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Alertness in work environments - on the role of indoor daylight exposure

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“Dedico esta edición a mis enemigos, que tanto me han ayudado en mi carrera”

- Camilo José Cela, La familia de Pascual Duarte (1946)

A mis padres, por darme alas para volar alto

A Daniel, porque amarse es *volar* juntos en la misma dirección

ABSTRACT

Light enables to see the world around us, while playing a key role in our biological functioning. During the last decades, light has become an important research topic for chronobiologists and neuroscientists, and their findings are increasingly interwoven with architectural research. The discovery of a third type of photoreceptors in the human retina, the non-rod non-cone intrinsically photosensitive retinal ganglion cells, has significantly advanced our knowledge about the role of light in human neurobehavior and physiology.

Based on existing studies pertaining to ipRGC-influenced effects of light, there is a general consensus that higher intensities and bluer conditions seem to promote alertness and/or cognitive functioning, and affect circadian regulation. In that sense, daylight – which is freely delivered and under which we have evolved – seems to have key properties when it comes to impacts on body functioning. Yet, the knowledge we have gathered so far is oftentimes based on either static or well-controlled and somehow extreme electric lighting conditions that have been mainly explored in the laboratory confinement, and which do not necessarily represent reality. Considering that current life and workstyles are driving us to spend more time indoors, the importance of understanding the added value of indoor daylight exposure in our daily routines seems unquestionable. Answering to what extent such biological responses may or may not be also observable under more realistic conditions will be the main focus of the work presented in this thesis.

More specifically, our research explores the cause-effect relationship between indoor daylight exposure and daytime human functioning in terms of alertness, attention and arousal. Ultimately, the idea is to gain a better understanding of the role of architectural design in daylight provision from a psycho-physiological perspective. Towards this end, two approaches have been taken in this thesis. First, three user studies were conducted in learning spaces to understand both the combined and individual effects of varying daylight spectrum, its intensity, the duration and the timing of exposure. Second, a further investigation of these effects was conducted through the application of three physiology-based, light-driven mathematical models, so as to get insights about the limitations and potential of experimental data and simulated values in the prediction of alertness. Based on the learnings gained from both perspectives, i.e., user studies and computational methods, a functional simulation workflow is proposed for the study of alertness in the context of architectural design.

Overall, the topic of this thesis was to investigate the impact of manipulating the spectrum or intensity of daylight entering an indoor space on its occupants, with a more specific focus on their alertness. The outcomes of the user studies showed that red-impoverished conditions, when compared to unfiltered ones in dim environments, resulted in higher alertness and attentional levels. They also showed that variations in indoor daylight intensity, both under blue-shifted and neutral conditions, led to observable effects on people's alerting responses. In addition, duration and timing of exposure were shown to have a key role in determining the magnitude of these responses, with longer exposures and afternoon sessions being subjectively reported as more influential.

To advance knowledge in the field of daylight integration in the built environment for supporting occupants' health and well-being with an evidence-based approach, lighting requirements should continuously be refined according to the latest knowledge available. Insights from this thesis can be seen as a first step towards anticipating the impact of daylighting strategies on human-centric performance.

Keywords: daylight, daytime, alertness, sustained attention, arousal, well-being, intensity, spectrum, light-driven model, lighting simulation, architecture, experimental, user study.

RÉSUMÉ

La lumière permet de voir le monde qui nous entoure et joue un rôle clé dans notre fonctionnement biologique. Au cours des dernières décennies, la lumière est devenue un sujet de recherche important pour les chronobiologistes et les neuroscientifiques, et leurs découvertes sont de plus en plus imbriquées dans la recherche dans le domaine de l'architecture. La découverte d'un troisième type de photorécepteurs dans la rétine humaine, les cellules ganglionnaires rétiniennes sans bâtonnet et sans cône intrinsèquement photosensibles, a fait progresser de manière significative nos connaissances sur le rôle de la lumière dans le neurocomportement et la physiologie humaine.

Sur la base des études existantes relatives aux effets de la lumière sur les cellules ganglionnaires rétiniennes intrinsèquement photosensibles (ipRGC), il existe un consensus général selon lequel des intensités plus élevées et des conditions lumineuses avec des composantes spectrales plus vers les couleurs bleues semblent favoriser la vigilance et/ou le fonctionnement cognitif, affectant ainsi la régulation du rythme circadien. En ce sens, la lumière du jour - qui est fournie gratuitement et sous laquelle nous avons évolué - semble avoir des propriétés essentielles en ce qui concerne les effets sur le fonctionnement de l'organisme. Pourtant, les connaissances que nous avons acquises jusqu'à présent sont souvent basées sur des conditions d'éclairage artificiel statique (ou très contrôlées) et en quelque sorte extrêmes, qui ont été principalement explorées en laboratoire et qui ne représentent pas nécessairement la réalité. Étant donné que les modes de vie et de travail actuels nous poussent à passer plus de temps à l'intérieur, l'importance de comprendre la valeur ajoutée de l'exposition à la lumière du jour dans nos activités quotidiennes semble incontestable. Répondre à la question de savoir dans quelle mesure ces réponses biologiques peuvent ou non être également observables dans des conditions plus réalistes est l'objectif principal du travail présenté dans cette thèse.

Plus précisément, cette recherche explore la relation de cause à effet entre l'exposition à la lumière du jour en intérieur et le fonctionnement humain diurne en termes de vigilance, d'attention et d'éveil. En fin de compte, l'idée est de mieux comprendre le rôle de la conception architecturale dans l'apport de lumière naturelle d'un point de vue psycho-physiologique. À cette fin, deux approches ont été adoptées dans cette thèse. Premièrement, trois expériences ont été menées avec des participants dans des espaces d'apprentissage réels afin de comprendre les effets combinés et individuels de la variation du spectre de la lumière du jour, de son intensité, de la durée et du moment de l'exposition. Deuxièmement, une étude plus approfondie de ces effets a été menée grâce à l'application de trois modèles mathématiques basés sur la

physiologie et la lumière, afin de mieux comprendre les limites et le potentiel des données expérimentales et issues de simulations dans la prédiction de la vigilance. Sur la base des enseignements tirés de ces deux approches, c'est-à-dire les études avec des utilisateurs et des méthodes de calcul, un workflow de simulation fonctionnelle est proposé pour l'étude de la vigilance dans le contexte de la conception architecturale.

Jettent une nouvelle lumière sur l'impact de la manipulation du spectre ou de l'intensité de la lumière du jour sur les occupants d'un espace intérieur, en mettant l'accent sur la vigilance induite par la lumière du jour. Les résultats de cette démarche ont montré que des conditions d'appauvrissement en rouge, comparées aux conditions non filtrées dans les environnements sombres, peuvent entraîner des niveaux de vigilance et d'attention plus élevés. Les variations de l'intensité de la lumière du jour à l'intérieur, tant dans des conditions de décalage vers le bleu que dans des conditions neutres, ont également eu des effets observables sur les réactions d'alerte des personnes. En outre, il a été démontré que la durée et le moment de l'exposition jouent un rôle clé dans la détermination de l'ampleur de ces réactions, les expositions plus longues et les séances de l'après-midi étant subjectivement rapportées comme étant plus influentes.

Afin de faire progresser les connaissances dans le domaine de l'intégration de la lumière du jour dans l'environnement bâti pour favoriser la santé et le bien-être des occupants de manière rigoureuse et démontrable, les critères d'éclairage doivent être affinés sans cesse en fonction des dernières connaissances disponibles. Les résultats de cette thèse peuvent être considérés comme un premier pas vers l'anticipation de l'impact des stratégies d'éclairage naturel sur la performance centrée sur l'humain.

Mots clés : lumière du jour, période diurne, vigilance, éveil, bien-être, intensité, spectre lumineux, modèle de contrôle de la lumière, simulation d'éclairage, architecture, expérimental, étude avec des utilisateurs.

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To my colleagues at LIPID.

To my friends, near and far. To my family, in Spain and Mexico.

To my parents. To Daniel, esta tesis es tan mía como tuya.

Lausanne, 27.05.2021

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1 [INTRODUCTION]

More than six decades ago, Richard Neutra anticipated in his book *Survival Through Design* that "designers will recognize that gradually but surely, they must underbuild their proposals and compositions with more solid physiological foundations rather than with mere speculative conversation or sales talk…new instruments and obligations have come to us from research penetrating into life's performance…we begin to wield tools which will enable us to do the patient spadework which must be done. It will be fascinating, because it is so novel" (Braham, 2006; 1954-Richard Neutra *Survival through design* (pages 111-113))

1.1 BACKGROUND

"A scientific ambition, inaugurated by the naturalists in literature and the impressionists in painting, had become one of the artists' permanent drives…(for example) late nineteenth-century painters decided to render the natural phenomena of light and colour, to paint according to scientific optics…" (Braham, 2006; 1954- Richard Neutra *Survival through design* (page 113)). The same way that science inspired art two centuries ago, and art shaped the biggest achievements in neuroscience in the past century (Figure 1.1), so advances in the field of photobiology will help us now define new yet unexplored paths in architecture.

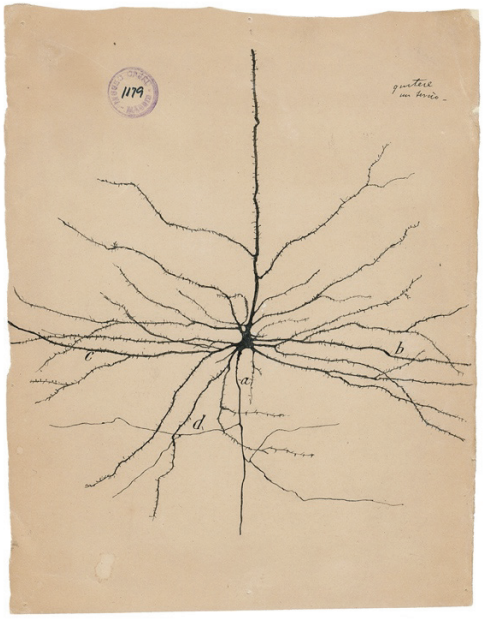


Figure 1.1 Drawing of a pyramidal neuron in the cerebral cortex by Santiago Ramón y Cajal - father of modern neuroscience- from his book "The beautiful brain" (image source: https://www.nytimes.com/2017/02/17/science/santiago-ramon-y-cajal-beautiful-brain.html)

Light has been said to influence individuals through three different pathways, the visual system, the perceptual system and the non-visual system, respectively determining visual capabilities, delivering the message perceived from the environment and defining the state of body entrainment to the local time and its behaviour (Boyce, 2003). Light enables us to see the world around us, while being a key element in our biological functioning. It affects the way we experience space, adds contrast, provides safety and makes our work easier improving visual performance. But it also elicits perceived – yet not necessarily seen – responses that are essential for our health, mood and well-being and are disconnected from the image forming pathway (Andersen, 2015).

Although the mechanisms behind the light-response stimulation have not yet been fully understood, in the case of non-visual responses it is the intensity, wavelength, prior light history, duration and timing of exposure that, in combination, all seem to influence the magnitude and direction of such effects in our body (Amundadottir, 2016). Unsurprisingly, the most ancient (and only freely delivered) source of light, i.e. daylight, seems to have ideal properties when it comes to the potential impact of light on body functioning, thanks precisely to its spectral content, intensity and temporal variations when compared to electric light (Knoop et al., 2020).

Outdoor exposure to daylight, received at the right time and for an adequate duration, might already provide a good starting point for biological entrainment (Boyce, 2016). However, because people spend a substantial proportion of their time – around 90% in the Western world according to Aries et al. (2015)– inside buildings, a deeper understanding of people's behavioural and physiological responses to light indoors seems critical. Experimental research in this direction has mostly been driven under well-regulated electric lighting conditions (Souman et al., 2018), so the extent to what indoor exposure to pure daylight might be beneficial from a psycho-physiological standpoint remains unclear.

Given the influence of daylight exposure on a building occupants' well-being, its potential benefits should be taken into account when evaluating architectural solutions for the promotion of health and vitality and thus be considered a key element in the design process. In this thesis we will examine the relationship between architecture and daytime human functioning through the evaluation of daylight exposure and its effects on alertness. Building features that affect the quality of the indoor luminous environment such as window glazing are tested in a series of user studies for their potential to elicit effects on participants' alertness, attention and arousal. Secondly, we will discuss the limitations and potential of existing computational light-driven models to predict alerting responses by testing them against collected datasets. Overall, this thesis aims to help paving the way towards better informed daylighting decisions in the built environment when it comes to the physiological aspects of daylight exposure.

1.1.1 'Healthy' architecture

[*Form follows function:*
the way something looks, should be determined by its purpose]

Modernism introduced a design philosophy where every element of an object was questioned based on its functionality. In that sense the Bauhaus School, founded by Walter Gropius in Germany, became a worldwide referent for its approach to design. They believed in science and standardization through mass production as a solution to improve life quality in the dense urban areas of the 1920's. They studied colour theory, basic elements and principles of design, and experimented with materials and

processes. Buildings in that period often maximized daylight and ventilation by prioritizing large window to wall ratios, movements through open floor plans, or directed views towards the outside or uncluttered scenes by means of clean and smooth lines.

Early twentieth century attitudes towards healthy architecture were forged all over the world by a few non-traditional architects. They understood that function was not a simple concept in itself, and that it required a human-centric assessment. For example, Frank Lloyd Wright believed in the integration of natural elements to improve well-being, in the idea of architecture as a facility to embrace nature. Or Richard Neutra, who valued the psychological, emotional and physiological needs of his clients. He believed in the idea of architecture as a stage for living, in the healing powers of a well-designed home that could actually cure illness or actively improved inhabitants' health.

Figure 1.2 Views of the inside (top) and the outside (bottom) of the "Health house" by R. Neutra, 1929 (top, source: architecturaldigest.com; bottom, source: metalocus.es).

In 1929, Neutra built the Lovell "Health House" in Los Angeles (Figure 1.2). He was passioned about the idea of integrating both environmental and biological aspects in his work, and he went so far as to adopt a self-ordinated therapist roll in his relationship with the clients. Neutra insisted that his clients complete detailed questionnaires and diaries about their daily activities, childhood homes and domestic habits so as to integrate them in the design process.

As much as these stories might sound anecdotical, they reflect an inquisitive and curious mindset that was driven by explicit interests in apparently disconnected disciplines: *progressive building technology* and *applied biology.* As he later explained, "physiology must direct and check the technical advance in constructed environment…it will come into question perhaps more often than anybody could imagine in our current drab disorder" (Braham, 2006; 1954-Richard Neutra *Survival through design* (page 111)). Neutra's Health House may be considered one of the first examples of the so-called trend of *healthy homes*, not just for its design attributes – open plans, extensive windows and lots of daylight –, but because his intuition and experience lead him to deduce that bringing the outside environment inside, would be beneficial to the indoor occupants.

In the last decades, research has pointed out the importance of daylight for health, well-being and sustainability (Aries et al., 2015). However, access or exposure to it is, to date, not an explicit target in most regulations and norms, neither is it part of global discussions by leading institutions worldwide such as the UN 2030 Agenda for Sustainable Development or the WHO's "health for all" policy (Münch et al., 2020). We have reached a new junction between disease and architecture in recent months where fear of contamination determines what kind of environment we want. As Lavin wrote, "windows both before and after Neutra were conceived as therapeutic tools. Modernist windows were said to cure tuberculosis through what might be described as the engineering of the physiological effects of the sun" (Lavin, 2004; page 115). We are living exceptional times where, the same way as tuberculosis shaped modernism, so COVID-19 will influence architecture's near future.

1.1.2 Architecture, daylight and human functioning

Light is the main input for the visual system to produce an image, and the perception of the world represents the eventual output from it, once the retinal image has been processed and delivered to the brain, which subjectively evaluates the situation. Vision is a whole perceptual system in itself, and it is according to this particular comprehension of what is seen that light has the ability to also alter mood and behaviour on people (Veitch and Newsham, 1998). For lighting designers, visual performance, visual comfort or aesthetics have been widely considered the most important factors driving architectural decisions. The quality of these aspects determines the extent to which a certain space will or will not be seen. To address

these questions, several metrics and guidelines have been developed to try help architects with their design solutions (Carlucci et al., 2015).

However, light has also a profound effect on human health and well-being through a different, non-visual and non-image forming pathway. Research tells us that people working near a window sleep better at night, are healthier and have a higher quality of life (Aries et al., 2015, 2010; Veitch, 2011). The discovery, back in 2002, of a third photoreceptor in the human retina, the non-rods non-cones, intrinsically photosensitive retinal ganglion cells (ipRGCs) (Berson et al., 2002; Brainard et al., 2001; Hattar et al., 2002), has significantly advanced our knowledge about the role of light on human neurobehavior and physiology. Unlike rod and cone photoreceptors (which serve as inputs for low-light and colour vision) ipRGCs serve no visual, image-forming function. Instead, they are responsible for converting light into a neural signal. These ipRGC-influenced responses (ILL) can be either positive or negative depending on the timing of the exposure and might be evident soon after the exposure or only after prolonged exposure, from minutes, hours days, weeks or even years (Cajochen, 2007). In healthy individuals, they are regulated by 24-hour cycles called circadian rhythms and are mainly responsible for the preparation of our body for the light vs. dark periods of the day (Lockley, 2009). If properly entrained, they ensure the synchronization of our internal biological clock with the external local time, which is fundamental to maintain adequate levels of daytime productivity in the form of concentration, alertness or cognitive performance, among others benefits (Boyce, 2004).

A closer look at the literature reveals that daylight represents a special case in the context of light exposure. It is not only preferred over electric light in most situations (Boyce et al., 2003), it also offers inherent properties that are key for us to align our biological clock and body functioning (i.e., a light-dark cycle and dynamic temporal variations in spectrum and intensity). Sufficient exposure to daylight has been associated with better health, both psychologically and physiologically. However, this correlation can only be found in limited statistically relevant and well established empirical evidence, and thus, health implications of daylight variations remain largely unclear (Aries et al., 2015). Yet, experimental research in the field of non-visual photoreception is mostly being conducted in laboratory settings under electric conditions (Lok et al., 2018; Münch et al., 2020; Souman et al., 2018). The main reasons for this being the unpredictability of daylight dynamics, and the seasonal and weather-dependent variations in spectral distribution and intensity, making it a difficult to control experimental variable as opposed to electric light. As a result, ILL responses to daylight in the built environment are still largely unknown, and the extent to which such effects may impact our daily life remains unclear, thus representing a challenge when trying to integrate findings from non-visual photoreception into real-world applications (Figure 1.3).

Modern lifestyles are driving us to spend increasing amounts of time indoors, which often translate into daytime hours spent in biological darkness. Periods outdoors are becoming the real privilege of a chronodisrupted society. As a consequence, the field

of building design is slowly starting to realize the added value of daylight integration beyond visual performance, comfort or delight, as a way to "embrace nature" in a resemblance of Frank Lloyd Wright's architecure. For the last two decades, light has become an important research topic for both chronobiologists and neuroscientists, and their findings are increasingly interwoven with architectural research (Amundadottir, 2016; Andersen, 2015; Webb, 2006; Wirz-Justice and Fournier, 2010). With the complexities of building design and higher efficiency criteria in terms of energy use and human well-being, lighting simulations are becoming increasingly important. As a result, recent approaches are building upon the latest findings about the non-visual impact of light to establish a holistic approach to evaluating light in the built environment.

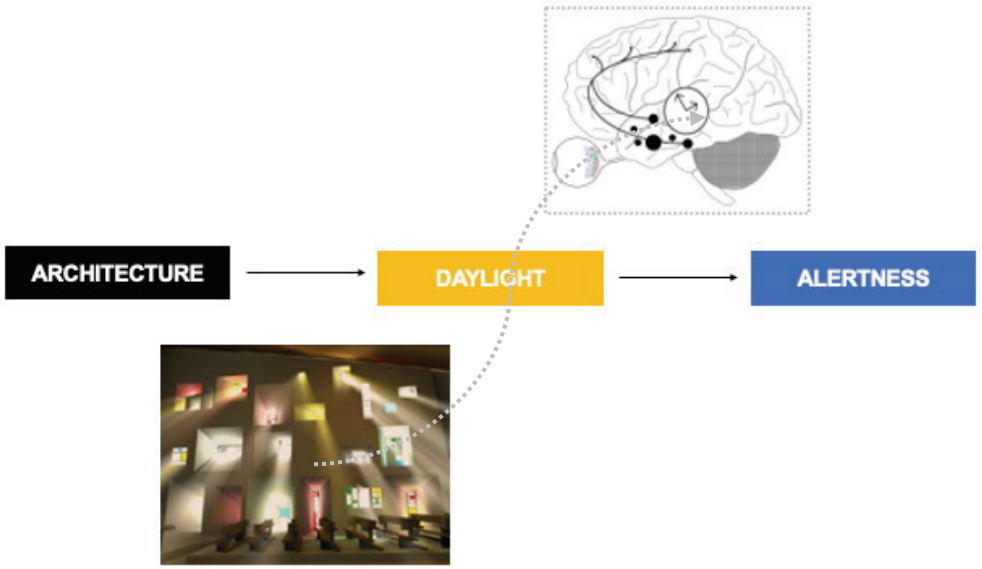


Figure 1.3 Outline of the relationship between architecture, daylight and human functioning by means of alertness (image credit (up, brain) after Amundadottir 2016; (bottom, Ronchamp chapel) https://discoverplaces.travel/en/tag/ronchamp/).

Also, current industrial trends and regulations are starting to focus their attention in other features such as health, mood or well-being (CIE, 2015; CIE, 2018), and new standards and certifications such as the WELL Building Standard (WELL) are starting to emerge in the building industry as a popular solution to fulfil these occupant-centred demands. The problem with such attempts is that, although commendable, they lack rigour and practical validity since the effects of daytime light exposure (either electric or daylight) have not been yet well understood (Soto Magán et al., 2018).

Architecture mediates the boundary between the outside world and individuals, becoming the most effective element for indoor daylight provision. "The history of

architecture has been the endless struggle for light, in other words, the history of windows" said Le Corbusier, master of modernism, in 1929 (Le Corbusier et al., 2012). Our indoor lighting environment is constantly changing due to natural dynamics, automated building control or even human interaction. There are many factors – from environmental to design or technical aspects – that influence the quantity and quality of daylight reaching indoor spaces, and ultimately, an individual's eye. The overall preconditions for daylight incorporation in terms of sunlight access, visual and thermal comfort, and energy efficiency are described by the prevailing climatic conditions of a building site. In the same way, latitude will also determine the length of daytime and solar availability at different seasons of the year. At the urban scale, parameters such as external reflections and obstructions – from other buildings, vegetation, urban canyon, ground surface, etc. – greatly influence daylight irradiance reaching the interior of a room. Unlike contextual aspects, architectural features such as geometry, materials, shading systems, windows or glazing type can be controlled and modified to our convenience, and have a huge impact as well on daylight's spectral irradiance (Arsenault et al., 2012). Therefore, design decisions at the building scale are critical and need to be carefully evaluated.

Figure 1.4 Schematic of the connection between architecture, daylight and human functioning

In order to comprehend how to provide healthy, alerting daylit spaces that do not disrupt but rather improve our routines, we need to start by studying how daylight is affected by architecture and how (filtered) daylight impacts our alertness (Figure 1.4). This involves two processes:

- Process (1): architecture (A) constrains the characteristics of the indoor luminous environment resulting from daylight (B).

- Process (2): the quantity and quality of a daylit indoor environment (B) defines its alerting potential for its occupants (C).

By understanding the cause-effect relationship between architecture, daylight and alertness, we will be able to move a step forward towards identifying which strategies are most effective for daytime human functioning.

1.2 RESEARCH SCOPE

This section will provide an overview of the research problem and objectives of the thesis, while presenting specific information about the approach adopted in this work.

1.2.1 Problem statement

The growth of a 24-hour society that spends about 90% of its time indoors, where access to daylight is oftentimes insufficient from a physiological standpoint, is rising evidence of the health impacts of inadequate light exposures. Electric systems in buildings typically produce light that is sufficient to perform visual tasks, but often lack the spectral composition and intensity levels that are best aligned with needs from the circadian system. Spaces with a luminous environment that is not adequate for the biological clock may be identified as biologically dark, and considered to be areas where long term, permanent occupancy can pose the risk of disrupting circadian rhythmicity.

Being threatened by a global pandemic that is disrupting our routines and forcing us to spend even more time indoors, it is vital to get a better understanding of the potential of the built environment to provide biological stimulation (i.e., to affect occupant health and well-being in a positive way), especially with regards to daylight exposure.

An overview of ongoing and past research identified a number of gaps regarding current knowledge about the role of daylight for humans, which are questions that have so far mostly been explored under electric conditions (Münch et al., 2020). We know that IIL responses originate in the eye (unlike other skin-mediated responses to optical radiation) and are influenced by retinal illumination through a novel type of photoreceptor, the intrinsically photosensitive retinal ganglion cells (ipRGCs) (Berson et al., 2002; Brainard et al., 2001; Hattar et al., 2002), even in the absence of rods and cones (Czeisler et al., 1995; Provencio et al., 2000). The photopigment melanopsin, contained in the ipRGCs, has been shown to be wavelength-dependent and to be most responsive to short wavelengths of the visible spectrum (Lockley et al., 2003) with a peak around 480 nm (Bailes and Lucas, 2013) and to higher intensities (Badia et al., 1991). Hence, for the circadian system, the action spectrum of light is shifted towards “blue” light compared to the visual system, which is maximally sensitive to “green” light.

For this reason, daylight is believed to be better aligned with our biological clock that electric light, and research has shown that daylight is also preferred over artificial conditions. Many studies have already pointed out the importance of daylight – and often, associated views (Aries et al., 2010; Beute and de Kort, 2014; Boyce et al., 2003; Veitch, 2011; Veitch et al., 2013) – for well-being, and exposure to it has been related

to health improvements by means of physical activity, cortisol levels, heart attacks or suicide rates, improved mood and better sleep quality (Aries et al., 2015; Boubekri et al., 2014; Hubalek et al., 2010).

However, despite the large presence of daylight in buildings and its implications in occupants' well-being, studies that involve daylight as the only source of illumination are very limited and rare. Research in this direction is, in general, much more challenging due to daylight's complex and less controllable nature, which is the most likely explanation, as mentioned earlier, of the scarcity of studies investigating alerting effects due to indoor daylight exposure. Although presence of electric light in workspaces is mandatory to ensure an adequate visual performance, and thus avoiding it might not be realistic, for the purpose of this thesis only non-visual effects due to daylight exposure will be explored.

In this thesis, we are particularly interested in understanding: (1) the physiological and psychological added value of daylight exposure inside buildings to prevent daytime sleepiness; (2) the potential of these findings to advance the field of daylighting performance optimization in the built environment by computational means. In other words, by better understanding the cause-effect relationship between variations on indoor daylight exposure and alertness, we aim to gain insights about the adequacy of using light-driven models to predict such effects. Ultimately, new workflows generated at the interface between photobiology and architecture for the estimation of non-visual responses to light will be required to help design decisions in the built environment.

1.2.2 Research questions and hypotheses

Two research questions originated the work that is presented in this thesis:

*(**RQ1**) Do certain characteristics of indoor daylight exposure significantly affect its ability to maintain us alert during working hours?*

*(**RQ2**) If so, is it possible to anticipate the effect of certain design decisions – and thus of modelled lighting conditions – on psycho-physiological responses in the built environment?*

Some key findings have served as premises to formulate our research hypotheses, notably as they relate to:

- the **intensity and spectrum of light**: a nonlinear intensity-response between alerting effects and night-time exposure exists, and research has shown that half of the maximum alerting response can be obtained with ambient illumination (90-180 photopic lux) of fluorescent light (CCT 4,000K) at night (Cajochen et al., 2000). Also, research has shown that maximal non-visual response for melatonin suppression

occurs at night at 480 nm, and hence, that the sensitivity of the circadian system is blue shifted compared to the photopic one (Brainard et al., 2001; Thapan et al., 2001).

- the **temporal characteristics of light**: studies investigating the effects of the interaction between light intensity and duration suggested, on the one hand, that longer durations require lower intensities to achieve a certain response (Aoki et al., 1998), and on the other hand, that longer periods of exposure to moderate light intensity might be more effective than shorter periods to higher intensities (Dewan et al., 2011). In addition, studies investigating dose-response relationships between light exposure and alertness confirmed, on the one hand, that 6,5 hours of light exposure at ambient levels during nighttime elicit half the maximum alerting response (Cajochen et al., 2000), while 1 hour of daytime exposure to brighter light shows no systematic effect on alertness (Smolders et al., 2018).

- the **effects of circadian timing**: studies investigating the effects of the interaction between light intensity and time of day showed a phase advance in the morning and a phase delay in the evening as a result of exposures to bright light (Khalsa et al., 2003). Moreover, subjective alertness and measures of performance are affected by natural increases in sleep propensity during mid-afternoon hours (i.e., post-lunch dip), which are the result of a combination between the status of individual's endogenous circadian pacemaker and the length of time since sleep (Monk, 2005).

These considerations led to the following **three research hypotheses** (formulated in the same order as the premises):

H1. Exposure to brighter and bluer environments should favour correlates of alertness when compared to dimmer and "less blue" conditions.

H2. Longer daytime exposure might induce stronger alerting effects (i.e., 6,5 hours might have more impact than 1 hour, and 2 or 3 days of exposure might have stronger effects than 1 day), even in ambient daylight conditions.

H3. While acute responses due to light exposure may be independent of time of day, morning versus afternoon exposure is expected to affect correlates of alertness differently due to the underlying circadian rhythmicity.

1.2.3 Research objectives and approach

The goal of this thesis is to get a better understanding of how indoor daylight exposure affects the alertness' state of an individual during daily working routines, with the ultimate intent to better inform lighting-related design decisions when it comes to promoting well-being in the built environment. To be able to answer our two research questions, ad hoc user experiments and model-based evaluations have been

conducted, that will be briefly summarized here and will be further described in subsequent chapters.

*(**RQ1**) Do certain characteristics of indoor daylight exposure significantly affect its ability to maintain us alert during working hours?*

To explore the relationship between indoor daylight exposure and profiles of daytime alertness, a series of user studies were conducted in real workspaces to understand the combined effects of variations in daylight's spectrum and/or intensity, duration and timing of exposure (Figure 1.4) based on three experimental studies.

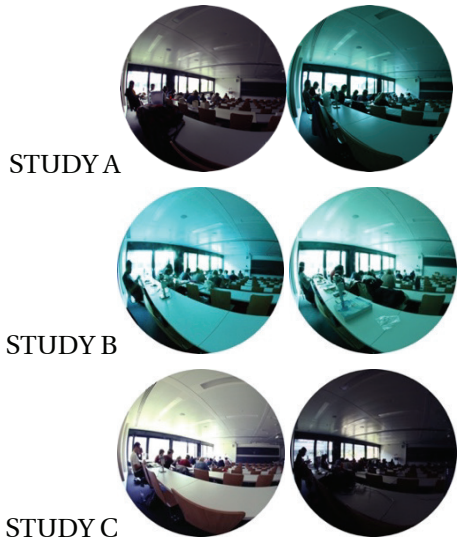


Figure 1.5 Overview of investigated daylight conditions

STUDY A explores the effects of the variations in daylight spectrum, by comparing conditions where a blue shift in the spectrum is introduced and compared to neutral conditions, while maintaining the associated photopic illuminance constant.

STUDY B evaluates the effects of variations in daylight spectrum and intensity levels, by comparing conditions where spectral shifts – and associated confounded intensity variations – are introduced in the blue range of visible daylight.

STUDY C analyses the effects of variations in daylight intensity levels, by comparing conditions where brightness is modified while maintaining a neutral spectrum.

*(**RQ2**) If so, is it possible to anticipate the effect of certain design decisions – and thus of modelled lighting conditions – on psycho-physiological responses in the built environment?*

To investigate the role of architectural design on daylight provision from a psycho-physiological perspective, responses from our studies were further investigated through the application of physiology-based, light-driven predictive models of alertness, so as to gain insights about the limitations and potential of experimental data and simulated values in the prediction of alertness.

In order to anticipate the impact of varying lighting conditions in a space and inform design decisions, an accurate characterisation of the luminous environment is required, especially with regards to its spectral content. A functional simulation workflow is thus also proposed for the study of alertness indoors (Figure 1.6).

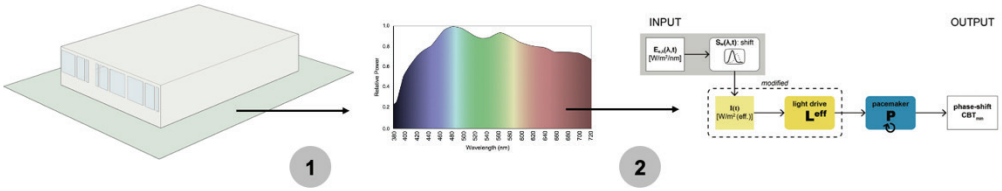


Figure 1.6 Diagram of the simulation workflow to study alertness within the design process

1.3 THESIS STRUCTURE

Building upon the general introduction of the research project presented in this chapter (**Chapter 1**), **Chapter 2** will provide a review of the current state of the art regarding alerting effects of light exposure. This overview will focus first on defining alertness, both as an acute response and as a circadian rhythm due to light exposure, while addressing internal and external factors that define the magnitude of such effects. Subsequently, methods to quantify alertness are described in detail, and a summary of the main findings from the relevant studies in the literature pertaining to alerting effects of light is also provided. Finally, a review of the most recent updates of alertness prediction models is introduced, to reconduct the conversation back to architectural design by means of simulation potential.

Chapter 3 describes the methodology developed to conduct user studies in real workspaces and the experimental design used to test conditions closer to real life, which will then be applied to the experiments presented in subsequent chapters.

The core content of this work is found in **Chapters 4 to 6**. Here, a detailed description of the different light stimuli used in each experiment is reported, and results of each study are presented and discussed within the general context of the literature in the field.

Chapter 7 introduces three physiology-based, light driven models that are used to predict daytime alertness using experimental data from Chapters 4 to 6, and gives insights about the potential of integrating non-visual responses into the design process.

Finally, the concluding **Chapter 8** provides a synthesis of the thesis, summarizing the main findings and contributions of each part, and gives an outlook of future research and potential next steps in the context of alerting effects of daylight in the built environment.

2 [STATE OF THE ART]

Light, and especially daylight, is important for many biological functions, but understanding its effects encompasses multiple dimensions. Unlike other skin-mediated responses to optical radiation, non-visual responses begin in the eye, and exist as a reaction to environmental stimuli. They are affected by retinal illumination by ipRGCs, also in the absence of rods and cones. This light signal is then projected via the retinohypothalamic tract (Gooley et al., 2003) to the suprachiasmatic nucleus (SCN), where our body is entrained to the 24-h light-dark cycles as a response from our biological clock (Czeisler et al., 1999). This occurs, together with rod and cone inputs, through an irradiance-dependent photopigment called melanopsin, which is most responsive to short wavelengths of the visible spectrum – peaking around 480 nm – (Bailes and Lucas, 2013; Lockley et al., 2003) and is believed to be more reactive to higher illuminance levels when compared to low doses (Cajochen, 2007; Chellappa et al., 2011; Vandewalle et al., 2009).

Among the existing ipRGC-influenced responses to light (IIL), often referred to as non-visual (NV) or eye-mediated non-image-forming (NIF) effects of light, we are, in this thesis, more specifically interested in alerting responses. Daytime sleepiness or decreases in cognitive performance are of key concern at the workplace, as they are likely to affect productivity (Lok et al., 2018). These situations are often connected to circadian misalignments or sleep disorders (Oken et al., 2006), but also to exogenous factors such as light exposure, among others.

2.1 ALERTNESS: NON-VISUAL PHOTORECEPTION

Since the definition of alertness is quite complex due to the multiple constructs and neurological mechanisms involved, it is useful to start by reviewing the most frequently used terminologies according to the different fields of expertise in which the term is involved.

The activation state of cerebral cortex that impacts the ability to process information has been defined with several terms, the most common ones being “alertness”, “sustained attention” or “arousal”. Psychologists and cognitive neuroscientists often refer to it to denote a state of vigilance or the ability to sustain attention to a certain task during a period of time, during which a cortical activation is implied (Oken et al., 2006). Neurophysiologists, however, refer to it as an arousal level on the sleep-wake spectrum without involving any cognitive or behavioural responsiveness (Oken et al., 2006). In the context of circadian research, alertness is commonly used to denote the opposite of sleepiness, which overlaps to some extent with arousal when used as a synonym of wakefulness (Cajochen, 2007).

The term alertness will thus be investigated in this thesis from all three of these perspectives: (1) as an indicator of subjective alertness, to measure the opposite of sleepiness or the desire to sleep, (2) as an output cognitive functioning, to measure the ability of an individual to sustain attention, and (3) as a marker of physiological

arousal, to measure changes in autonomous nervous system activity. As such, different markers or indicators that best represent these approaches are discussed in the next section, but first, an overview of the different processes involved -directly or indirectly- on the regulation of alertness state is provided.

2.1.1 Acute effects vs. circadian regulation of alertness

The effects of light on circadian rhythms have been thoroughly studied. We refer to this as the *indirect* pathway by which light can shift the timing of circadian rhythms, and indirectly lead to alterations in psycho-physiological responses, which might not be immediately obvious right after the exposure. In addition to circadian responses, light has been shown to elicit direct effects, which can be observed almost immediately in healthy people, and do not necessarily influence the circadian system. This is demonstrated by the different hypothalamic regions involved in alertness control, which are also regulated by ipRGC predictions, in addition to SCN activation by light (Gooley et al., 2003; Hattar et al., 2002; Vandewalle et al., 2009).

Alerting responses, in particular, might be observed over time as the combined influence of the endogenous body clock and exogenous factors such sleep schedule, activity, meals or environmental conditions (Folkard, 1990; Oken et al., 2006), or after a short period of time if elicited by certain external factors, light being the most powerful stimulus (Cajochen, 2007). However, the differentiation between circadian and acute effects might be controversial and hence, not straightforward:

- First, there is a dichotomy in the literature regarding cause-effect definitions: while CIE refers to acute responses (i.e., effect or reaction) to light exposure (CIE, 2018), other authors refer instead to acute stimuli (i.e., cause or action) that affect light-mediated effects (Spitschan et al., 2019).

- In addition, although the magnitude of the response may be independent of circadian timing, the observed reaction might be the sum of both circadian and direct effects (Amundadottir, 2016).

Thus, hour-to-hour responses of alertness should be analyzed from both perspectives, evaluating on the one hand, the main effect of daylight condition understood in this case as the *direct* cause of a certain response, and on the other hand, the circadian dependency of those responses in terms of time-of-day and duration of exposure (e.g., differences between morning vs afternoon exposures or longitudinal effects over days).

2.1.2 Endogenous components

Since we are diurnal animals, our alertness and productivity seem to be lower at night. This is reflected not only in our regular sleeping hours, but also in our endogenous body clock, which, when combined with exogenous stimuli like the timing of meals and exercise, produces repetitive 24-hour cycles in our physiological processes (Figure 2.1). There are endogenous circadian rhythms in performance ability or alertness, just like there are in physiological cues in the sleep-wake cycle, hormone secretion, core body temperature or melatonin production. These cycles are based on two processes: the status of the endogenous circadian pacemaker and the duration of time awake (which ultimately affect sleep inertia or circadian drive for wakefulness and sleep onset or homeostatic drive for sleep) (Folkard, 1990).

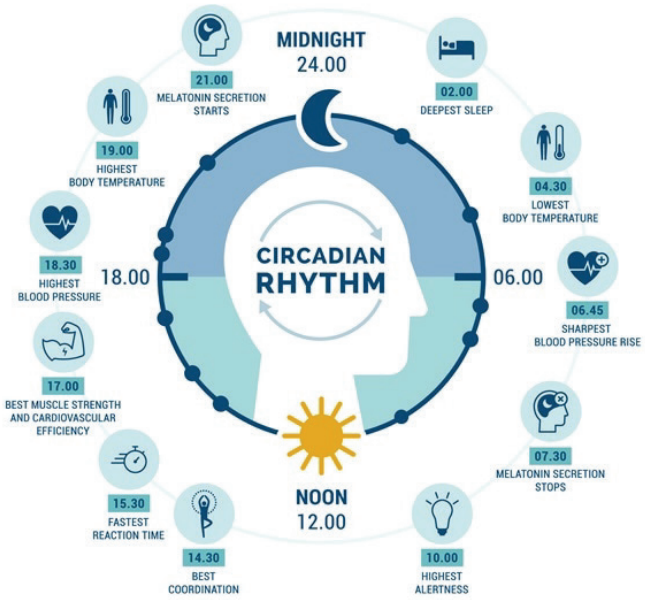


Figure 2.1 Infographic of a conventional circadian rhythm (image credit elenabsl / Shutterstock.com)

2.1.3 Exogenous factors

The circadian clock, by adjusting its timing due to phase advances or delays, is often affected by a number of exogenous factors. These variables are referred to as *zeitgebers*, and one of the strongest known stimuli for affecting the circadian pacemaker is light. Through a dedicated neural path that connects the retina with the SCN, light exposure has different consequences based on the timing of exposure compared to the circadian phase of the biological clock. If lighting conditions prevent

entrainment to an imposed schedule, the circadian clock runs “free” (Czeisler et al., 1999). It is the desynchronization between the circadian clock and the sleep-wake cycle schedule that most likely cause decrements in alertness and performance.

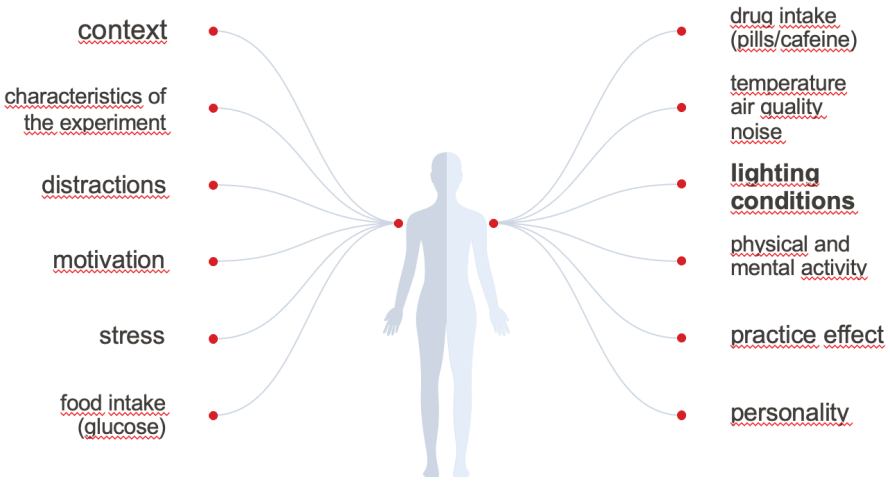


Figure 2.2 Exogenous factors influencing alerting responses

Measures of alertness, and in particular self-assessment reports, are subject to numerous confounding influences, which might be masking the circadian rhythmicity behind these responses. These can range from psychological aspects (such as boredom and motivation or stress), to executive brain functions (such as demand characteristics of the experiment) and/or to distractions by environmental conditions (such as noise, ambient temperature or lighting conditions). Activity, meals and drug intake (i.e., sugar caffeine, etc.), or conditions associated with alterations in the habitual sleep schedules (i.e., sleep or behavioral disorders such as sleep apnoea, narcolepsy or attention-deficit hyperactivity), may also interfere with the normal state of alertness (for a full review please refer to Gabehart and Van Dongen (2017) and Oken et al. (2006)). As such, in studies investigating alertness profiles it is important to account for both internal and external factors (other than light), and to control or balance as many of these as possible so as to be able to really isolate the one dependent variable object of study (e.g., lighting conditions) (Figure 2.2).

2.2 QUANTIFICATION OF ALERTNESS

As the definition of alertness is already complex by itself due to the multiple constructs and neurological mechanisms involved, the evaluation of this kind of activation state cannot be easily rendered on a one-dimensional scale. Therefore, it is generally

recommended to control and report more than one measure of alertness (i.e., physiological and behavioral markers), so as to get a holistic understanding based on the three perspectives mentioned above (i.e., as the opposite of sleepiness, as the ability to sustain attention, or as an indicator of the activity in the nervous system). Thus, alertness can be quantified in three different ways: (1) with self-reports, (2) with performance tasks or (3) with physiological indicators (Curcio et al., 2001). The first ones are inexpensive, simple and not time consuming, whereas the second and the third methods involve more rigorous, and typically (but not always) more intrusive and expensive techniques.

2.2.1 Subjective self-reports

A non-clinical but broadly used method to measure alertness levels on individuals is to resort to self-rated questionnaires. These are often easy and quick to conduct, which is a key feature when targeting groups with large sample sizes and/or semi-controlled experimental conditions (such as non-laboratory studies). Three types of evaluations are possible in this case: short-term (also called point-in-time) measurements, where participants are asked to report their current perceived level of alertness on a predefined anchored scale; long-term reports, where participants are asked to express perceived alertness during a given period of time (e.g. in the last two weeks); and overall or global measurements, where participants have to assess their feelings of sleepiness in general, implying long-term experiences that could be influenced by personality or other characteristics.

For point-in-time assessments of alertness, there are two established scales, the Karolinska Sleepiness Scale (KSS) (Akerstedt and Gillberg, 1990) and the Stanford Sleepiness Scale (SSS) (Hoddes and Dement, n.d.). These are Likert-type scales where participants have to define their perceived level of alertness on a 1-item predefined anchored scale, with 9 or 7 options to choose from respectively. This same idea could be also replicated on a visual analog scale (VAS) by simply asking the participants to report their feelings of alertness on a 10-cm line that goes from 0 to 100. There are also several types of short-term evaluations that combine assessment of alertness with other non-visual and well-being related responses. Some of these are the Global Vigour and Global Affect scale (GV and GA) (Monk, 1989), a VAS that includes 8 items (being alertness and sleepiness two of them), or the FACES scale (Shapiro et al., 2006), which includes five subscales (i.e. fatigue, energy, consciousness, energized and sleepiness), among others. While structurally different, self-reporting alertness measurements appear to be very correlated over time and used consistently during the day to assess circadian rhythmicity. In previous research, certain subjective indicators used to study alertness, such as the KSS, were validated with other objective correlates of alertness (Kosuke Kaida et al., 2006).

