in publications, reports, web pages, and other research outputs, only if they agree to preserve the confidentiality of the information as requested in this form.	☐	☐
I give permission for the test results that I provide to be deposited with the researchers (Nima Hafezparast Moadab, Aysheh Alshdaifat)and the project supervisor (Professor Steve Fotios), so it can be used for future research and learning.	☐	☐
So that the information you provide can be used legally by the researchers		
I agree to assign the copyright I hold in any materials generated as part of this project to The University of Sheffield.	☐	☐

Name of participant [printed] Signature Date

Name of Researcher [printed] Signature Date

Appendix G. Normality check for DVs, experiment 2

Statistical normality: (not normal if p<0.05). Central Tendency: Normal if the median is in 95% CI for the mean. Graphical: Include histogram and box blot. Measures of dispersion: Kurtosis: normal if (within ±1.0), Skewness: normal if (within ±0.5)

Table G.1 Normality check for Melatonin level at each interval, 40 participants, experiment 2

Tests of Normality													
	Statistical			***Graphical***	***Measures of Dispersion***			***Central Tendency***					**Overall Normality**
Interval (min)	Kolmogorov-Smirnov	Shapiro-Wilk	Normal	Normal	Kurtosis	Skewness	Normal	Mean	95% CI of mean		Median	Normal	
	Sig.	Sig.							lower	upper			
5	.000	.000	No	No	37.178	6.024	No	2.99	-0.798	6.778	0.7	No	No
60	.000	.000	No	No	25.231	4.712	No	4.195	1.126	7.264	0.9	No	No
110	.000	.000	No	No	11.633	3.037	No	7.178	3.737	10.618	3.9	Yes	No
130	.000	.000	No	No	21.938	4.241	No	8.625	4.189	13.061	5.3	Yes	No
150	.000	.000	No	No	22.568	4.278	No	10.513	5.391	15.634	7.3	Yes	No
180	.000	.000	No	No	12.846	3.107	No	12.788	7.742	17.833	10.1	Yes	No

Table G.2 Normality check for PVT at each interval, 40 participants, experiment 2

Tests of Normality													
	Statistical			***Graphical***	***Measures of Dispersion***			***Central Tendency***					**Overall Normality**
Interval (min)	Kolmogorov-Smirnov	Shapiro-Wilk	Normal	Normal	Kurtosis	Skewness	Normal	Mean	95% CI of mean		Median	Normal	
	Sig.	Sig.							lower	upper			
5	.000	.000	No	No	2.952	1.774	No	424.95	379.97	469.93	378.5	No	No
60	.000	.000	No	No	2.263	1.628	No	397.75	360.87	434.63	352	No	No
110	.000	.000	No	No	2.366	1.667	No	393.15	356.59	429.71	349.5	No	No
130	.000	.000	No	No	5.68	2.139	No	384.43	351.63	417.22	348.5	No	No
150	.000	.000	No	No	5.553	2.055	No	375.63	345.27	405.98	344.5	No	No
180	.000	.000	No	No	5.681	2.069	No	363.28	333.44	393.11	328.5	No	No

Table G.3 Normality check for KSS score at each interval, 40 participants, experiment 2

Tests of Normality													
	Statistical			***Graphical***	***Measures of Dispersion***			***Central Tendency***					**Overall Normality**
Interval (min)	Kolmogorov-Smirnov	Shapiro-Wilk	Normal	Normal	Kurtosis	Skewness	Normal	Mean	95% CI of mean		Median	Normal	
	Sig.	Sig.							lower	upper			
5	0.028	0.032	No	No	-0.697	0.078	Yes	5.65	5.18	6.12	6	Yes	No
30	0.001	0.011	No	No	-0.486	0.392	Yes	4.95	4.53	5.37	5	Yes	No
60	0.000	0.001	No	No	1.672	0.952	No	3.98	3.56	4.39	4	Yes	No
90	0.000	0.000	No	No	0.782	0.994	Near	3.85	3.46	4.24	4	Yes	No
110	0.000	0.000	No	No	1.882	1.157	No	3.4	2.96	3.84	3	Yes	No
130	0.000	0.000	No	No	-0.015	0.906	Near	4.35	3.78	4.92	4	Yes	No
150	0.000	0.000	No	No	-0.561	0.817	Near	4.03	3.43	4.62	3	Yes	No
180	0.000	0.000	No	No	1.35	1.207	No	3.58	3.01	4.14	3	Yes	No