For long-term assessments, the Daytime Sleepiness Scale and the Nocturnal Sleep Onset Scale (DSS and NSOS) were designed to report feelings of alertness in the

previous 2-weeks. They were originally part of the Sleep Wake Activity Inventory (SWAI) (Rosenthal et al., 1993), that combines different assessments of sleepiness over the previous week, similarly to the Toronto Hospital Alertness Test (THAT) (Shapiro et al., 2006) where several items are used to provide a global score of alertness. To date, the only known scale to measure *general* levels of daytime sleepiness is the Epworth Sleepiness Scale (ESS) (Johns, 1991) , which rates daily life situations on a 4-points scale.

2.2.2 Objective indicators

Physiological indicators

In addition to controlling our behavioural state, the SCN also modulates a range of physiological pathways, making it is reasonable to infer that light might also induce changes on biological indicators of cardiovascular activity, brain activity, body temperature, pupillary reflexes, respiratory rates, etc. (Amundadottir, 2016; Chellappa et al., 2017). As a consequence, a quite large range of indicators pertaining to these body processes have been used in different studies to assess alerting effects of light. These physiological indicators are often divided into markers of central nervous activity and autonomic nervous activity.

Tests such as the Multiple Sleep Latency Test (MSLT) (Carskadon and Dement, 1977), where participants are required to lie down in a dark room until asleep, or the Maintenance of Wakefulness Test (MWT), where individuals are adviced to remain awake in a dimly lit room for 30 minutes, have both been used to assess state of wakefulness. During the procedure, standard electroencephalography (EEG) is monitored, thus reflecting activity in the central nervous system (CNS).

Changes in activity in the autonomic nervous system (ANS) are hypothesized to also serve as a predictor of alertness (Kosuke Kaida et al., 2006). In particular, the sympathetic division, which promotes arousal and energy generation, is often associated with higher alertness, whereas increases in parasympathetic division, which promotes rest activities, could be translated into increases in sleepiness (Shaffer and Ginsberg, 2017). This transition from wakefulness to sleep (or vice versa) in the ANS might be associated with a number of physiological biomarkers, which have also been suggested to correlate to some extent with alertness. For instance, changes in body temperature (i.e. core body temperature (CBT), skin temperature (ST) or skin conductance (SCL), measured with electrodermal (EDA) activity), and melatonin or cortisol concentration levels (Amundadottir, 2016).

Autonomic nervous stimulation also includes parameters such as heart rate and heart rate variability, which indicate changes in physiological arousal and are measured through electrocardiograms (ECG). Although alertness and arousal are two terms that might differ from a physiological point of view – the former refers to a specific

cognitive state, while the latter is a more general term that encompasses brain activation (Oken et al., 2006) –, they are related (and even overlap in definition) in that the state of cognitive alertness, a state of high alertness is also an attentive state, frequently accompanied by a high level of physiological arousal (Brown and Bowman, 2002). Hence, increased alertness might also represent an increased in arousal, and vice versa, even if the two processes are psycho-physiologically distinct.

Several indicators exist that describe the fluctuation between adjacent heartbeats (Berntson et al., 2016). This can be either assessed over time, such as the heart rate (HR), the root mean square difference among successive inter-beat-intervals (rMSSD) or the standard deviation of normal IBI (SDNN), or be based on their own pattern, such as the low-frequency (LF) and high-frequency (HF) power bands. Moreover, the SNS activity can be estimated based on the LF power of the HRV, while the HF component would instead be relied upon to represent PNS activity (Kaida et al., 2007). The ratio of LF to HF power (LF/HF ratio of ANS activity, also known as HRV index of sympathovagal balance) is in fact frequently used in sleep research to estimate the ratio between SNS and PNS activity under controlled conditions (Burr, 2007), so that a higher variability is associated with more pronounced sympathetic activation (SNS dominance over PNS), which ultimately translates into physiological arousal and potentially into higher alertness. Despite increasing evidence of the importance of light for our physiology, relatively few studies to date have investigated its impact on cardiovascular activity; when they have, the outcomes are oftentimes rather mixed or non-significant (Chellappa et al., 2017).

Cognitive performance

Many researchers have often used performance metrics rather than just focusing on subjective measures to obtain objective indicators of variations in sustained attention (which implies not only physiological arousal, but also the ability to perform a task over extended periods (Drummond et al., 2005)) and executive performance (which reflects alertness in combination with other cognitive functions such as inhibitory control or working memory (Lok et al., 2018)) (Gabehart and Van Dongen, 2017; Oken et al., 2006)

There are multiple performance indicators that reflect alertness. Among those included in the first group, a commonly used one in lighting research is the Psychomotor Vigilance Task (PVT) (Dinges and Powell, 1985). The Mackworth Clock Test (MCT) (Mackworth, 1948) is less known, but both are able to account for symptoms of sleepiness by recording reaction times of participants to a repetitive visual stimulus. The duration of the PVT test can be personalized from 1 to 10 minutes, and intervals of randomized appearance of stimuli can range from 1 to 10 seconds. Both an auditory and a visual version of this test exist. For the MCT, the task duration is restricted to 30 minutes. In general, the shorter the reaction time (in milliseconds), the more ability to sustain attention (i.e., higher levels of alertness). Other performance tests exist that measure executive performance, such as the Go/NoGo

task or the N-back task (among others) but will not be further discussed since the real contribution of alertness is difficult to isolate from other cognitive processes involved in such performance evaluations.

In previous studies, correlations were shown between subjective alertness and performance (Akerstedt et al., 1994). Still, improvements in one indicator might not reflect a parallel behaviour in the other, as decreases in alertness do not necessarily imply decline in performance.

2.3 ALERTING RESPONSES IN THE BUILT ENVIRONMENT

Multiple factors influence one's ability to remain awake for prolonged hours, from environmental stimuli – light in particular – to psychological constructs and metabolic processes. Daytime sleepiness, or a decrease in cognitive performance in terms of decision-making capabilities, are of key concern at the workplace as they are likely to affect productivity (Lok et al., 2018), as well as, ultimately, our more general health and well-being. They are often connected to symptoms of sleep deprivation, depression, circadian misalignment or sleep disorders (Oken et al., 2006), but this might as well be the result of spending prolonged hours in an inadequately lit environment. Given that our society spends most of their time indoors, understanding light-mediated effects in the built environment and the underlying mechanisms behind daytime wakefulness is particularly relevant. In that sense, scientific evidence has enabled to put forward the existence of various psycho-physiological processes that mediate our reactions to light exposure (Amundadottir, 2016).

Various studies have hypothesized about the processes behind light-induced alertness regulation and the cause-effect relationship of light exposure. In general, light in the blue part of the spectrum or light of higher intensity is thought to affect alertness both indirectly, by altering circadian patterns, and directly, prompting acute effects. Yet, the optimal light quantity (dose) and quality (colour) for psycho-physiological functioning is still uncertain.

2.3.1 Dose-response investigations

Some of the first attempts to establish a dose-response association between light exposure and human functioning were based on night-time studies, using fluorescent lamps (that typically have a CCT of 4,000K) and a variety of intensity level choices, ranging from 3 to 9,100 lux of photopic vertical illuminance. They helped demonstrate a non-linear relationship between light intensity and different non-visual effects at night, such as circadian phase resetting, suppression of plasma melatonin or alertness. As a result, it was discovered that, under such conditions, the half-maximum effect on these responses was achieved with 6.5 hours of exposures to

illuminances ranging from 80 to 160, 50 to 130, and 90 to 180 photopic lux, respectively (Cajochen et al., 2000; Zeitzer et al., 2000) (Figure 2.3). However, as mentioned earlier in this chapter, systematic changes over the course of the 24-h day exist in our body in response to the environment, so what works during the night may or may not be directly translatable to daytime situations.

To date, the only attempt at exploring a similar path but during working hours is an investigation conducted by Smolders et al. (2018). In that case, dose-response relationships of white light (i.e., with a CCT of 4,000K as well), with intensity levels that ranged from 20 to 2,000 lux of photopic vertical illuminance, were investigated on correlates of alertness. Results showed no clear dose-dependent relationships between light exposures of 1-hour duration and non-visual responses (i.e., very moderate for subjective alertness, and not significant for cognitive of physiological indicators). This finding suggests that brighter light during daytime does not systematically benefit alertness. Unfortunately, no further explorations have been conducted during daytime with regard to the effect of exposure (e.g., longer durations or light of different spectral compositions), so further research is needed in that direction.

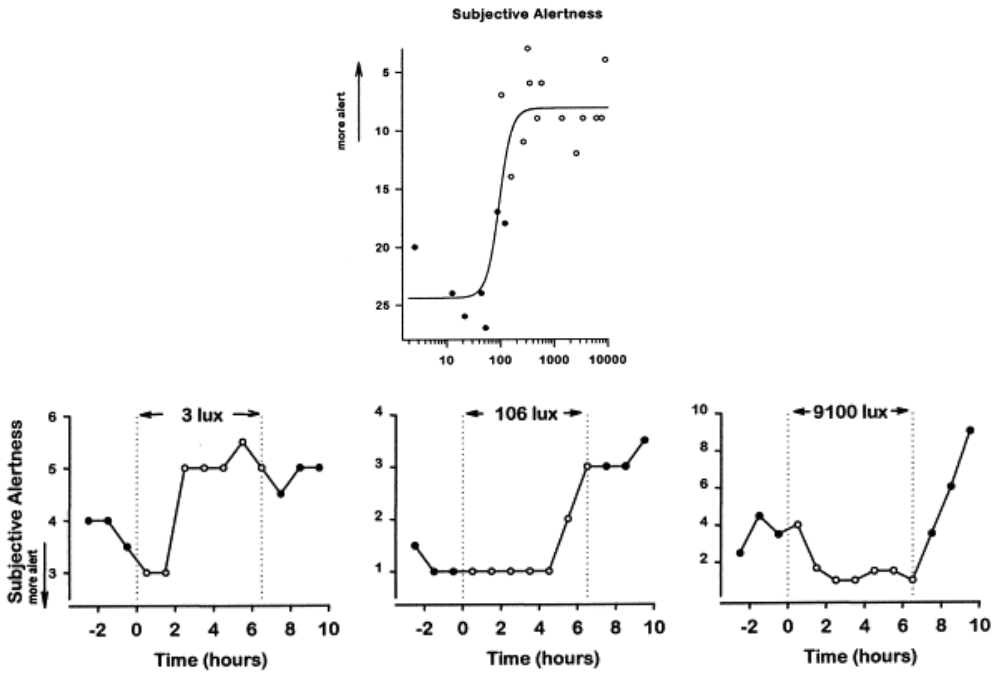


Figure 2.3 Dose-response relationship between subjective alertness and different levels of illuminance (image source: Cajochen et al. (2000))

2.3.2 Variations in light intensity and spectrum

Enabled by the advances made in the field of photobiology, a number of studies have successfully tested how diverse yet limited number of light scenarios result in different alerting responses. Still, no agreement has been reached regarding the general behaviour of the non-visual system to light exposure. In addition, most of these studies still resort to electric light as a proxy for daylight, making it difficult to understand whether natural compared to artificial stimuli may actually have a significant beneficial effect from a neurobehavioural or physiological standpoint.

Light intensity

The largest group of studies investigating differences in alertness due to exposure to light corresponds to those that focused on exploring variations of intensity levels of polychromatic white light (Souman et al., 2018). Among the reviewed studies, most agree that brighter conditions led to higher subjective alertness (Lok et al., 2018).

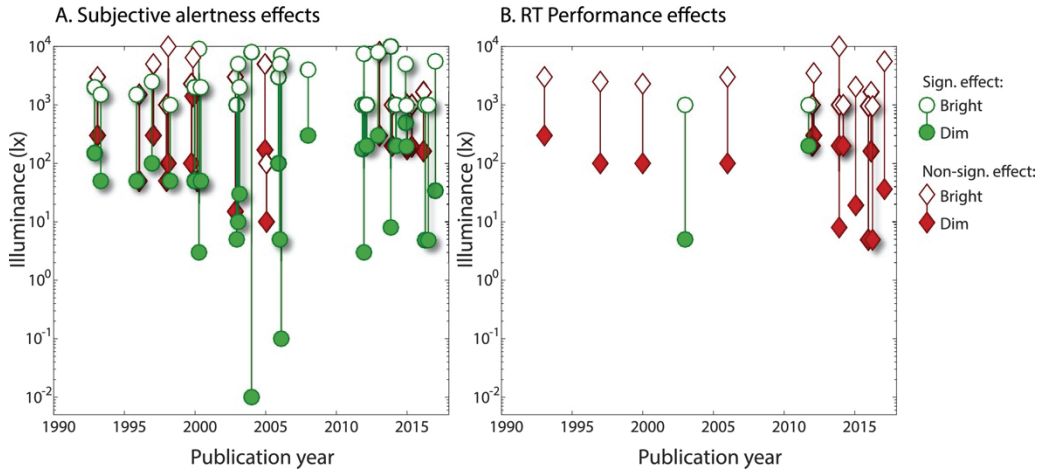


Figure 2.4 Overview of variations in intensity levels of polychromatic white light from studies investigating alertness and performance levels that founds significant results (image source: Souman et al. (2018))

From those that were daytime studies, most still agree that higher intensities increase subjective alertness (Åkerstedt et al., 2003; Huiberts et al., 2017, 2015; Iskra-Golec and Smith, 2008; Kaida et al., 2006; Leichtfried et al., 2015; Maierova et al., 2016; Münch et al., 2017; Phipps-Nelson et al., 2003; Rüger et al., 2006; Smolders et al., 2012; Smolders and de Kort, 2014; te Kulve et al., 2017; Vandewalle et al., 2006; Weisgerber et al., 2017). A few also found positive effects on sustained attention (Huiberts et al., 2017; Münch et al., 2016a; Phipps-Nelson et al., 2003; Smolders et al., 2016, 2012) and on physiology (Huiberts et al., 2016; Smolders et al., 2016, 2012; te Kulve et al., 2017).

However, due to differences in experimental designs, lighting conditions (Figure 2.4), duration of exposures and sample sizes, results during the day have generally been described as inconclusive (Lok et al., 2018; Souman et al., 2018). This is because many other studies failed to find significant effects, both in terms of subjective indicators (Borisuit et al., 2015; Borragán et al., 2018; Crasson and Legros, 2005; Huiberts et al., 2016; Sahin et al., 2014), and especially, in performance markers (Borragán et al., 2018; Huiberts et al., 2016; Kaida et al., 2006; Maierova et al., 2016; Slama et al., 2015; Smolders et al., 2012; Smolders and de Kort, 2014; te Kulve et al., 2017; Weisgerber et al., 2017). In such cases, bright conditions consisted of values between 100 and 10,000 lux, and dim conditions ranged from <1 to 400 lux (photopic illuminance). Duration of exposure varied between 30 minutes and 3 hours, and sample size ranged from 18 to 39 participants (within-subjects exposure; 16 participants per condition for the only between-subjects exposure).

Spectral content

The second-largest group of studies exploring light-induced effects on alertness corresponds to those than explored lighting scenarios with different spectral content, either by manipulating polychromatic white light (i.e., adding or removing energy in the blue part of the visible spectrum) (Cajochen et al., 2011; Chellappa et al., 2013; Chellappa et al., 2011; Figueiro et al., 2013; Rahman et al., 2013, 2011; Wahnschaffe et al., 2013) or by testing monochromatic light sources with different wavelengths [15](Cajochen et al., 2005; Figueiro and Rea, 2011; Lockley et al., 2006; Phipps-Nelson et al., 2009; Rahman et al., 2014; Revell et al., 2010, 2006). Based on their findings, there is also a general agreement that bluer environments tend to increase subjective alertness and cognitive performance (Souman et al., 2018). Most of them used electric light as the only source of illumination, and only one study explored the combined effects of daylight (polychromatic) and night-time intermittent exposure to electric (monochromatic) light (Figueiro et al., 2013).

Those that filtered out the blue part of the spectrum – thus creating a yellowish looking environment – found a significant effect on night-time melatonin suppression when compared to an unfiltered white light scenario, but found no negative effect on reports of alertness (Higuchi et al., 2011; Kayumov et al., 2005; Rahman et al., 2013, 2011; Sasseville et al., 2015; van de Werken et al., 2013). It is important to highlight, however, that in these experiments, illuminance covaried with spectrum manipulation, which means that it is no longer possible to differentiate whether spectrum or intensity are eliciting such responses. Two further studies investigated the effects of polychromatic white light on alertness and performance in comparison to monochromatic red light conditions. One of them found no difference in subjective alertness between the two light scenarios (Sahin et al., 2014) and the other obtained inconclusive results: while better night-time performance was obtained after a period of daylight exposure when compared to an equivalent monochromatic red light dark exposure (<1 lx), no clear effect could be found on subjective alertness after an intermittent exposure to either blue or red monochromatic light (Figueiro et al., 2013).

Among the studies that focused on the comparison of higher versus lower correlated colour temperatures (CCT), some found no significant effects. Since illuminance covaried with spectrum manipulations in such cases, conclusions about the effect of colour on alertness or performance are difficult to render (Canazei et al., 2017; Santhi et al., 2013, 2011). Others, however, reported subjective alerting effects in the higher CCT condition (Cajochen et al., 2011; Wahnschaffe et al., 2013). The most relevant study here might be the one conducted by Chellappa and colleagues (Chellappa et al., 2011), where it was possible to successfully demonstrate the effect of "blueness" by exposing participants to higher vs. lower CCT at a constant, dim illuminance (40 lx). Results showed not only higher alertness but also better performance under the bluer condition compared to the reddish one.

However, only a small group of the studies investigating effects of spectral manipulations on alertness and performance were daytime experiments (Figueiro and Rea, 2011; Münch et al., 2016b; Rahman et al., 2014; Revell et al., 2006). Yet, patterns of light exposure during our daily routines are often very different to those tested in such studies. In conditions closer to real-life (i.e. with dynamic lighting conditions, prolonged exposures, no prior sleep restrictions, no pre-treatment conditions, normal sleep pressure, etc.) and especially during daytime, identifying the impact of light exposure on alertness or sustained attention becomes a real challenge, also because brain activity and other biological processes are, under normal circumstances, already synchronised with task demands (de Kort, 2019).

Furthermore, it is believed that the magnitude of hour-to-hour responses relies not only on the intensity and spectral distribution of light (i.e., on irradiance), but also on the time of day, duration, and prior history of exposure. From the literature, however, it is not yet clear whether these factors systematically affect alerting responses, nor how they may moderate them (Souman et al., 2018). In addition to exogenous components such as activity, sleep schedule or meals that can also affect alertness profiles, longitudinal responses are intrinsically driven by endogenous processes such as the phase of the biological clock, sleep onset and sleep inertia (Gabehart and Van Dongen, 2017). Very little can be found on the potential dependency of these effects with exposure duration, measured in hours (Lok et al., 2018; Souman et al., 2018) or days (Münch et al., 2016a), or with time of day (morning or afternoon sessions (Huiberts et al., 2017; Iskra-Golec and Smith, 2008)). Further investigation is therefore definitely needed in this direction.

2.4 PREDICTION MODELS OF ALERTNESS

Prediction models that incorporate findings about the non-visual effects of light exist in various forms, from attempts at modelling the specific contribution of light stimuli to the non-visual system through the development of spectral sensitivity functions, to physiology-based models that aim to predict specific non-visual responses such as

circadian phase, sleep propensity, alertness or cognitive performance. In this section we will give an overview of the most prominent achievements from both perspectives, while focusing and further elaborating on the latter one, since our goal is to evaluate the performance of such models in the prediction of daytime alertness due to daylight exposure.

One of the first examples of a circadian sensitivity curve model was the one proposed by Gall and Bieske (Gall and Bieske, 2004), which they called C (λ) and was based on data from nocturnal melatonin suppression (Brainard et al., 2001; Thapan et al., 2001) with a maximum sensitivity peak at around 460 nm. Enezi et al. (Enezi et al., 2011) later suggested, instead, the use of a sensitivity curve that could better approximate that of the photopigment melanopsin in the ipRGCs (which peaks closer to 480 nm) and proposed a new melanopic spectral efficiency function. However, none of this models considered the involvement of other photoreceptors, nor did they addressed light exposure dynamics i.e., exposure that would change over time. In 2014, Lucas and colleagues (Lucas et al., 2014) suggested (based on the assumption that non-visual responses are initiated by more than one photoreceptor (i.e., other than ipRGCs)) that since no spectral weighting function for non-visual responses was yet accepted, irradiance should be represented by the activity of the five photoreceptors instead (i.e., rods, cones (S, M and L) and ipRGCs). This recommendation was later adopted by CIE (CIE, 2018) for studies addressing non-visual responses to light. In line with this argument, and in a further attempt at modelling the relative contribution of the different photoreceptors, Amundadottir developed the ipRGC-cone shift model (Amundadottir, 2016). Based on suggestions from previous studies that showed that cone photoreceptors lead to non-visual reactions at the start of light exposure with low irradiances, but ipRGCs dominate the response to long-term exposures and high irradiance, the model combined two spectral weighting functions (i.e., ipRGCs and L+M cones) that dynamically adapt to changes on intensity and duration of exposure.

In addition, mathematical models exist that are able to predict alertness or cognitive performance based on pure endogenous processes such as circadian rhythms, sleep inertia or homeostatic processes (Achermann and Borbély, 1994; Folkard and Akerstedt, 1992), and others that rely on exogenous non-photic components such as sleep schedules instead. Only a few consider also the effects of light (for a full review, please refer to Klerman and Hilaire (2007)). Among this last group, we can find different models: those that have been developed to understand the effects of light on the phase and the amplitude of the circadian pacemaker (for full review see Stone et al. (2020)), and those that are also able to predict dynamics of sleep, performance and alertness (for full review see Postnova et al. (2018)).

One of the first models that attempted to simulate the effects of a given light stimuli on our biological clock was the circadian pacemaker model, often referred to as the Kronauer model (Jewett and Kronauer, 1998; Kronauer et al., 1982). Initially, it was able to accurately describe the response of the circadian system to extended, bright

light stimuli (4-8 hours at 10,000 lux) but was later revised to also account for lower intensities (ambient room light at 150 lux) and intermittent pulses (Forger et al., 1999; Kronauer et al., 1999a). In addition, the model was further calibrated with neurobehavioural data from sleep deprivation studies to also predict levels of subjective alertness (SA) and cognitive throughput (CT) (Jewett and Kronauer, 1999).

However, a model of the circadian system should include not only a self-sustaining endogenous rhythm, but also account for effects of exogenous stimuli and a mechanism by which both components interact. Some years later, in an effort to extend the effects of ocular light exposure, St. Hilaire and colleagues (St Hilaire et al., 2007) implemented the model by modifying its photic sensitivity to account for dimmer light levels (<100 lux) and single pulses. In addition, she added a non-light dependent component to the circadian pacemaker. In particular, the effect of the sleep-wake cycle was included to also account for external non-photic entrainment capacities on the circadian clock. To date, St. Hilaire's (St Hilaire et al., 2007) modification of the oscillator model has been proved to be the best validated method for predicting circadian phase (Stone et al., 2020). Based on the procedure for integrating the SA and CT equations (Jewett and Kronauer, 1999) to the Kronauer model (Kronauer et al., 1999a) by Dean and Jewett (for the Circadian Performance and Simulation Software (CPSS), Brigham and Women's Hospital and Harvard Medical School) (Dean II and Jewett, 2002), St. Hilaire's model was further extended to predict non only core body temperature, but also levels of neurobehavioural functioning.

Other models exist that built upon the Kronauer model (Kronauer et al., 1999a) and have used it as basis to take light intensity, timing, duration and pattern of exposure into account for the prediction of various neuroendocrine and physiological process (for full review see Postnova et al. (2018)). Among those, the model of arousal state dynamics (Postnova et al., 2016), which originates from a combination of two earlier models on the arousal system (non light-driven, by Phillips and Robinson (2007)) and the dynamic circadian oscillator (light-driven, by St Hilaire et al., 2007), was initially formulated to accurately predict sleep propensity. It was later calibrated with experimental data to create new metrics that could relate model outputs with alertness and performance, while still reproducing dynamics of sleep propensity (Postnova et al., 2018). This refinement did not account, however, for the direct alerting effect of light that can occur independently of timing or circadian phase (Cajochen et al., 2000; Lockley et al., 2006; Vandewalle et al., 2006a), thus being only valid for dim light conditions (<15 lx). In line with that argument, St. Hilaire's model (St Hilaire et al., 2007) was further refined in an attempt to incorporate this direct alerting behaviour of light (St. Hilaire et al., 2012), which is also believed to reduce complaints of sleep inertia (Gimenez et al., 2010). Unfortunately, it was never validated, nor has it been further developed since.

One of the main but common limitations of the aforementioned models and their refined versions is that they are limited to evaluations of polychromatic white light quantified via photopic illuminance, which represents a problem when making predictions in occupational settings with light of different spectra. Recently, new

models were developed to account for melanopsin-mediated effects of light. One of them corresponds to a further refinement of the Postnova and colleagues' model (Postnova et al., 2018) by Tekieh et al. (Tekieh et al., 2020), where the contribution of ipRGCs and the direct alerting effect of light was included, and has that been already validated with experimental data under electric light conditions. Still, this model, as well as the previous ones, incorporates a feedback mechanism (i.e., dynamic oscillator) in order to predict potential phase-shifts, that requires personal information such as sleep schedules, this

Also, these models have been either trained or developed with experimental data obtained from laboratory controlled night-time studies. When analysing indoor daylight exposure in the built environment (i.e., in the real world), environmental cues are far from being static, extreme or controlled. On the one hand, the light stimulus behaves in a dynamic, unpredictable way (i.e., following weather conditions and the sun course) that can rapidly change depending on a range of factors (individual behaviour, automated controls, shading systems, etc.). On the other hand, no pre-treatment or sleep-deprived conditions define most situations in the real world. However, in order to consider the dynamic behaviour of the non-visual system (where one's current state is based on prior actions) and thus the potential of circadian desynchronization, these models include a feedback mechanism that requires the input of a sleep schedule (i.e., thus imposing the need for specific, personal information).

If we translate these requirements to the field of architecture, the amount of data thus needed to identify a long-term light-response relationship (e.g., when trying to conduct an annual evaluation of a certain design), becomes unmanageable. In order to advance knowledge in the field of non-visual daylight integration in the built environment, designers need computationally efficient methods instead, and models that are able to anticipate such responses in real life.

A model for predicting dynamic, wavelength-dependent effects of light on non-visual responses has been proposed by Amundadottir (Amundadottir, 2016). It is based on a linear structure with no feedback mechanisms (i.e., representing a person with no prior light exposure or with an entrained, static oscillator), and accounts for qualities such as light intensity, duration, history or timing of light exposure. In addition, this method incorporates time-varying spectral sensitivity functions, which are used as inputs to the light-driven model. This approach thus offers a very interesting potential in terms of applicability to architecture and daylighting design as it does not require personal information, and light exposure patterns can be assessed with regard to their potential to influence human health.

2.5 CHALLENGES AHEAD

The state of the art in this chapter identified a number of research gaps and challenges regarding current knowledge about the role of daylighting for human psycho-physiological functioning, which are questions that have instead been explored mainly under electric conditions (and in the laboratory).

First, the uncertainty as to "optimal" daylight conditions needed for biological time-keeping systems. Reviewed studies gave us insights and an overview about how light of different wavelengths and intensity levels affect our alerting capacities. Overall, both higher intensity and higher colour temperatures have been shown to increase the sensitivity to polychromatic white light exposure subjectively. However, it is important to highlight that subjective alerting effects of light intensity were not seen in a significant proportion of reviewed studies and moreover, only some of the examined investigations comparing subjective alertness with exposure to different colour temperatures found that higher CCT resulted in higher self-rated alertness. Those that filtered out short wavelengths if light instead, did not report negative effects on subjective alertness. In addition, just a few experiments have shown that sensitivity to blue light increases subjective alertness as compared to longer wavelengths. Moreover, according to Cajochen et al. (2000), the change from low to high subjective alertness for illumination level at the eye tends to be about 100 lx during the night, although colour temperature can affect this.

As a result, no strong conclusions can be drawn from this overview, and more investigation is needed both to determine whether variations in spectral content or intensity levels of daylight indoors may also have any observable effect on our psycho-physiological behaviour, and to facilitate the development of dose-response curves for daytime alertness.

Secondly, the lack of consensus on assessment methods to monitor daylight exposure in real life. In particular, no established guidelines existed regarding what to report in studies of ipRGC-related effects of light. Only four months ago a new publication from CIE introduced, for the first time, a template to document such protocols (Veitch and Knoop, 2020). Hopefully, this new guidance will help further studies in moving closer to standards. Still, the challenges associated with measuring and evaluating alerting responses in realistic settings and under daylight conditions are numerous.

The most important one is probably the unpredictable and complex nature of daylight, which explains to some extent the preference for electric lighting in the majority of the reviewed studies. However, daylight represents a special case in the context of light exposure. It is not only preferred over electric light in most situations (Peter Boyce et al., 2003), it also offers key unique properties that favour non-visual stimulation when compared to static exposures found in electrically lit environments: it is abundant, naturally rich in the blue component of the spectrum, it has a dynamic nature that generates temporal variations and a light-dark cycle to which our

biological clock has aligned through evolution. Many studies have already pointed out the importance of daylight and associated views for well-being (Aries et al., 2010; Beute and de Kort, 2014; Peter Boyce et al., 2003; Veitch, 2011; Veitch et al., 2013), and exposure to it has been associated with better health (Aries et al., 2015; Boubekri et al., 2014; Hubalek et al., 2010). Yet, the extent to which exposure to actual daylight indoors and variations in spectral content or intensity levels may have an observable effect on our psycho-physiological behaviour, remains unclear.

Last, an insufficient transdisciplinary work effort in terms of knowledge exchange from different disciplines (Münch et al., 2020). To this end, the lack of experimental data and the limited connection between architecture and photobiology continues to be a barrier in advancing current knowledge on daylight performance optimization for the integration of non-visual effects in the design process. The emergence of new tools and simulation methods for prediction of alertness such as the ones reviewed in this chapter should thus facilitate the next steps in this direction.

3 [METHOD AND EXPERIMENTAL DESIGN]

To help elucidate the effectiveness of daylight exposure for maintaining productive levels of attention, arousal and alertness during working hours, a series of user studies have been conducted, referred to as studies A, B and C. Based on hypotheses established in Chapter 1 (section 1.2.2), the aim was to understand, on the one hand, whether variations on available ambient daylight (i.e., non-controlled conditions in real workspaces) can induce measurable changes on occupants' psycho-physiological behaviour, and on the other hand, whether such effects are sensitive to temporal variations and timing of daylight exposure.

Based on the evaluation of existing techniques of alertness quantification, and on lessons learnt from similar investigations, a novel methodology to conduct user studies in realistic, non-controlled conditions outside the laboratory confinement is proposed (Soto Magán and Andersen, 2019). In this chapter, we present a detailed overview of the adopted experimental approach for all three studies, which combines both environmental monitoring (lighting conditions) and data collection procedures (individual responses).

In this chapter, the details of the experimental design and set-up, including specifications about the environment and context, daylight control strategies and monitoring equipment used, are reported in sections 3.1 and 3.2. The different stages of the recruitment process together with the criteria used to select participants are described in section 3.3. The experimental protocol adopted in the studies, both in terms of light exposure and hourly tasks, are presented in section 3.4. Finally, measures of alertness including subjective self-reports, attentional tasks and physiological markers, as well as statistical methods used to analyse the magnitude of the effect of daylight conditions on each dependent variable are reported in sections 3.5 and 3.6.

3.1 OBJECTIVES AND APPROACH

The main purpose of the experimental approach selected in this thesis is to understand daytime effects of daylight exposure during office work routines. By means of neurobehavioral monitoring, the idea is to identify a cause-response relationship dependent on the lighting environment. There are two ways of creating such an experimental context: either using a within-subjects design, where each participant is exposed to more than one condition, or resorting to between-subjects designs, where participants are divided into groups (as many as conditions to be tested) and are exposed to only one treatment scenario. In the first ones, causal estimates can be obtained by examining changes on individual behaviour (as long as there independence between the multiple exposures is guaranteed), whereas in the second ones, group behaviour is analysed instead (as long as group assignment is random) and changes are compared to one another (Charness et al., 2012).

Both approaches have their advantages and disadvantages. While the earlier might cause participants to respond in a demand-effect way in an attempt to predict researchers' expectations (and hence, result in biased or confounded outcomes), they often provide more statistical power and are naturally aligned with most theoretical mindsets. The latter, instead, are likely to provide a clearer cause-effect identification and to have more external validity but offer less statistical power, which is difficult to overcome in these situations. In the end, the decision regarding which experimental design to choose will depend on whether the interest of the researcher arises from providing an exact and statistically powerful test of theory at the expense of obtaining biased effects (within-subjects design), or rather, providing a proper identification of the cause-effect relationship at the expense of a less powerful statistical outcome.

Most of the reviewed studies in Chapter 2 (section 2.3) adopted a within-subject design exposure. In such cases, it is not possible to keep participants blind to light manipulations, as bias almost unavoidably arises from expectations or result associations, particularly in subjective measure of alertness. In all three studies included in this thesis, a mixed factorial design was used instead, adding statistical power and helping to rule out threats to internal validity. This mixed design consisted of a between-subjects exposure, where participants would only experience one *daylight condition* at a time (per study), alongside a within-subjects assessment, since participants are being tested repeatedly throughout the study. Taking advantage of both approaches, the combined effects of spectral shifts and/or intensity variations, timing and duration of daylight exposure were tested on subjective responses of alertness and well-being, on sustained attention and on physiological arousal.

As a result, *daylight condition* was used in our experiments as a between-groups independent variable, whereas *duration* and *timing* of exposure were both used as within-subjects, independent variables (i.e., accounting for participants' repeated measurements). *Duration* of exposure, which here corresponds to the number of days that any experiment lasted, ranged from two to three days depending on the experiment. *Timing* of exposure, which basically refers to time of day, consisted of two sessions (morning and afternoon) in all cases. As a result, and although daylight availability did vary throughout the day and during the entire duration of the study as a result of the sun course, weather variability and changing sky conditions, the adopted between-subject approach offers an unbiased exposure. Participants were indeed randomly assigned to experience only one *daylight condition* in each study, and both groups simultaneously underwent the same natural dynamics throughout the experiment. The adopted between-subjects exposure to different daylight conditions helped to balance confounding effects derived from external factors such as view out, background, motivation or stress for instance (cf. Chapter 2, section2.1) while offering the opportunity to evaluate the effect of a certain light characteristic (i.e., spectrum and/or intensity) in isolation.

3.2 EXPERIMENTAL SET-UP

All three studies took place on the EPFL campus in Lausanne, Switzerland (46°31'13"N 6°33'56"E). This location presents a temperate oceanic climate (group C, subgroup Cfb, according to Köppen-Geiger climate classification (Beck et al., 2018), very common in continental Europe. The amount of visible solar radiation available at a given location depends on latitude (that also defines the duration of daytime) and local climate, and is here illustrated for the whole year by Figure 3.1, which describes the normalized data of global horizontal illuminance and cloud cover corresponding to the time-period 2000-2019. The underlying data were obtained from Meteonorm 8 (Meteonorm, 2020) using data from the nearest weather station (Pully, VD).

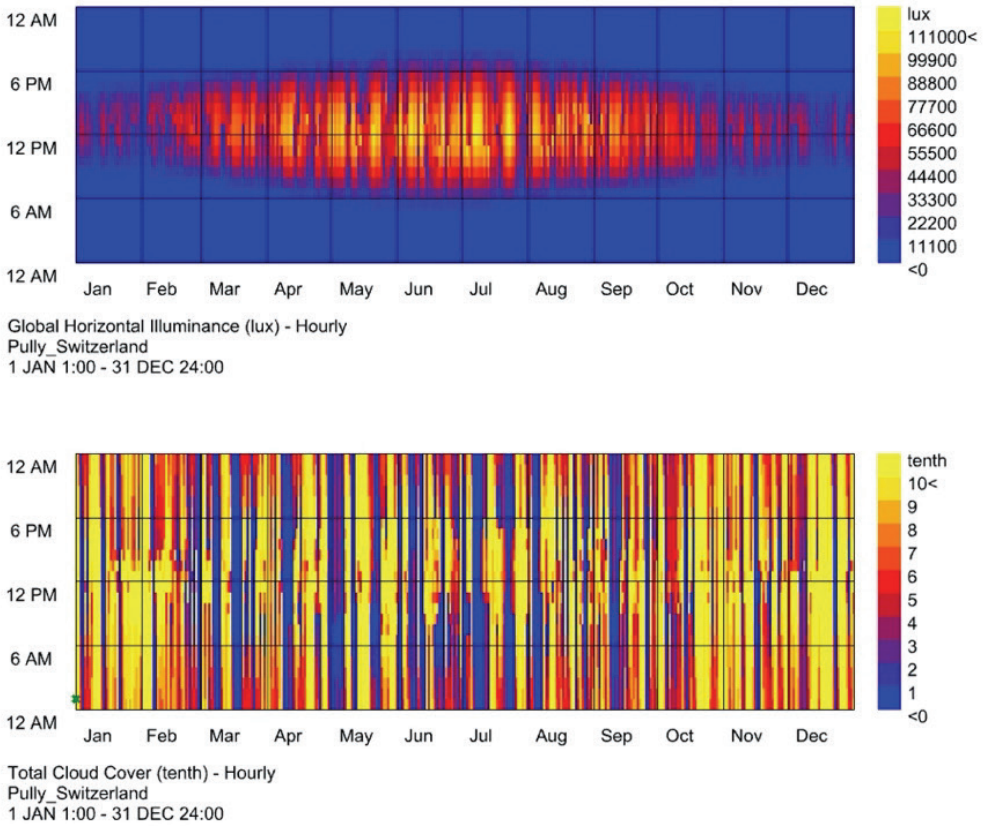


Figure 3.1 Overview of hourly yearly values of global horizontal illuminance in lux (upper part) and average total cloud cover (bottom part)

3.2.1 Context

Two adjacent classrooms (numbered CM4 and CM5) were used to conduct the experiments (Figure 3.2) in all three studies (A, B and C), whose simplified model is shown in Figure 3.3. Temperature in these spaces is regulated with a central heating system through radiators (as is the case for most classrooms of the campus), and a mechanical ventilation system ensures the necessary air changes and adequate CO2 levels, since windows are not operable for safety and security reasons. In addition, no air conditioning system is installed in any of the workspaces at EPFL (except specific lab spaces with special needs) for sustainability reasons, according to Swiss building norms (SIA, 2007, p. 382). Since experiments were conducted over the weekend, minimum noise or external distractions from the outside was granted.

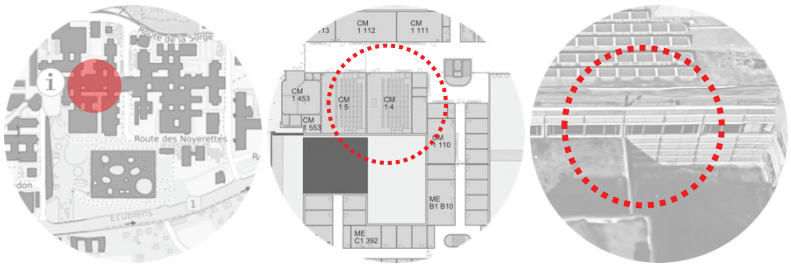


Figure 3.2 Location of the classrooms within EPFL campus.

Interior surfaces had the same characteristics (colour, materials) in both spaces (Figure 3.4), ensuring a similar influence on the classroom's perceived spectral conditions: white walls and ceiling (70-80%), dark-blue carpet on the floor (16%), grey desks (52%) and soft wood chairs (51%). The dimensions of the rooms are 15 m in length by 10 m in width.

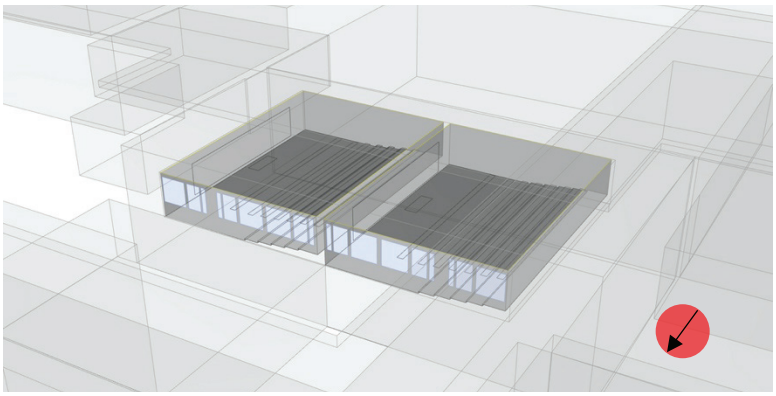


Figure 3.3 Schematic of the classrooms.

3.2.2 Lighting conditions

Daylight provision was ensured from a South-oriented façade, with window openings of 1.6 x 10 m and similarly obstructed views, which granted similar daylight access at any given moment of time. The room was already equipped with a commercially available electrochromic glazing (namely SageGlass, manufactured by Saint-Gobain), a technology that is more and more widely used in architectural design nowadays, especially for office buildings.

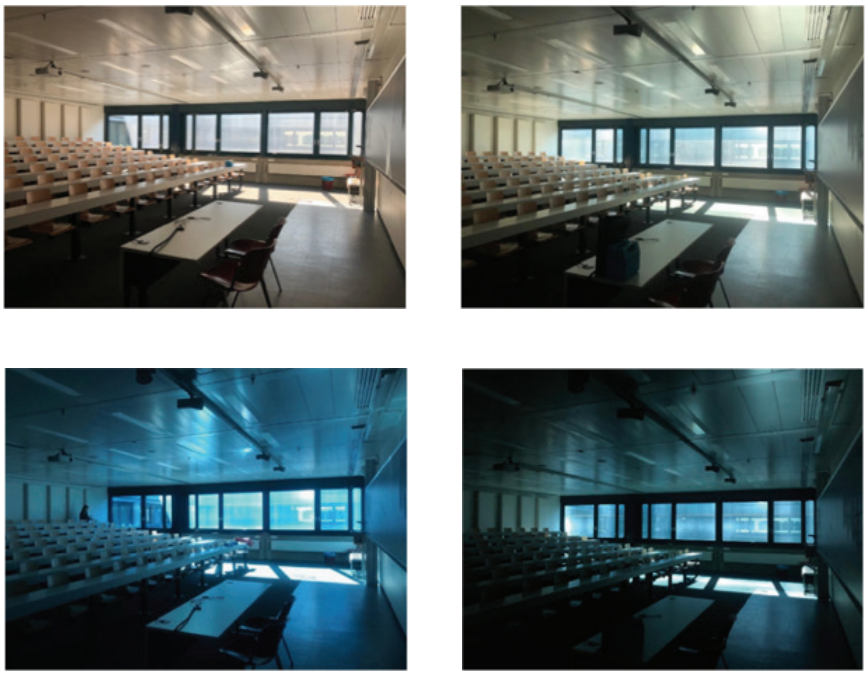


Figure 3.4 Levels of tint of electrochromic glazing in one of the classrooms. From left to right and top to bottom: clear state (EC-0), intermediate state 1 (EC-1), intermediate state 2 (EC_2) and fully tinted mode (EC-3).

This electronically tintable glass offers the opportunity to manipulate the appearance of indoor daylight's intensity and spectrum through a change of tint and transmittance in the glazing (Figure 3.4). It uses a control (outdoor sensor), which is usually configured to automatically regulate the visible transmittance of the glazing based on thresholds of outdoor illuminance. However, for the purpose of our studies, the automatic controls were overwritten and deactivated. Instead, tint variations were manually controlled by the researcher at the beginning of each experiment.

As described in Table 3.1, visible transmission varies between 55% in clear state to 1% when fully tinted. As the glass darkens, long wavelengths are diminished proportionally to an increase in the shorter ones, transitioning from a neutral appearance to the eye in the clear state, to a progressively deeper blue hue. As a consequence, the peak in visible transmission is shifted towards the blue part of the spectrum (from 565 nm in the clear mode to 460 nm at full tint, Figure 3.5), thus filtering spectral and intensity characteristics of indoor daylight.

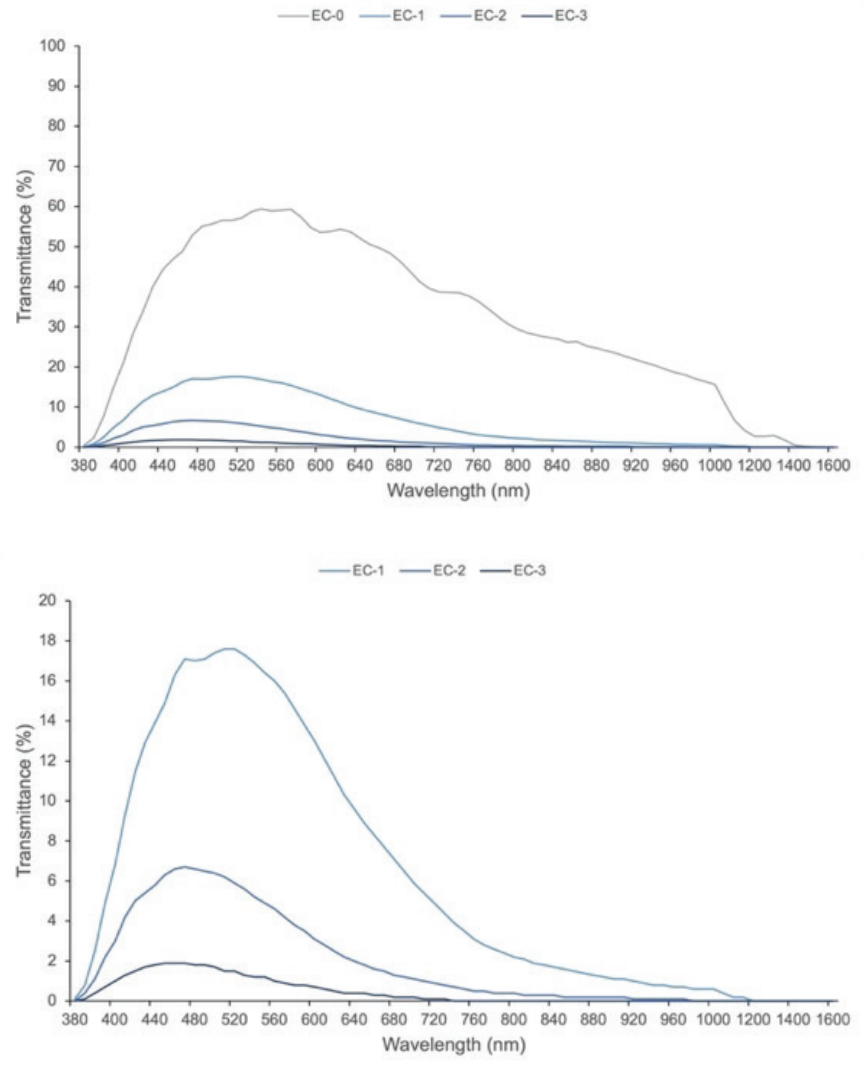


Figure 3.5 (a) Spectral transmission curves for electrochromic glazing in clear state (EC-0), fully tinted (EC-3) and two intermediate states. (b) Detail of the peak shift in visible transmission towards the blue end of the spectrum for the three levels of blue tint (EC-1, EC-2, EC-3)

Table 3.1 Transmittance values (Tvis) for filters and electrochromic glazing, and levels of tint for the electrochromic glazing.

Glazing/filter type	Tvis (%)
Electrochromic glazing (EC)	
Clear (EC-0)	55
Intermediate 1 (EC-1)	16
Intermediate 2 (EC-2)	6
Fully tinted (EC-3)	1
Neutral filter (NF)	13
NF + EC-0	*7*
Blue filter (BF)	53
BF + EC-0	*29*

3.3 EXPERIMENTAL DESIGN

Each study (A, B and C) was designed to investigate the combined effects of selected daylight qualities (intensity and/or spectrum), of timing and of duration of exposure on occupants' profiles of alertness, attention and arousal, during a normal work schedule. The main goal was to understand whether the occupants' psycho-physiological responses of the occpuants were affected differently depending on which lighting scenario they were exposed to, and whether these responses were further moderated temporally.

An overview of the three pairs of daylight scenarios involved in this work are presented in Figure 3.6.

- STUDY A explored the effects of variations in daylight spectrum, by comparing conditions where a blue shift in the spectrum was introduced to neutral ones while maintaining the associated photopic illuminance constant.

- STUDY B evaluated the effects of variations in daylight spectrum and intensity levels, by comparing conditions where spectral shifts in the blue range of visible daylight (and associated confounded intensity variations) were introduced.

- STUDY C analysed the effects of variations in daylight intensity levels, by comparing conditions where brightness was modified while maintaining a constant, neutral spectrum.

Figure 3.6 Overview of pairs of daylighting conditions studied (conditions listed from left to right for each study): study A (dim neutral vs dim blue), study B (bright blue vs moderate bright blue) and study C (brighter and dim neutral))

3.3.1 Protocol and timing of exposure

Studies were conducted over the course of two to three consecutive days for study B and studies A and C respectively, over two sessions per day (morning and afternoon). On each experimental day, participants were exposed to given lighting conditions for seven continuous hours, including a 55-minute break for lunch (from 12:05 p.m. to 1:00 p.m.) to be taken inside the room (so as to avoid exposure to significantly different lighting conditions e.g., outdoors). Morning sessions ran from 9:00 to 12:00 while afternoon sessions were conducted from 13:00 to 16:00. Starting earlier or finishing later was not envisioned since the goal was to maximize daylight availability (only source of illumination in the rooms) on the one hand, and to avoid endogenous effects of sleep inertia (i.e., circadian drive for wakefulness) and sleep onset (i.e., homeostatic drive for sleep) on the other hand (Oken et al., 2006). To control for these external factors, participants were asked to keep a regular sleep schedule based on their habitual routines (i.e., no schedule was imposed), which was qualitatively monitored through sleep diaries filled at their arrival in the classrooms. This information was only used to check for compliance with the requirements of the studies.

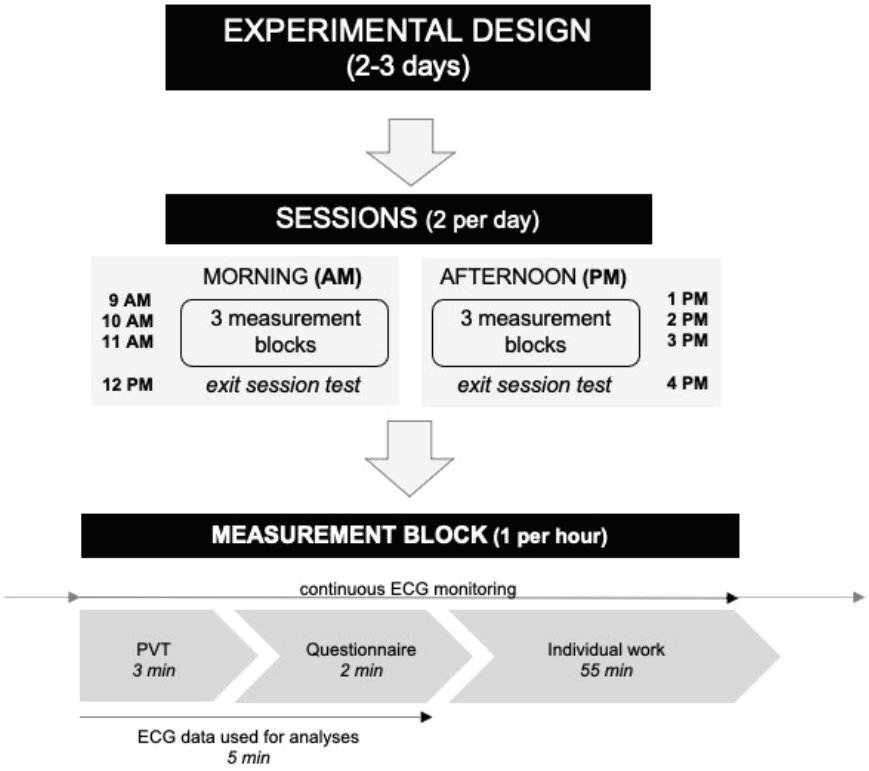


Figure 3.7. Overview of the experimental design and procedure.

Each session (morning and afternoon) consisted of three measurement blocks of one hour each, and followed the same procedure: during the first 5 minutes, subjects were asked to complete a 3-minutes visual Psychomotor Vigilance Task, available in an app-based version called PVT-touch (Kay et al., 2013), and a short 2-minutes self-reported questionnaire, which included questions about feelings of alertness, vigour, affect and vitality (more details about this in section 3.5). These tasks (PVT and questionnaire) were presented in a randomised order every time, and the order of appearance of the questions within the questionnaire were also randomized. Both assignments were performed on a smartphone that was provided by the researcher. Although ECG activity was continuously monitored and recorded (more details in section 3.5.2), only the first 5 minutes of data recorded within each measurement block were actually used for the analyses, during which the reaction time task was performed, and the self-report questionnaire was filled. This allowed us to ensure that all participants were performing the same type of activity during useable data collection, and thus a fair comparison of physiological conditions between rooms and among subjects. The remaining 55-minutes in each measurement block could be dedicated to any type of individual work, as long as it complied with the rules of the study, namely: no use of screen devices (phone, tablet, laptop, etc.) and no distractions (Figure 3.7).

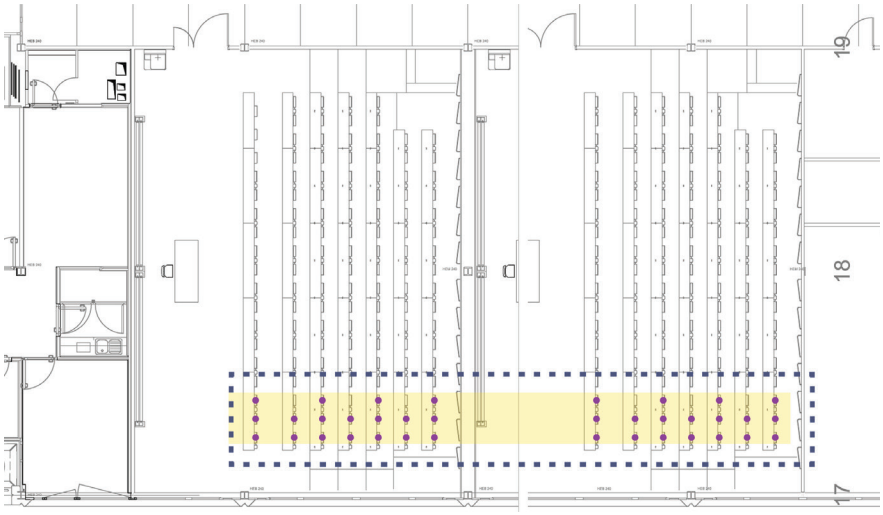


Figure 3.8 Distribution and positioning of participants inside the classrooms (CM4 and CM5).

More specifically, participants were not allowed to talk to each other, move from their places or listen to music except during their lunch break. As a general rule, drinking water was allowed during the experiment, but consumption of any stimulant such as coffee, tea, carbonated drinks or sugar were strictly forbidden. Only during lunch was a light meal allowed. During this break, participants were also allowed to stand-up,

talk to each other and move around the room, but leaving was not allowed at any moment except for exceptionally using the restroom. All these requirements were imposed as part of the studies' protocol to try to avoid bias from external factors as much as possible.

In each study, subjects arrived on campus 30 minutes before the start of the first session (i.e., at 8:30 a.m.), on the first day of the experiment. They were randomly and blindly assigned to one of the two rooms. Classrooms were already equipped and ready to use with the corresponding filters (or level of tint in the case of electrochromic glazing). Fifteen minutes before the start, participants entered the rooms and were individually assigned for the duration of the experiment to a given seat near the window (cf. Figure 3.8), again to maximize daylight illumination.

Their first task in the room was to complete a sleep diary before the start of the session, which allowed to keep track of their sleep schedules on a daily basis and to give them a few minutes to settle down. Right after that, measurement blocks started at 9:00 a.m. and went until 12:00 p.m., when a fourth visual PVT and sampling survey were administered to conclude the morning session. At 1:00 p.m. the afternoon session started again with another 3 measurement blocks and concluded at 4:05 p.m. with the last PVT and sampling survey for the day.

3.3.2 Monitoring equipment

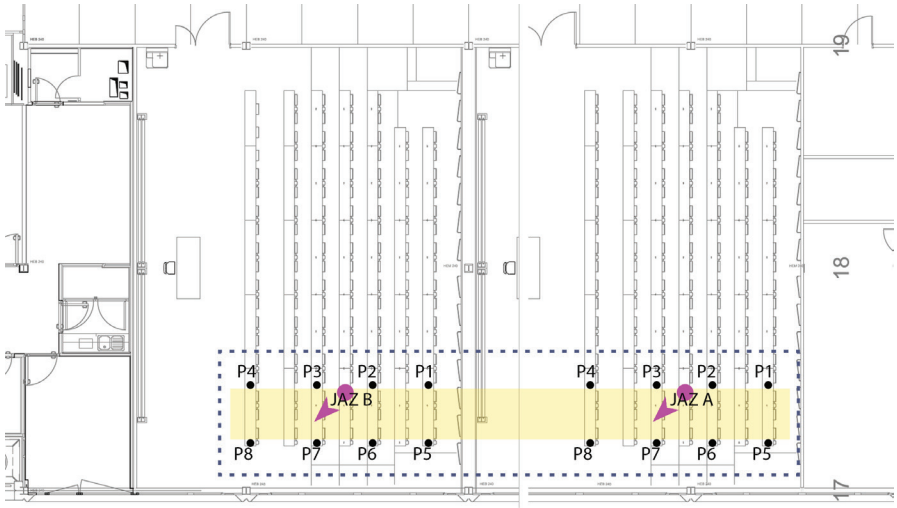


Figure 3.9 Placement of spectroradiometers (red dots) and photometers (numbered smaller black dots) across classrooms.

The rooms were provided with equipment for continuous monitoring of environmental conditions. In each room, eight photometers (Delta Ohm), with data loggers (HOBO) attached, were placed on the desk of every other participant. They measured horizontal illuminance at the work plane, as well as temperature and humidity levels, in minute intervals. In addition, one spectroradiometer (Ocean Optics, Jaz series) per room, placed at eye level for a seated individual (i.e., at 1.30 m height) and oriented as indicated in Figure 3.9, was used to continuously record changes on indoor spectral power distribution (SPD). All instruments were calibrated before the experiment to ensure accuracy of the readings.

3.4 RECRUITMENT STRATEGY

For all three studies, different participants were recruited from the EPFL campus (Lausanne, Switzerland) with flyers and email invitations. As explained in section 2.1.3, several endogenous and exogenous components may cause either a desynchronization between the circadian clock and the sleep-wake cycle, or a masking effect on circadian rhythmicity. As these will most likely cause alterations in alertness profiles, candidates were carefully screened before being considered admissible for the study, with the intent to control for these confounding factors. This pre-screening was based on the following criteria:

- age between 18 to 35 years old, to limit the effect of age difference regarding, for example, lens yellowing

- full availability on the days of the study

- no use of drugs (to limit obvious factors influencing alertness state)

- no colour vision impairment or other vision disorders

Sleep disorders or neurobehavioral disorders, such as sleep apnoea, narcolepsy or attention-deficit hyperactivity, may generate declines in alertness. Selected volunteers were thus asked to complete a baseline questionnaire addressing these and other potential confounding factors, including but not limited to sleep quality, chronotype, mental health or personality profile. They were also asked about recent travel between time zones (to avoid desynchronized circadian phases) and caffeine consumption.

Candidates with extreme chronotypes, as assessed by the Morning-Evening Self-Assessed Questionnaire (MEQ) (Horne and Östberg, 1976), were excluded, as well as those with poor quality scores in the Pittsburgh Sleep Quality Index (PSQI) (Buysse et al., 1989). All successful participants had to be free from sleep or psychological disorders as assessed by the Patient Health Questionnaire (PHQ9) (Kroenke et al., 2001), and should not suffer from personality disorders according to the Big Five

Inventory test (BFI) (John and Srivastava, 1999). Finally, only candidates who did not report any eye discomfort nor complained about their general health were retained. After this filtering process, eligible candidates were invited to an informative session.

During this meeting, subjects received explanations regarding the rules of the study and instructions on the use of individual devices. They were asked to read and keep an information sheet, together with a booklet containing this same rationale. Those still willing to participate in the corresponding study signed a written informed consent form for their involvement in the study, but were not informed about the specific objectives of the experiment. This highly selective recruitment process ensured that the population sample was not flawed in any obvious way, but had an unavoidable effect on sample size given the strict expectations in terms of presence and diligence (three full days in a row for each study, with no use of screens whatsoever and a somewhat intrusive individual monitoring). This point is further discussed in section 3.7.

The common protocol used in these studies (which concerns Chapters 4 to 6) was reviewed and approved by the board of the Cantonal Ethics Committee, Canton Vaud (CER-VD, ref. No. 2018-00507). All participants were paid for their time. The entire baseline questionnaire used in these studies can be found in appendix A, at the end of the thesis.

3.5 REPORTED MEASURES

As introduced in Chapter 2 (section 2.4), alertness cannot be well described using a unidimensional approach, i.e., based on just subjective indicators or in objective markers alone (cognitive or physiological), since they evaluate different mechanisms involved in alertness state. A diversity of assessment measures were therefore selected for our studies (even at the expense of building certain amount of redundancy), in order to provide not only information about the psychological perception of sleepiness, but also about the general state of cognitive readiness, reflected in cortical arousal (i.e., a state of high alertness is an attentive state, whereas a state of high physiological arousal may or may not be associated with a particular attentive state).

As a result, the following evaluations were included, as summarized in Figure 3.10:

- self-reports, in the form of validated sleepiness scales (KSS and SSS), allowed us to evaluate changes in subjective alertness by means of perceived levels of sleepiness (assuming an opposite definition of the two terms), and are further described in section 3.5.1

- performance tasks, in the form of reaction time tests, were used to evaluate declines in attentional state over time (and thus, in alertness), and included a 3-minutes visual exercise, as detailed in section 3.5.2

- physiological indicators, such as heart rate and heart rate variability, allowed us to assess variations in cardiovascular activity throughout the day, but more specifically, changes in the sympathetic and parasympathetic division of the autonomous nervous system, as explained in section 3.5.3.

Subjective indicators of alertness and well-being (namely vigour, affect and vitality), as well as objective markers of cognitive performance, were investigated on an hourly basis during the studies using self-reported questionnaires and performance tasks (cf. sections 3.5.1 and 3.5.2, respectively). Physiological arousal was investigated through cardiovascular activity (e.g., using heart rate and heart rate variability indicators), which was instead continuously monitored, allowing to measure variations in the autonomous nervous system and thus indirectly to infer changes in alertness by means of variations in sympathetic or parasympathetic activity, as discussed in 3.5.3. In addition to changes on alertness, performance and physiology, research has also shown an effect of light on vitality and emotional responses (Cajochen et al., 2005; Partonen and Lönnqvist, 2000; Vandewalle et al., 2010, 2007). Thus, such variables were also included in the experimental design so as to also control for changes in well-being related state.

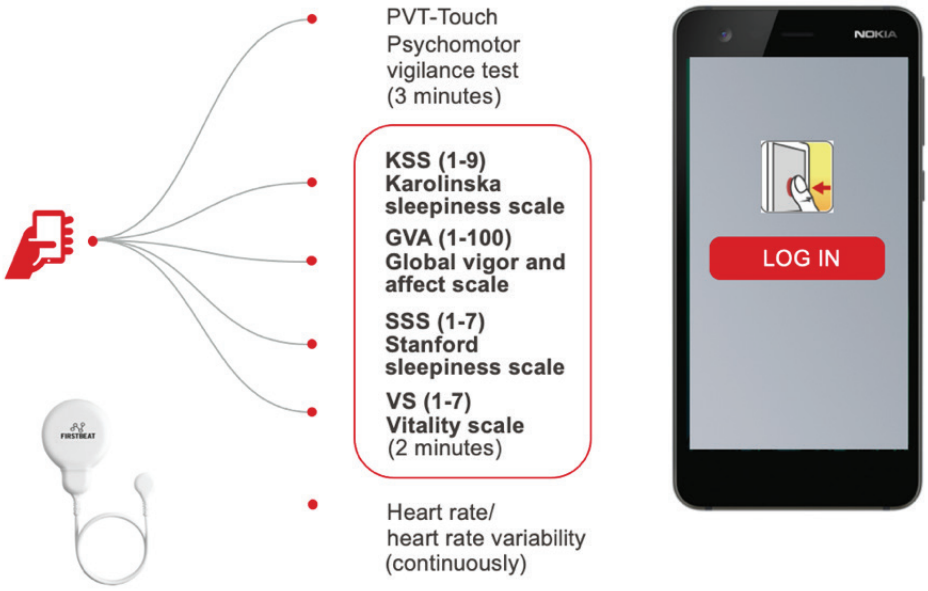


Figure 3.10 Diagram of participants' hourly measurements and tasks

Since alertness state follows a circadian rhythmicity that is adjusted or entrained over time, it is thus expected to vary throughout the day (section 2.1). For this reason, participants completed their measurements every hour (while cardiovascular activity was being continuously monitored), so that we could examine changes in their

psycho-physiological state as a function of time (both in terms of duration and timing of exposure) in response to the daylit environment. More specifically, differences between morning and afternoon sessions are explored (H3), as well as the effect of longer exposure durations (H2).

The full questionnaires used in these studies can be found in Appendix A.

3.5.1 Self-reported alertness and well-being

A non-clinical but broadly used method to assess alertness levels on individuals is to resort to self-rated questionnaires. These are often easy and quick to conduct, which is a desirable asset in both uncontrolled and semi-controlled experimental conditions involving numerous subjects. Subjective alertness was evaluated in this case using two scales, the Karolinska Sleepiness Scale (KSS) (Akerstedt and Gillberg, 1990) and the Stanford Sleepiness Scale (SSS) (Hoddes and Dement, n.d.). Both rely on Likert-type scales where participants have to define their perceived level of alertness in a 1-item predefined dichotomous anchored scale. For the KSS, ratings range from (1) 'extremely alert' to (9) 'extremely sleepy', whereas in the SSS, levels go from (1) 'feeling active, vital, alert or wide awake' to (7) 'no longer fighting sleep, sleep onset soon, having dream-like thoughts'. The reason for building such redundancy was, on the one hand, to check the consistency in the participants' own self-assessments, and on the other hand, to check the reliability of the questionnaires themselves in assessing sleepiness when compared to one another.

Two additional scales were actually used to complement sleepiness indicators with variables related to individual well-being such as subjective vigour and affect, as well as feeling of vitality. The Global Vigour and Affect Scale (GVA/GV-GA) (Monk, 1989), a visual analogue scale (VAS), ranges from (0) 'not at all' to (100) 'very much' and was the third scale used: four indicators address subjective vigour ('alert', 'sleepy', 'weary', 'effort') and another four address subjective affect ('happy', 'sad', 'calm', 'tense'). Subjective vitality was assessed using a fourth scale called Vitality Scale (VS) that relies on a six-item test (Ryan and Frederick, 1997). In this latter test, participants indicate, on a 7-point scale ranging from (1) not true to (7) very true, how they were feeling at that moment: either (a) 'alive and vital', (b) 'not very energetic', (c) 'so alive I just want to burst', (d) 'I have energy and spirit', (e) 'look forward to each new day', (f) 'alert and awake' or 'energized'.

3.5.2 Sustained attention

In the fields of psychology and cognitive neuroscience, alertness is oftentimes used as an indicator of vigilance, which is in turn associated with the ability of an individual to sustain attention to a task over prolonged periods of time (Oken et al., 2006). In general, a shorter reaction time (in milliseconds) represents a higher ability to sustain

attention and hence, a higher level of alertness. Based on the Psychomotor Vigilance Task (PVT) developed by Dinges and Powell (1985), an app-based version of the test (i.e., namely PVT-touch (Kay et al., 2013) was used to account for symptoms of attention depletion on participants (i.e. reduction of cognitive alertness) by recording their reaction times (RT) on a visual task.

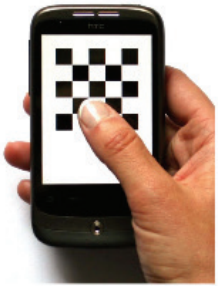


Figure 3.11 Appearance of the visual stimulus used by the PVT-touch app (image source: Kay et al. (2013)).

During the test, a visual stimulus in the form of a geometrical black shape is presented on a white screen, at random intervals of 1-10 seconds, and repeated during 3 consecutive minutes (cf. Figure 3.11). The goal for participants is to react as fast as possible by touching the screen right after seeing the image.

3.5.3 Physiological arousal

Another way of assessing alertness objectively is by means of changes in an individual's physiological state. Measurements of activity of the autonomic nervous system (ANS) have been used before as correlates of alertness. In particular, changes on heart rate (HR) and on heart rate variability (HRV) have been associated to different levels of sympathetic (SNS) and parasympathetic (PNS) activation, and hence, of physiological arousal (Soto Magán and Andersen, 2019).

By definition, HRV is the fluctuation in the time intervals between adjacent heartbeats (inter-beat-interval (IBI)) and presents several indicators of quantification that are mainly divided into time-domain and frequency-domain measures. The first ones quantify the amount of variability of the IBI, such as the heart rate (HR), the root mean square difference among successive IBI (rMSSD) or the standard deviation of normal IBI (SDNN). The second ones transform the beat-to-beat (RR) variations into several frequency power bands (namely ultra-low-frequency (ULF), very-low-frequency (VLF), low-frequency (LF) and high-frequency (HF)) (Berntson et al., 2016). While the SNS activity, related to arousal promotion and energy generation, can be estimated by LF power, the HF component, which is associated with rest activities, might be

used to represent PNS activity (Kaida et al., 2007; Shaffer and Ginsberg, 2017). In particular, the ratio of LF to HF power (LF/HF ratio of ANS activity, also known as HRV index of sympathovagal balance) is frequently used in sleep research to estimate the ratio between SNS and PNS activity under controlled conditions (Burr, 2007), so that a higher variability is associated with more pronounced sympathetic activation (SNS dominance over PNS), which ultimately translates into physiological arousal and potentially into higher alertness.

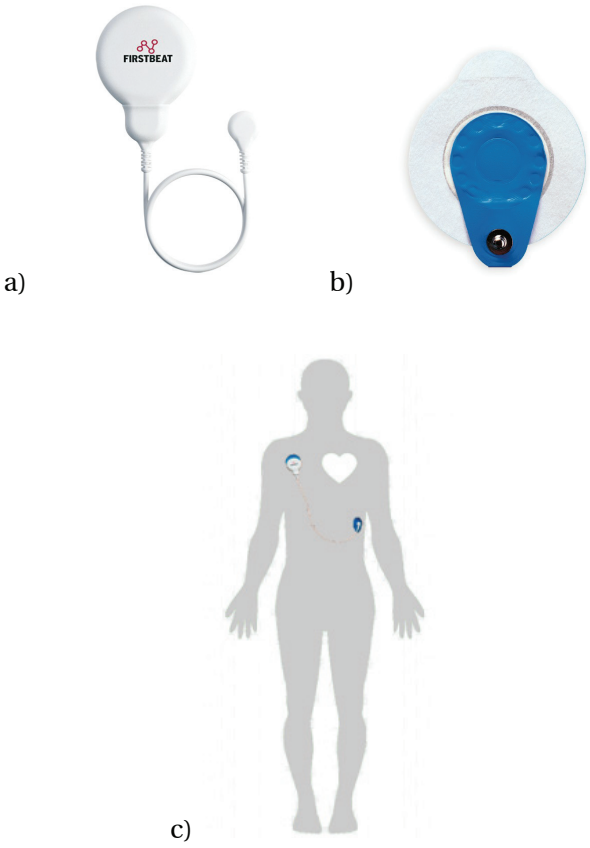


Figure 3.11 Electrocardiogram monitoring device Bodyguard 2 (BG2) (a), shown alongside associated high-adherence ECG electrodes (Ambu BlueSensor L) necessary to properly connect BG2 sensor to the body (b) (source https://international-shop.firstbeat.com/product/bodyguard-2), according to diagram shown on the right (c).

Four indicators of cardiovascular activity were used in this investigation to estimate physiological arousal in response to the daylit environment: heart rate (HR) in beats per minute (bpm), low frequency (LF) power (band 0.04-0.15 Hz) and high frequency (HF) power (band 0.15-0.4 Hz) both in ms^2, and finally, the ratio of LF to HF power (LF/HF). These physiological indicators were monitored with individual, non-intrusive electrocardiogram (ECG) devices available commercially, namely the

Bodyguard-2 and manufactured by Firstbeat Technologies Oy, depicted in Figure 3.11a. These devices are lightweight and easy to use and start recording data automatically just by attaching the device directly to the skin using two disposable electrodes (Figure 3.11b), one in the region of the right collar bone, and the other over the lower left ribcage (Figure 3.11c). Participants were asked to wear them every day, from wake up to bedtime, including two days before the actual start of the study to ensure enough baseline data monitoring.

3.6 STATISTICAL ANALYSIS METHODS

As explained at the beginning of this chapter (section 3.1), a mixed factorial design was used to account for both between- and within-subjects independent variables. Due to the nested structure of the data in all three studies, linear mixed model analyses were used to evaluate the combined effects of spectral variations, timing and duration of daylight exposure on subjective feelings of alertness (KSS, SSS) and well-being (GV, GA, VS), on sustained attention (PVT) and on physiological arousal (HR, LF, HF, LF/HF). This type of statistical test was chosen as a solution to overcome the limitations of a standard between-subjects analysis due to participants' repeated measurements (i.e., for the non-independence of their responses across days or hours of exposure, assuming a certain hierarchy in the data structure).

Two types of factors are included in the linear mixed models: fixed factors, which are variables that are of main interest for the experiment (i.e., namely daylight condition, duration and timing of exposure in our case), and random factors, which, as their own name indicate, represent a random source of variance in the model (i.e., participants that have been chosen as a representation of a bigger population or group). As we are not only interested in the main effect of daylight conditions, but rather on the potential moderation effects by duration or timing of exposure, we will look at two interaction terms: duration of exposure*daylight condition and timing of exposure*daylight condition.
In particular:

- daylight condition consisted of two levels (light 1 and light 2, one of them used as a reference), and referred to the investigated light property (i.e., (dim) blue vs (dim) neutral for study A, blue filter vs EC-1 for study B, and brighter (neutral) vs dim (neutral) for study C).

- duration of exposure consisted of two or three levels depending on the experiment (day 1, day 2 and/or day 3, with day 1 used as a reference);

- timing of exposure was also defined by two levels (morning (a.m.) and afternoon (p.m.), with morning used as a reference);

Since the goal is to look at overall differences in correlates of alertness and at larger between-room comparisons where daylight dynamics are experienced simultaneously, lighting conditions are assumed as a "static" quantity and hence, their variability within and throughout the experiment is not evaluated. In other words, temporally-resolved measurements are not included in these analyses.

The participants' ID (identifier), the duration of exposure and the different experimental sessions were all included as random factors in the model, or more specifically, as nested intercepts. The reason for this decision arises, on the one hand, from the assumption of individual differences or personal variations exist among participants (Chellappa, 2021), and on the other hand, from responses following a specific hierarchy in the data structure (i.e., hourly responses are enclosed within sessions, sessions are enclosed within days, daily responses are enclosed within participants, and participants are enclosed within lighting condition). In other words, because all dependent variables are being measured multiple times for the same subject through a given experiment.

Baseline values of physiological indicators (HR, LF, HF, LF/HF) are also included as covariates in the models when analysing dependent variables of cardiovascular activity, and they are derived from physiological data that was collected two days before the start of either of the three studies (as explained in section 3.5.3). Since participants physical activity was not controlled during this outpatient period, resting values were calculated as the 10^{th} percentile of the data, and assumed as the baseline indicator for each of the aforementioned variables. The purpose is to control for individual characteristics of the participants.

In terms of data analysis, when an interaction fails to reveal a significant effect (i.e., if the effect of daylighting condition is moderated neither by duration nor by timing of exposure), the term is excluded from the model. On the contrary, if the interaction is found significant, additional *post-hoc* tests are performed and contrast analyses are investigated in both directions of the interaction (i.e., for all levels of both factors involved). For main effects pertaining to daylighting condition, duration or timing of exposure (i.e., when they are not involved in an interaction), pairwise comparisons for all levels of that factor are conducted. The package *emmeans* (Searle et al., 1980) and the Tukey HSD adjustment for multiplicity correction are used in these analyses, and the significance level is set at 0.05 (95% confidence interval). To further investigate the practical significance of our results, marginal and conditional R^2 values are reported for each LMM. While the former indicates the proportion of the total variance in the model that is explained solely by fixed effects, the latter corresponds to the proportion that is instead explained by the full model, that is, both fixed and random effects. This calculation was conducted using the *r.squaredGLMM* function (Nakagawa et al., 2017) of the package *MuMIn* (Bartoń, 2019). All statistics were performed using *R* (R Core Team, 2018) with the RStudio integrated environment. Linear mixed models were determined using the *lmer* function in the *lme4* package for R (Bates et al., 2015) and p-values were obtained with the *lmerTest* package (Kuznetsova et al., 2017).

As the choice of a statistical method is a very important decision to make and may in some cases affect the significance – or even the nature – of the findings, it was decided to complement these analyses with a different method, based on non-parametric tests. This statistical approach allows inference of non-normally distributed data while relying on fewer assumptions regarding model structure (i.e., not specified a priori but is instead determined from the data itself). Using such a method in our experimental design can thus also be considered as a valid approach given that, with a careful selection of statistical tests, one can reliably evaluate both dependent and independent data samples, and hence, to account for between- and within-subjects variables. As in LMM, lighting condition (between-subjects), duration and timing of exposure (within-subjects) were the independent variables used in this second analysis, while KSS, SSS, GV, GA, VS and PVT were our investigated dependent variables.

In this case, statistical analyses were performed using MATLAB R2019a (The MathWorks, Inc., Natick, MA, USA) and SPSS (IBM Corp. Released 2019. IBM SPSS Statistics for Windows, Version 26.0. Armonk, NY, USA) software. As an initial approach to the datasets, Shapiro-Wilk tests and Q-Q plots, and non-parametric Kolmogorov-Smirnov tests and histograms were performed to investigate the distribution of the data. Then, separate analyses were performed for all dependent variables as follows:

- First, Mann-Whitney U tests were conducted to assess the statistical significance of the difference between lighting conditions for each dependent variable (i.e., the main effect of daylight). The Mann–Whitney tests the null hypothesis of whether it is equally likely that a randomly selected value from one population will be less than or greater than a randomly selected value from a second population. Results are declared significant when the probability that a difference between these two values could have appeared by chance is below 5% ($p \leq 0.05$).

- Second, effects of time and duration of exposure were tested separately per daylight scenario and study using a Skillings-Mack test. The Skillings-Mack test is a general Friedman-type statistical that can be used in almost any block design with an arbitrary missing-data structure. The Friedman test is a non-parametric statistical test, similar to the parametric repeated measures ANOVA, used to detect differences in experimental conditions across multiple test attempts (i.e., in this case, across days or hours). Later, *post-hoc* analyses are performed using the Wilcoxon signed-rank test, with a Bonferroni-corrected significance ((α') of 0.05/3 = 0.01667 to account for the number of days and of 0.05/8 = 0.00625 to account for the number of hours, respectively), to check the difference between pairs of days or hours within the same lighting scenario. The Wilcoxon signed-rank test is a non-parametric statistical hypothesis used to compare two related samples and to assess whether their population mean ranks differ or not. In addition, to assess the significance of the difference between rooms or lighting conditions on a daily and hourly basis, Mann-

Whitney tests were performed using the same Bonferroni correction to account for the number of days and hours as described above.

Overall, the main difference between these two approaches relies on the assumptions regarding model structure and of interactions between factors. Unlike in LMMs, where a hierarchical model structure is assumed as well as interactions between dependent variables, with non-parametric tests instead, separate evaluations are conducted for each level of the three dependent variables without assuming any hierarchy in the data or interactions between factors.

Although we will rely on the linear mixed model's findings by default, for selected analyses we were also interested in the consistency and robustness of findings when confronted to an alternative approach. This confrontation was conducted in particular for subjective measurements and reaction time tests, in both studies A and C. An overview of the main outcomes will be provided in sections 4.5, 5.5 and 6.5, while further detailed results are available in Appendix B.

3.7 LIMITATIONS OF THE STUDIES

Many questions remain open regarding the role of light in triggering alerting responses from humans, and how factors such as duration of exposure or time of day may influence them. In this thesis, we chose to investigate the combined effects of daylighting condition, duration and timing of exposure on indicators of subjective alertness and well-being, attention and physiology, with a dedicated focus on the effects of daylight spectrum and intensity variations. However, various limitations about the experiments themselves should be acknowledged.

Due to the specifics of the room, the use of daylight (with its dynamic nature) and spectral filtering glazing technology, illuminance levels throughout the studies were in general quite low compared to recommended targets for similar workspaces (300-500 lx measured at the work plane). However, previous studies have reported that illuminance levels to which people in urban environments are commonly exposed to for most of the day – mainly due to the emergence of a 24-hour society that spends much more time indoors than outdoors – can be as low as a 100 lux (Lucas et al., 2014). Furthermore, university students in particular (which the population target in our studies) have been shown to experience lighting conditions as low as 50 lux (on average) during a regular day (Münch et al., 2016b). These circumstances are therefore not so distant from our experimental conditions, but there is no doubt that brighter daylight would be recommended for an adequate visual comfort and performance in workspaces.

On the other hand, despite the dynamics of daylighting conditions inherent to sun course and weather variability, the mixed-design with a between-subjects exposure allowed both groups to simultaneously experience these changes throughout the

study while being immersed in their own scenario. The use of real classrooms for these studies, which implied a fixed and quite deep-plan layout, led to the need to optimize the rather small daylit area of the room and thus to a dense seat allocation. Although the distance from each participant to the window (i.e. to the light source) within the classroom was not exactly the same – resulting in an unavoidable fluctuation in spatial light distribution – the arrangement of subjects was replicated in both rooms, minimizing differences in the experienced light exposure between groups.

Regarding sample size, the highly selective recruitment process combined with the cost and limited availability of the equipment (and in fact of the classroom equipped with electrochromic windows) had an unavoidable effect on sample size. Participants had to fulfil many eligibility criteria and be ready to follow strict expectations in terms of presence (three full days in a row covering the weekend for eight hours per day) and diligence (no use of screens whatsoever), while coping with a somewhat intrusive individual monitoring. Although we were still able to recruit a number of participants comparable to other studies with similar objectives and number of variables (Chellappa et al., 2013; Chellappa et al., 2011; Revell et al., 2006), having a larger sample size (e.g. twice as many participants, as discussed below) would clearly be beneficial to the statistical power of the study.

To estimate what would have been a more optimal sample size, an *a priori* power analysis was calculated using GPower 3.0 (Faul et al., 2009), considering a between-subjects exposure (two independent groups). To detect a medium effect size (Cohen's d=0.5), a sample size of 88 subjects per group – and a total of 176 participants – was suggested. So, if cost, availability of equipment and/or resources limitations can be overcome in future studies (which was not the case in our investigations), the recruitment process could lead to larger sample sizes. Fortunately, as mentioned above, all three studies discussed in this thesis still had participant numbers consistent with sample sizes typically found in similar studies (Souman et al., 2018).

Finally, the lack of non-intrusive, accurate and affordable eye-level, wearable sensors still remains one of the major constraints for the adequate characterisation of individual light exposures, as well as for spatially resolved spectral measurements. The first of the studies presented in this thesis (study A) originated as a joint project with a fellow PhD student, and pursued two separate -but related- objectives: (1) the development of a wearable light sensor for spectral data monitoring, and (2) the assessment of alerting responses due to daylight manipulations (which is the focus of this thesis). As a result, study A included the use of three wearable light sensors, which were intended to continuously record participants' daily light experience (i.e., including hours outside experimental sessions, from 4 p.m. until 9 a.m.). However, due to the inaccuracy of the readings and malfunctioning of the devices, the limited available data was only used by our colleague for feasibility purposes and hence, will not be included or discussed in this manuscript. In addition, to understand at least in a qualitative way what happened outside experimental sessions (i.e., from 4 p.m. until 9 a.m.) in terms of light history, participants were asked to keep track of time spent outdoors or engaged in social activities on a self-reported activity diary. As their

reports varied quite significantly in rigor and level of detail, they were not included in the analyses and only remain a qualitative proxy for prior light history and activity. Being able to rely on actual light exposure data collected over entire days and with sufficient level of detail (e.g., spectrum, to differentiate indoors from outdoors for instance, or daylight from electric light, as well as activity) would at least partially solve this issue.

Under normal circumstances, healthy and active people often report high levels of alertness state during the day (Akerstedt et al., 2017). Therefore, investigating daytime changes in alertness due to variations of light exposure, represents a huge challenge. Despite these aforementioned constraints, the proposed methodology will allow us to investigate, for the first time, effects of diverse manipulations in daylights' irradiance on various psycho-physiological correlates of alertness over time.

4 EFFECTS OF [DAYLIGHT SPECTRUM] STUDY A

This chapter describes the conditions and results of the first experiment of this thesis, conducted to investigate whether variations in daylight's spectrum can induce measurable effects on participants' alertness, sustained attention and arousal levels. Our initial hypotheses were that:

- exposure to bluer daylight, when compared to a neutral environment with similar photopic illuminance levels, might reduce subjective sleepiness, increase subjective well-being, improve attention and favour arousal (H1 but without brightness aspects).

- light-induced changes on alertness, attention and arousal might be moderated not only by (day)light conditions but also by both duration and timing of exposure due to the undelying circadian rhythmicity: longer exposure durations are expected to have stronger effects (H2), and morning versus afternoon exposure is expected to impact responses differently (H3).

4.1 ENVIRONMENTAL CONDITIONS

The experiment was conducted in the late Spring of 2018, on May 19th, 20th and 21st from 9:00 a.m. to 4:00 p.m.

The outdoor environmental conditions (i.e., daylight availability and cloud cover), which were by design experienced simultaneously in both rooms, while not fully monitored during the experiment, were still evaluated based on weather data collected from the closest weather station. This data could be obtained for the specific days of the experiment from station ID: 06711099999, located in Pully (Vaud, Switzerland), while weather files were obtained from the Swiss Meteorological office through the World Meteorological Organization (WMO) database (World Meteorological Organization, 2018). They were downloaded using the American National Climatic Data Center (NCDC) online interface (NCEI DAGDT Agile, 2021) and data was then processed using the Dragonfly Toolkit from Ladybug Tools, in Grasshopper for Rhino (Roudsari and Pak, 2013).

Table 4.1 Environmental conditions in the classrooms. Average values and associated standard deviation of temperature and humidity levels per lighting condition, for the entire duration of the experiment.

	Dim neutral (CM4)	Dim blue (CM5)
Temperature (°C)	22.3 ± 0.5	22.2 ± 0.9
Humidity (%)	47.6 ± 3.5	47.9 ± 3.7

The resulting sky condition visualization is plotted in Figure 4.1 and corresponds – based on human observation during the experimental days – to partly cloudy skies with sun; the conditions remained stable for the entire duration of the experiment. Environmental conditions inside the rooms, including temperature and humidity levels, were monitored more carefully (though not directly controlled by the researcher) using new HOBO dataloggers that recorded these parameters continuously throughout the experiment. The collected data is provided in Table 4.1.

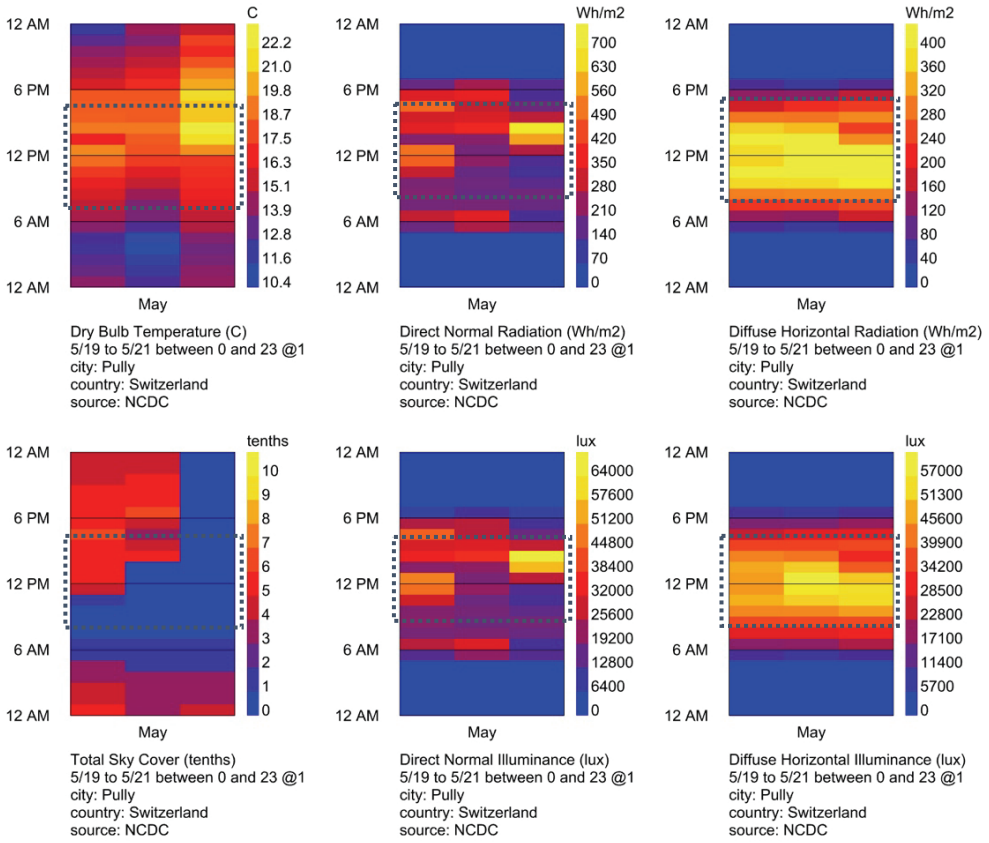


Figure 4.1 Overview of weather conditions throughout the experiment. From left to right, from first to second row: dry bulb temperature (°C), direct normal radiation (Wh/m²), diffuse horizontal radiation (Wh/m²), total sky cover (tenths), direct normal illuminance (lux) and diffuse horizontal illuminance (lux).

4.2 LIGHT STIMULI

The lighting scenarios of this experiment (bluer vs. neutral daylight, illustrated in Figure 4.2) were obtained using two filtering approaches. In one room (CM5), a specific level of tint was applied to the electrochromic glazing (EC Intermediate 2), which resulted in a red-impoverished spectrum that looks “blue”. The visual transmittance (Tvis) of the glazing at this particular level of tint was 6%, and resulted in a correlated colour temperature of 10651 K. In the other room (CM4), no spectral shift was imposed on daylight, but neutral filters were added on the glazing (Neutral filter + EC clear), which resulted in a CCT of 5355 K and a Tvis 7%, that allowed us to maintain the same (low) visual photopic illuminance at the work plane in both spaces.