Appendix H. Normality check for DVs, experiments 1 and 2

Statistical normality: (not normal if p<0.05). Central Tendency: Normal if the median is in 95% CI for the mean. Graphical: Include histogram and box blot. Measures of dispersion: Kurtosis: normal if (within ±1.0), Skewness: normal if (within ±0.5)

Table H.1 Normality check for PVT at each interval, 60 participants (Data from experiments 1 and 2)

Tests of Normality													
	Statistical			***Graphical***	***Measures of Dispersion***			***Central Tendency***					**Overall Normality**
Interval (min)	Kolmogorov-Smirnov	Shapiro-Wilk	Normal	Normal	Kurtosis	Skewness	Normal	Mean	95% CI of mean		Median	Normal	
	Sig.	Sig.							lower	upper			
130	0.002	0.000	No	No	7.701	2.144	No	368.55	345.3	391.7	347	Yes	No
150	0.000	0.000	No	No	7.207	2.033	No	366.28	344.6	387.9	346	Yes	No
180	0.000	0.000	No	No	6.358	1.974	No	360.42	338.9	381.9	339	Yes	No

Table H.2 Normality check for Melatonin levels at each interval, 60 participants (Data from experiments 1 and 2)

Tests of Normality													
	Statistical			***Graphical***	***Measures of Dispersion***			***Central Tendency***					**Overall Normality**
Interval (min)	Kolmogorov-Smirnov	Shapiro-Wilk	Normal	Normal	Kurtosis	Skewness	Normal	Mean	95% CI of mean		Median	Normal	
	Sig.	Sig.							lower	upper			
130	0.000	0.000	No	No	23.437	4.064	No	9.907	6.811	13.002	7	Yes	No
150	0.000	0.000	No	No	18.689	3.57	No	13.212	9.469	16.955	10	Yes	No
180	0.002	0.000	No	No	13.312	2.803	No	15.85	12.39	19.317	14	Yes	No

Table H.3 Normality check for KSS score at each interval, 60 participants (Data from experiments 1 and 2)

Tests of Normality													
	Statistical			***Graphical***	***Measures of Dispersion***			***Central Tendency***					**Overall Normality**
Interval (min)	Kolmogorov-Smirnov	Shapiro-Wilk	Normal	Normal	Kurtosis	Skewness	Normal	Mean	95% CI of mean		Median	Normal	
	Sig.	Sig.							lower	upper			
130	.000	.000	No	No	0.422	0.893	Near	3.7	3.24	4.16	3	No	No
150	.000	.000	No	No	1.362	1.246	No	3.15	2.71	3.59	3	Yes	No
180	.000	.000	No	No	4.476	1.703	No	2.73	2.35	3.11	2	No	No

Appendix I. Extra analysis: Experiments 1 and 2

The aim of this analysis is to examine the effect of physical activity on reaction time, subjective alertness and melatonin level during the test phases at 130 min, 150 min and 180 min intervals. The analysis involved data from three light condition groups (C1, C2 and C3) from experiment 1 and identical light conditions (L1, L2 and L3) from experiment 2, as well as groups performing seated (S), walking at a self-selected speed (C) and walking at a moderate speed (M). These specific light conditions were selected because they were not found to be significantly different. The analysis used two methods: firstly, independent sample tests were used to compare the three physical activity groups under the same light condition at the same interval (Figure I.1). Secondly, related sample tests were conducted to determine if there were any significant differences within the same physical activity group at different test phase intervals under the same light condition (Figure I.2).