(dim) blue (CM5) (dim) neutral (CM4)

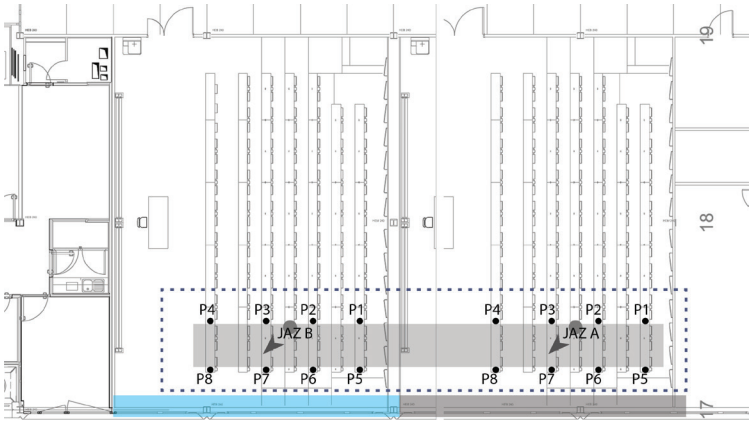


Figure 4.2 View of daylight manipulations in the classrooms; left, classroom CM5, (dim) blue conditions (EC Intermediate 2, 6% Tvis) and right, classroom CM4, (dim) neutral conditions (Neutral filter + EC clear, 7% Tvis).

4.2.1 Daylight exposure

Throughout the experiment, spectral power distribution (SPD) was measured at the eye level and view direction of a seated participant (indicated in Figure 4.2 as big black dots), and horizontal illuminance was measured at the working plane (desk level), indicated in Figure 4.2 as small black dots (p1-p8).

The resulting distribution of absolute irradiances (µW/cm²/nm), based on the SPD recorded measurements mentioned above, are shown in Figure 4.3 as average mean, maximum and minimum values for the entire duration of the experiment, for both daylighting conditions (blue and neutral). Although some variability is unavoidable in daylit conditions, one can see from this graph that spectrally, the two conditions were clearly distinct. In addition, we can observe that while the SPD of the blue condition actually peaks around 480 nm, the other one (neutral) peaks towards the red part of the spectrum.

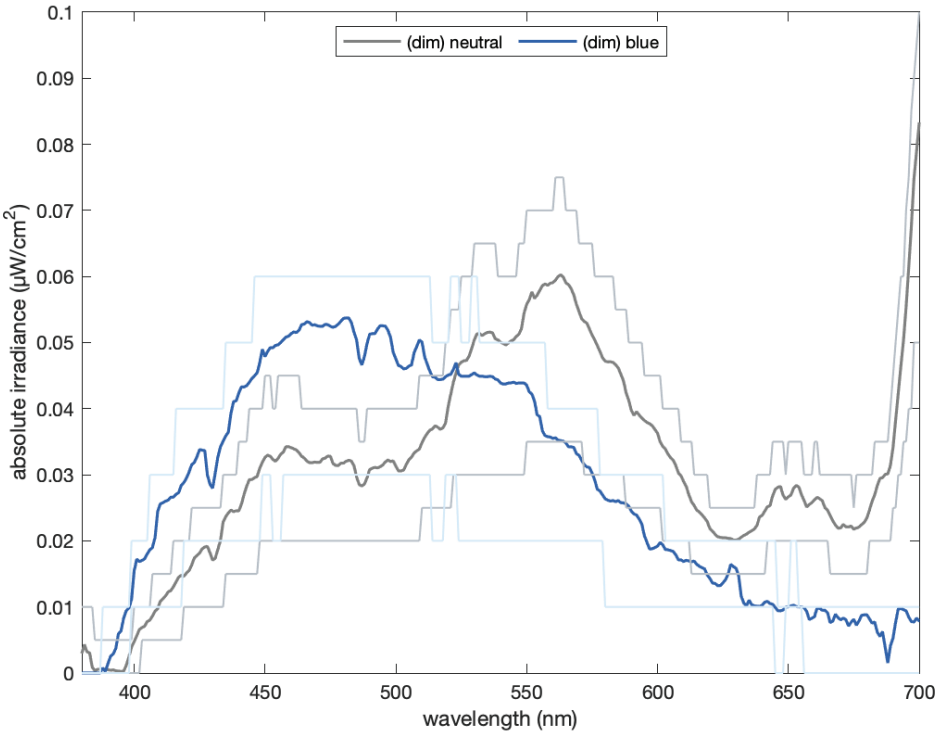


Figure 4.3 Average mean, maximum and minimum irradiance values per wavelength, measured at the eye level for both daylight conditions

In addition, average α-opic quantities of efficacy luminous radiation [W/lm] and equivalent daylight (D65) illuminance [lux](CIE, 2018) (Table 4.2) were derived for each of the five human photoreceptors from the spectrally-weighted irradiance values measured at eye level by the spectroradiometer (cf. Figure 4.2) using the CIE S026 calculation toolbox (based on Lucas et al. (2014)). Unsurprisingly, both melanopic efficacy luminous radiation and melanopic equivalent daylight (D65) illuminance values were higher in the blue room, as shown in Table 4.2.

Table 4.2 Average spectrally weighted α-opic efficacy luminous radiation in W/lm (ELR) and equivalent daylight (D65) illuminance in lux (EDI) measured at the eye level, for each daylighting condition.

		(Dim) neutral (CM4)		(Dim) blue (CM5)	
Illuminance	**Sensitivity**	*ELR (W/lm)*	*EDI (lux)*	*ELR (W/lm)*	*EDI (lux)*
photopic	Visibility		31.88		25.04
cyanopic	S-cone	0.47	18.30	0.96	29.37
melanopic	**ipRGC**	**0.95**	**22.92**	**1.65**	**31.23**
rhodopic	Rod	1.15	25.28	1.78	30.72
chloropic	M-cone	1.40	30.62	1.63	28.09
Erythropic	L-cone	1.58	30.87	1.59	24.44

Patterns of horizontal photopic illuminance are described in Figure 4.4 and presented as average hourly values per day of experiment, photometer and daylight condition. Again, keeping in mind that a perfect control is unrealistic in sky-dependent conditions, the data shows that horizontal illuminance remained reasonably close between the two rooms throughout the experiment. A more quantitative view on this is provided through daily average values and associated standard deviations, which are summarized in Table 4.3 for each day of experiment and daylight scenario.

Table 4.3 Average daily values (± standard deviation) of horizontal photopic illuminance at the desk, per daylighting condition.

	Daylight illuminance (lx)		
Lighting condition	*Day 1*	*Day 2*	*Day 3*
(Dim) neutral	30 ± 34	24 ± 25	24 ± 29
(Dim) blue	30 ± 28	20 ± 18	20 ± 24

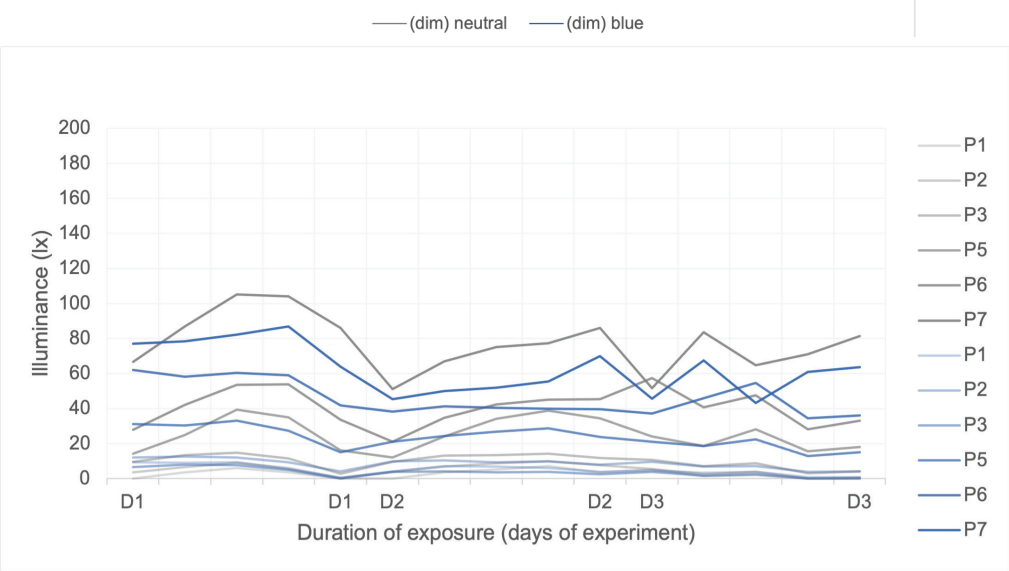


Figure 4.4 Average hourly values of horizontal photopic illuminance at the work plane, over time (days of exposure) and per photometer.

4.2.2 Timing and duration of exposure

The experiment was conducted over a long weekend (Saturday, Sunday and Pentecost Monday) due to room availability. Each experimental day was split into two identical sessions: one in the morning, from 9:00 am to 12:00 pm, and one in the afternoon, from 1:00 pm to 4:00 pm. This led to a total of six sessions, but presence in the room was uninterrupted during the entire day (i.e., no changes of light scenario between sessions).

4.3 PARTICIPANTS

In total, 35 subjects joined the experiment, of which 14 were female participants and 21 were males. They were divided between lighting conditions, so that 17 were assigned to the room with neutral daylight (CM4, Figure 4.2 left) and the other 18 to the room with blue daylight (CM5, cf. Figure 4.2 right). Each participant was assigned a given desk location within the room for the whole duration of the experiment (see section 3.2). Gender was counterbalanced, with 7 female and 11 male participants in the first condition, and 7 female and 10 male participants in the blue one. The age of participants was on average 21.7 (± 3.4) years old.

4.4 DATA ANALYSIS

As introduced in Chapter 3, a 2 x 3 x 2 mixed factorial design was used to test the effects of spectral variations, timing and duration of daylight exposure on subjective feelings of alertness (KSS, SSS) and well-being (GV, GA, VS), on sustained attention (PVT) and on physiological arousal (HR, LF, HF, LF/HF). As mentioned in section 3.5, daylight condition consisted of two levels (blue and neutral, with blue as the reference in this case), duration of exposure consisted of three levels (days 1 to 3), while timing of exposure was defined by two levels, morning (a.m.) vs. afternoon (p.m.). Linear mixed effects models were thus separately performed on each dependent variable, and daylight condition, duration and timing of exposure were used as fixed factors while participants' identifier, duration of exposure and sessions were included as random nested intercepts in the model.

4.5 RESULTS

First, we examined whether at the beginning of each day of experiment (i.e., at 9:00 am) there were no variations in alertness state (i.e., whether scores on the different dependent variables were not statistically different between groups). Subsequently, the effects of daylighting condition, duration and timing of exposure, as well as of their interactions on correlates of alertness were assessed.

Table 4.4 Results of marginal and conditional R^2 values per LMM and dependent variable

Dependent variable	$R^2_{marginal}$	$R^2_{conditional}$
KSS	0.09	0.28
SSS	0.05	0.21
GV	0.07	0.38
GA	0.02	0.70
VS	0.01	0.47
PVT	0.07	0.24
HR	0.01	0.18
LF	0.11	0.26
HF	0.09	0.43
LF/HF	0.05	0.23

In order to assess the practical significance of the results that are presented in the next sections, marginal and conditional R^2 values were calculated for the LMM of each dependent variable. As it can be observed in Table 4.4, the variance explained by the models considerably increased when random effects were included in the analyses (i.e., conditional R^2). Moreover, we found that daylighting condition, duration and

timing of exposure, explained up to 70% of the variance in participants responses (i.e., in the case of global affect) when controlling for repeated measurements. According to Ferguson (Ferguson, 2009), these conditional R^2 values can be considered as moderate in the case of KSS, GV, VS,LF and HF, strong in the case of GA, and small for SSS, PVT, HR and LF/HF. Yet, none of them classified as negligible.

In addition, and to test the sensitivity of these outcomes to the selected statistical method, further non-parametric analyses were conducted (as described in section 3.6). Results of linear mixed model analyses and *post-hoc* tests are discussed in the following subsections, while an overview of the main findings from the non-parametric evaluation will be provided in the next section (4.6). Detailed tables of results for the latter can be found in Appendix B.

4.5.1. Baseline analyses

Preliminary LMM analyses were performed for all dependent variables on data corresponding to the first measurement block (i.e., 9:00 am values) per day of experiment. In this case, daylight condition and duration of exposure (i.e., days), as well as their interaction, were included in the model as fixed factors. Overall, results revealed that there were no significant differences lighting conditions in either of the variables investigated (all p>.05), as described in Table 4.5. No interactions were found either, indicating that results did not change throughout the experiment (i.e., over the days).

Table 4.5 Results of linear mixed model analyses for baseline values (i.e., 9:00 am)

	Day 1		Day 2		Day 3	
	estimate	p-value	estimate	p-value	estimate	p-value
KSS	0.27	0.65	-0.12	0.83	-0.29	0.61
SSS	0.48	0.29	0.29	0.52	-0.22	0.63
GV	-4.27	0.51	1.75	0.78	5.91	0.35
GA	11.36	0.11	6.14	0.33	-3.85	0.54
VS	-0.19	0.64	-0.27	0.48	-0.10	0.81
PVT	-16.22	0.52	-32.31	0.38	-5.95	0.83
HR	-4.15	0.32	-0.13	0.97	-1.94	0.64
LF	-219.8	0.74	-25.4	0.97	687.5	0.12
HF	-111.1	0.69	88.4	0.75	470.6	0.10
LF/HF	-0.64	0.27	-0.05	0.93	0.21	0.72

4.5.2. Subjective alertness and well-being

As discussed in section 3.5.1, subjective alertness was evaluated with two similar scales, the KSS and the SSS, while feelings of well-being were assessed by means of vigour (GV), affect (GA) and vitality (VS). LMM analyses were performed to investigate the combined effects of daylighting condition, duration and timing of exposure on these responses, and all three dependent variables were used as fixed factors in the model. The interactions between light and duration, and between light and timing were used to assess whether day of experiment or session were responsible for moderating the effect of daylight in any of the dependent variables.

The effect of lighting condition on alertness (measured with the KSS) was moderated by duration of exposure, indicating that there was a significant interaction between daylight and day of the experiment ($F(2,825) = 3.13$, $p<0.05$). Analyses conducted at each daylight level showed that differences across days were significant under the blue condition ($X^2(2) = 25.04$, $p<.001$) but not under the neutral one. *Post-hoc* tests (simple contrasts for duration of exposure) revealed that, under blue conditions, participants felt more alert during day 2 ($p<.01$) and during day 3 ($p<.001$) compared to day 1 (but not during day 3 compared to day 2). Under neutral conditions, participants felt equally alert from the beginning until the end of the experiment. In addition, simple contrasts for daylight showed that, from day 2 onward, sleepiness was higher in the neutral condition compared to the blue one (Figure 4.5). There was no interaction between daylight and timing of exposure, though the latter had a significant effect on KSS responses ($F(1,829) = 12.54$, $p<0.001$): independently of the daylighting condition, sleepiness decreased throughout the day. *Post-hoc* tests revealed that participants felt more alert in the afternoon than in the morning (β_{PM}=-0.39, $p_{adj}<.001$) (Figure 4.5).

Responses of subjective alertness on the SSS were significantly influenced by light condition ($F(1,830) = 7.62$, $p<0.01$). No moderation effects by duration or timing were detected. The main effects of duration and timing of exposure on alertness scores were nearly significant ($F(2,826) = 2.93$ and $F(1,830) = 2.98$, respectively, with both $p<0.1$), revealing that sleepiness scores decreased during the experiment and over the day, independently of daylighting condition. *Post-hoc* tests showed that SSS scores in day 3 slightly decreased compared to day 1 (β_{D3}=-0.35, p_{adj}=0.05) (but not during day 2 compared to day 1, or during day 3 compared to day 2) (Figure 4.6), and that participants felt slightly more alert after lunch (β_{PM}=-0.17, $p_{adj}<.10$) (Figure 4.6).

Vigour (GV) was affected by daylight colour ($F(1,830) = 5.01$, $p<0.05$), with no interactions with duration or timing of exposure. The main effect of duration of exposure on vigour was also significant ($F(2,826) = 7.09$, $p<0.01$), indicating increasing feelings of vigour during the experiment independently of lighting scenario. *Post-hoc* tests revealed that GV scores were higher during day 2 compared to day 1 (β_{D2}=5.33,

p_{adj}<.05), and also during day 3 compared to day 1 (β_{D3}=7.83, p_{adj}<.01) (but not during day 3 compared to day 2) (Figure 4.7). A marginal effect of timing of exposure on vigour was also found (F(1,830) = 2.85, p=0.09), and participants reported themselves as feeling more vigorous during the afternoon sessions than during the morning ones (β_{PM}=1.93, p_{adj}=0.09) (Figure 4.7).

The effect of lighting condition on affect (GA) was moderated by timing of exposure, meaning that there was a significant interaction between daylight and session (F(1,830) = 5.04, p<0.05). Analyses conducted at each daylight level showed that differences across experimental sessions were significant under the neutral condition (X^2(1) = 7.64, p<.05) but not under the blue one. *Post-hoc* tests (simple contrasts for timing of exposure) revealed that, under neutral conditions, participants felt more affective during the afternoon than during the morning (p<.001). Under blue conditions, participants felt equally affective during both sessions. In addition, simple contrasts for daylight showed no difference between neutral and blue conditions in either session (Figure 4.8). There was no interaction between daylight and duration of exposure, but the main effect of duration of exposure on GA was nearly significant (F(2,826) = 5.75, p<0.1), revealing that affect scores changed during the experiment independently of daylighting condition. *Post-hoc* tests showed that GA scores in day 3 increased compared to day 1 (β_{D3}=3.43, p_{adj}<.05), and also during day 2 compared to day 1 (β_{D2}=4.40, p_{adj}<.01) (but not during day 3 compared to day 2) (Figure 4.8).

The main effect of duration of exposure was a significant factor for vitality (VS) (F(2,825) = 4.23, p<0.05), indicating an increase in vitality during the experiment but independently of daylighting condition. *Post-hoc* tests revealed that participants felt more vital during day 3 compared to day 1 (β_{D3}=0.33, p_{adj}<.05) (but not during day 2 compared to day 1 or during day 3 compared to day 2) (Figure 4.9). Neither daylight nor timing of exposure affected vitality responses (Figure 4.9), and no interactions effects were detected either.

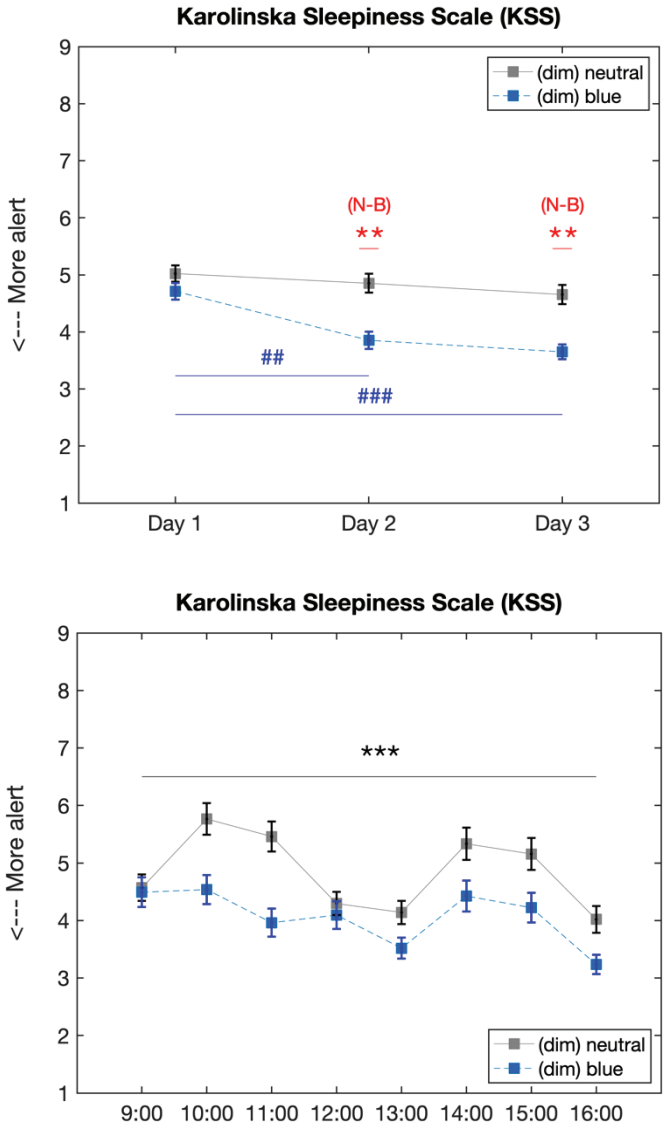


Figure 4.5 Mean values and associated standard errors of the effect of duration (up) and of timing of exposure (bottom) on subjective alertness (KSS). Significant main effects of duration (left) or timing (right) of exposure are represented with "+" ($p<0.10$), "*" ($p<0.05$), "**" ($p<0.01$), "***" ($p<0.001$). Interaction effects are represented with "#" ($p<0.05$), "##" ($p<0.01$), "###" ($p<0.001$) (simple contrasts for duration and/or timing of exposure) and with red asterisks ("*" ($p<0.05$), "**" ($p<0.01$), "***" ($p<0.001$)) for simple contrast of daylight.

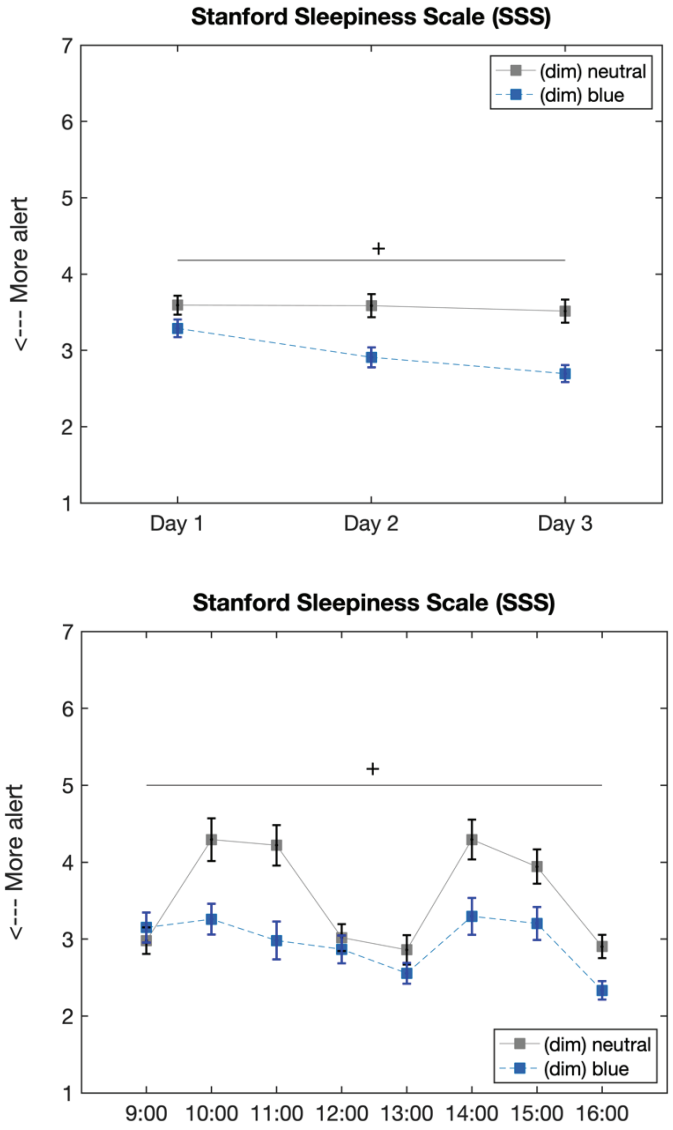


Figure 4.6 Mean values and associated standard errors of the effect of duration (up) and of timing of exposure (bottom) on subjective alertness (SSS). Significant main effects of duration (left) or timing (right) of exposure are represented with "+" ($p<0.10$), "*" ($p<0.05$), "**" ($p<0.01$), "***" ($p<0.001$). Interaction effects are represented with "#" ($p<0.05$), "##" ($p<0.01$), "###" ($p<0.001$) (simple contrasts for duration and/or timing of exposure) and with red asterisks ("*" ($p<0.05$), "**" ($p<0.01$), "***" ($p<0.001$)) for simple contrast of daylight.

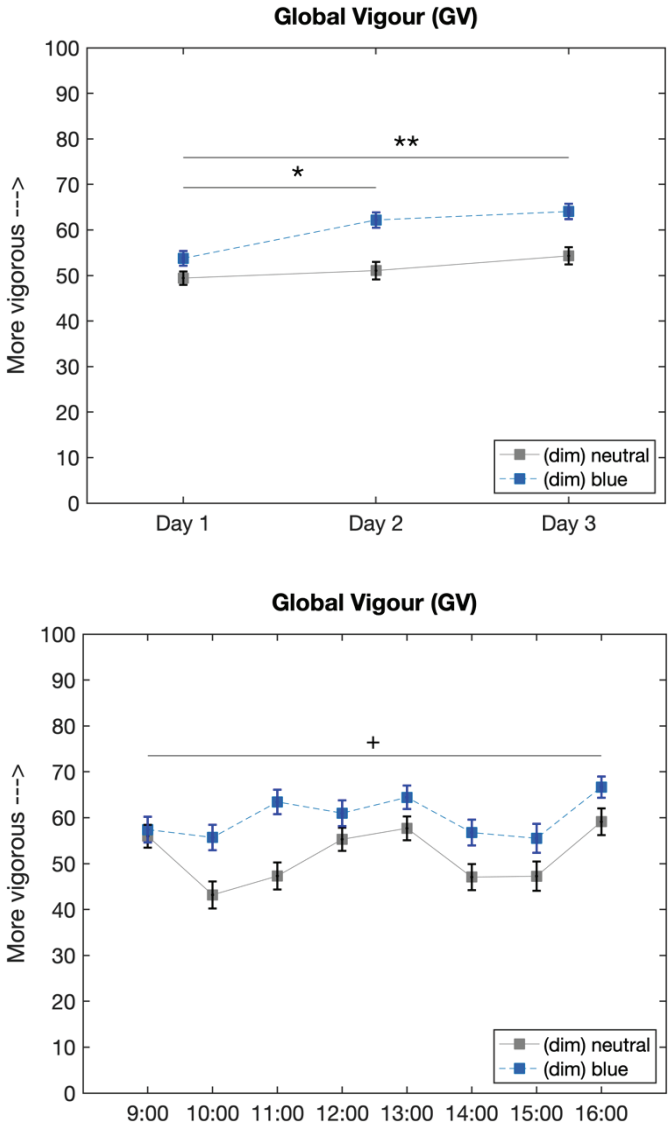


Figure 4.7 Mean values and associated standard errors of the effect of duration (up) and of timing of exposure (bottom) on subjective well-being (GV). Significant main effects of duration (left) or timing (right) of exposure are represented with "+" ($p<0.10$), "*" ($p<0.05$), "**" ($p<0.01$), "***" ($p<0.001$). Interaction effects are represented with "#" ($p<0.05$), "##" ($p<0.01$), "###" ($p<0.001$) (simple contrasts for duration and/or timing of exposure) and with red asterisks ("*" ($p<0.05$), "**" ($p<0.01$), "***" ($p<0.001$)) for simple contrast of daylight.

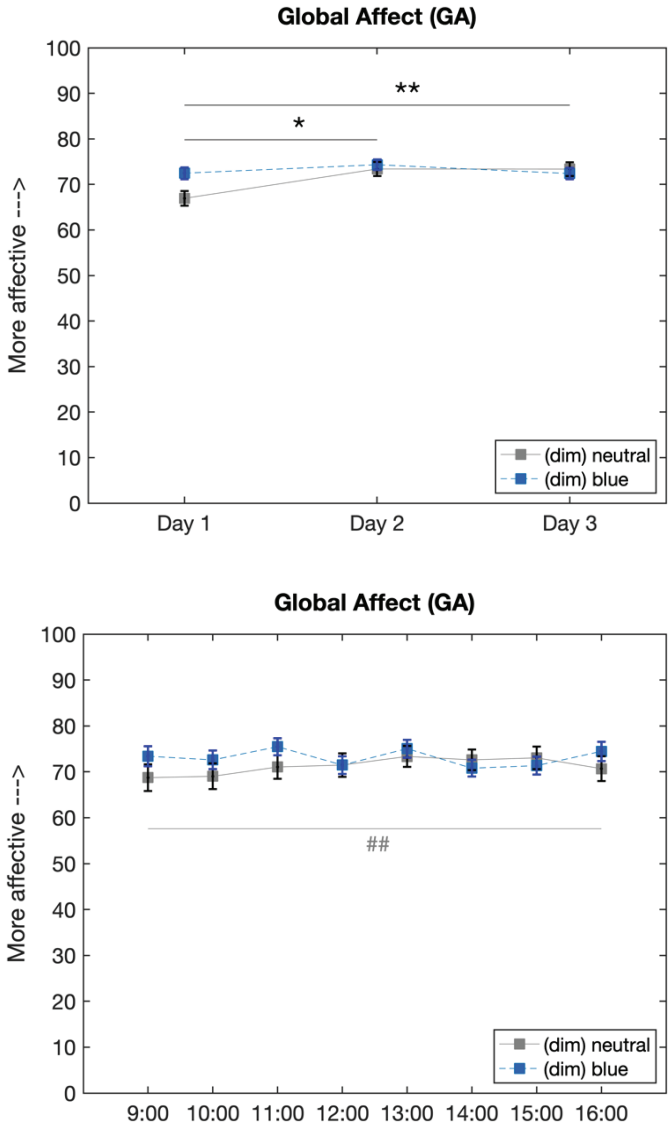


Figure 4.8 Mean values and associated standard errors of the effect of duration (up) and of timing of exposure (bottom) on subjective well-being (GA). Significant main effects of duration (left) or timing (right) of exposure are represented with "+" ($p<0.10$), "*" ($p<0.05$), "**" ($p<0.01$), "***" ($p<0.001$). Interaction effects are represented with "#" ($p<0.05$), "##" ($p<0.01$), "###" ($p<0.001$) (simple contrasts for duration and/or timing of exposure) and with red asterisks ("*" ($p<0.05$), "**" ($p<0.01$), "***" ($p<0.001$)) for simple contrast of daylight.

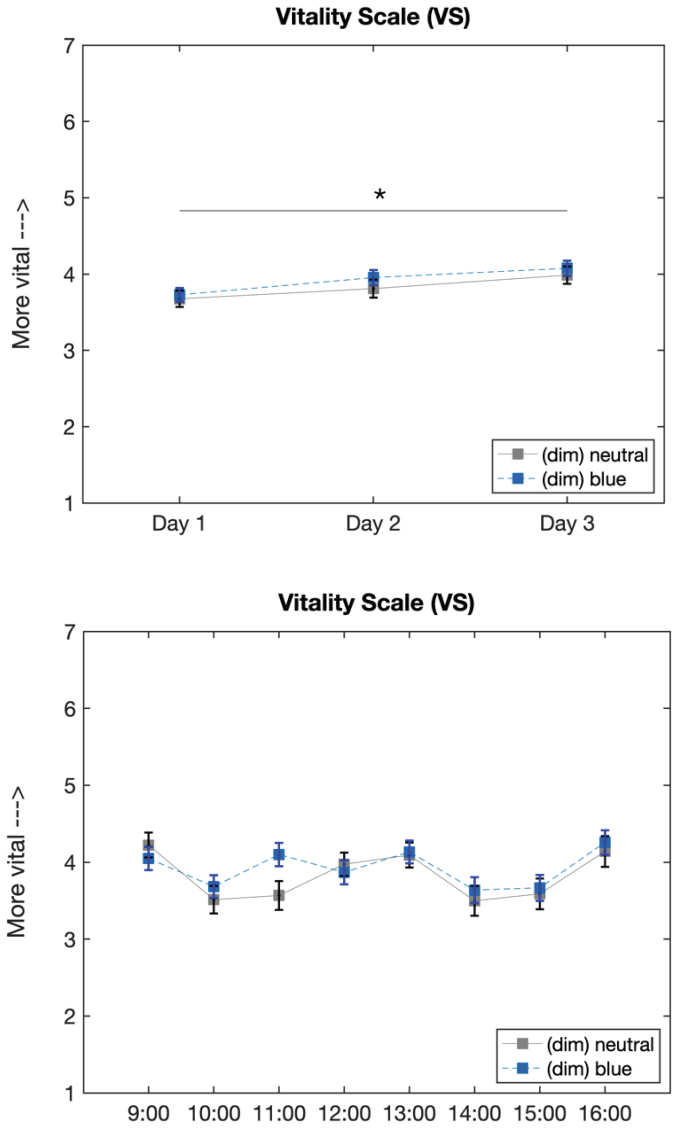
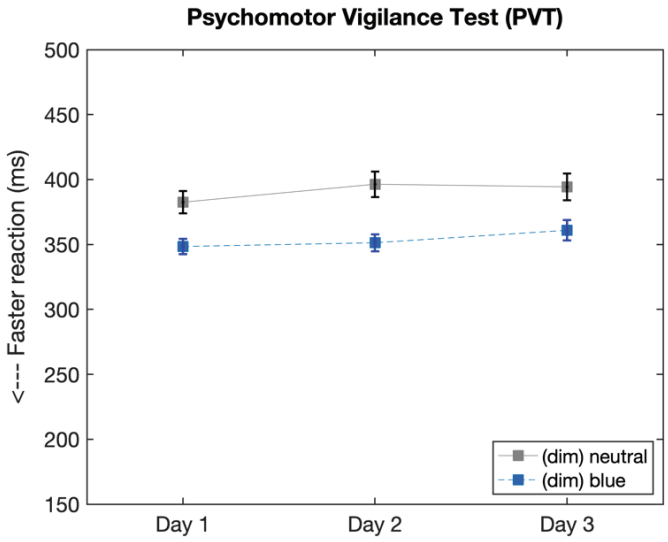


Figure 4.9 Mean values and associated standard errors of the effect of duration (up) and of timing of exposure (bottom) on subjective well-being (VS). Significant main effects of duration (left) or timing (right) of exposure are represented with "+" ($p<0.10$), "*" ($p<0.05$), "**" ($p<0.01$), "***" ($p<0.001$). Interaction effects are represented with "#" ($p<0.05$), "##" ($p<0.01$), "###" ($p<0.001$) (simple contrasts for duration and/or timing of exposure) and with red asterisks ("*" ($p<0.05$), "**" ($p<0.01$), "***" ($p<0.001$)) for simple contrast of daylight.

4.5.3. Performance in sustained attention

Sustained attention was evaluated through a performance task that allowed to monitor reactivity to a visual task (section 3.5.2). Main and interaction effects of daylighting condition, duration and timing of exposure were also investigated with LMM for these responses. Reaction times lower than 150 ms or higher than 500 ms were excluded from the analysis since these responses are often categorized as anticipation or lapses, respectively (Münch et al., 2016b).

As observed in Figure 4.10, neither main nor interaction effects were found for duration nor by timing of exposure. However, PVT performance was affected by daylight condition ($F(1,577) = 12.32$, $p<0.01$).



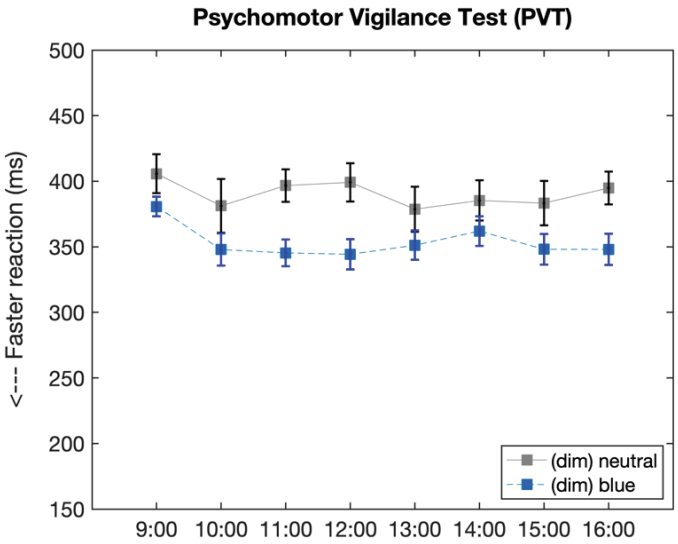


Figure 4.10 Mean values and associated standard errors of the effect of duration (up) and of timing of exposure (bottom) on sustained attention (PVT). Significant main effects of duration (left) or timing (right) of exposure are represented with "+" ($p<0.10$), "*" ($p<0.05$), "**" ($p<0.01$), "***" ($p<0.001$). Interaction effects are represented with "#" ($p<0.05$), "##" ($p<0.01$), "###" ($p<0.001$) (simple contrasts for duration and/or timing of exposure) and with red asterisks ("*" ($p<0.05$), "**" ($p<0.01$), "***" ($p<0.001$)) for simple contrast of daylight.

4.5.4. Physiological arousal

As for physiological arousal, cardiovascular activity was monitored throughout the study to assess changes in the autonomous nervous system by means of heart rate and heart rate variability (section 3.5.3). In particular, indicators of LF and HF power were used to assess sympathetic (i.e., related to arousal promotion and energy generation) and parasympathetic activity (i.e., associated with rest activities), respectively. Mean values of HR (in beats per minute), of LF and HF (both in milliseconds), and of the LF/HF ratio were used to perform the analyses, collected during the 5-minute hourly tasks when the participants' activity was controlled (i.e., while they were replying to the self-reported questionnaire and PVT).

Only the main effect of timing of exposure was a significant factor for HR ($F(1,4168) = 6.99$, $p<0.01$), indicating a decrease in cardiovascular activity throughout the day independently of daylighting condition. *Post-hoc* tests revealed a faster HR in the morning than in the afternoon ($\beta_{PM}=-0.76$, $p_{adj}<.001$) (Figure 4.11). However, by looking at that same figure (Figure 4.11) we can observe that, when excluding 9:00 am results – which correspond to the first measurement block of the day –, heart rate was actually faster during the afternoon than during the morning ($\beta_{PM}=2.70$, $p_{adj}<.001$). The covariate corresponding to the baseline value for HR was significant ($p<0.001$).

The main effect of timing of exposure was a marginally significant factor for LF power despite condition ($F(1,4168) = 3.32$, $p<0.1$), which indicated a decrease in cardiovascular activity throughout the day. *Post-hoc* tests revealed a slightly higher LF power in the morning than in the afternoon ($\beta_{PM}=-154$, $p_{adj}<0.1$) (Figure 4.12). No interactions were detected, and no significant effects due to lighting condition or duration of exposure were reported either (4.12). The covariate corresponding to the baseline value for LF power was significant ($p<0.001$).

The effect of lighting condition on HF power was moderated by timing of exposure, meaning that there was a significant interaction between daylight and session ($F(1,4168) = 6.99$, $p<0.01$). Analyses conducted at each daylight level showed that differences across experimental sessions were significant under blue conditions ($X^2(1) = 195.86$, $p<.01$) but not under neutral ones. *Post-hoc* tests (simple contrasts for timing of exposure) revealed that, under blue conditions, the participants' HF power was higher in the afternoon than in the morning ($p<.01$). Under neutral conditions, the participants' HF power did not change between sessions. In addition, simple contrasts for daylight showed no difference between neutral and blue conditions in either session (Figure 4.13). No main effect or interactions with duration of exposure were reported either (Figure 4.13). The covariate corresponding to the baseline value for HF power was significant ($p<0.01$).

As for the LF/HF ratio, the main effect of lighting condition was moderated by timing of exposure ($F(1,4168) = 3.90$, $p<0.05$), and significant differences across sessions (morning vs afternoon) were found under both neutral ($X^2(1) = 53.74$, $p<.001$) and blue conditions ($X^2(1) = 16.14$, $p<.001$). *Post-hoc* tests (simple contrasts for timing of exposure) revealed that, under both neutral and blue conditions, participants' variability on LF/HF ratio was higher in the morning than in the afternoon (both $p<.001$), even if excluding 9:00 a.m. values. In addition, simple contrasts for daylight showed no difference between neutral and blue conditions in either session (Figure 4.14). The main effect of duration of exposure was also a significant factor for the LF/HF ratio ($F(2,4167) = 62.56$, $p<0.001$), indicating an increase in variability during the experiment but independently of daylighting condition. *Post-hoc* tests revealed that a higher LF/HF ratio during day 3 compared to day 1 ($\beta_{D3}=0.33$, $p_{adj}<.05$), and nearly higher also during day 2 compared to day 1 ($\beta_{D2}=0.32$, $p_{adj}=0.06$) (but not during day 3 compared to day 2) (Figure 4.14). The covariate corresponding to the baseline value for the LF/HF ratio was significant ($p<0.05$).

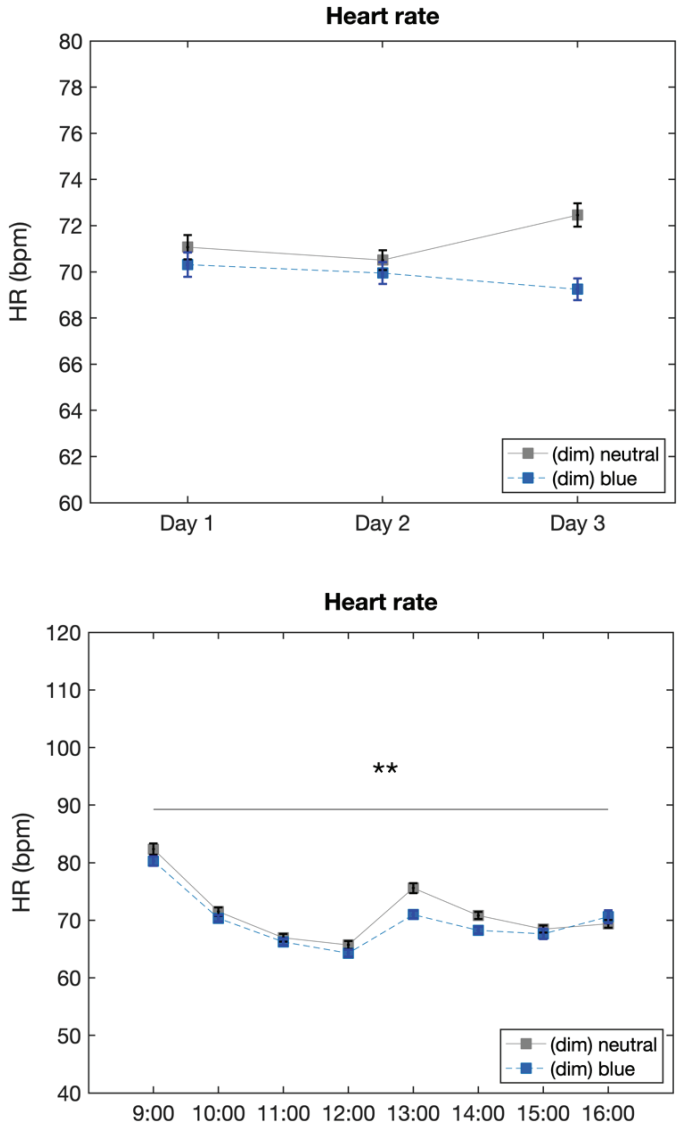


Figure 4.11 Mean values and associated standard errors of the effect of duration (up) and of timing of exposure (bottom) on physiological arousal based on HR. Significant main effects of duration (left) or timing (right) of exposure are represented with "+" ($p<0.10$), "*" ($p<0.05$), "**" ($p<0.01$), "***" ($p<0.001$). Interaction effects are represented with "#" ($p<0.05$), "##" ($p<0.01$), "###" ($p<0.001$) (simple contrasts for duration and/or timing of exposure) and with red asterisks ("*" ($p<0.05$), "**" ($p<0.01$), "***" ($p<0.001$)) for simple contrast of daylight.

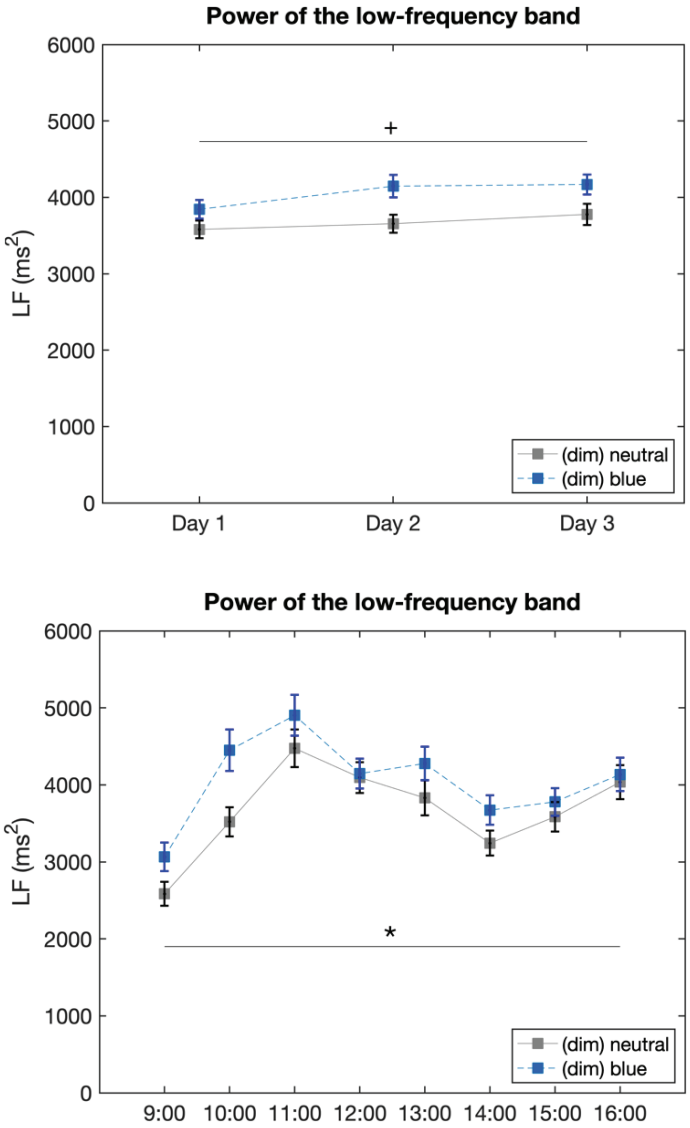


Figure 4.12 Mean values and associated standard errors of the effect of duration (up) and of timing of exposure (bottom) on physiological arousal based on LF power. Significant main effects of duration (left) or timing (right) of exposure are represented with "+" ($p<0.10$), "*" ($p<0.05$), "**" ($p<0.01$), "***" ($p<0.001$). Interaction effects are represented with "#" ($p<0.05$), "##" ($p<0.01$), "###" ($p<0.001$) (simple contrasts for duration and/or timing of exposure) and with red asterisks ("*" ($p<0.05$), "**" ($p<0.01$), "***" ($p<0.001$)) for simple contrast of daylight.

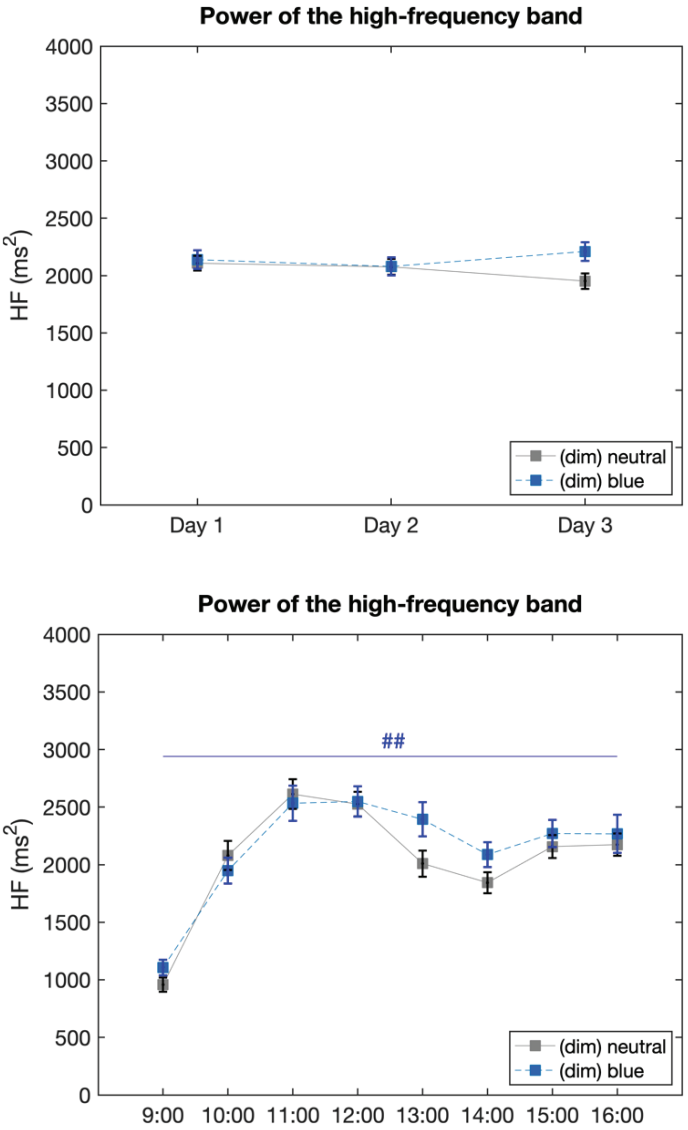


Figure 4.13 Mean values and associated standard errors of the effect of duration (up) and of timing of exposure (bottom) on physiological arousal based on HF power. Significant main effects of duration (left) or timing (right) of exposure are represented with "+" ($p<0.10$), "*" ($p<0.05$), "**" ($p<0.01$), "***" ($p<0.001$). Interaction effects are represented with "#" ($p<0.05$), "##" ($p<0.01$), "###" ($p<0.001$) (simple contrasts for duration and/or timing of exposure) and with red asterisks ("*" ($p<0.05$), "**" ($p<0.01$), "***" ($p<0.001$)) for simple contrast of daylight.

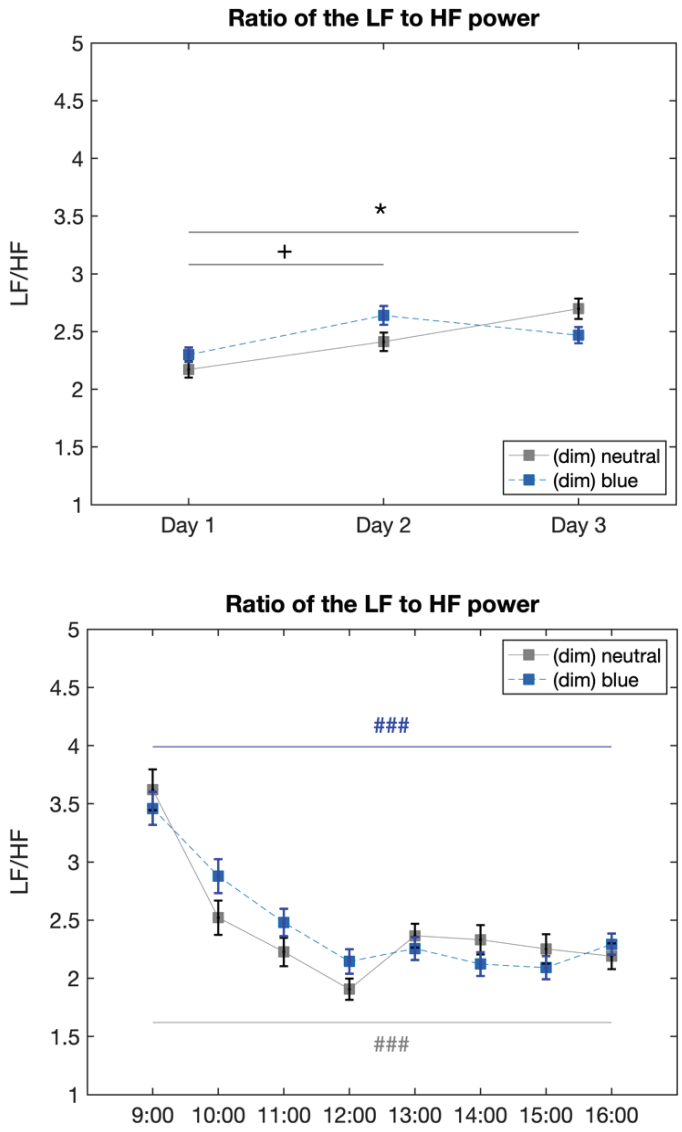


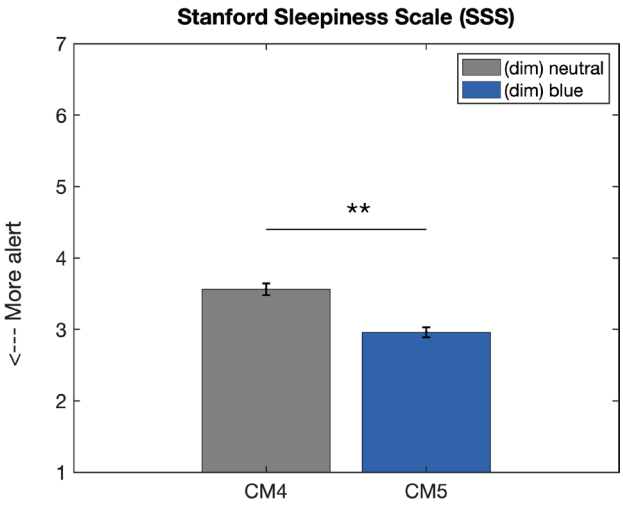
Figure 4.14 Mean values and associated standard errors of the effect of duration (up) and of timing of exposure (bottom) on physiological arousal based on the ratio of the LF/HF power. Significant main effects of duration (left) or timing (right) of exposure are represented with "+" ($p<0.10$), "*" ($p<0.05$), "**" ($p<0.01$), "***" ($p<0.001$). Interaction effects are represented with "#" ($p<0.05$), "##" ($p<0.01$), "###" ($p<0.001$) (simple contrasts for duration and/or timing of exposure) and with red asterisks ("*" ($p<0.05$), "**" ($p<0.01$), "***" ($p<0.001$)) for simple contrast of daylight.

4.6. STUDY A OUTCOMES

This study investigated daytime effects of dynamic and prolonged exposures to variations on daylight spectrum (blue vs. neutral conditions), on subjective reports of alertness and well-being, sustained attention and arousal. More specifically, our work explored whether findings from previous studies on the alerting effects of polychromatic white light could be replicated in a daylit environment (i.e., in the absence of any electric illumination) and under conditions closer to those experienced in our daily routines (i.e., prolonged exposures, no pre-treatment conditions, no sleep deprivation, etc.).

4.6.1 Main effect of daylight condition

Higher levels of alertness and performance have, in previous studies, often been associated with blue-shifted lighting conditions (Cajochen et al., 2011; Chellappa et al., 2011; Wahnschaffe et al., 2013). As can be observed in Figure 4.15, our results reinforce this hypothesis by showing that bluer daylight, when compared to non-filtered neutral conditions (both associated with low levels of illuminance), tends to reduce subjective sleepiness (SSS, β_N=0.60, p_{adj}=0.01), increase subjective well-being (GV, β_N=-8.29, p_{adj}<.05) and improve performance (i.e., reaction times) on a sustained attention task (PVT, β_N=41.2, p_{adj}<.01), even under dim intensity levels and during daily work routines. This was the case irrespective of day or experimental session, indicating that no interaction occurred between daylight, duration and timing of exposure (i.e., effects of daylight were not moderated by time or day). Non-parametric analyses reinforced our results by showing similar statistically significant differences between lighting conditions on indicators of subjective alertness, vigour and sustained attention as well, showing also an improvement in all three variables under the bluer daylight condition (Table 1, Appendix B).



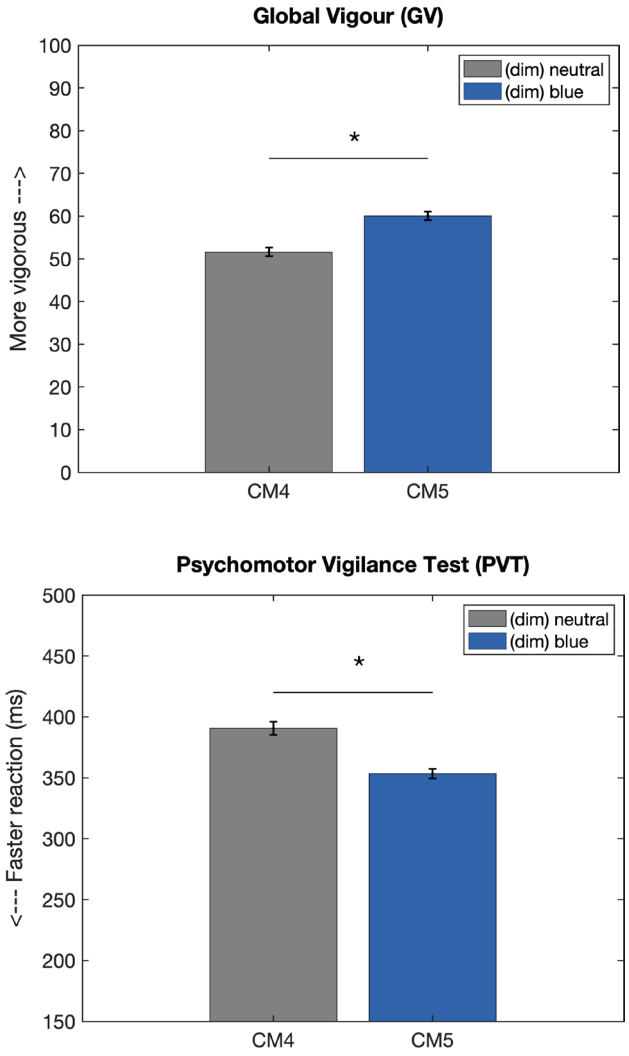


Figure 4.15 Mean value ± standard error of the main effect of daylight condition on SSS (a), GV (b) and PVT (c). Significance is represented with "+" ($p<0.10$), "*" ($p<0.05$), "**" ($p<0.01$), "***" ($p<0.001$).

This outcome is also in line with results from previous studies using electric lighting (Cajochen et al., 2011; Wahnschaffe et al., 2013), where higher CCTs resulted in higher subjective alertness and better performance. It aligns particularly well with results from another -evening- study, also conducted under dim conditions (40 lx) and that also manipulated light spectrum -of electric, fluorescent sources in that case- without compromising illuminance levels (Chellappa et al., 2011): a very similar outcome was observed in that study as the bluer condition lead to higher subjective alertness and well-being, and to faster reaction times in a sustained attention test (PVT). Most experiments looking into the effects of "blue" light, either through manipulations of polychromatic white or monochromatic light were conducted at night, which may or

may not be applicable in daytime. But even if their findings could be extrapolated to daytime conditions, it is unfortunately still unclear whether, among the studies that did report positive effects of blue conditions, the results could actually be attributed to spectral content or rather to confounded variations in illumination level (Figueiro et al., 2013; Figueiro and Rea, 2011; Wahnschaffe et al., 2013).

The fact that the effect of blue light in our study persisted throughout the day and over the entire duration of the experiment on indicators of subjective alertness, well-being and sustained attention, confirms our initial hypothesis (H1) that bluer environments favour correlates of alertness. This was not the case, however, for any of the indicators of physiological arousal.

4.6.2 Effects of duration and timing of exposure

The analysis of the collected data showed that the number of days of experiment (that we refer to as the duration of exposure) significantly affected self-reports of alertness (SSS), vigour, affect and vitality, and cardiovascular activity (LF and LF/HF ratio), independently of light condition. This means that for GV, GA and the LF/HF ratio, scores improved during the second day compared to the first one, and even more during day 3 compared to day 1. For VS and SSS, scores only improved after two days of exposure, when comparing results from day 3 with day 1. This happened irrespective of lighting condition in most variables as a slight decrease (rather than increase) of horizontal illuminance could be observed over the duration of the experiment (due to weather conditions thus similarly for both rooms, see Table 4.3 and Figure 4.4 in section 4.2.1). This suggests a systematic adaptation to experimental conditions over the days, which would confirm our hypothesis (H2) that longer daytime exposures induce stronger effects on correlates of alertness.

In the case of KSS scores, duration of exposure mediated the effect of "blue" daylight on alertness. Yet, the outcome was very similar among dependent variables: there was an agreement in that the peak reaction happened only after at least one entire day of exposure and remained as effective afterwards. No significant changes were indeed reported for any variable between days 2 and 3 of exposure. These results imply a photic effect due to blue daylight that, at the same time, becomes stronger over time (even though illuminance levels decreased throughout the experiment, as pointed out earlier), thus confirming both our first and second hypothesis presented in Chapter 1: both bluer conditions (H1) and longer exposures (H2) do seem to elicit stronger effects on alertness at least in dim conditions, based on the outcomes of this study.

Non-parametric tests for the effect of duration of exposure also showed very similar results as those found in LMMs. Significant differences between days of experiment were found for GV and VS, irrespective of light condition (i.e., in both scenarios), and in this case also for KSS (unlike in LMM, where the effect of duration was observed only in the blue condition). For SSS and GA, the effect of duration of exposure was

only observed under the blue or the neutral condition, respectively (Tables 3 and 4, Appendix B). Since light scenarios are analysed separately with this second approach, what was described as an interaction between light and duration for LMMs, here is instead evaluated by means of significant differences per day between lighting conditions. Since in LMMs interaction terms are excluded from the model when non-significant, no possible further pairwise comparisons between lighting scenarios are possible. As a result, this extra information provided by non-parametric tests is not present in LMMs, unless a significant interaction occurred. This was the case of KSS, and both methods agreed in that significant differences between lighting conditions existed on days 2 and 3 of experiment (Table 7, Appendix B).

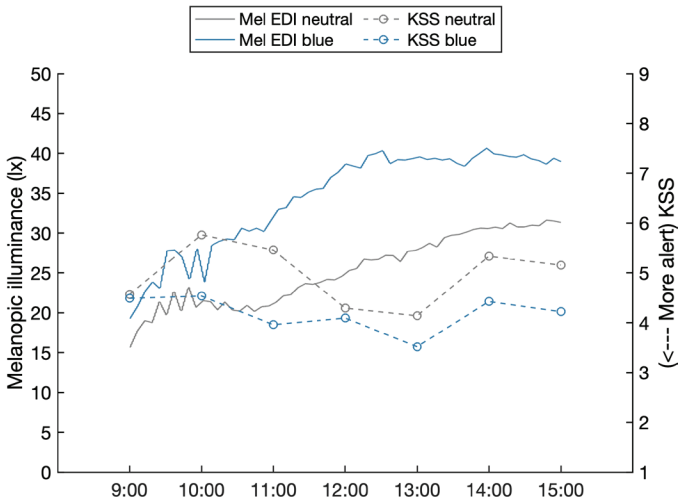


Figure 4.16 Mean values of KSS values vs melanopic EDI (lx) over time.

Time of day also affected self-reports of alertness (KSS, SSS) and vigour, and physiological indicators of heart rate independently of daylight condition. However, since quantitative dynamics of daylight were not included in the analyses, it is unclear whether the main effect of timing of exposure arises from the hypothesized underlying circadian rhythmicity or, instead, from a systematic variation in illuminance levels between morning and afternoon sessions within classrooms (Figure 4.16). Nonetheless, these results to some extent do confirm our third hypothesis, since we expected morning and afternoon sessions to behave differently.

For subjective affect and heart rate variability, timing of exposure was responsible for mediating the way daylight elicited such responses. This means that when it comes to scores of GA, morning and afternoon differences were only spotted under (dim) neutral daylight, whereas in the LF/HF ratio, differences in power were observed under both lighting conditions. These could imply, as suggested earlier, a photic effect due to daylight's spectrum that changes based on the time of day, but contradicts our hypothesis H1: it was indeed unexpected that neutral conditions would elicit stronger effects on GA when compared to bluer ones.

4.6.3 Discussion on STUDY A

Investigations comparing subjective alertness for exposure to different colour temperatures reported greater self-rated alertness with higher CCT (i.e., bluer content) (Cajochen et al., 2011; Chellappa et al., 2013, 2011c; Figueiro et al., 2013; Wahnschaffe et al., 2013), and a few others discovered that exposure to monochromatic blue light increases subjective alertness when compared to longer wavelengths (Cajochen et al., 2005; Lockley et al., 2006; Revell et al., 2006). In our case, the red-impoverished polychromatic daylight scenario (which looks "bluer" due to a higher CCT and ELR) also reported lower scores of subjective sleepiness.

Regarding performance measurements, very few studies have identified significant effects of higher CCT on PVT performance (Chellappa et al., 2011c). However, studies using monochromatic light appear to demonstrate a distinct pattern in the sense that several of these found that blue light decreased reaction times when compared to longer wavelengths (Chellappa et al., 2011c; Figueiro and Rea, 2011; Lockley et al., 2006; Phipps-Nelson et al., 2009; Rahman et al., 2014). In our study, the bluer condition also favour performance on a sustained attention task.

However, as discussed in section 3.7, illuminance levels were very low throughout the study compared to suggested objectives for comparable workspaces (i.e., between 300-500 photopic lux at the work plane). We propose that future research undertake greater variations in illuminance levels when comparing daylight of different spectra in order to draw more applicable conclusions about the effect of coloured and neutral daylight to the built environment.

In general, very little can be found in the literature about the potential dependency of alerting effects on exposure duration or time of day during daytime. Our investigation showed that overall, afternoon exposures were more effective for subjective indicators whereas morning sessions showed stronger physiological effects. At the same time, they showed that longer durations (i.e., more than one day) did improve responses whether subjectively assessed or based on physiological markers. However, further investigating the influence of natural daylight dynamics on such experiments would be necessary: though they applied in parallel to both lighting conditions, it would be interesting to understand whether the fact that these conditions are maintained different enough between the two conditions rather than being effectively controlled (i.e. static) could explain part of these inconsistencies.

Results from this study confirmed in general all our three hypotheses about the effectiveness of bluer conditions for correlates of alertness (H1), stronger effects derived from longer exposure durations (H2) and mornings performing differently compared to afternoons (H3), at least in dim conditions, thus opening the door to further refinements of existing protocols to investigate daytime responses due to light exposure.

5 EFFECTS OF [DAYLIGHT INTENSITY UNDER BLUE SPECTRA] STUDY B

This chapter describes the circumstances and findings of the thesis's second experiment, which was carried out to investigate whether variations in daylight's intensity levels under blue-shifted conditions can induce measurable effects on participants' alertness, sustained attention and arousal levels. Our initial hypotheses were as follows:

- exposure to bluer and brighter daylight might reduce subjective sleepiness, increase subjective well-being, improve attention and favour arousal (H1).

- same expectations are maintained regarding exposure duration and timing as in study A (H2 and H3).

5.1 ENVIRONMENTAL CONDITIONS

The experiment was conducted in the late Spring of 2019, with one year difference with respect to study A. It was conducted in this case during two consecutive days (May 25th and 26th) due to availability of the classrooms but consisted also of seven continuous hours of exposure per day, from 9:00 a.m. to 4:00 p.m.

While outdoor environmental conditions were not monitored during this study either, they were still assessed based on weather data gathered from the same station as in study A (i.e., located in Pully, Vaud (Switzerland)), but for the particular days of the current experiment. Figure 5.1 depicts the resulting sky condition visualization, which was derived using the same simulation software as in Chapter 4, and corresponds – based on human observation during the experimental days – to a partly cloudy sky to mostly cloudy in day 1, and to a clear sky to partly cloudy in day 2.

Table 5.1 Environmental conditions in the classrooms. Average values and associated standard deviation of temperature and humidity levels per lighting condition, for the entire duration of the experiment.

	Blue filter (CM4)	EC-1 (CM5)
Temperature (°C)	22.8 ± 0.6	22.6 ± 0.4
Humidity (%)	47.1 ± 2.8	46.9 ± 2.7

Temperature and humidity levels inside the classrooms are reported in summarized form in Table 5.1.

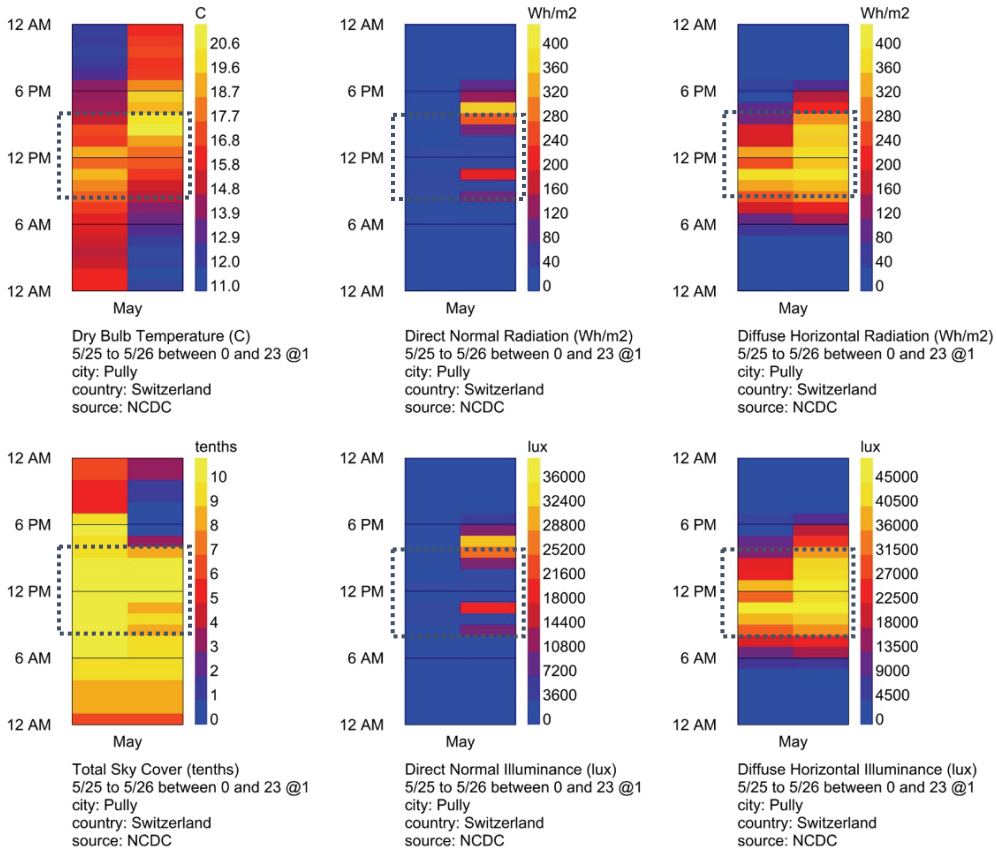


Figure 5.1 Overview of weather conditions throughout the experiment. From left to right, from first to second row: dry bulb temperature (°C), direct normal radiation (Wh/m²), diffuse horizontal radiation (Wh/m²), total sky cover (tenths), direct normal illuminance (lux) and diffuse horizontal illuminance (lux).

5.2 LIGHT STIMULI

Two filtering methods based on blue-shifts and associated illuminance variations were used to achieve the lighting scenarios for this study, namely blue vs brighter blue (Figure 5.2). In classroom CM5, a specific level of tint was applied to the electrochromic glazing (EC Intermediate 1). The visual transmittance (Tvis) of the glazing at this particular level of tint was 16%, and resulted in a correlated colour temperature of 6,651 K. In classroom CM4, blue filters were added on the glazing (Blue filter + EC clear, resulting in a CCT of 9,765 K, Tvis 29%). These combinations resulted in a red-impoverished spectrum that looks “blue”, although the amount of blue content in each room differed, and so intensity levels (which were confounded with spectral shifts).

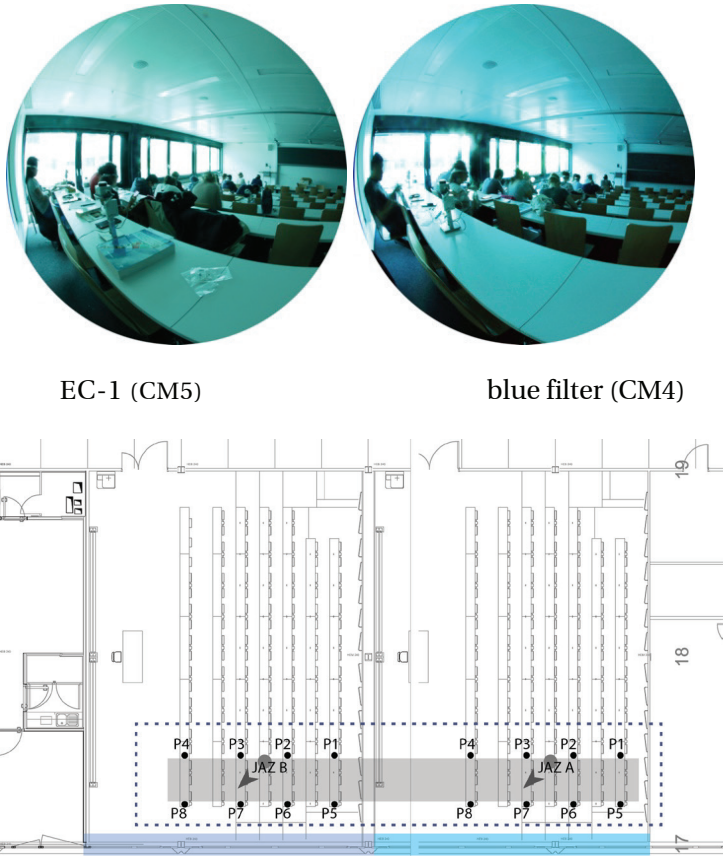


Figure 5.2 View of daylight manipulations in the classrooms; left, classroom CM5, moderate bright blue conditions (EC Intermediate 1, 16% Tvis) and right, classroom CM4, bright blue conditions (Blue filter + EC clear, 29% Tvis).

5.2.1 Daylight exposure

Throughout the experiment, spectral power distribution (SPD) was measured at the eye level and view direction of a seated participant (Figure 5.2, big black dots), and horizontal illuminance was measured at the working plane -desk level- as described in Figure 5.2 (small black dots, p1-p8).

Resulting absolute irradiances (μW/cm²/nm), based on the aforementioned SPD measurements, are shown in Figure 5.3 as average mean, maximum and minimum values for the entire duration of the experiment, for both daylighting conditions (blue, EC-1 and brighter blue, blue filter). This graph shows that spectrally, the two conditions were different in terms of intensity, but also regarding blue content (as factors are confounded one another), as the brighter peaks closer to 480 nm while the EC-1 is shifted towards the green part (i.e., closer to daylights' unfiltered spectrum).

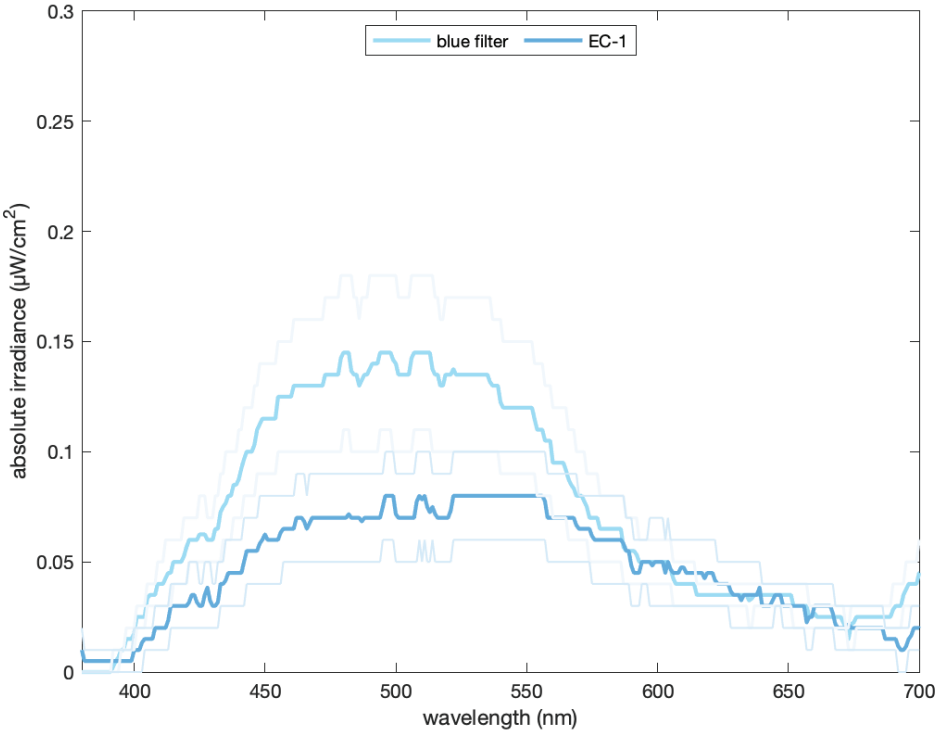


Figure 5.3 Average mean, maximum and minimum irradiance values per wavelength, measured at the eye level for both daylight conditions

Using the CIE S026 calculation toolbox, average α-opic quantities of efficacy luminous radiation [W/lm] and equivalent daylight (D65) illuminance [lux](CIE, 2018) (Table 5.2) were derived for each of the five human photoreceptors from the spectrally-weighted irradiance values measured at eye level by the spectroradiometer (cf. Figure 5.2). Values for both melanopic efficacy luminous radiation and melanopic equivalent daylight (D65) illuminance were higher in the room with the blue filter than in the one with electrochromic glazing (EC-1) (Table 5.2).

Table 5.2 Average spectrally weighted α-opic efficacy luminous radiation in W/lm (ELR) and equivalent daylight (D65) illuminance in lux (EDI) measured at the eye level, for each daylighting condition.

		Blue filter (CM4)		EC-1 (CM5)	
Illuminance	**Sensitivity**	*ELR (W/lm)*	*EDI (lux)*	*ELR (W/lm)*	*EDI (lux)*
photopic	Visibility		68.51		47.60
cyanopic	S-cone	0.82	68.87	0.62	36.16
melanopic	**ipRGC**	**1.62**	**83.71**	**1.26**	**45.24**
rhodopic	Rod	1.77	83.71	1.43	46.91
chloropic	M-cone	1.64	77.38	1.50	48.92
Erythropic	L-cone	1.57	66.22	1.59	46.40

Patterns of horizontal photopic illuminance are presented as average hourly values per day of experiment, photometer and daylight condition. As mentioned before, blue-shifts in daylights' spectrum led to unavoidable variations of illuminance. Although not very extreme, these differences can be observed in Figure 5.4. Table 5.3 provides a more quantitative perspective of the daily average variations per day of experiment and daylight scenario.

Table 5.3 Average daily values (± standard deviation) of horizontal photopic illuminance at the desk, per daylighting condition.

	Daylight illuminance (lx)	
Lighting condition	*Day 1*	*Day 2*
Blue filter	132 ± 143	92 ± 93
EC-1	106 ± 102	77 ± 72

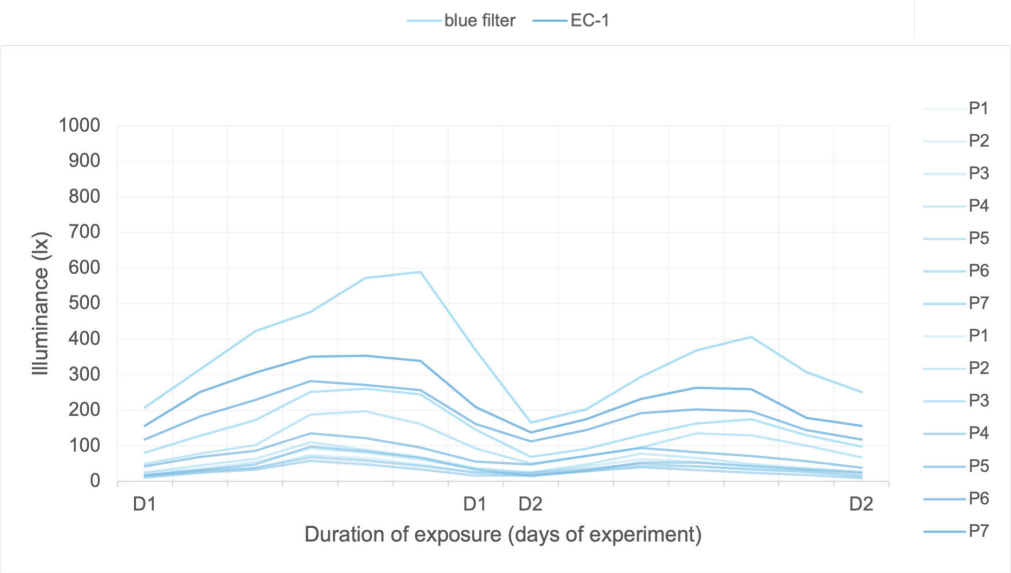


Figure 5.4 Average hourly values of horizontal photopic illuminance at the work plane, over time (days of exposure) and per photometer.

5.2.2 Timing and duration of exposure

The experiment was conducted over two consecutive days as mentioned earlier (Saturday and Sunday in this case), and as introduced in section 3.3.1, the same protocol was used for all three studies, including the number of sessions and hours of experiment per day.

5.3 PARTICIPANTS

In total, 33 subjects joined the experiment, of which 12 were female participants and 21 were males. They were divided between lighting conditions, so that 17 were assigned to the room with brighter blue daylight (CM4, Figure 5.2 left) and the other 16 to the room with blue daylight (CM5, cf. Figure 5.2 right). Each participant was assigned a given desk location within the room for the whole duration of the experiment (see section 3.2). Gender was counterbalanced, with 6 female and 11 male participants in the first condition, and 6 female and 10 male participants in the blue one. The age of participants was on average 23.1 (± 2.8) years old.

5.4 DATA ANALYSIS

A 2 x 2 x 2 mixed factorial design was used to test the effects of intensity variations under blue-shifted conditions, timing and duration of daylight exposure on psycho-physiological correlates of alertness (i.e., namely KSS, SSS, GV, GA, VS, PVT, HR, LF, HF and the LF/HF ratio. The main difference with regards to studies A and C consists of the levels of the factor duration of exposure, which in this case were of two instead of three, and on the daylight conditions (blue, described as EC-1 and brighter blue, used as a reference and referred to as blue filter). As described in section 4.4 for study A, LMM were conducted separately per dependent variable, accounting for both main and interaction effects of fixed factors.

5.5 RESULTS

We first investigated whether there were no significant alertness fluctuations at the start of each experiment day (i.e., at 9 am). The effects of daylight, exposure duration and time of day as well as their interaction on alertness correlates were evaluated subsequently.

Table 5.4 Results of marginal and conditional R^2 values per LMM and dependent variable

Dependent variable	$R^2_{marginal}$	$R^2_{conditional}$
KSS	0.05	0.41
SSS	0.04	0.38
GV	0.04	0.46
GA	0.01	0.73
VS	0.07	0.62
PVT	0.01	0.10
HR	0.04	0.27
LF	0.27	0.38
HF	0.16	0.58
LF/HF	0.05	0.23

As in study A, marginal and conditional R^2 values were calculated for the LMM of each dependent variable. Table 5.4 describes how the variance explained by the models considerably increased for conditional R^2. Moreover, our three investigated factors - daylighting condition, duration and timing of exposure- explained up to 73% of the variance in participants responses (GA) when controlling for repeated measurements.

These conditional R^2 values can be considered as moderate for all dependent variables, except for GA (strong) and PVT or LF/HF (small) (Ferguson, 2009), and none of them represent a negligible practical effect.

5.5.1. Baseline analyses

For all dependent variables on the data that corresponds to the first measurement block (i.e., 9:00 am) per day of experiment, preliminary LMM testing was conducted. Daylight and exposure duration (i.e., days) were then taken together with their interaction as fixed factors in the model. In general, findings showed that the lighting conditions of any of the variables studied do not vary significantly (all p>.05), as can be seen in Table 5.5. No interactions were found either, indicating that results did not change throughout the experiment (i.e., over the days).

Table 5.5 Results of linear mixed model analyses for baseline values (i.e., 9:00 am)

	Day 1		Day 2	
	estimate	p-value	estimate	p-value
KSS	-0.14	0.81	0.94	0.12
SSS	0.02	0.96	0.67	0.16
GV	-5.26	0.40	-7.53	0.29
GA	-1.94	0.74	-4.48	0.44
VS	0.33	0.33	-0.14	0.67
PVT	-0.45	0.99	-28.41	0.32
HR	0.37	0.97	13.25	0.16
LF	-157	0.88	-987	0.33
HF	-574	0.25	-196	0.69
LF/HF	-0.15	0.93	-1.14	0.47

5.5.2. Subjective alertness and well-being

As in study A, LMM analyses were performed to investigate the combined effects (i.e., main and interactions) of daylighting condition, duration and timing of exposure on subjective alertness (KSS and SSS) and well-being (GV, GA and VS).

Responses of subjective alertness on the KSS were significantly influenced by daylight condition ($F(1,524) = 4.71$, $p<0.05$). No moderation effects by duration or timing of

exposure were detected (Figure 5.5). The main effect of duration of exposure on alertness scores was marginally significant ($F(1,524) = 3.62$, $p<0.10$), revealing that sleepiness scores decreased during the experiment, independently of daylighting condition. *Post-hoc* tests showed that KSS scores in day 2 slightly decreased compared to day 1 ($\beta_{D2}=-0.33$, $p_{adj}<.10$) (Figure 5.5 a, left) (Figure 5.5).

The main effect of lighting condition had a significant effect on subjective alertness measured by the SSS ($F(1,524) = 4.32$, $p<0.05$). There were no moderation effects with duration or timing of exposure. For duration of exposure, significant differences were also observed ($F(1,524) = 4.39$, $p<0.05$), whereas timing of exposure showed no significant differences between sessions (Figure 5.6). Participants' alertness increased during the experiment, independently of daylighting condition, indicating that SSS scores decreased in day 2 compared to day 1 ($\beta_{PM}=-0.31$, $p_{adj}<.05$) (Figure 5.6).

Scores about vigour (GV) were only marginally affected by duration of exposure ($F(1,524) = 2.91$, $p<0.10$), indicating an increase in vigour during the experiment but independently of daylighting condition. *Post-hoc* tests revealed that participants felt slightly more vigorous during day 2 compared to day 1 ($\beta_{D2}=2.85$, $p_{adj}<.10$) (Figure 5.7). Neither main effects due to lighting conditions or timing of exposure, nor significant interactions were detected (Figure 5.7). Neither daylight condition, nor duration or timing of exposure affected significantly scores of GA. No significant interactions were detected either. (Figure 5.8).

The effect of lighting condition on vitality (VS) was moderated by timing of exposure, meaning that there was a significant interaction between daylight and session ($F(1,523) = 16.04$, $p<0.01$). Analyses conducted at each daylight level showed that differences across experimental sessions were significant under EC-1 and marginally significant under bright blue conditions ($X^2(1) = 0.57$, $p<.001$ and $X^2(1) = -0.25$, $p<.10$, respectively). *Post-hoc* tests (simple contrasts for timing of exposure) revealed that, under EC-1 conditions, participants felt more vital during the morning session than during the afternoon one ($p<.001$), whereas in the brighter room, participants felt slightly more vital in the afternoon than in the morning ($p<.10$). In addition, simple contrasts for daylight showed a significant difference between EC-1 and brighter conditions during the morning session ($p<.01$) but not during the afternoon one (Figure 5.5 e, right). There were no main or interaction effects with duration of exposure (Figure 5.9).

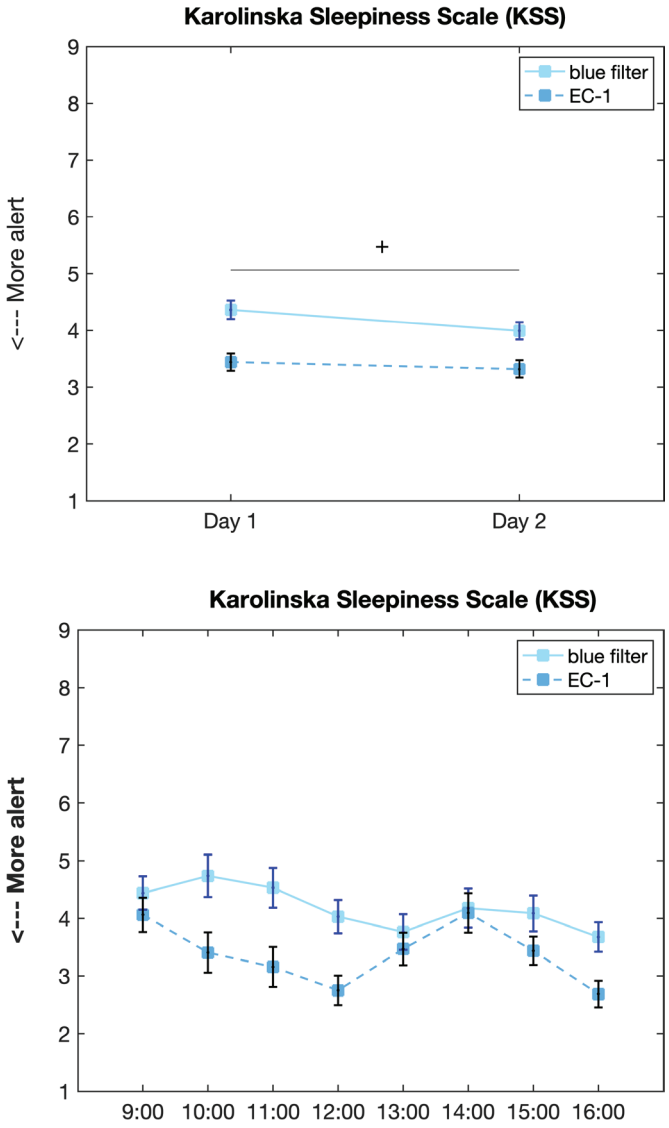


Figure 5.5 Mean values and associated standard errors of the effect of duration (up) and of timing of exposure (bottom) on subjective alertness (KSS). Significant main effects of duration (left) or timing (right) of exposure are represented with "+" ($p<0.10$), "*" ($p<0.05$), "**" ($p<0.01$), "***" ($p<0.001$). Interaction effects are represented with "#" ($p<0.05$), "##" ($p<0.01$), "###" ($p<0.001$) (simple contrasts for duration and/or timing of exposure) and with red asterisks ("*" ($p<0.05$), "**" ($p<0.01$), "***" ($p<0.001$)) for simple contrast of daylight.

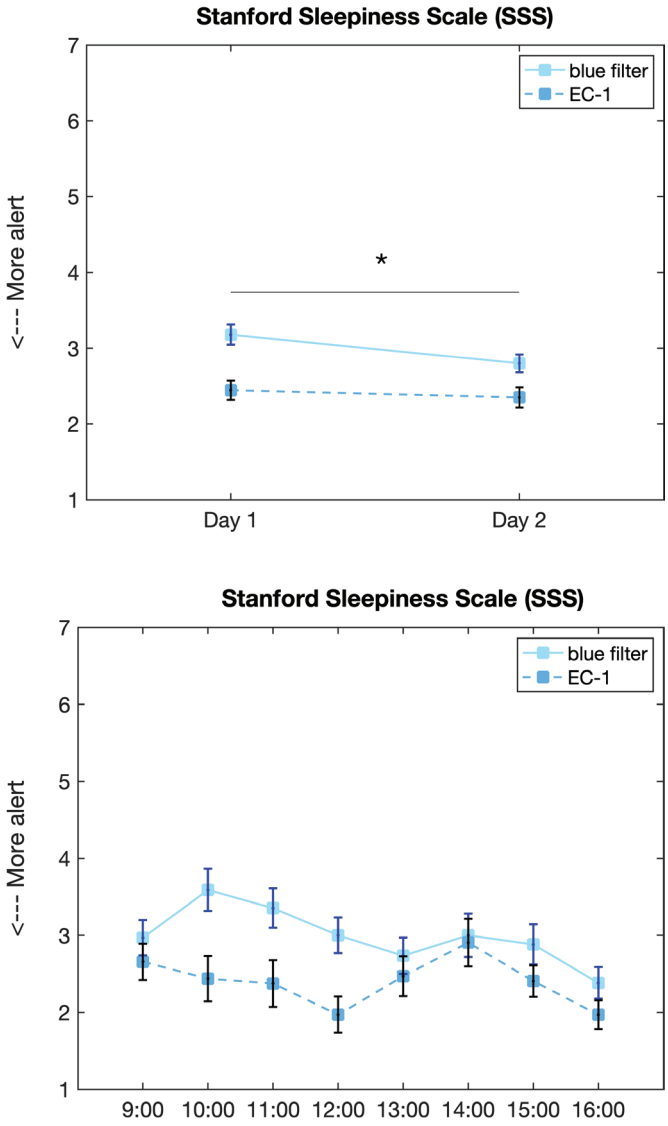


Figure 5.6 Mean values and associated standard errors of the effect of duration (up) and of timing of exposure (bottom) on subjective alertness (SSS). Significant main effects of duration (left) or timing (right) of exposure are represented with "+" ($p<0.10$), "*" ($p<0.05$), "**" ($p<0.01$), "***" ($p<0.001$). Interaction effects are represented with "#" ($p<0.05$), "##" ($p<0.01$), "###" ($p<0.001$) (simple contrasts for duration and/or timing of exposure) and with red asterisks ("*" ($p<0.05$), "**" ($p<0.01$), "***" ($p<0.001$)) for simple contrast of daylight.