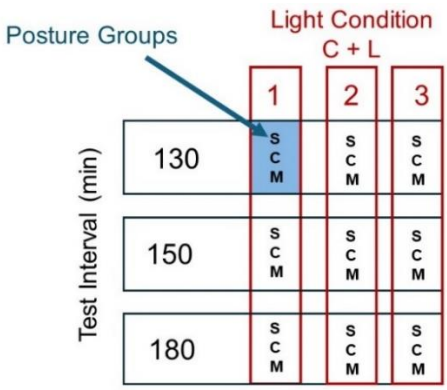

Figure I.1 The nine independent sample tests conducted to reveal any differences between the three physical activity groups (S: seated; C: walking at a comfortable speed M: walking at a moderate speed) under the same light condition at the same interval.

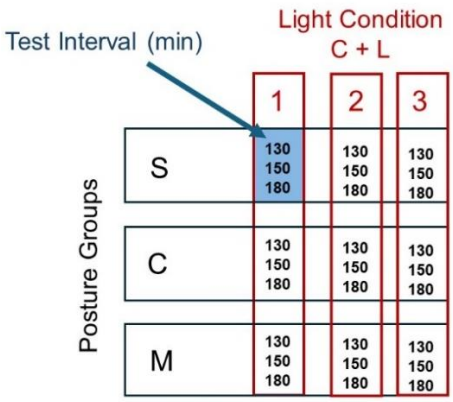

Figure I.2 The nine related sample tests conducted to reveal any differences between the three test intervals (130 min, 150 min and 180 min) under the same light condition and same physical activity (S: seated; C: walking at a comfortable speed M: walking at a moderate speed).

I.1. Psychomotor Vigilance Test

The Friedman test compares changes in responses within each light condition and each physical activity group across the measurement intervals in the test phase. For light conditions C1+L1 (*1)* and C2+L2 (*2)*, the Friedman test did not suggest any differences in reaction time between the measurement intervals within the same physical activity group to be significant ($p \geq 0.497$; $p \geq 0.076$; in each case) respectively. For light condition C3+L3 (*3)*, for S and C groups: The Friedman test did not suggest any differences in reaction time between the measurement intervals to be significant. For the (M) group, the Friedman test suggested a significant difference across the test intervals, Pairwise comparisons using the Wilcoxon test suggested that there are no significant differences between the intervals.

For each light condition *1*, *2* and *3*, the Kruskal-Wallis test was used to determine physical activity group differences at the same interval. The Kruskal Wallis test did not suggest significant differences between the three physical activity groups under light conditions: *1* ($p \geq 0.725$ in each case), *2* ($p \geq 0.669$ in each case) and *3* ($p \geq 0.108$ in each case).

I.2. Melatonin levels

The Friedman test compares changes in responses within each light condition and physical activity group across the measurement intervals in the test phase. For light conditions *1*, *2* and *3*, the Friedman test suggested significant differences in melatonin levels between the measurement intervals within the different physical activity groups, pairwise comparisons suggested that the significant changes are related to the expected increase in melatonin levels approaching the habitual bedtime.

For each light condition *1*, *2* and *3*, the Kruskal Wallis test was used to determine physical activity group differences at the same interval at each test phase interval. The Kruskal Wallis test did not suggest significant differences between the three physical activity groups under light conditions *1* ($p \geq 0.654$ in each case), *2* ($p \geq 0.901$ in each case) and *3* ($p \geq 0.133$ in each case).

I.3. The Karolinska Sleepiness Scale

The Friedman test indicates a significant differencein KSS scores between the intervals within the seated and C walk groups (under light condition *2*; $p \leq 0.011$) and within the C and M groups (under light condition *3* $p \leq 0.021$). Pairwise comparisons using the Wilcoxon test suggested that there were no significant differences between the intervals for any physical activity groups under the three light conditions *1*, *2* and *3*. The Kruskal Wallis test was used to determine physical activity group differences at the same interval at each test

phase interval. This suggested a significant difference between the three physical activity groups under light conditions: *1* ($p \geq 0.086$ in each case), *2* ($p \geq 0.286$ in each case) and *3* ($p \geq 0.072$ in each case).

I.4. Summary

The results suggested that there was no significant effect of the physical activity groups on reaction time, subjective alertness and melatonin level.

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