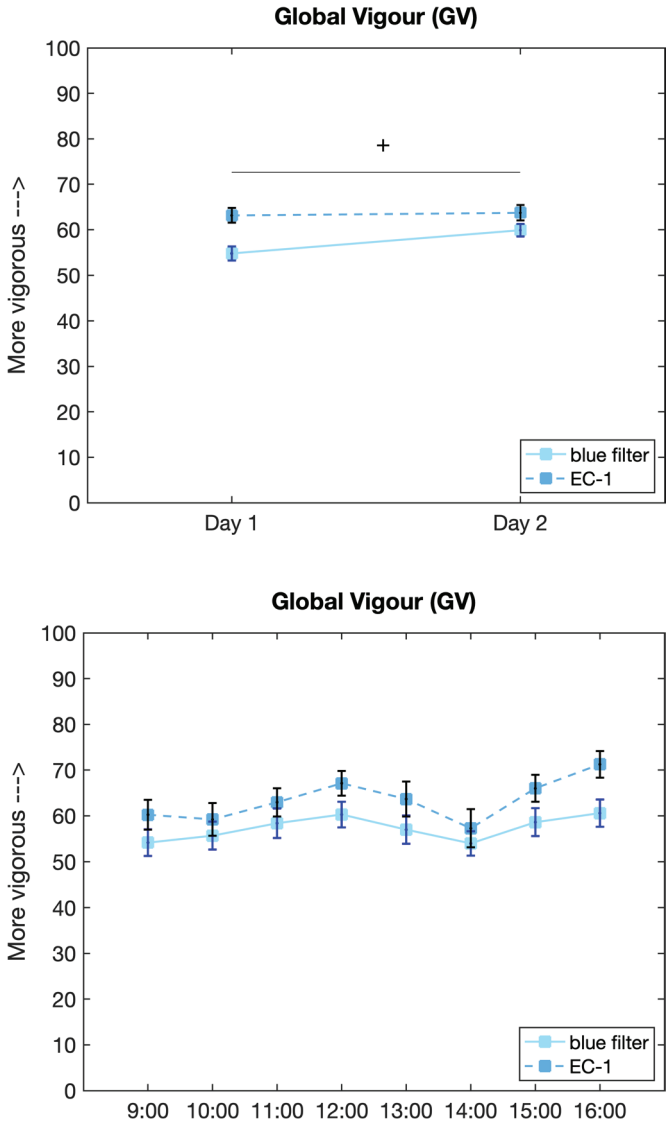


Figure 5.7 Mean values and associated standard errors of the effect of duration (up) and of timing of exposure (bottom) on subjective well-being (GV). Significant main effects of duration (left) or timing (right) of exposure are represented with "+" ($p<0.10$), "*" ($p<0.05$), "**" ($p<0.01$), "***" ($p<0.001$). Interaction effects are represented with "#" ($p<0.05$), "##" ($p<0.01$), "###" ($p<0.001$) (simple contrasts for duration and/or timing of exposure) and with red asterisks ("*" ($p<0.05$), "**" ($p<0.01$), "***" ($p<0.001$)) for simple contrast of daylight.

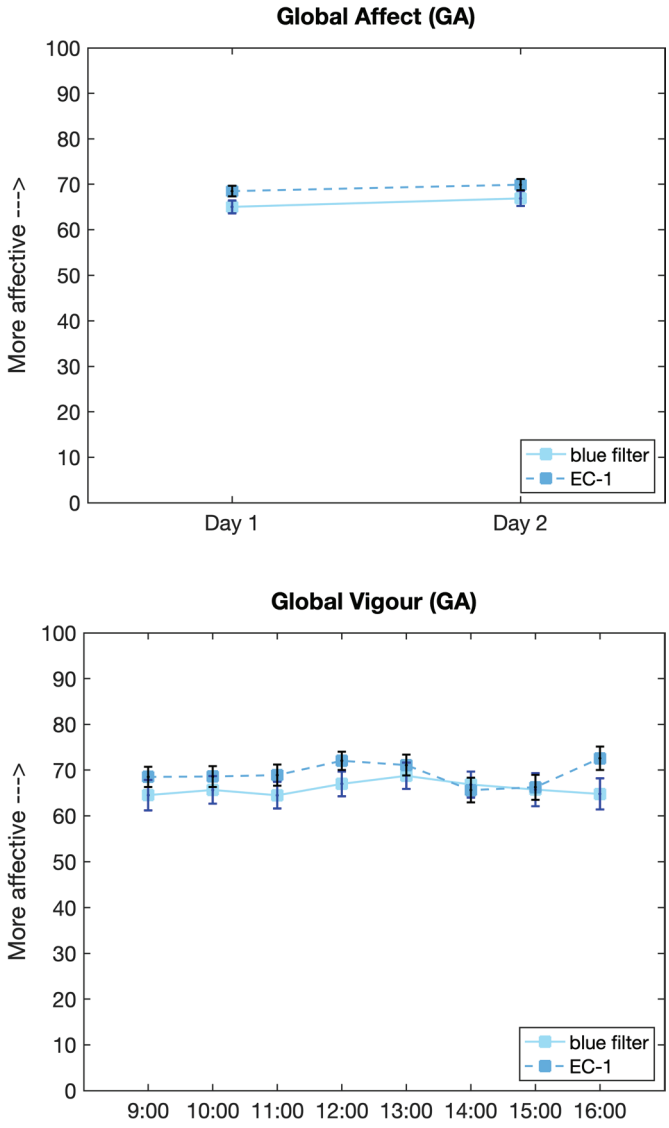


Figure 5.8 Mean values and associated standard errors of the effect of duration (up) and of timing of exposure (bottom) on subjective well-being (GA). Significant main effects of duration (left) or timing (right) of exposure are represented with "+" ($p<0.10$), "*" ($p<0.05$), "**" ($p<0.01$), "***" ($p<0.001$). Interaction effects are represented with "#" ($p<0.05$), "##" ($p<0.01$), "###" ($p<0.001$) (simple contrasts for duration and/or timing of exposure) and with red asterisks ("*" ($p<0.05$), "**" ($p<0.01$), "***" ($p<0.001$)) for simple contrast of daylight.

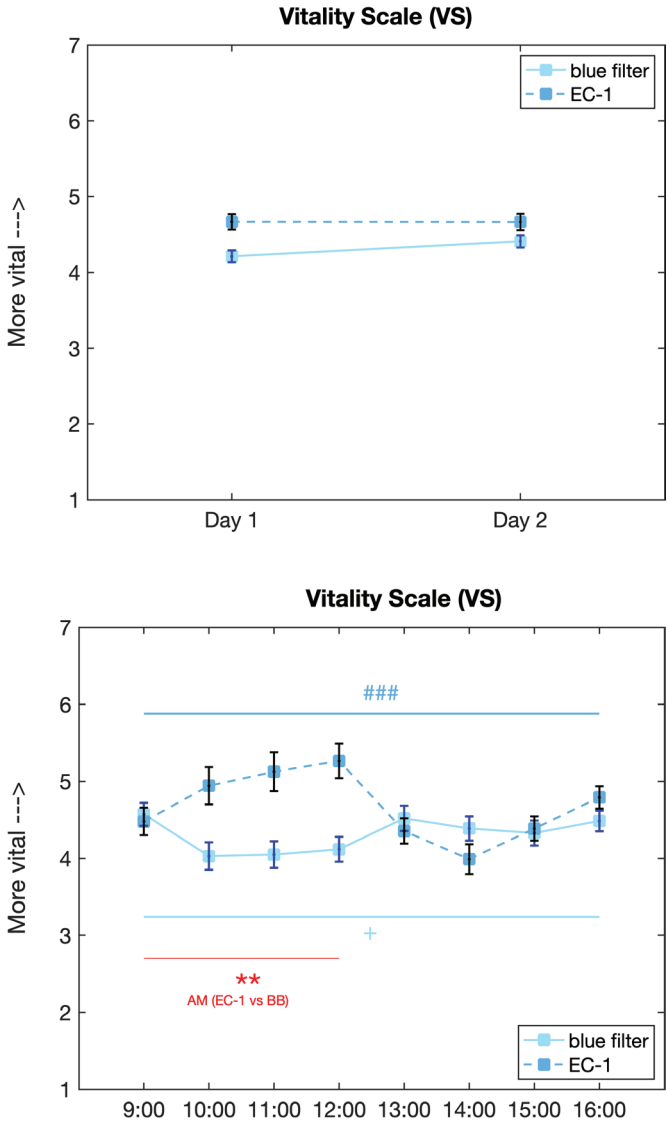


Figure 5.9 Mean values and associated standard errors of the effect of duration (up) and of timing of exposure (bottom) on subjective well-being (VS). Significant main effects of duration (left) or timing (right) of exposure are represented with "+" ($p<0.10$), "*" ($p<0.05$), "**" ($p<0.01$), "***" ($p<0.001$). Interaction effects are represented with "#" ($p<0.05$), "##" ($p<0.01$), "###" ($p<0.001$) (simple contrasts for duration and/or timing of exposure) and with red asterisks ("*" ($p<0.05$), "**" ($p<0.01$), "***" ($p<0.001$)) for simple contrast of daylight.

5.5.3. Performance in sustained attention

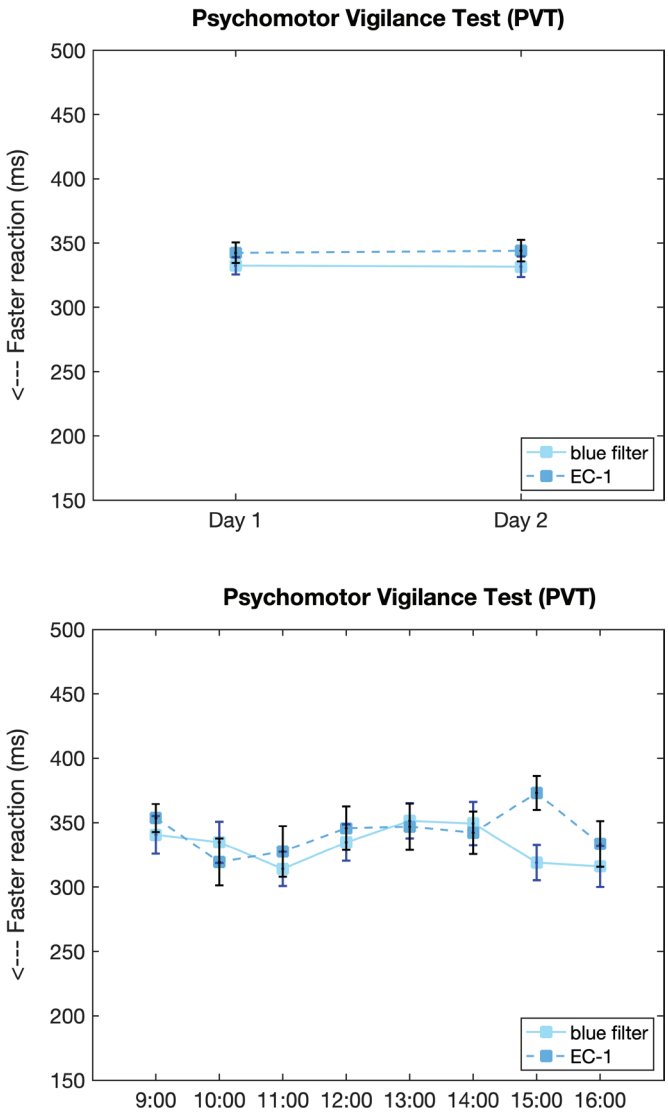


Figure 5.10 Mean values and associated standard errors of the effect of duration (up) and of timing of exposure (bottom) on sustained attention (PVT). Significant main effects of duration (left) or timing (right) of exposure are represented with "+" ($p<0.10$), "*" ($p<0.05$), "**" ($p<0.01$), "***" ($p<0.001$). Interaction effects are represented with "#" ($p<0.05$), "##" ($p<0.01$), "###" ($p<0.001$) (simple contrasts for duration and/or timing of exposure) and with red asterisks ("*" ($p<0.05$), "**" ($p<0.01$), "***" ($p<0.001$)) for simple contrast of daylight.

Sustained attention was evaluated here by means of reactivity to a visual task (section 3.5.2), and also main and interaction effects of daylighting condition, duration and timing of exposure were investigated with separate LMM. Reaction times lower than

150 ms or higher than 500 ms were excluded from the analysis since these responses are often categorized as anticipation or lapses, respectively (Münch et al., 2016b).

PVT performance was not affected neither by daylight condition nor by duration or timing of exposure, and no significant interactions were found either (Figure 5.10).

5.5.4. Physiological arousal

As discussed in section 3.5.3, cardiovascular activity was monitored continuously throughout the study to record changes in heart rate and on sympathetic (i.e., related to arousal promotion and energy generation) and parasympathetic activity (i.e., associated with rest activities). Mean values of HR (in beats per minute), LF and HF (both in milliseconds), and of the LF/HF ratio during the 5-minute hourly tasks when the participants' activity was controlled (i.e. while they were replying to the self-reported questionnaire and PVT), were used to perform the analyses.

The effect of lighting condition on HR was moderated by duration of exposure, indicating that there was a significant interaction between daylight and day of the experiment ($F(1,1701) = 11.21$, $p<0.01$). Analyses conducted at each daylight level showed that differences across days were significant under the EC-1 condition ($\chi^2(1) = -3.03$, $p<.01$) and marginally significant under the brighter one ($\chi^2(1) = 1.81$, $p<.10$). *Post-hoc* tests (simple contrasts for duration of exposure) revealed a slower HR during day 2 compared to day 1 ($p<.01$) under EC-1 condition, and slightly faster during day 2 compared to day 1 ($p<.10$) in the brighter room. In addition, simple contrasts for daylight showed no significant differences between conditions in either day (Figure 5.11). There was no interaction between daylight and timing of exposure, although the latter had a significant effect on HR ($F(1,1703) = 158.47$, $p<0.001$): independently of the daylighting condition, HR decreased throughout the day. *Post-hoc* tests revealed that participants HR was lower in the afternoon than in the morning ($\beta_{PM}=-6.76$, $p_{adj}<.001$) (Figure 5.11). The covariate corresponding to the baseline value for HR was significant ($p<0.001$).

The main effect of daylight condition was a marginally significant factor for LF ($F(1,1703) = 3.32$, $p<0.1$). There were no moderation effects with duration and timing of exposure. Both duration and timing of exposure reported significant differences between levels ($F(1,1703) = 5.72$, $p<0.05$ and $F(1,1703) = 21.40$, $p<0.001$), independently of daylighting condition. They indicated, respectively, that participants LF power decreased during the experiment but increased over the day. *Post-hoc* tests revealed that LF was lower during day 2 compared to day 1 ($\beta_{D2}=-306$, $p_{adj}<.05$) (Figure 5.12), and higher in the afternoon than in the morning ($\beta_{PM}=576$, $p_{adj}<.001$) (Figure 5.12).

Values of the HF power were only affected by timing of exposure ($F(1,1703) = 48.79$, $p<0.001$), indicating an increase in HF during the day but independently of daylighting condition. *Post-hoc* tests revealed that HF power was higher during the afternoon sessions than during the morning ones ($\beta_{PM}=528$, $p_{adj}<.001$) (Figure 5.13). Neither main effects due to lighting conditions or timing of exposure, nor significant interactions were detected (Figure 5.13). The covariate corresponding to baseline values for both LF and HF was significant ($p<0.001$ and $p<0.05$, respectively).

As for the LF/HF ratio, only timing of exposure showed significant differences ($F(1,1703) = 43,84$, $p<0.001$), indicating a decrease during the day independently of daylighting condition. *Post-hoc* tests revealed that the LF/HF ratio was higher in the morning than in the afternoon ($\beta_{PM}=-0.68$, $p_{adj}<.001$) (Figure 5.14). Neither main effects due to lighting conditions or duration of exposure, nor significant interactions were detected (Figure 5.14).

When looking at Figures 5.11 and 5.14, we can notice that hourly results have a particularly high peak 9:00 a.m. If we exclude those values from the analyses -which correspond to the first measurement block of the day-, heart rate still shows a significant difference between morning and afternoon sessions ($\beta_{PM}=-1.48$, $p_{adj}<.05$), whereas the LF/HF ratio does not anymore ($\beta_{PM}=-0.18$, $p_{adj}>.10$).

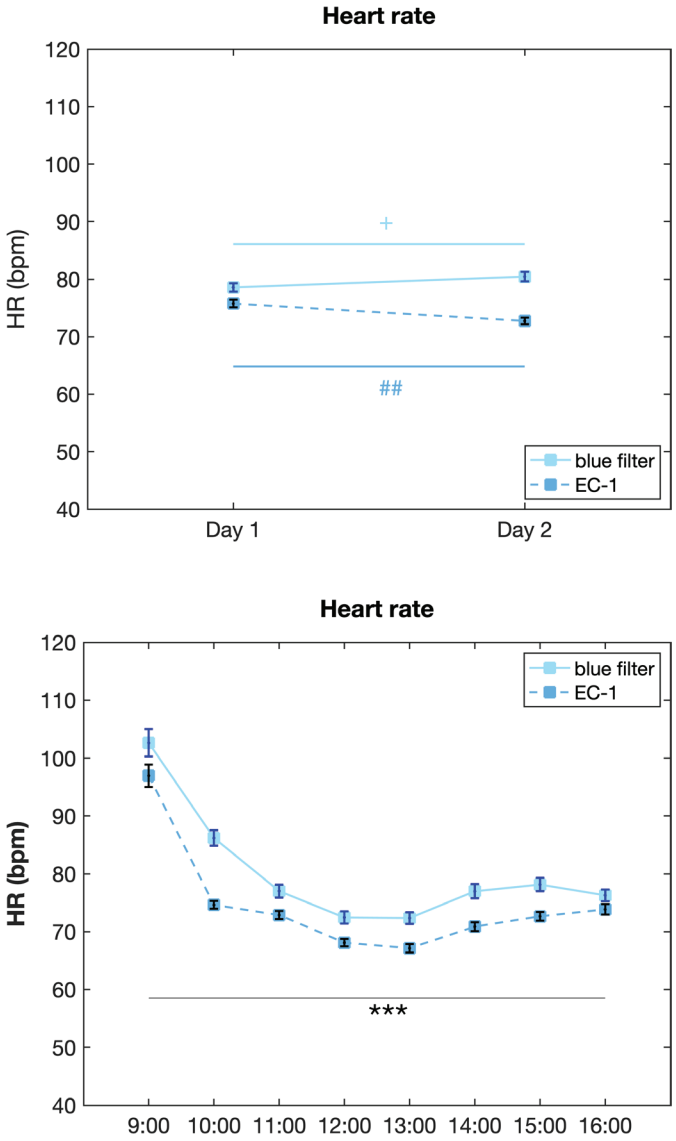


Figure 5.11 Mean values and associated standard errors of the effect of duration (up) and of timing of exposure (bottom) on physiological arousal based on HR. Significant main effects of duration (left) or timing (right) of exposure are represented with "+" ($p<0.10$), "*" ($p<0.05$), "**" ($p<0.01$), "***" ($p<0.001$). Interaction effects are represented with "#" ($p<0.05$), "##" ($p<0.01$), "###" ($p<0.001$) (simple contrasts for duration and/or timing of exposure) and with red asterisks ("*" ($p<0.05$), "**" ($p<0.01$), "***" ($p<0.001$)) for simple contrast of daylight.

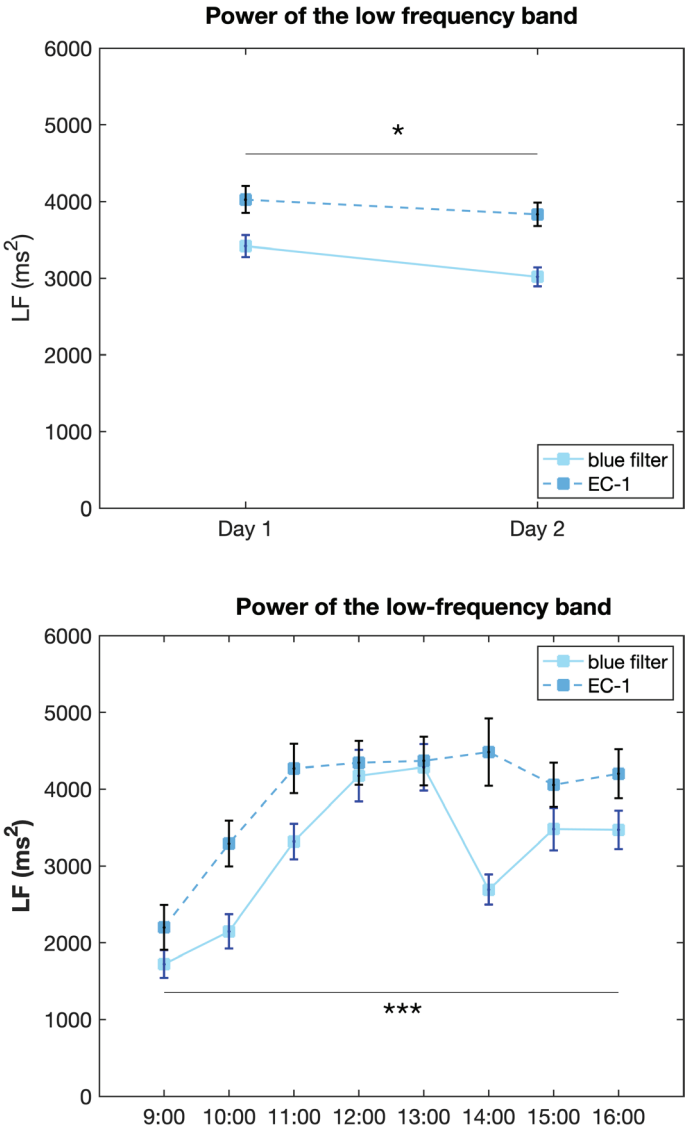


Figure 5.12 Mean values and associated standard errors of the effect of duration (up) and of timing of exposure (bottom) on physiological arousal based on LF power. Significant main effects of duration (left) or timing (right) of exposure are represented with "+" ($p<0.10$), "*" ($p<0.05$), "**" ($p<0.01$), "***" ($p<0.001$). Interaction effects are represented with "#" ($p<0.05$), "##" ($p<0.01$), "###" ($p<0.001$) (simple contrasts for duration and/or timing of exposure) and with red asterisks ("*" ($p<0.05$), "**" ($p<0.01$), "***" ($p<0.001$)) for simple contrast of daylight.

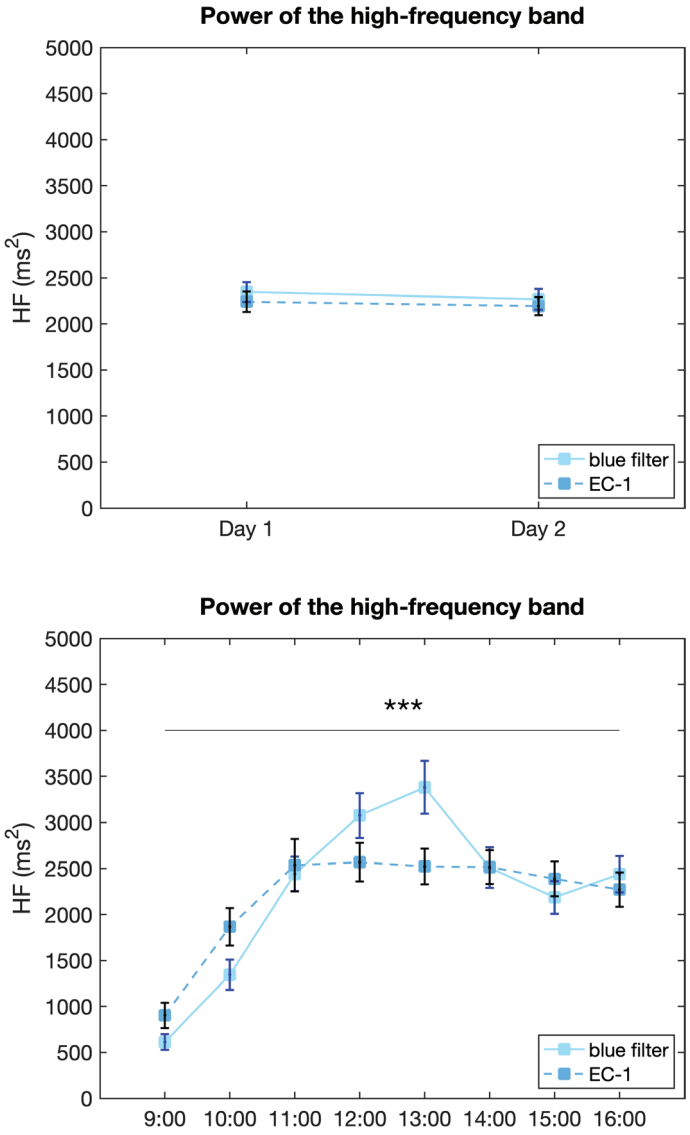


Figure 5.13 Mean values and associated standard errors of the effect of duration (up) and of timing of exposure (bottom) on physiological arousal based on HF power. Significant main effects of duration (left) or timing (right) of exposure are represented with "+" ($p<0.10$), "*" ($p<0.05$), "**" ($p<0.01$), "***" ($p<0.001$). Interaction effects are represented with "#" ($p<0.05$), "##" ($p<0.01$), "###" ($p<0.001$) (simple contrasts for duration and/or timing of exposure) and with red asterisks ("*" ($p<0.05$), "**" ($p<0.01$), "***" ($p<0.001$)) for simple contrast of daylight.

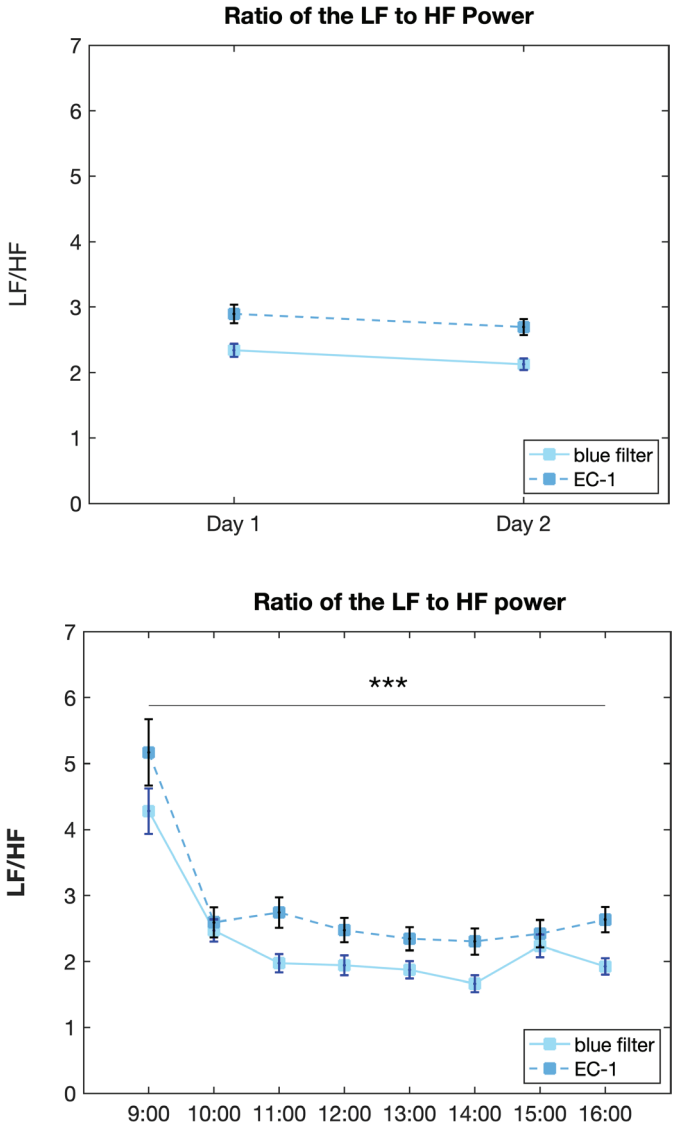


Figure 5.14 Mean values and associated standard errors of the effect of duration (up) and of timing of exposure (bottom) on physiological arousal based on the ratio of the LF/HF power. Significant main effects of duration (left) or timing (right) of exposure are represented with "+" ($p<0.10$), "*" ($p<0.05$), "**" ($p<0.01$), "***" ($p<0.001$). Interaction effects are represented with "#" ($p<0.05$), "##" ($p<0.01$), "###" ($p<0.001$) (simple contrasts for duration and/or timing of exposure) and with red asterisks ("*" ($p<0.05$), "**" ($p<0.01$), "***" ($p<0.001$)) for simple contrast of daylight.

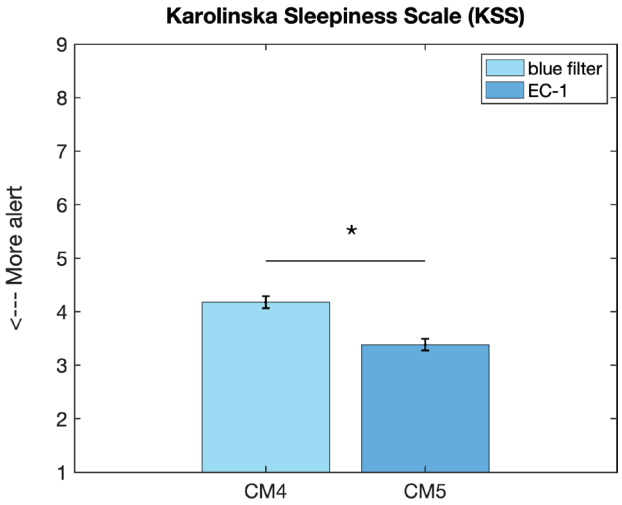
5.6. STUDY B OUTCOMES

Daytime effects of prolonged exposures to variations in daylight's intensity levels under blue-shifted conditions have been examined in this study on subjective reports of alertness and well-being, sustained attention and arousal. More specifically, we investigated whether previous research on the alerting effects of polychromatic white (with variations in CCT) or monochromatic light (with variations in wavelength) could be reproduced in a daylit environment (i.e., without any electric illumination) and under circumstances similar to those encountered in our daily lives.

5.6.1 Main effect of daylight condition

In this study, where intensity levels were confounded with spectral-shifts, surprising results were obtained regarding the effect of daylight intensity variations under blue-shifted spectra (Figure 5.15). According to the literature, and confirmed by our previous study (Chapter 4, study A), bluer environments often lead to higher alertness and better performance (Cajochen et al., 2011; Chellappa et al., 2011; Wahnschaffe et al., 2013), and higher intensities have also been proved to increase subjective alertness and sustained attention (Lok et al., 2018; Souman et al., 2018).

The brighter scenario (average EDI of 84 vs 45 lx of vertical illuminance), which also looks "bluer" (average ELR of 1.62 vs 1.26 and CCT of 9,765 K vs 6,651 K), resulted in higher sleepiness scores (measured by both the KSS (β_{BF}=0.72, p_{adj}<0.05) and the SSS (β_{BF}=0.52, p_{adj}=.05)) and in slightly lower LF power (β_{BF}=-726, p_{adj}=0.10), irrespective of day or experimental session, indicating that the effect persisted throughout the day and over the entire duration of the experiment.



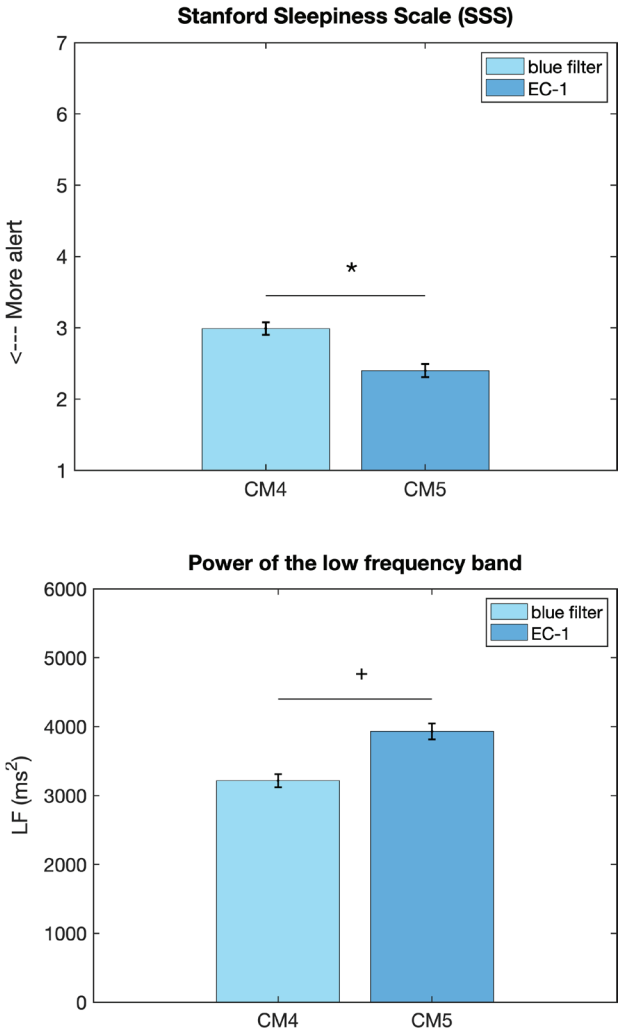


Figure 5.15 Mean value ± standard error of the main effect of daylight condition on KSS (a), SSS (b) and LF (c). Significance is represented with "+" ($p<0.10$), "*" ($p<0.05$), "**" ($p<0.01$), "***" ($p<0.001$).

As introduced in Chapter 3, LF power has been associated with the sympathetic division of the autonomic nervous system, in charge of arousal promotion and energy generation (Kaida et al., 2007; Shaffer and Ginsberg, 2017). This means that, although our results cannot replicate findings from previous studies or confirm our initial hypothesis (H1), they are consistent among themselves: dimmer and "less" blue daylight tends to increase alertness and to promote physiological arousal. These results remain nonetheless quite unexpected and do not follow intuition.

5.6.2 Effects of duration and timing of exposure

Like in study A, the duration of exposure (i.e., number of experimental days) significantly affected self-reports of alertness (KSS and SSS), vigour and cardiovascular activity (LF), independently of the lighting condition. For all these variables, scores improved during the second day compared to the first one (participants felt more alert and more vigorous throughout the experiment), except in terms of LF power, where measurements decreased from day 1 to day 2. The fact that this happened irrespective of the lighting condition, even though illuminance levels generally decreased slightly throughout the experiment (due to weather changes i.e. simultaneously for both rooms, cf. Table 5.3 and Figure 5.4 in section 5.2.1) suggests a systematic adaptation to experimental conditions over the days and partially confirms our hypothesis (H2) that longer daytime exposures induce stronger effects on correlates of alertness. However, this was not the case when it comes to LF power, where values decreased instead, indicating a weaker sympathetic activity in Day 2 compared to Day 1.

For HR measurements, duration of exposure was shown to mediate the effect of daylight conditions in alertness and led to very interesting results: while HR slightly increased in the bright blue condition, it significantly decreased with the EC-1 glazing state. These results seem to imply a photic effect due to brighter blue conditions that becomes stronger over time (even though illuminance levels decreased throughout the experiment, as pointed out earlier), thus confirming both our first and second hypothesis presented in Chapter 1: bluer and brighter conditions (H1), as well as longer exposures (H2) may elicit stronger effects on correlates of alertness.

Time of day in particular affected physiological indicators (HR, LF and HF), independently of light condition. As highlighted in study A, the fact that the natural dynamics of daylight were not explicitly quantified in the analyses makes it difficult to differenciate whether the main effect of timing of exposure arises from the hypothesized underlying circadian rhythmicity or instead from a systematic variation in illuminance levels between morning and afternoon sessions within classrooms (Figure 5.16). Such insights could lead the path to better inform our third hypothesis (H3), since we expected morning and afternoon sessions to behave differently.

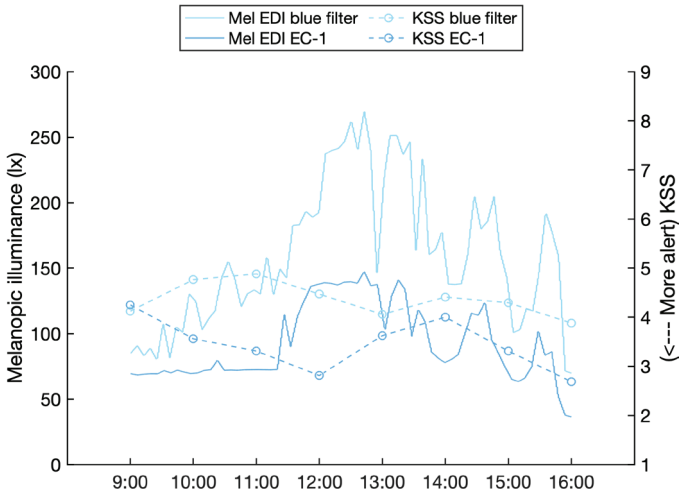


Figure 5.16 Mean values of KSS values vs melanopic EDI (lx) over time.

For subjective reports of vitality, timing of exposure was responsible for mediating the way daylight elicited such responses. Although differences in scores were observed under both conditions, in the EC-1 room participants felt significantly less vital in the afternoon than in the morning, whereas in the bright blue one, an opposite but marginal outcome was found: participants felt slightly more vital in the afternoon than in the morning. This could imply, as suggested earlier, a photic effect due to daylighting conditions that changed based on the time of day, thus confirming hypothesis H3 (morning and afternoon sessions behave differently). However, it clearly contradicts hypothesis H1, since dimmer and "less blue" conditions unexpectedly elicited stronger effects than brighter, bluer ones.

5.6.3 Discussion on STUDY B

We decided to further investigate our hypothesis (i.e., exposure to bluer and brighter daylight might reduce subjective sleepiness, increase subjective well-being, improve attention and favour arousal) by confronting current results with those in study A. The idea was to compare a third blue condition (namely EC-2, or dim blue as described in Chapter 4), which has a similar melanopic efficacy luminous radiation, but a much lower illuminance level compared to that in the blue filter (see Table 5.4), so as to try to understand whether the effectiveness of the intermediate condition (EC-1) is actually derived from the lower amount of "blue" or rather, from the lower illuminance level, which in any case will be difficult to explain (Figure 5.15).

Table 5.4 Average spectrally weighted α-opic efficacy luminous radiation in W/lm (ELR) and equivalent daylight (D65) illuminance in lux (EDI) measured at the eye level, for each daylighting condition.

		Blue filter		EC-1		EC-2	
Illumin.		*ELR (W/lm)*	*EDI (lux)*	*ELR (W/lm)*	*EDI (lux)*	*ELR (W/lm)*	*EDI (lux)*
photopic	Visibility		118.53		89.17		25.04
melanopic	ipRGC	**1.62**	144.92	**1.25**	84.32	**1.65**	31.23

Since experiments were conducted in different years, changes in weather but also in daylight dynamics were not experienced in parallel between groups (as was the case when comparing lighting scenarios from the same study). In order to avoid potential moderation effects of duration of exposure, only data from the first day of this and study A will be considered for the follow up evaluation. Therefore, a simple linear mixed model, including daylight condition (bright blue (BB), EC-1 and EC-2) as fixed factor and participant identifier as random intercept (i.e., to account for repeated measurements throughout the day on the same subject), was used to analyse differences between the three scenarios in all subjective and objective dependent variables.

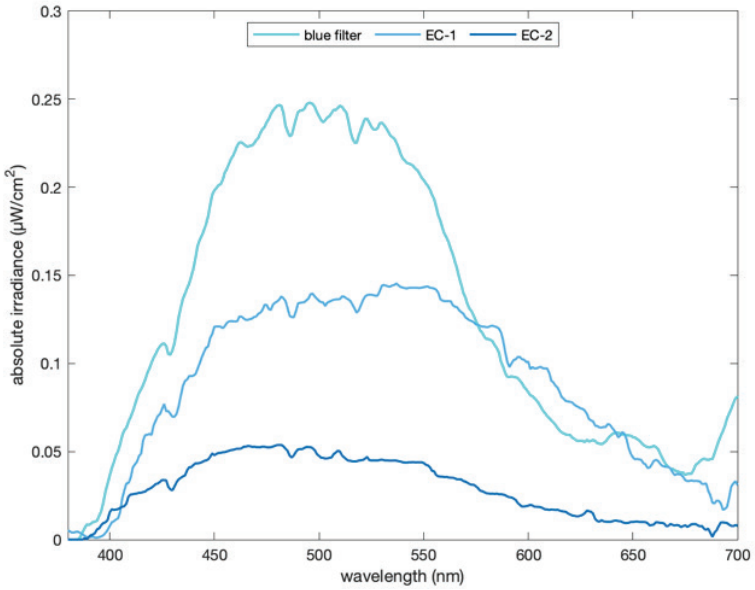
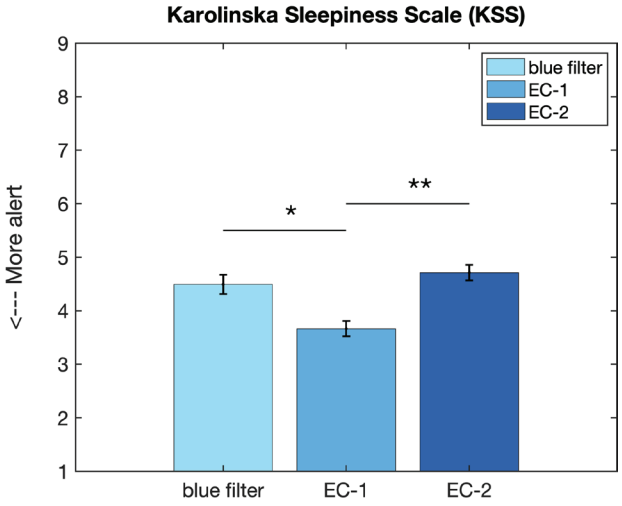
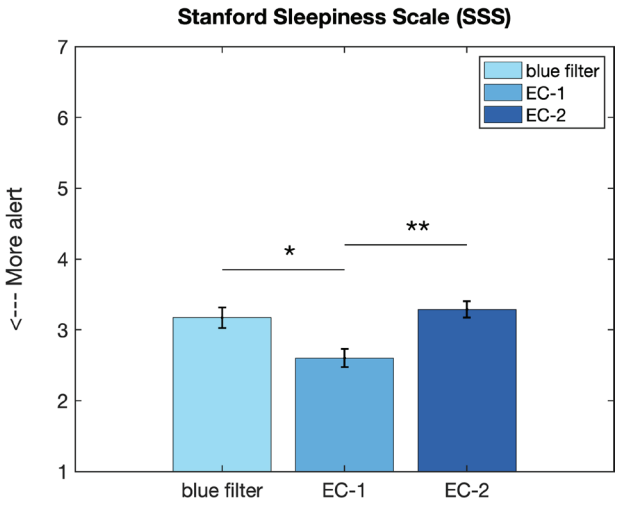
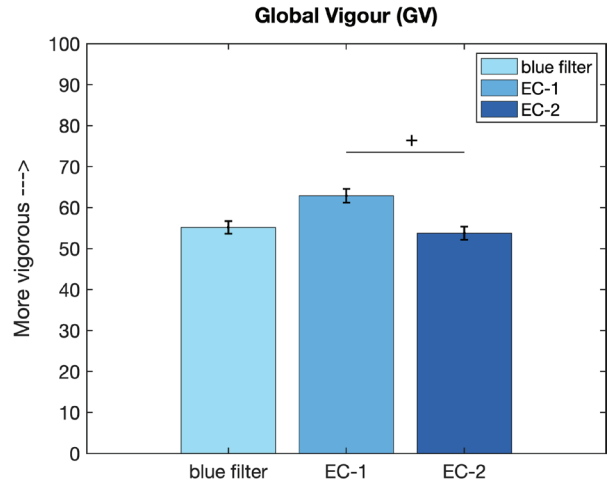


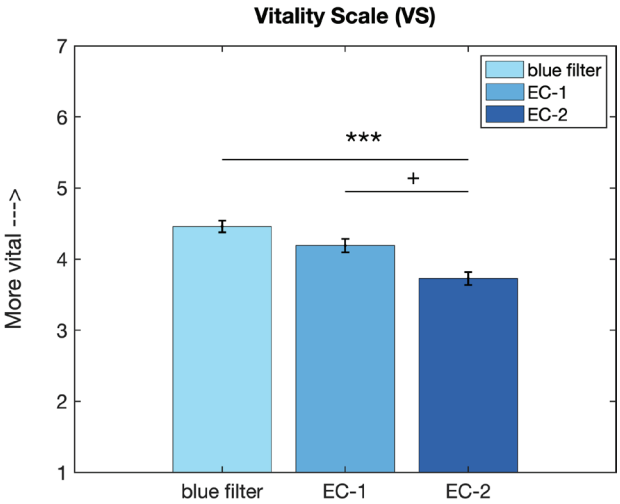
Figure 5.16 Average mean, maximum and minimum irradiance values per wavelength, measured at the eye level during DAY 1 for all three daylight conditions.

Daylight condition had an effect on indicators of subjective sleepiness (KSS ($F(1,399) = 6.55$, $p<0.0$) and SSS ($F(1,399) = 5.48$, $p<0.01$)), vigour (GV ($F(1,399) = 3.31$, $p<0.05$)), vitality (VS ($F(1,400) = 9.68$, $p<0.001$)) and heart rate (HR ($F(1,1552) = 2.80$, $p<0.10$)) (Figure 5.17). Regarding subjective sleepiness, when measured with the KSS scale, participants felt significantly more alert in the EC-1 condition than in the EC-2 one ($\beta_{EC2}=1.29$, $p_{adj}<.01$), and in the EC-1 condition than in the bright blue one ($\beta_{EC1}=-0.92$, $p_{adj}<.05$) (Figure 5.17 a). If measured with the SSS scale, significant differences between the EC-2 and the EC-1 condition, as well as between the EC-1 and the bright blue condition, were also observed, with participants feeling again more alert under EC-1 conditions in both cases ($\beta_{EC2}=0.86$, $p_{adj}<.01$ and $\beta_{EC1}=-0.74$, $p_{adj}<.05$, respectively) (cf. Figure 5.17 b). For scores on GV, only marginal differences were observed between EC-1 and EC-2 conditions. Participants felt slightly more vigorous in the former than in the latter ($\beta_{EC2}=-9.70$, $p_{adj}<.10$) (cf. Figure 5.17 c). As for vitality levels (VS), participants felt significantly more vital in the bright blue condition than in the EC-2 one ($\beta_{EC2}=-0.95$, $p_{adj}<.001$), but also, slightly more vital in the EC-1 one than in EC-2 ($\beta_{EC2}=-0.49$, $p_{adj}<.10$) (cf. Figure 5.17 d). Finally, when evaluating HR measurements, only a marginal difference was found between participants in the bright blue condition and those in EC-2, indicating that their HR was slightly higher in the bright blue condition ($\beta_{EC2}=-8.16$, $p_{adj}<.10$) (Figure 5.17 e). No significant differences were found for other physiological indicators (LF, HF or the ratio of LF/HF), and no significant differences were found either between lighting conditions for GA scores or reaction times, which is consistent with findings shown at the beginning of this section.




Stanford Sleepiness Scale (SSS)
<--- More alert
blue filter
EC-1
EC-2
*
**
1
2
3
4
5
6
7
blue filter
EC-1
EC-2


Global Vigour (GV)
More vigorous --->
blue filter
EC-1
EC-2
+
0
10
20
30
40
50
60
70
80
90
100
blue filter
EC-1
EC-2


Vitality Scale (VS)
More vital --->
blue filter
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+
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blue filter
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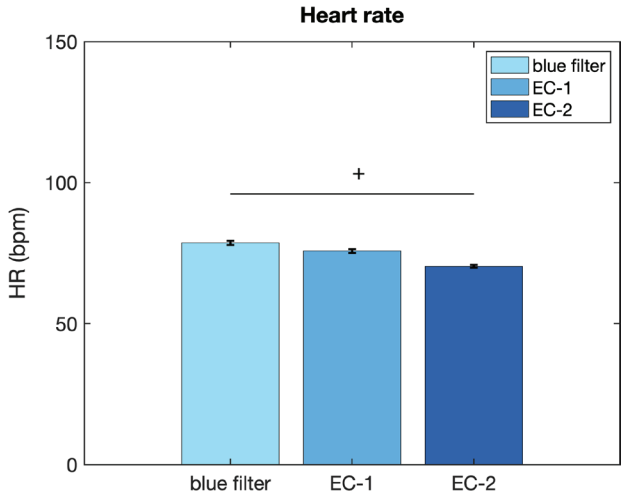


Figure 5.17 Mean value ± standard error of the main effect of daylight condition on KSS (a), SSS (b), GV (c), VS (d) and HR (e). Significance is represented with "+" ($p<0.10$), "*" ($p<0.05$), "**" ($p<0.01$), "***" ($p<0.001$).

One of the first conclusions that can be drawn just by observing the graphs in Figure 5.16 is that variations in illuminance levels (measured as both photopic and melanopic quantities) were effective in all included variables, namely KSS, SSS, GV, VS and HR, independently of the blue content of their associate light scenario.

Higher intensities, when compared to dimmer ones, favoured stimulation of alertness, well-being, and arousal. For HR, the difference was only marginal when comparing bright blue with EC-2 (more arousal in the brighter condition). For VS, the difference was significant when comparing bright blue with EC-2 and was marginal when comparing EC-1 with EC-2 (more vitality in the brighter conditions in both cases). For GV, the difference was also marginal when comparing EC-1 with EC-2 (more vigour in the brighter condition), whereas for SSS, the difference was significant when comparing EC-1 with EC-2 (higher alertness in the brighter condition). Finally, for KSS, the difference was also significant when comparing EC-1 with EC-2 (higher alertness in the brighter condition). For most variables, whenever a significant effect was found for a brighter (compared to a dimmer) condition, it also happened to be the "least blue" condition of the two (i.e., the light scenario with the lowest ELR), except for VS and HR, where the brightest condition (bright blue) and the dimmest one (EC-2) actually had a similar ELR (1.62 vs 1.65 *W/lm* respectively). Surprisingly though, when it comes to subjective alertness (KSS, SSS), a detrimental effect was observed with regards to brightness, and more specifically, when comparing bright blue with EC-1: the former led to lower alertness compared to the latter. This is actually consistent with results found at the beginning of this chapter, in which participants felt more alert in the dimmer condition (EC-1), which also happened to be the "least blue" one (1.25 *W/lm* of melanopic ELR).

Overall, it seems that intensity variations (although modest) of blue-shifted daylight were in general more effective in eliciting non-visual responses than the manipulation of blue content itself (i.e., changes on the blue part of the spectrum) in this study, especially when it comes to subjective well-being and arousal. In other words, it seems like once a certain amount of "blue" content is guaranteed, intensity manipulations are generally more effective, even at low levels like the ones tested in our studies. Yet, this was not the case for measurements of subjective alertness (assessed with both the KSS and the SSS), where the brighter blue environment resulted in a detrimental (i.e., negative) effect when compared to a moderate bright one (EC-1), which seems at least counterintuitive. The latter condition (EC-1), however, significantly improved subjective alertness when compared to the dimmest scenario (EC-2), as expected. These outcomes are not easy to explain since both the EC-2 condition and the bright blue condition have a very similar ELR (i.e., 1.65 and 1.62, respectively), and where the "bluest" ones when compared to EC-1 (ELR of 1.25 instead). Therefore, it might be that this particular combination of bright and blue light (blue filter) used in the study is not optimal for promotion of subjective alertness.

Therefore, further investigation is needed in this direction. On the one hand, and as discussed in section 4.6.3, higher illuminances are to be tested so as to match required values in standards and regulations for visual performance (i.e., at least 300 lx). However, since in study A the blue scenario was consistently able to improve alertness throughout the experiment compared to the non-filtered one despite of the very dim conditions tested, a dose-response investigation seems pertinent in future steps. This might help elucidate whether a similar threshold such as the one pointed out by Cajochen and colleagues (Cajochen et al., 2000) for nighttime alertness under fluorescent light can instead be found for daytime effects of blue-shifted (day)light. On the other hand, different "blue" scenarios in which illuminance levels are not compromised (i.e., not confounded with spectral manipulations) should be tested so as to clarify and reveal the actual contribution of blue energy.

6 EFFECTS OF [DAYLIGHT INTENSITY UNDER NEUTRAL SPECTRA] STUDY C

This chapter describes the conditions and results of the third and last experiment of this thesis, conducted to investigate whether variations in daylight's intensity levels under non-spectrally shifted conditions can induce measurable effects on participants' alertness, sustained attention and arousal levels. Our initial hypotheses were that:

- exposure to brighter daylight, when compared to dimmer conditions with similar non-filtered (neutral) spectrum, might reduce subjective sleepiness, increase subjective well-being, improve attention and favour arousal (H1 but without the spectral aspects).

- same hypotheses as in study A and B (H2 and H3) are tested here with regards to duration and timing of exposure.

6.1 ENVIRONMENTAL CONDITIONS

This study was conducted in the late Spring of 2019 during three consecutive days (June 8th, 9th and 10th), and with two weeks difference with respect to study B. It followed the same protocol as the previous two studies, both in terms of duration and timing of exposure.

Outdoor environmental conditions were not monitored but evaluated for the specific days of the study, as we did for studies A and B, based on weather data gathered from the closest weather station located in Pully (VD, Switzerland). Figure 6.1 represents the resulting sky condition visualization, which was generated using the same simulation workflow as described in Chapter 4. It corresponds – based on human observation during the experimental days – to partly cloudy with sun in day 1, to overcast with light to moderate rain in days 2 and 3.

Table 6.1 Environmental conditions in the classrooms. Average values and associated standard deviation of temperature and humidity levels per lighting condition, for the entire duration of the experiment.

	Brighter (neutral) (CM4)	Dim (neutral) (CM5)
Temperature (°C)	23.1 ± 0.9	22.5 ± 0.6
Humidity (%)	47.4 ± 2.9	46.6 ± 2.2

Temperature and humidity levels inside the classrooms are reported in summarized form in Table 6.1.

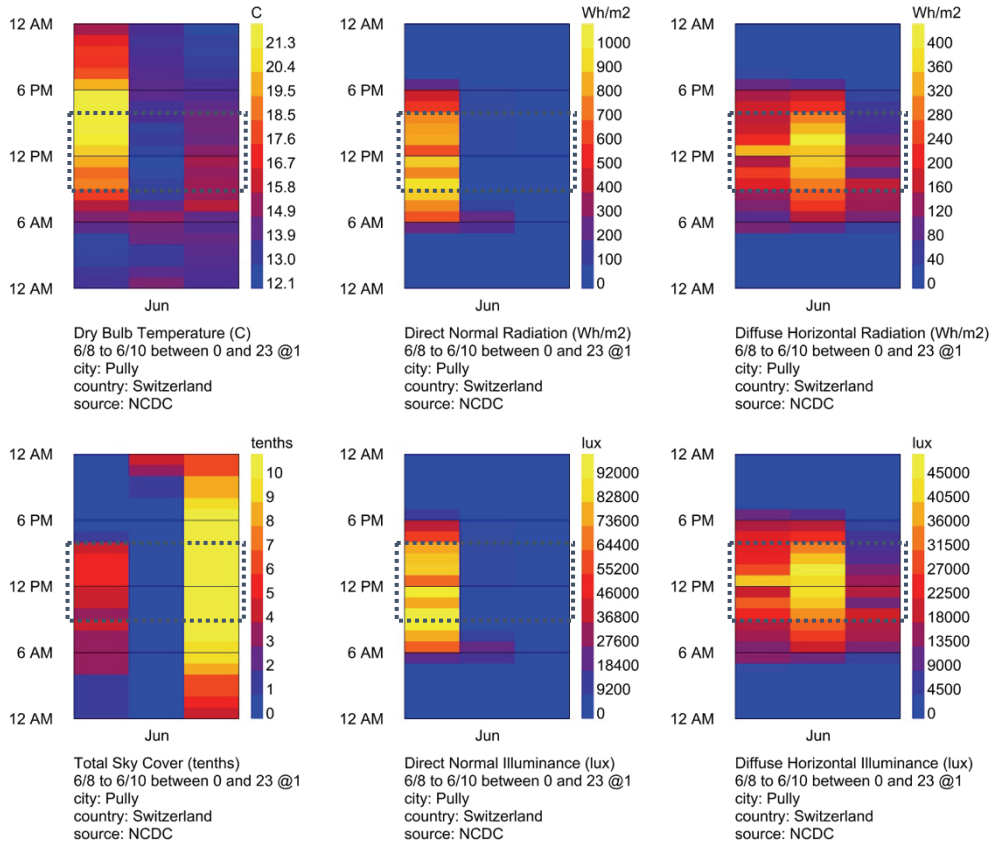


Figure 6.1 Overview of weather conditions throughout the experiment. From left to right, from first to second row: dry bulb temperature (°C), direct normal radiation (Wh/m²), diffuse horizontal radiation (Wh/m²), total sky cover (tenths), direct normal illuminance (lux) and diffuse horizontal illuminance (lux).

6.2 LIGHT STIMULI

While in studies A and B manipulations or comparisons to blue environments were explored, in this study two optically neutral, non-spectrally modified conditions were instead investigated. They correspond to a brighter vs. dim (neutral) daylit scenario (Figure 6.2), with similar CCT (5,399 K and 5,602 K respectively) and similar melanopic efficacy luminous radiation values (Table 6.2). Intensity levels were obtained using the clear state of the electrochromic glazing (EC clear) in one of the rooms, and neutral filters were applied to diminish illuminance levels at the work plane in the other room (Neutral filter + EC clear). The visual transmittance (Tvis) of the clear glazing was 55%, while the combination of clear state plus filters resulted in a 7% Tvis.

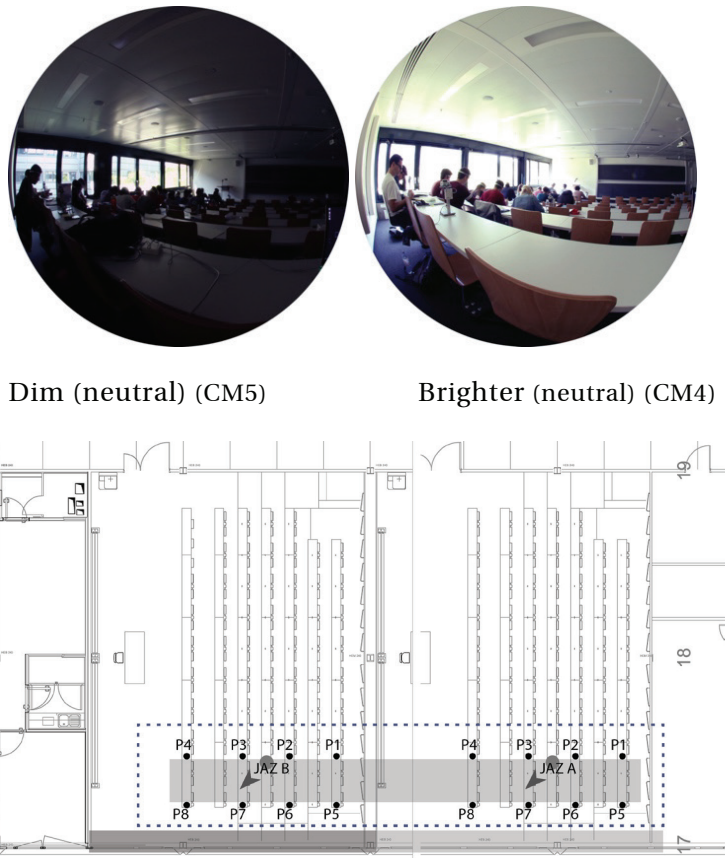


Figure 6.2 View of daylight manipulations in the classrooms; left, classroom CM5, dim (neutral) conditions (Neutral filter + EC clear, 7% Tvis) and right, classroom CM4, brighter (neutral) conditions (EC clear, 55% Tvis).

6.2.1 Daylight exposure

Spectral power distribution (SPD) was measured at the eye level and view direction of a seated participant throughout the experiment (Figure 6.2, large black dots), and horizontal illuminance was measured at the working plane -desk level- as outlined in Figure 6.2. (small black dots, p1-p8).

Figure 6.3 depicts absolute irradiance (W/cm2/nm) (SPD recorded measurements) as average mean, maximum, and minimum values for the entire duration of the experiment, for both daylighting conditions (dim vs brighter). This graph shows that the two conditions were entirely different in terms of intensity, but very close in terms of spectral distribution, with both conditions peaking near 550 nm.

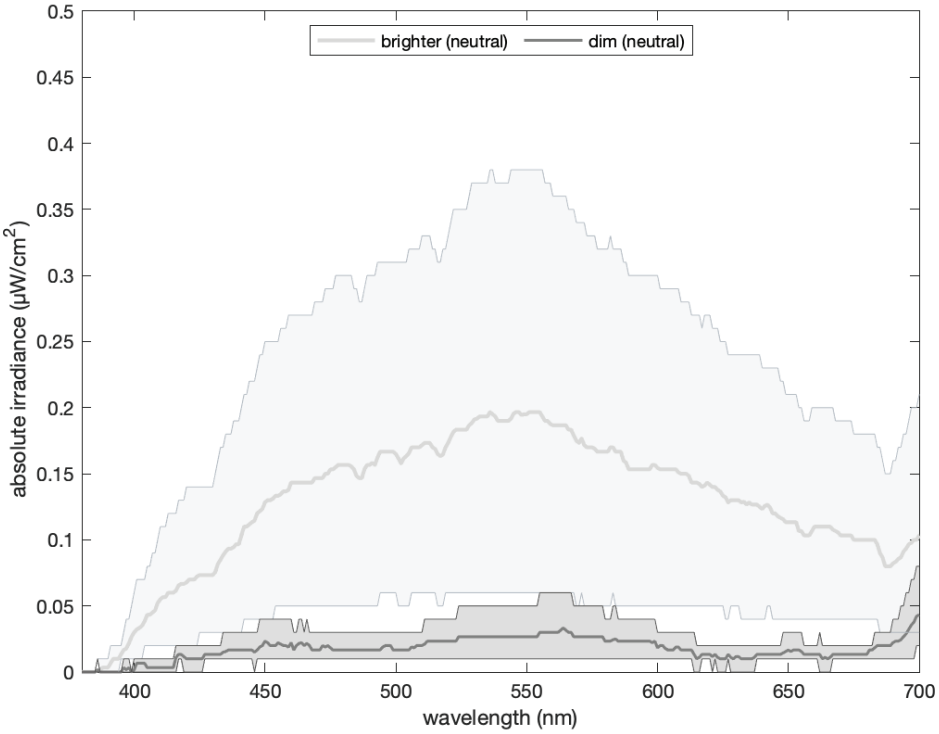


Figure 6.3 Average mean, maximum and minimum irradiance values per wavelength, measured at the eye level for both daylight conditions

For each one of five human photoreceptors, spectrally-weighted irradiance values measured by an eye-level spectroradiometer were derived using the CIE S026 toolbox (based on Lucas et al. (2014)). α-opic quantities of efficacy luminous radiation [W/lm] and equivalent daylight (D65) illuminance values [lux] (CIE, 2018) are described in Table 6.2. Quantities of both photopic and melanopic EDI were, unsurprisingly, higher in the room with the brightest conditions than in the dimmer one.

Table 6.2 Average spectrally weighted α-opic efficacy luminous radiation in W/lm (ELR) and equivalent daylight (D65) illuminance in lux (EDI) measured at the eye level, for each daylighting condition.

		Brighter (neutral) (CM4)		**Dim (neutral) (CM5)**	
Illuminance	**Sensitivity**	*ELR (W/lm)*	*EDI (lux)*	*ELR (W/lm)*	*EDI (lux)*
photopic	Visibility		124.01		17.03
cyanopic	S-cone	0.51	78.01	0.53	11.15
melanopic	**ipRGC**	**1.09**	**101.67**	**1.02**	**13.04**
rhodopic	Rod	1.26	107.81	1.20	14.11
chloropic	M-cone	1.41	120.28	1.41	16.49
Erythropic	L-cone	0.20	122.02	1.58	16.57

Patterns of horizontal photopic illuminance are described in Figure 6.4 and presented as average hourly values per day of experiment, photometer and daylight condition. Considering that in sky-dependent conditions the luminous environment changes rapidly, the data shows that horizontal illuminance remains distinct enough through the whole experiment between the two rooms. A more quantitative view of this is provided by means of average values and related standard deviations for every day and daylight scenario, summarised in Table 6.3.

Table 6.3 Average daily values (± standard deviation) of horizontal photopic illuminance at the desk, per daylighting condition.

	Daylight illuminance (lx)		
Lighting condition	*Day 1*	*Day 2*	*Day 3*
Brighter (neutral)	233 ± 181	85 ± 95	119 ± 181
Dim (neutral)	27 ± 18	17 ± 31	16 ± 22

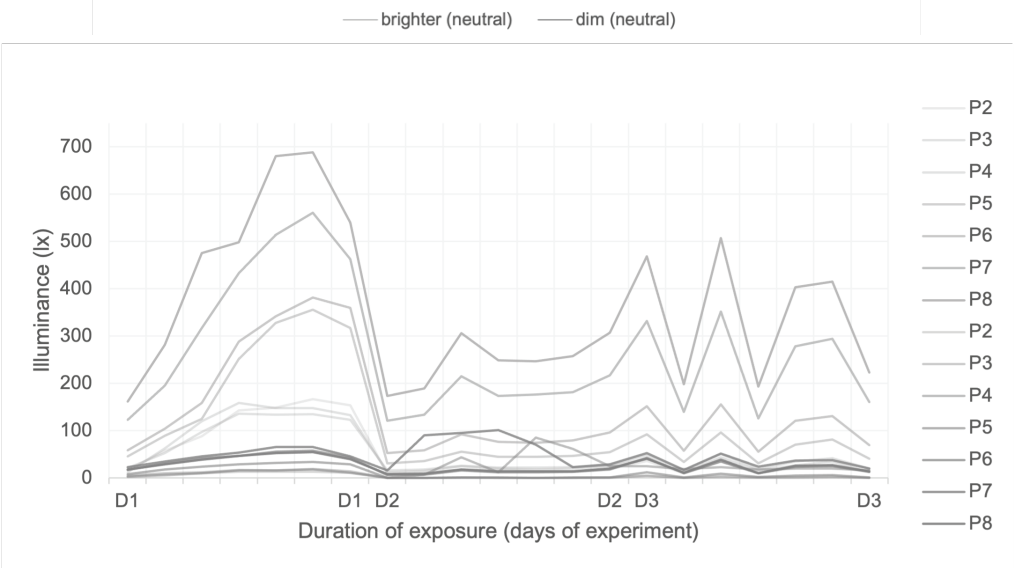


Figure 6.4 Average hourly values of horizontal photopic illuminance at the work plane, over time (days of exposure) and per photometer.

6.2.2 Timing and duration of exposure

The experiment was conducted over three consecutive days (Saturday, Sunday and Monday) as in study A, and the same protocol was used for all three experiments as outlined in section 3.3.1, including the number of sessions and the hours of exposure per day.

6.3 PARTICIPANTS

The same participants that joined study B, came back to the campus two weeks later for this experiment. Both seating and room assignment was re-randomized among the 33 participants while still accounting for gender balance. Again, 16 subjects were assigned to the room with brighter neutral daylight (CM4, Figure 6.2 left) and the 17 others to the room with dim neutral daylight (CM5, Figure 6.2 right). Both seating and room assignment was re-randomized. Each participant was assigned a given desk location within the room (which was re-randomized as explained earlier), which remained for the whole duration of the experiment (see section 3.2). 6 female and 10 male participants participated in the first condition, while 6 female and 11 male participants joined the second one.

6.4 DATA ANALYSIS

A 2 x 3 x 2 mixed factorial design was used in this case (as in study A) to test the effects of intensity variations under neutral conditions (brighter and dim, with brighter conditions as the reference), as well as of timing and duration of daylight exposure on ten dependent variables (i.e., KSS, SSS, GV, GA, VS, PVT, HR, LF, HF and the LF/HF ratio. As described in sections 4.4 and 5.4, LMM analyses were conducted separately per dependent variable, accounting for both main and interaction effects of fixed factors.

6.5 RESULTS

As in studies A and B, the first approach to the data was to understand whether there were significant differences between light scenarios during the first measurement block of each day of experiment (i.e., at 9 am). Following that, the effects of daylighting condition, duration and timing of exposure, as well as of their interaction on alertness correlates were evaluated.

Table 6.4 Results of marginal and conditional R^2 values per LMM and dependent variable

Dependent variable	$R^2_{marginal}$	$R^2_{conditional}$
KSS	0.04	0.45
SSS	0.03	0.38
GV	0.02	0.49
GA	0.02	0.71
VS	0.03	0.58
PVT	0.03	0.18
HR	0.31	0.51
LF	0.22	0.38
HF	0.23	0.50
LF/HF	0.04	0.26

Table 6.4 describes marginal and conditional R^2 values for the LMM of each dependent variable. It shows how the variance explained by the models increased once again for conditional R^2, except in this case for most physiological indicators (LF, HF and HR), where part of the variance in the models was already explained by fixed factors (marginal R^2). Our three investigated factors -daylighting condition, duration and timing of exposure- explained up to 71% of the variance in participants responses

(GA) when controlling for repeated measurements. These conditional R^2 values can be considered as small to moderate for all dependent variables (Ferguson, 2009), and just PVT represented a negligible practical effect.

As for study A, further non-parametric analyses were conducted (following the description in section 3.6) to test the sensitivity of outcomes to LMM. Results of linear mixed model analyses and *post-hoc* tests are discussed in the following subsections, while an overview of the main findings from the non-parametric evaluation will be provided in the next section (6.6). Detailed tables of results for the latter can be found in Appendix B.

6.5.1. Baseline analyses

Preliminary LMM analyses on data corresponding to the first measurement block (i.e., 9:00 am values) revealed no significant differences between lighting conditions in either of the investigated dependent variables (all p>.05), as further described in Table 6.5. No interactions were found either, indicating that results did not change throughout the experiment (i.e., over the days).

Table 6.5 Results of linear mixed model analyses for baseline values (i.e., 9:00 am)

	Day 1		Day 2		Day 3	
	estimate	p-value	estimate	p-value	estimate	p-value
KSS	-0.54	0.44	-0.52	0.47	-0.33	0.65
SSS	0.17	0.76	-0.04	0.94	0.07	0.91
GV	1.16	0.87	3.69	0.62	-4.75	0.52
GA	-0.06	0.99	-6.84	0.28	-3.82	0.54
VS	-0.02	0.96	0.18	0.62	-0.13	0.71
PVT	-19.90	0.42	21.40	0.44	42.10	0.11
HR	-0.59	0.90	1.42	0.75	3.49	0.44
LF	-232	0.80	-1530	0.10	-1057	0.25
HF	-731	0.31	-751	0.29	-922	0.20
LF/HF	-0.23	0.71	0.50	0.42	0.72	0.24

6.5.2. Subjective alertness and well-being

LMM studies were used, as in study A and B, to analyse the combined effects of daylighting condition, duration, and timing of exposure on subjective alertness (KSS and SSS) and indicators of well-being (GV, GA and VS).

Timing of exposure had a significant effect on alertness, measured with both KSS ($F(1,774) = 21.44$, $p<0.001$) and SSS ($F(1,774) = 11.94$, $p<0.001$), and on vigour (GV) ($F(1,774) = 17.48$, $p<0.001$): independently of daylighting condition, alertness and vigour scores increased during the day. *Post-hoc* tests showed that subjects self-reported being more alert and more vigorous during the afternoon session than during the morning one ($\beta_{PM}=-0.48$, $p_{adj}<.001$, $\beta_{PM}=-0.32$, $p_{adj}<.001$ and $\beta_{PM}=4.36$, $p_{adj}<.001$, respectively) (Figures 6.5, 6.6 and 6.7). Neither brightness nor duration of exposure had a significant effect on either of these indicators. In addition, neither daylight nor duration or timing of exposure influenced subjective responses of affect (GA) (Figure 6.8). No interactions effects were detected either in any of the aforementioned scales.

The effect of lighting condition on vitality (VS) was moderated by timing of exposure, indicating that there was a significant interaction between daylight and session ($F(1,774) = 4.77$ $p<0.05$). Analyses conducted at each daylight level showed that differences across experimental sessions were significant under the bright conditions ($\chi^2(1) = 11.65$, $p<.01$) but not under the dim ones. *Post-hoc* tests (simple contrasts for timing of exposure) revealed that, under brighter conditions, participants felt more vital during the afternoon than during the morning ($p<.001$), though no influence of timing was observed under dim conditions, as participants felt equally vital during both sessions. In addition, simple contrasts for daylight showed no difference between dim and brighter conditions in either session (Figure 6.9). Duration of exposure, however, did not affect responses in either daylight condition, with which no interaction could be found either (Figure 6.9).

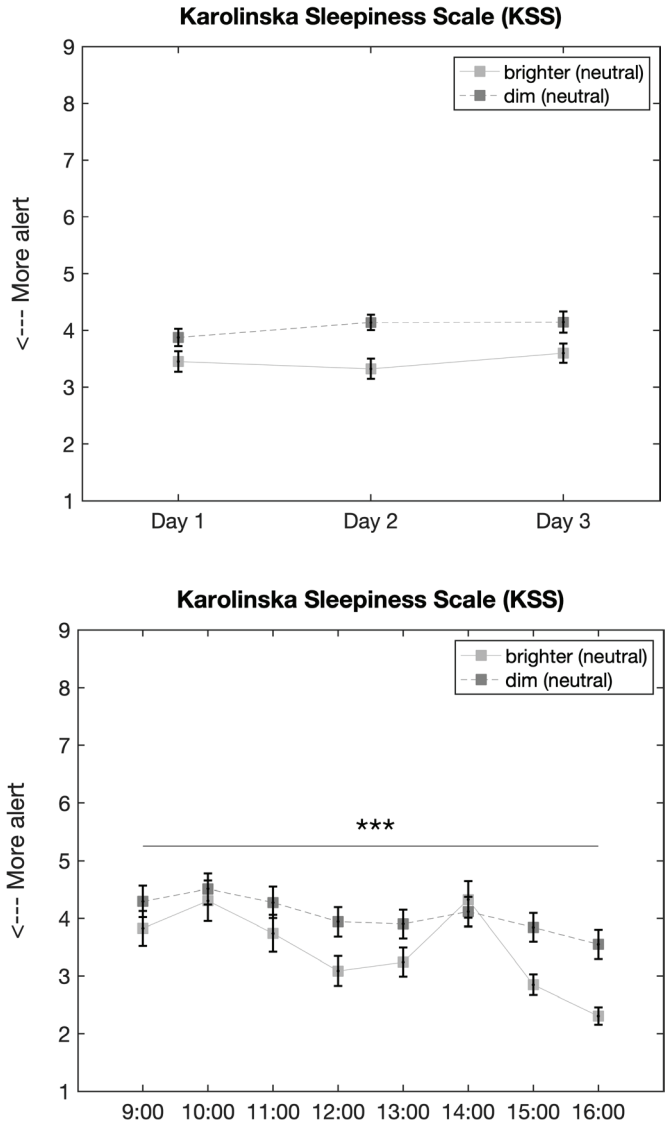


Figure 6.5 Mean values and associated standard errors of the effect of duration (up) and of timing of exposure (bottom) on subjective alertness (KSS). Significant main effects of duration (left) or timing (right) of exposure are represented with "+" ($p<0.10$), "*" ($p<0.05$), "**" ($p<0.01$), "***" ($p<0.001$). Interaction effects are represented with "#" ($p<0.05$), "##" ($p<0.01$), "###" ($p<0.001$) (simple contrasts for duration and/or timing of exposure) and with red asterisks ("*" ($p<0.05$), "**" ($p<0.01$), "***" ($p<0.001$)) for simple contrast of daylight.

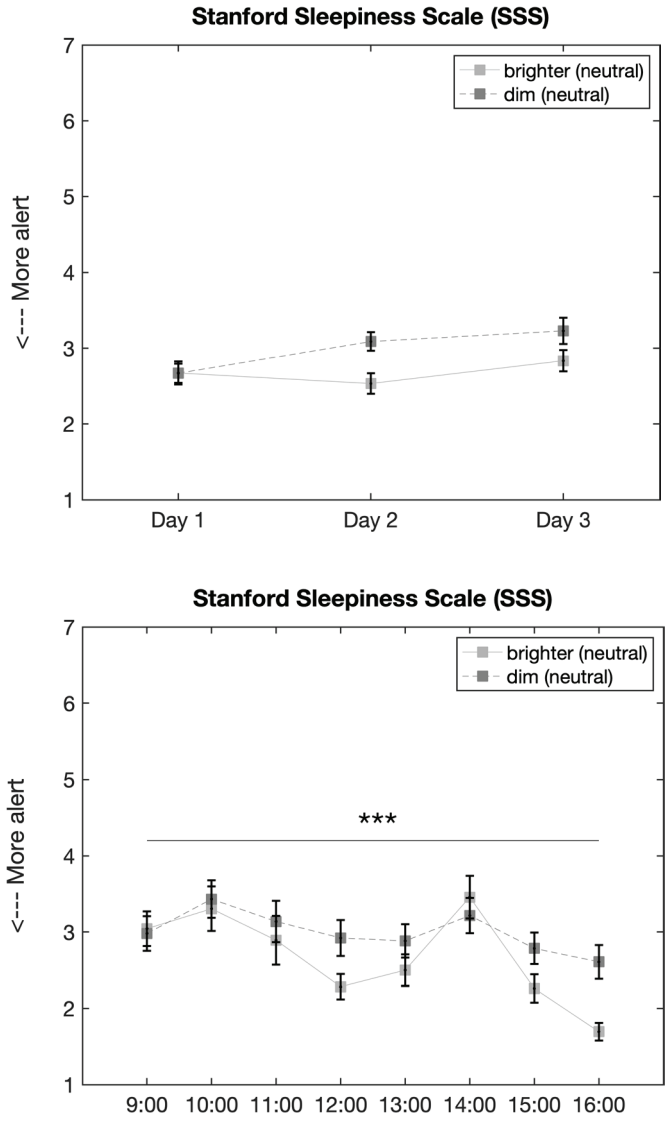


Figure 6.6 Mean values and associated standard errors of the effect of duration (up) and of timing of exposure (bottom) on subjective alertness (SSS). Significant main effects of duration (left) or timing (right) of exposure are represented with "+" ($p<0.10$), "*" ($p<0.05$), "**" ($p<0.01$), "***" ($p<0.001$). Interaction effects are represented with "#" ($p<0.05$), "##" ($p<0.01$), "###" ($p<0.001$) (simple contrasts for duration and/or timing of exposure) and with red asterisks ("*" ($p<0.05$), "**" ($p<0.01$), "***" ($p<0.001$)) for simple contrast of daylight.

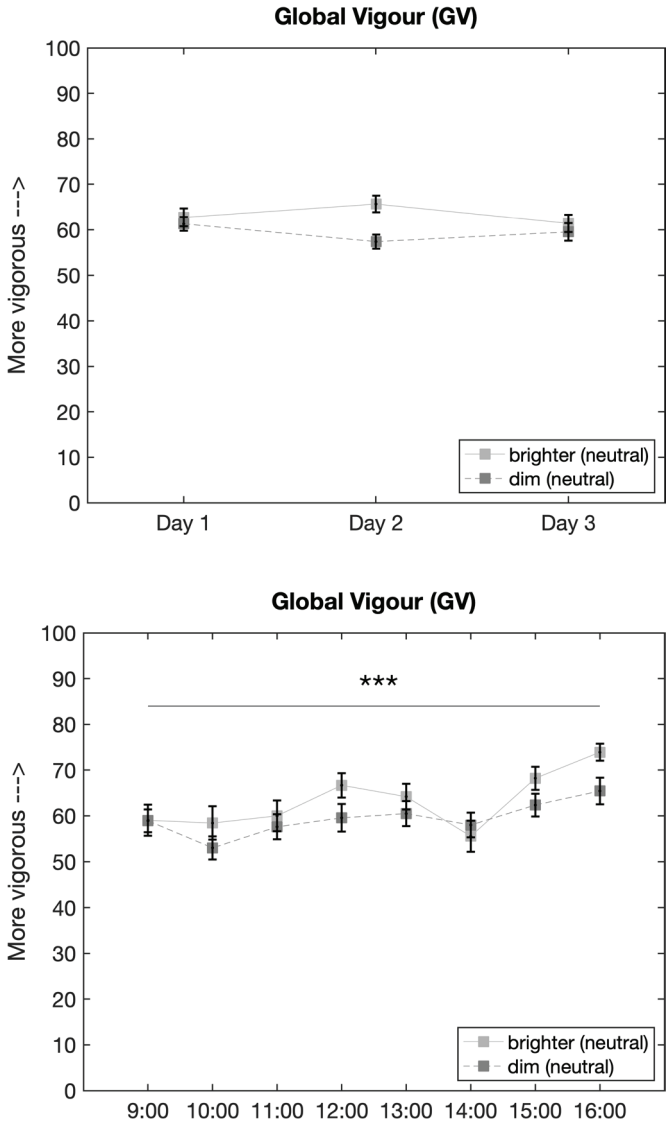


Figure 6.7 Mean values and associated standard errors of the effect of duration (up) and of timing of exposure (bottom) on subjective well-being (GV). Significant main effects of duration (left) or timing (right) of exposure are represented with "+" ($p<0.10$), "*" ($p<0.05$), "**" ($p<0.01$), "***" ($p<0.001$). Interaction effects are represented with "#" ($p<0.05$), "##" ($p<0.01$), "###" ($p<0.001$) (simple contrasts for duration and/or timing of exposure) and with red asterisks ("*" ($p<0.05$), "**" ($p<0.01$), "***" ($p<0.001$)) for simple contrast of daylight.

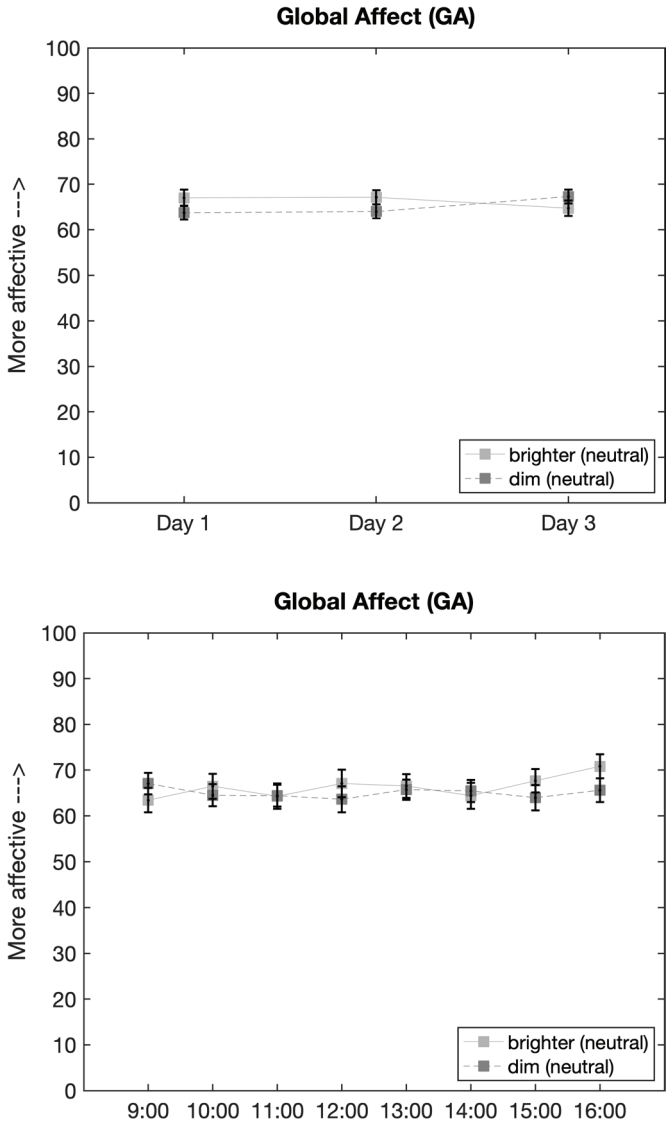


Figure 6.8 Mean values and associated standard errors of the effect of duration (up) and of timing of exposure (bottom) on subjective well-being (GA). Significant main effects of duration (left) or timing (right) of exposure are represented with "+" ($p<0.10$), "*" ($p<0.05$), "**" ($p<0.01$), "***" ($p<0.001$). Interaction effects are represented with "#" ($p<0.05$), "##" ($p<0.01$), "###" ($p<0.001$) (simple contrasts for duration and/or timing of exposure) and with red asterisks ("*" ($p<0.05$), "**" ($p<0.01$), "***" ($p<0.001$)) for simple contrast of daylight.

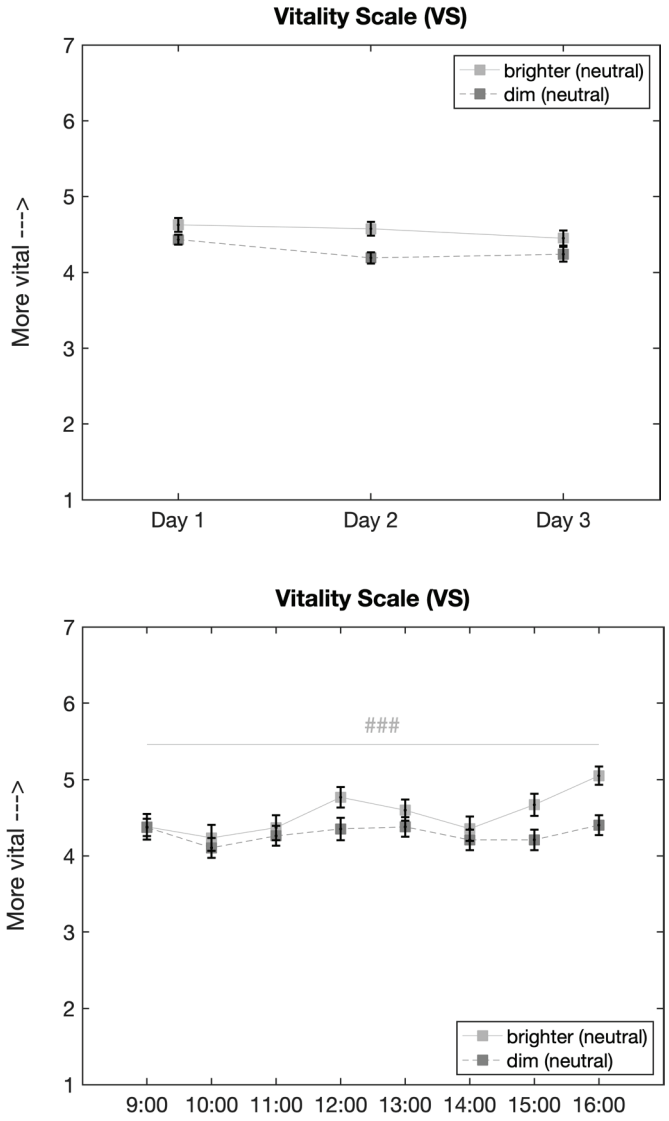


Figure 6.9 Mean values and associated standard errors of the effect of duration (up) and of timing of exposure (bottom) on subjective well-being (VS). Significant main effects of duration (left) or timing (right) of exposure are represented with "+" ($p<0.10$), "*" ($p<0.05$), "**" ($p<0.01$), "***" ($p<0.001$). Interaction effects are represented with "#" ($p<0.05$), "##" ($p<0.01$), "###" ($p<0.001$) (simple contrasts for duration and/or timing of exposure) and with red asterisks ("*" ($p<0.05$), "**" ($p<0.01$), "***" ($p<0.001$)) for simple contrast of daylight.

6.5.3. Performance in sustained attention

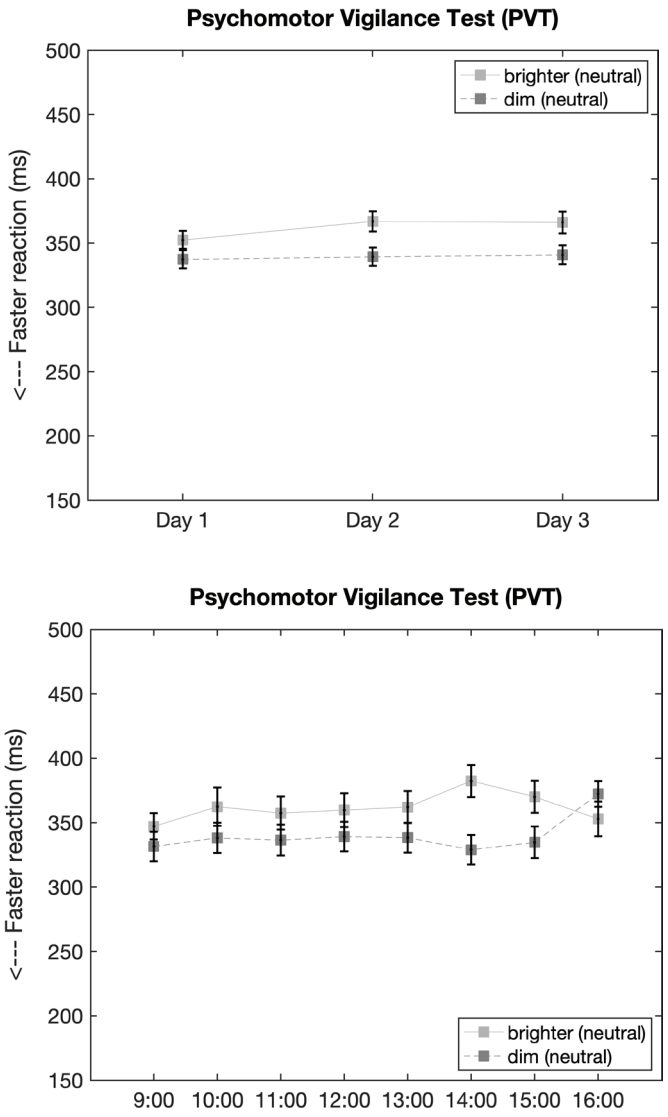


Figure 6.10 Mean values and associated standard errors of the effect of duration (up) and of timing of exposure (bottom) on sustained attention (PVT). Significant main effects of duration (left) or timing (right) of exposure are represented with "+" ($p<0.10$), "*" ($p<0.05$), "**" ($p<0.01$), "***" ($p<0.001$).

Sustained attention was evaluated through a performance task that monitored reaction times (section 3.5.2), and values below 150 ms or above 500 ms were excluded from the analysis since these responses are often categorized as anticipation or lapses, respectively (Münch et al., 2016b). PVT was found to be significantly influenced by lighting condition ($F(1,561) = 5.93$, $p<0.05$) (Figure 10). As observed in Figure 6.10, no moderation effects neither by duration nor by timing of exposure were found.

6.5.4. Physiological arousal

In terms of physiological arousal, cardiovascular activity was continuously monitored throughout the study to assess changes in the autonomous nervous system through heart rate and heart rate variability (section 3.5.3). In particular, LF and HF power indicators were used in the assessment of sympathetic and parasympathetic activity (i.e., linked to arousal and energy generation, and to rest activities, respectively). Mean values of HR (in beats per minute), LF and HF (both in milliseconds), and of the LF/HF ratio during the 5-minute hourly tasks when the participants' activity was controlled (i.e. while they were replying to the self-reported questionnaire and PVT), were used to perform the analyses.

Neither main effects due to lighting condition were detected in any of the physiological markers, nor moderations by duration or timing of exposure were found. There was a marginal effect of duration of exposure on HR, indicating an increase in participants' heart rate during the experiment, independently of daylighting condition ($F(2,2620) = 2.62$, $p=0.08$). *Post-hoc* tests showed that participants' heart rate was slightly faster during day 3 compared to day 1 ($\beta_{D3}=1.86$, $p_{adj}=0.09$) (but not during day 2 compared to day 1 or during day 3 compared to day 2) (Figure 6.11). The main effect of timing of exposure was also significant independently of daylighting condition, showing a decrease in heart rate throughout the day ($F(1,2621) = 13.40$, $p<0.001$). *Post-hoc* analyses revealed that participants' heart rate was higher in the morning than in the afternoon ($\beta_{PM}=-1.11$, $p_{adj}<.001$) (Figure 9a, right)). However, by looking at that same figure (Figure 6.11) we can observe that, when excluding 9:00 a.m. results -which correspond to the first measurement block of the day- heart rate was actually faster during the afternoon than during the morning ($\beta_{PM}=1.52$, $p_{adj}<.001$). The covariate corresponding to the baseline values for HR was significant as well ($p<0.001$).

The main effect of timing of exposure was a marginally significant factor for LF despite condition ($F(1,2621) = 3.03$, $p<0.1$), which indicated a decrease in cardiovascular activity throughout the day. *Post-hoc* tests revealed a higher LF in the morning than in the afternoon ($\beta_{PM}=-209$, $p_{adj}<0.1$) (Figure 6.12). No interactions were detected, and no significant effects due to lighting condition of duration of exposure were reported either (Figure 9b, left).

Neither lighting condition, nor duration or timing of exposure affected HF in any noticeable way. No interactions were reported either (Figure 6.13). The covariate corresponding to baseline values for both LF and HF was significant (both $p<0.001$).

As for the LF/HF ratio, only timing of exposure affected heart rate variability (LF/HF) ($F(1,2621) = 32.24$, $p<0.001$), showing a decrease in variability throughout the day independently of light condition. *Post-hoc* analyses revealed a higher LF/HF ratio in the morning than in the afternoon ($\beta_{PM}=-0.35$, $p_{adj}<.001$) (Figure 6.14).

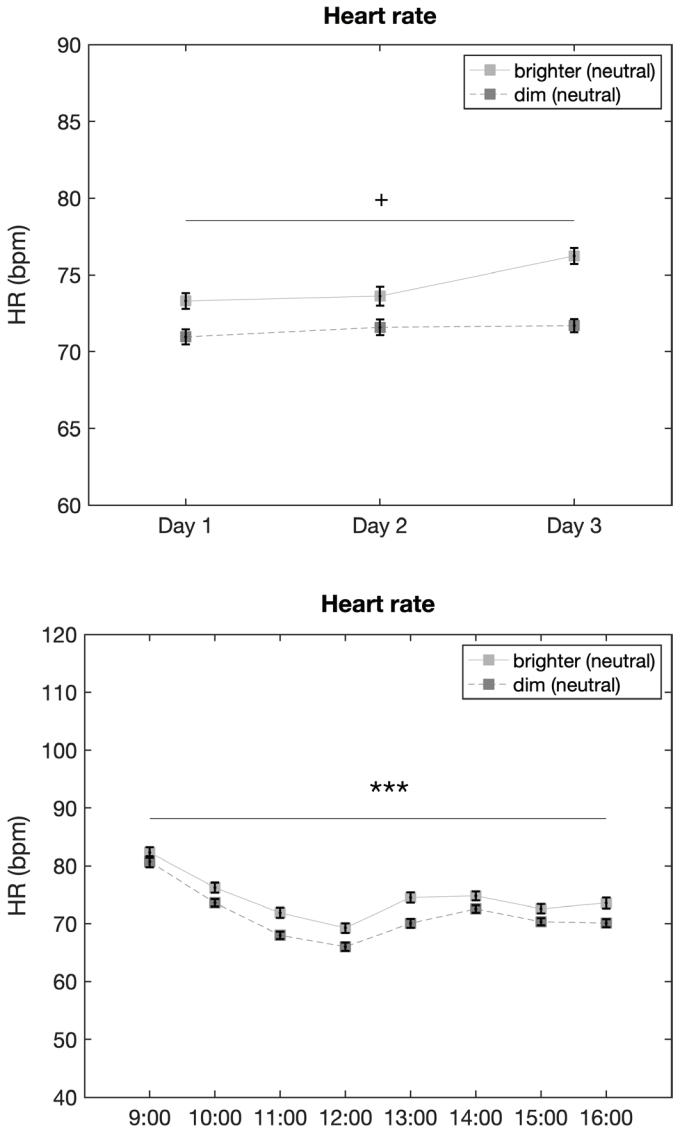


Figure 6.11 Mean values and associated standard errors of the effect of duration (up) and of timing of exposure (bottom) on physiological arousal based on HR. Significant main effects of duration (left) or timing (right) of exposure are represented with "+" ($p<0.10$), "*" ($p<0.05$), "**" ($p<0.01$), "***" ($p<0.001$). Interaction effects are represented with "#" ($p<0.05$), "##" ($p<0.01$), "###" ($p<0.001$) (simple contrasts for duration and/or timing of exposure) and with red asterisks ("*" ($p<0.05$), "**" ($p<0.01$), "***" ($p<0.001$)) for simple contrast of daylight.

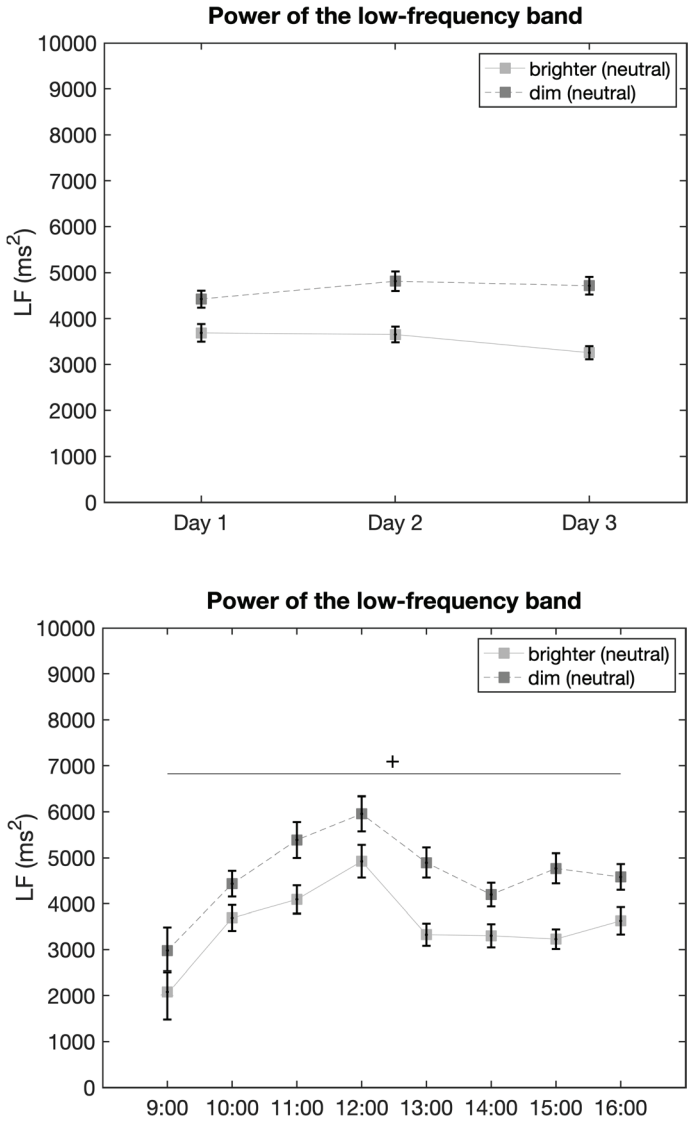


Figure 6.12 Mean values and associated standard errors of the effect of duration (up) and of timing of exposure (bottom) on physiological arousal based on LF power. Significant main effects of duration (left) or timing (right) of exposure are represented with "+" ($p<0.10$), "*" ($p<0.05$), "**" ($p<0.01$), "***" ($p<0.001$). Interaction effects are represented with "#" ($p<0.05$), "##" ($p<0.01$), "###" ($p<0.001$) (simple contrasts for duration and/or timing of exposure) and with red asterisks ("*" ($p<0.05$), "**" ($p<0.01$), "***" ($p<0.001$)) for simple contrast of daylight.

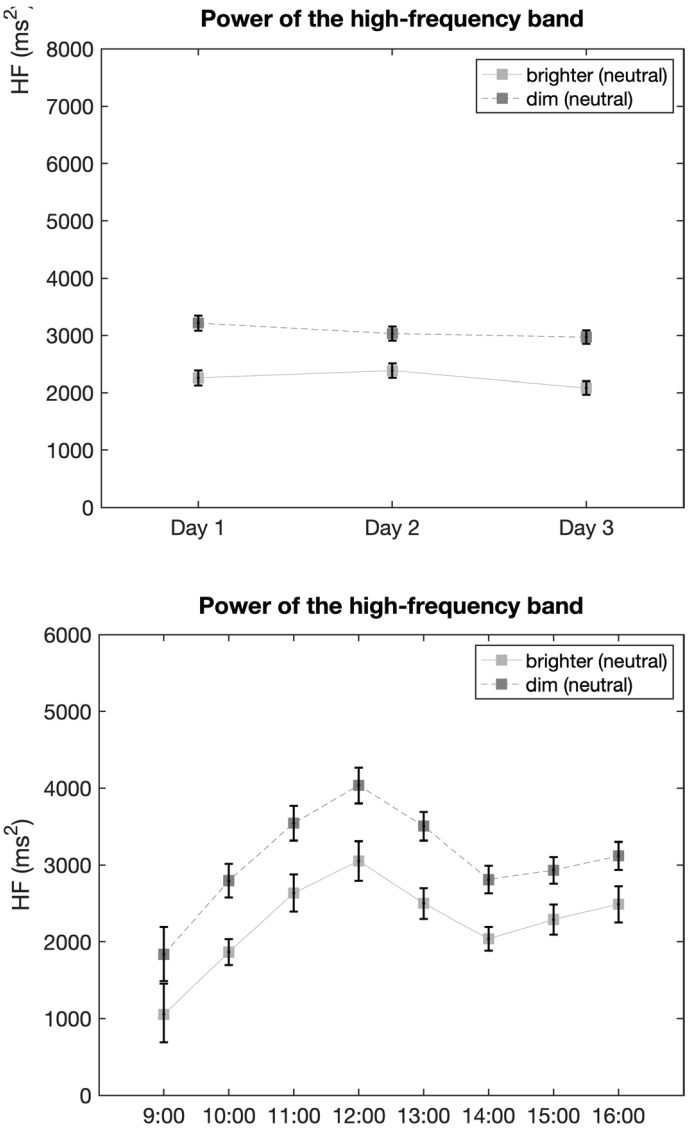


Figure 6.13 Mean values and associated standard errors of the effect of duration (up) and of timing of exposure (bottom) on physiological arousal based on HF power. Significant main effects of duration (left) or timing (right) of exposure are represented with "+" ($p<0.10$), "*" ($p<0.05$), "**" ($p<0.01$), "***" ($p<0.001$). Interaction effects are represented with "#" ($p<0.05$), "##" ($p<0.01$), "###" ($p<0.001$) (simple contrasts for duration and/or timing of exposure) and with red asterisks ("*" ($p<0.05$), "**" ($p<0.01$), "***" ($p<0.001$)) for simple contrast of daylight.

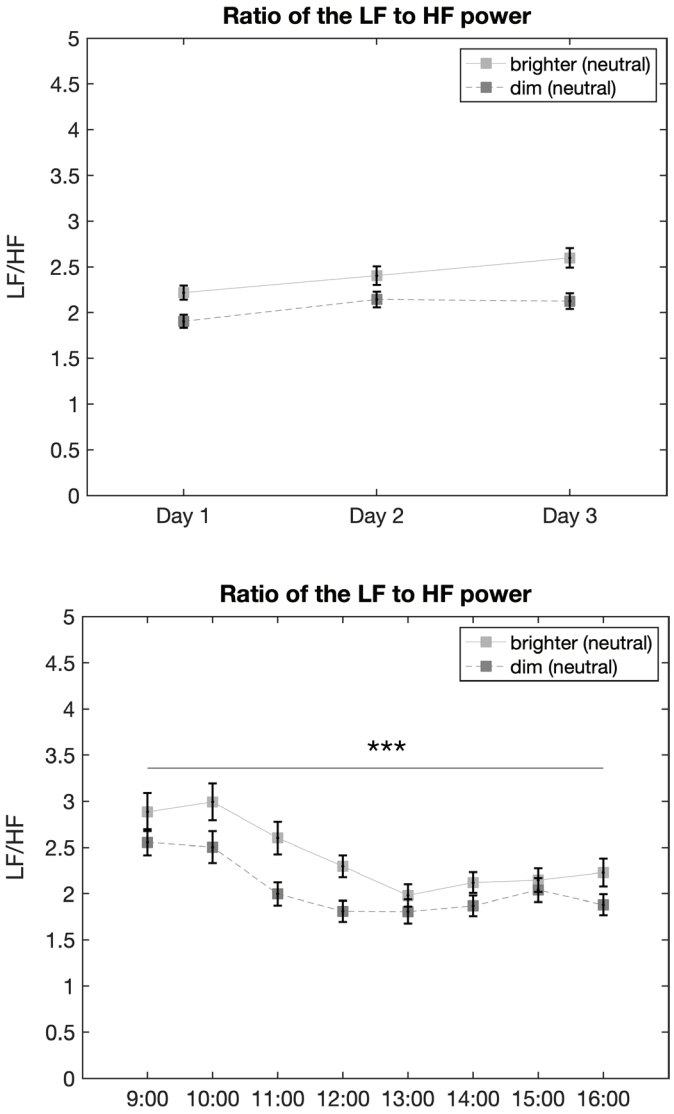


Figure 6.14 Mean values and associated standard errors of the effect of duration (up) and of timing of exposure (bottom) on physiological arousal based on the ratio of the LF/HF power. Significant main effects of duration (left) or timing (right) of exposure are represented with "+" ($p<0.10$), "*" ($p<0.05$), "**" ($p<0.01$), "***" ($p<0.001$). Interaction effects are represented with "#" ($p<0.05$), "##" ($p<0.01$), "###" ($p<0.001$) (simple contrasts for duration and/or timing of exposure) and with red asterisks ("*" ($p<0.05$), "**" ($p<0.01$), "***" ($p<0.001$)) for simple contrast of daylight.

6.6. STUDY C OUTCOMES

The effects of dynamic and extended exposures to variations in daylight intensity levels under non-spectrally shifted conditions (i.e., neutral) on subjective reports of alertness and well-being, sustained attention, and arousal were analysed in this study. Our work explores in more particular whether results from previous study on the alerting effects of polychromatic white light can be reproduced in a daylit environment (i.e., in the absence of electric light) and under circumstances similar to those encountered in our daily lives (i.e., prolonged exposures, no pre-treatment conditions, no sleep deprivation, etc.).

6.6.1 Main effect of daylight condition

From previous studies, we know that higher intensities of polychromatic white light often lead to an observed increase in subjective alertness, and sometimes, also to an increase in sustained attention (Lok et al., 2018; Souman et al., 2018).

In our experiment, daylight condition only affected reaction times, although in a different direction to what was expected (Figure 6.15): as opposed to what was found in Phipps-Nelson et al. (2003) and Smolders et al. (2012), our brighter conditions created a detrimental effect on the participants' ability to sustain attention compared to those in the dim scenario, which reacted faster (β_D=-24.7, p_{adj}<.05).

These results are not easy to explain and seem counter intuitive, and thus would tend to contradict our initial hypothesis (H1) that brighter environments favour correlates of alertness when compared to dimmer conditions. However, they do align with results from study B (Chapter 5), where a detrimental effect of brightness (under blue spectra in that case) was also found for subjective reports of alertness and physiological indicators of cardiovascular activity (Figures 5.8 and 5.10). There are very few precedents of a similar outcome in the literature, where negative effects on performance due to night time exposure to bright light were also found (Borisuit et al., 2014; Iskra-Golec et al., 2016). However, participants in one of these studies were extreme chronotypes, lighting conditions were more radically different (100 vs 2300 lx) than the ones tested in this study, and exposure duration lasted only 30 minutes. In that case, detrimental effects of light can be considered as an instantaneous, acute response (<1 hour of exposure), whereas in our experiment responses were consistent across days and hours. Non-parametric analyses also confirmed this unexpected outcome about reactivity in PVT, but disagreed with LMMs in that significant effects were found for most variables except for GA (Table 2, Appendix B).

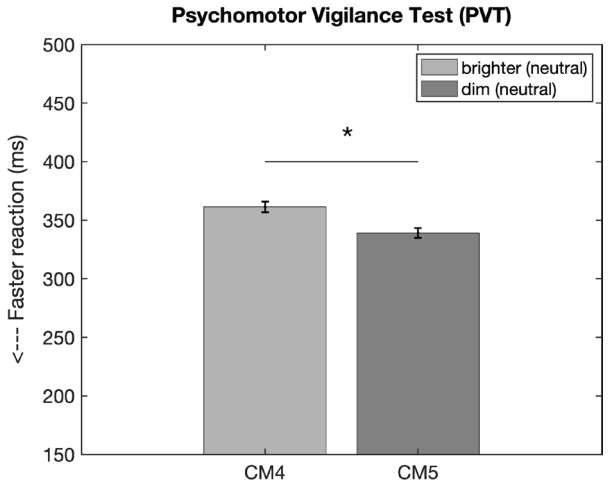


Figure 6.15 Mean value ± standard error of the main effect of daylight condition on KSS (a), SSS (b) and LF (c). Significance is represented with "+" ($p<0.10$), "*" ($p<0.05$), "**" ($p<0.01$), "***" ($p<0.001$).

Previous studies that failed to report significant effects of light intensity on alertness or performance sometimes used high baseline intensities (O'Brien and O'Connor, 2000). It is important to note that the effects from our study were not induced by either extreme conditions nor by high baselines values. If at all, they were triggered by the very dim conditions we had when compared to those from previous studies. The fact that light condition was not a significant effect for subjective responses or arousal might indicate that our illuminance levels were not distinct enough from one another to elicit any observable psycho-physiological change on participants. This limitation in brightness range was mainly due to the specificities of the room and glazing, to our choice of using exclusively daylight as the source of light, and to the fact that we had to combine rather low transmittance glazing with filters to ensure both enough control over the spectral composition of daylight and its resulting photopic illuminance.

6.6.2 Effects of duration and timing of exposure

No significant main or moderation effects due to duration of exposure were found on any of the dependent variables, and all participants felt equally alert, vigorous, affective, vital, vigilant and aroused during the 3 days of experiment, except for heart rate measurements: for the latter, a marginal increase from day 1 to day 3 was observed, independently of daylight scenario. Our initial hypothesis H2 that longer exposures might induce stronger effects, even with ambient light conditions, was thus not confirmed in this study. These findings are particularly revealing because they show that having not only low illuminance levels throughout the experiment but also levels that inconsistently varied between days (i.e., increased from day 1 to day 2 and

decreased from day 2 to day 3 and shown in Table 6.3 and Figure 6.4 in section 6.2.1) seemed to "mask" the potential of duration of exposure to elicit stronger effects (unlike in studies A and B, where illuminance levels consistently decreased throughout the experiment). However, no moderation effect was detected either, so it is difficult to draw any strong conclusion regarding longitudinal effects on the observed responses.

Non-parametric tests for the effect of duration of exposure also showed very similar results as those found in LMMs. Almost no significant differences between days of experiment were found for any of the variables except for GV, irrespective of light condition (i.e., in both scenarios), and for SSS, GA or VS, as significant differences were found in the dimmer condition (always when comparing day 2 or day 3 with day 1, but not between days 2 and 3) (Tables 5 and 6, Appendix B). Since light scenarios are analysed separately with this second approach, what was described as an interaction between light and duration for LMMs, here is instead evaluated by means of significant differences per day between lighting conditions. Since in LMMs interaction terms are excluded from the model when non-significant, no possible further pairwise comparisons between lighting scenarios are possible. As a result, this extra information provided by non-parametric tests is not present in LMMs, unless a significant interaction occurred (which did not happen in this study) (Table 8, Appendix B).

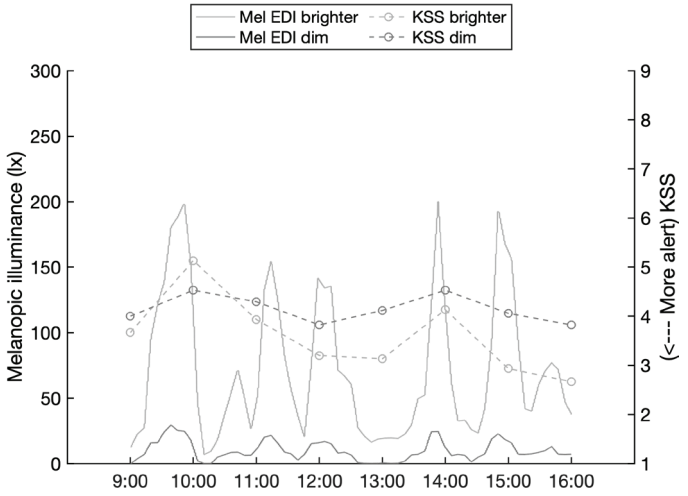


Figure 6.16 Mean values of KSS values vs melanopic EDI (lx) over time.

Time of day, however, much more clearly appeared as the main driver behind the significant differences observed between experimental sessions, whether on indicators of subjective alertness (KSS, SSS) and vigour, or on physiological arousal (HR and LF/HF), independently of daylighting condition. Similarly to studies A and B, since the natural dynamics of daylight were not explicitly included or quantified in the analyses, it is unclear whether the main effect of timing of exposure arises from the

hypothesized underlying circadian rhythmicity or instead from a systematic variation in illuminance levels between morning and afternoon sessions within classrooms (Figure 6.16). What these results do support is the hypothesis H3 that morning and afternoon sessions would behave differently.

Time of day was also a moderating factor on the effect of daylight intensity on vitality (VS), and the difference in scores between sessions was only significant in the brighter room. In this particular case, brighter conditions performed as expected following our initial hypothesis H1 and were more effective in positively influencing subjective well-being than low intensity ones. These results suggest a photic effect due to brighter daylighting conditions that could change based on the time of day.

6.6.3 Discussion on STUDY C

Studies comparing subjective alertness for exposure to various intensities of polychromatic white light found that the brighter condition resulted in higher self-rated alertness (Åkerstedt et al., 2003; Huiberts et al., 2015; Iskra-Golec and Smith, 2008; K Kaida et al., 2006; Leichtfried et al., 2015; Maierova et al., 2016; Phipps-Nelson et al., 2003; Rüger et al., 2006; Smolders et al., 2012; Vandewalle et al., 2006b; Weisgerber et al., 2017), as well as, in some cases, to an increase in sustained attention (Phipps-Nelson et al., 2003; Smolders et al., 2012). However, none of these investigations were conducted in daylit environments. Only one study attempted to explore effects of daylight by combining it with an electric light source (Borisuit et al., 2015), but unfortunately led to non-significant effects.

Yet, many other studies failed to reveal positive effects on subjective alertness when comparing bright and dim conditions (Borisuit et al., 2015; Borragán et al., 2018; Crasson and Legros, 2005; Huiberts et al., 2016; Sahin et al., 2014; Smolders and de Kort, 2014). In addition, most studies reported non-significant effects of light intensity on performance indicators of sustained attention (Borragán et al., 2018; Huiberts et al., 2016; K Kaida et al., 2006; Maierova et al., 2016; Slama et al., 2015; Smolders and de Kort, 2014; te Kulve et al., 2017; Weisgerber et al., 2017). Among the few that also investigated physiological indicators of cardiovascular activity, most – again – reported non-significant effects on arousal during daytime (Rüger et al., 2006; Smolders and de Kort, 2014).

As a result, insights from these investigations have been described as inconclusive. The chosen light scenarios in our study failed to confirm our initial hypothesis (H1) that brighter conditions will favour alertness, and instead, a detrimental response in reaction times to a sustained attention task was found. As already discussed in study B, higher daylight levels than the ones tested here are, however, expected in a working environment. We propose that future research undertake greater variations in illuminance levels and finer temporal variations as that would help define the yet non-existent dose-response curve for daytime alerting effects, following the example set

by Cajochen and colleagues (Cajochen et al., 2000) or Smolders et al. (Smolders et al., 2018).

Also, participants felt more alert and more vigorous during afternoon sessions than during morning ones, but more aroused during the morning than during the afternoon. These findings replicate those discussed in Chapter 4 (afternoon exposures also resulted as more effective for subjective responses while morning sessions for cardiovascular activity) and tend to support overall our initial hypothesis (H3) regarding distinct alerting responses depending on time of day. Once again, a further investigation of the influence of natural daylight dynamics on such experiments would be necessary to better understand to what extent they may help explaining some of these unexpected findings.

7 [ADEQUACY OF LIGHT-DRIVEN MODELS TO ANTICIPATE ALERTING EFFECTS OF DAYLIGHT]

Daylight's ability for maintaining productive levels of attention, arousal and alertness during work activities has been investigated in Chapters 4 to 6 under specific luminous conditions, which has opened new questions and shed light both on the robustness of some findings and the inconsistency of others. Even if all findings were perfectly consistent both with the literature and with one another, an important question emerges anyway as to how to make these findings applicable to the built environment and help inform design decisions. Building upon the review of existing prediction models of alertness presented in Chapter 2, and on the outcomes of the user studies presented in Chapters 4 to 6, a follow up investigation is presented in this chapter. The purpose is to explore the adequacy of existing physiology-based, light-driven models to anticipate what responses to expect and evaluate this adequacy by confronting the model's outcomes to the collected data i.e., the reported self-assessments. The ultimate goal is to gain insights about the limitations and the potential of extrapolation of experimental data vs reliance on simulated values when it comes to predicting daylight-induced daytime alertness variations.

This final core chapter is the result of a collaboration between various institutions (namely École Polytechnique Fédérale de Lausanne, University of Sydney and Harvard Medical School) and the authors of three prediction models of alertness (Amundadottir, 2016; St Hilaire et al., 2007; Tekieh et al., 2020). The lack of experimental work outside of controlled laboratory settings when discussing alerting responses to daily light exposure (which was now made available from our user studies), as well as a shared interest in exploring the feasibility of these models to predict daytime alertness in daylit environments, drove this interdisciplinary investigation.

The models were selected due to their differences both in terms of input data and of the mechanisms and considerations involved in their development, which ultimately allowed us to:

- (1) assess variations in performance between models with different types of photic components (i.e., photopic (St Hilaire et al., 2007) vs spectral-dependent (Amundadottir, 2016; Tekieh et al., 2020)) for their ability to predict alertness due to daylight exposures

- (2) examine the limitations of the models due to input requirements (and consequently, the advantages of their associated structure) for their integration in the design process and thus, their applicability to the built environment

First, an overview of the three selected models, including a brief description of their key components and functioning, is provided in section 7.1. Then, a method for investigating the adequacy of such approaches in the prediction of alertness due to daylight exposure is proposed in section 7.2, and builds upon experimental data collected during studies A, B and C (Chapters 4 to 6). Measured light data (i.e., irradiance in $\mu W/m^2$) are used as an input to the models (section 7.2.1), while collected subjective self-reports are used in the comparison with the models' output

(section 7.2.2). Statistical analyses employed in the process are described in section 7.2.3. Their results are presented in section 7.3, followed by a discussion about the potential of integrating non-visual effects into the built environment in section 7.4, where the requirements of a simulation workflow for the study of alertness are discussed in the context of architectural design.

7.1 MODELS' OVERVIEW

As introduced in Chapter 2, various methods exist that quantify changes in alertness states in response to light exposure. We will now focus on understanding the main components and functioning mechanisms behind three of these models, that will help us elucidate their potential for anticipating daytime alerting responses in a daylit working environments.

7.1.1 Model 1: effects of sleep and circadian rhythms on alertness

The *model of the effects of sleep and circadian rhythms* was first published in 2007 by Melissa St Hilaire, and colleagues in a paper entitled "A physiologically based mathematical model of melatonin including ocular light suppression and interactions with the circadian pacemaker", in the *Journal of Pineal Research*, volume 43 (St Hilaire et al., 2007).

This model proposes to transform the light signal (i.e., photopic illuminance) and sleep-wake information (i.e., bedrest timing) into direct driving forces on the circadian pacemaker to predict non-visual responses.

Main components

This model builds upon the Kronauer model (Kronauer et al., 1999a), which, as summarized graphically in Figure 7.5, consists of a linear structure that includes two systems: a dynamic light processor (Process L) and the circadian pacemaker or circadian drive (Process P). While Process L represents the physiology by which light interacts with the retinal photoreceptors through photopigments, Process P receives the light drive via the circadian sensitivity modulator: the latter characterises the varying human sensitivity to light throughout the day depending on the prior light exposure and according to phase and dose-response curves. It then converts it into a direct drive onto the pacemaker. In addition, this model, that we will refer to as model 1, includes a non-photic component, Process N, to reflect physiological differences between photic and non-photic pathways. This component therefore acts on the pacemaker independently from light and represents stimuli due to the sleep-wake cycle (i.e., time) instead.

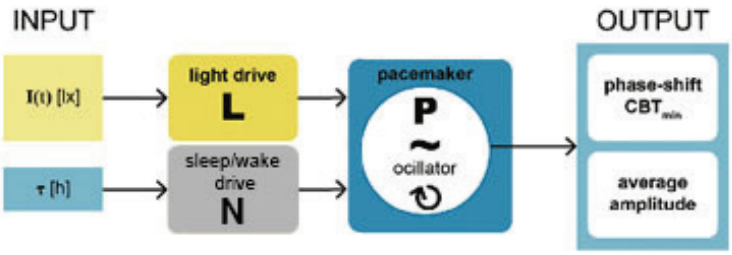


Figure 7.1 Diagram of the structure of the model of the effects of sleep and circadian rhythms on alertness (image source: after Amundadottir (2016)).

Model functioning

Photopic illuminance values are given as an input to the model, weighted according to the V(λ) sensitivity curve of the visual system. This light signal (L) entrains the circadian pacemaker (P) together with sleep information (N), which in turn results into measures of phase-shifting effects and circadian amplitude. Originally the model was trained to produce core body temperature (CBT) information but was later recalibrated to reflect neurobehavioural dynamics as well (i.e., alertness and cognitive performance). For the purpose of the present analysis, only alertness scores will be considered.

7.1.2 Model 2: arousal dynamics

The *model of arousal dynamics* was published very recently, in 2020, by Tara Tekieh, Svetlana Postnova and colleagues, in a paper entitled "Modeling melanopsin-mediated effects of light on circadian phase, melatonin suppression, and subjective sleepiness" in the *Journal of Pineal Research*, volume 69 (3) (Tekieh et al., 2020).

Like model 1, it simulates the interaction between the sleep-wake cycle and light (i.e., melanopic illuminace) and the dynamic circadian oscillator to predict non-visual responses. One of the main differences with the previous approach is that the non-photic pathway, while using information on time awake similarly to the previous model to introduce the sleep drive on the pacemaker, takes into account the activity of two wake-active neural populations, regulated by the homeostatic and the circadian drives.

Main components

This light-driven model consists of a light processor that converts spectral light properties ($E_{e,mel}$) into a drive that acts on the circadian pacemaker through a circadian sensitivity modulator (C), and a non-photic processor (defined by

component H) that transforms sleep information into a sleep-wake state drive for the interaction with the biological clock. The sleep-wake switch or transition is defined by the mutual inhibitory reaction of two components (MA and VLPO), whose activity is regulated by homeostasis (H) and circadian rhythmicity of the pacemaker (C), thus explaining the interaction of both pathways (i.e., photic and non-photic). A constant defines the strength and timing (parameters ν_{LA} and τ_L) of the direct alerting effect of light in the model. The general structure of the model is described in Figure 7.2.

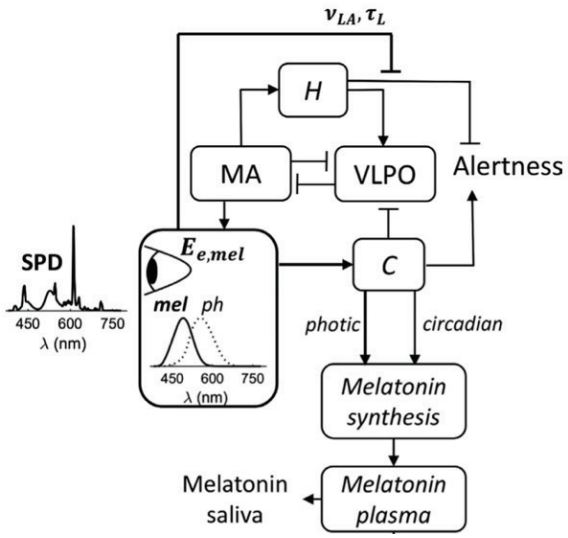


Figure 7.2 Diagram of the model of arousal dynamics structure (image source: Tekieh et al. (2020)).

Model functioning

The input to the model is the spectral distribution of light (i.e., irradiance at any given wavelength) weighted according to the ipRGCs' spectral sensitivity curve. This implies that only the contribution of melanopsin is considered, even though there is evidence that cone photoreceptors contribute equally to non-visual responses at the start of the light exposure and at low irradiance, but ipRGCs dominate the response in the long term (i.e., longer exposures) and at high irradiance (Gooley et al., 2012, 2010). Spectral irradiance is converted into melanopic irradiance, and subsequently into melanopic illuminance, to be used as the melanopsin-mediated effect of light to the model. This light signal entrains the circadian pacemaker (C) together with sleep information, which in turns controls alertness and melatonin dynamics. Several output responses are thus produced, but for the purpose of this analysis, only alertness scores will be used.

7.1.3 Model 3: non-visual direct response

The *non-visual direct response model* (nvR_D) was developed by Maria Lovisa Amundadottir in her PhD thesis entitled "Light-driven model for identifying indicators of non-visual health potential in the built environment", completed in 2016 at EPFL (Amundadottir, 2016).

It presents a linear, dynamic structure to predict various ILL effects in response to different light exposures, but in a computationally efficient manner. While the previous two models include a feedback mechanism (which requires "long-term" (>24 hours) light data and personal information such as individuals' sleep schedules), this model was designed instead to predict light responses from an average subject that has no memory regarding prior exposure. The model proposes the transformation of the light signal into a relative response (that can be interpreted as the direct driving force of light on the circadian pacemaker), and this response function into a cumulative one. The latter can be then interpreted as the capacity of light to have an effect over time and may be associated with alertness levels during the day or with melatonin suppression at night.

Main components

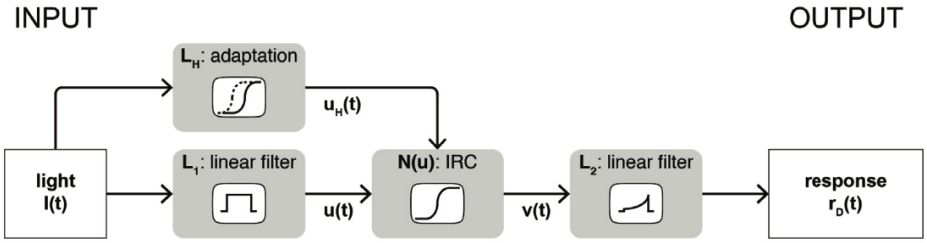


Figure 7.3 Diagram of the nvR_D model structure (image source: Amundadottir (2016)).

This light-driven model includes four main components, namely an intensity-response function for melatonin suppression, a spectral sensitivity function, linear filters and a multiplicative adaptation function. Their joint processing reflects the interaction between the light input and the output response. Since the model was trained with the only data available at the time i.e., nighttime data of melatonin suppression, it was developed under the assumption that the mechanisms behind this process could be extrapolated to daytime alertness. A schematic of the model structure is presented in Figure 7.3.

Model functioning

Spectral distribution of light (i.e., irradiance at a given wavelength) is given as an input to the model, weighted according to the spectral sensitivity of the non-visual system. In this case, a dynamic approach is considered instead of a static one (as in models 1 and 2), in the sense that it accounts for the contribution of multiple photoreceptors (and of their interaction) to the non-visual light-mediated effect: spectral irradiance is here converted into "effective" irradiance according to the ipRGC-cone shift model, that accounts for differences in sensitivities between different photoreceptors (i.e., cones, rods and ipRGCs) (Amundadottir et al., 2016) based on previous research (Gooley et al., 2012, 2010), even though the actual contribution of each photoreceptor remains unclear. This effective irradiance is then transformed into a relative (r_D) or cumulative (R_D) response that accounts for intensity-response relationships, duration and patterns of exposure, and prior light history adaptation mechanisms. The output response is the predicted direct non-visual response which, as explained before, could be interpreted as subjective alertness during daytime. Hence, higher values would correspond to stronger alerting effects.

To summarize, the models differ from one another primarily because of their following characteristics:

- input data: different light quantities are required by the three models, so while model 1 requires photopic illuminance, model 2 relies on melanopic illuminance, and model 3 uses effective irradiance instead.

- main components and functioning: although the effect of light on the non-visual system depends on the timing of exposure with respect to the underlying circadian rhythm, the drive for the circadian pacemaker is defined differently in all three models. On the one hand, models 1 and 2 assume moving oscillations (i.e., a phase-shift capacity) that are constantly changing driven by both photic and non-photic stimuli; on the other hand, model 3 assumes an already entrained behavior of the circadian pacemaker that only requires light data as an input to the model (i.e., compared to time awake in models 1 and 2).

7.2 METHOD

To evaluate the adequacy of selected models to reliably anticipate alerting responses in the built environment (i.e., with conditions closer to real life), we used the experimental datasets from the three studies presented earlier in this thesis (studies A, B and C). As discussed in section 7.2.1, light profiles were defined based on the irradiance values measured at the eye level of a seated participant (1.3 m height) over the duration of the experiment and were used as the input to all three models. Subjective user assessments were then compared against simulated alertness or model output, a process detailed in section 7.2.2. After that, statistical analyses could

be performed to determine how well models are effectively able to describe observed subjective alertness, from which an estimate of "modelling error", representative of the mismatch between measured and simulated values, could be evaluated (section 7.2.3).

Figure 7.4 Overview of daylight manipulations for all three studies, corresponding to: dim neutral vs. dim blue (study A), bright blue vs. moderate bright blue (study B) and bright neutral vs. dim neutral conditions (study C).

Chapters 4, 5 and 6 already provided a detailed description of the daylighting scenarios selected for our three studies, summarized in Figure 7.4. As a brief reminder, spectral and intensity manipulations of daylight were obtained either through a change of tint and transmittance in the existing electrochromic glazing of the rooms, or by using additional coloured and neutral filters. More specifically, study A investigated the effects of a red-impoverished daylight spectrum – that looks bluer – when compared to a non-filtered, neutral scenario with similar visual photopic illuminance; study B explored the effects of daylight intensity variations in two spaces that both look bluer than usual but have distinct blue spectral contents; study C, instead, looked at the effects of daylight intensity variations for non-spectrally manipulated conditions, i.e., which look neutral. A summary of the main characteristics of each study regarding duration of exposure, investigated light characteristics and sample size is presented in Table 7.1.

Table 7.1 Description of the main characteristics in each study

Study	Exposure duration	Manipulated light property	Constant light property	Light condition	CCT	Sample size
A	3 days	Spectrum	Intensity	Dim neutral vs dim blue	5,355K 10,651K	N=17 N=18
B	2 days	Intensity and spectrum	None	Blue filter vs EC-1	9,765K 6,651K	N=17 N=16
C	3 days	Intensity	Spectrum	Brighter neutral vs dim neutral	5,399K 5,602K	N=16 N=17

As described in Chapter 3, light data was continuously monitored during all three studies using photometers placed regularly among participants to record horizontal photopic illuminance (in lux) and using one spectroradiometer per room that measured absolute irradiance, in μW/m²/nm. The outcomes of this light monitoring, notably the resulting mean absolute irradiance values per nm, general lighting conditions and horizontal illuminance distributions across days, have been reported in detail for each study in Chapters 4 to 6.

7.2.1 LIGHT STIMULI

Measured spectral irradiance from the three studies will be used as a basis to derive the light input to the models. As illustrated in Figure 7.5, while all three models build upon the dynamic stimulus processor (Process L, L for light) from the Kronauer model (Kronauer et al., 1999b) as a foundation to introduce the effect of light on the circadian oscillator (Process P), each model requires different light quantities. Therefore, spectral irradiance needs to be rescaled accordingly.

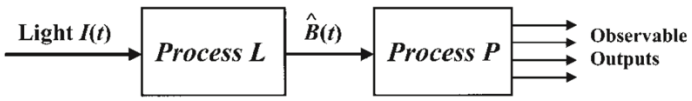


Figure 7.5 Schematic of the Kronauer model structure (image source: Kronauer et al. (1999))

On the one hand, model 1 uses a vision-based measure of light intensity (i.e., photopic illuminance, in lux), and on the other hand, models 2 and 3 instead incorporate spectrum-dependent measures that are unrelated to vision.

In model 2, melanopic illuminance (I_{mel}) is used as the input to the model (in lux as well), and is derived from melanopic irradiance ($E_{e,mel}$):

$$I_{mel} = \frac{E_{e,mel}}{K_{mel,v}} \qquad \text{(Eq. 7.1)}$$

where $K_{mel,v}$ is the melanopic efficacy radiation coefficient (which in this case corresponds to 832.41). Melanopic irradiance corresponds to the spectral irradiance weighted by the melanopsin action spectrum (CIE, 2018), where the relative sensitivity of melanopsin to light incident at the cornea is normalized to have a maximum value of 1 at 490 nm.

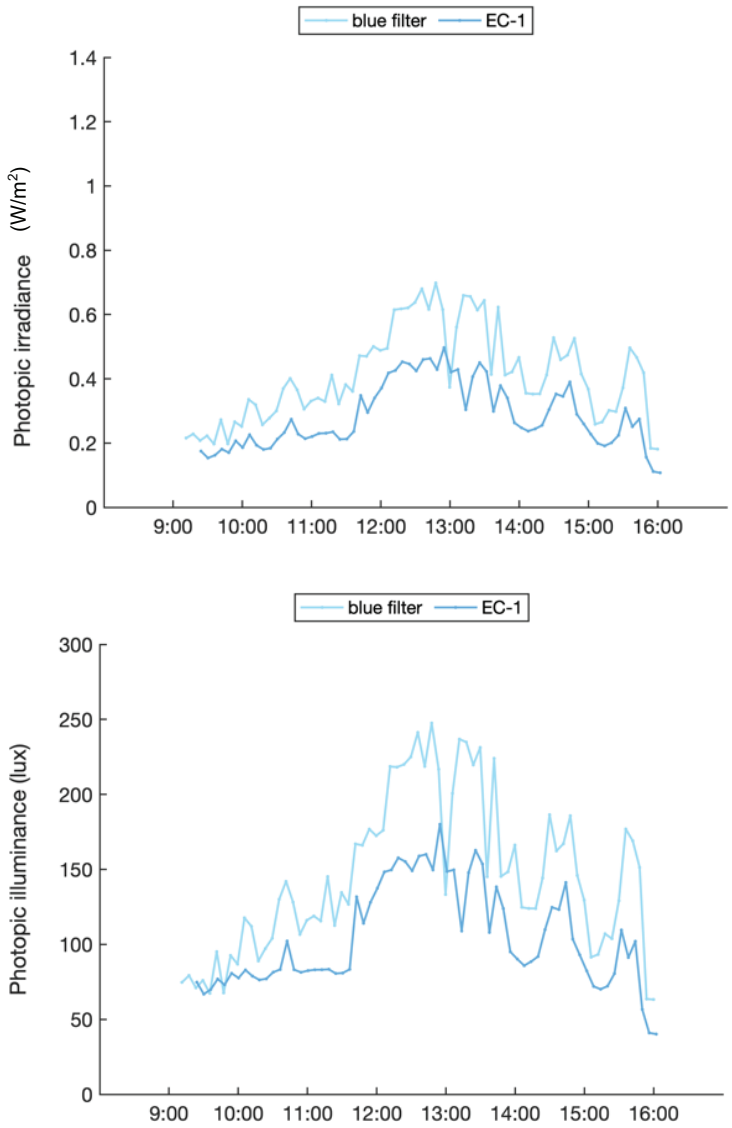
For model 3, it is effective irradiance (W/m²) that is used as an input. This quantity is derived from spectral irradiance of light weighted according to the ipRGC-cone shift

model (M. Amundadottir et al., 2017), which assumes an ipRGC spectral sensitivity that changes over time depending on the duration of light exposure and includes inputs from several photoreceptors. It is calculated as:

$$I(t) = E_{e,\lambda}(\lambda,t) S_w(\lambda,t)\, \delta\lambda \qquad \text{(Eq. 7.2)}$$

where $S_w(\lambda,t) = w(t) S_{L+M}(\lambda) + (1 - w(t)) S_{ipRGC}(\lambda)$. In this case, the relative sensitivity of melanopsin is normalized to have a maximum value of 1 at 480 nm.

An example of how the original measured data (i.e., spectral irradiance (W/m^2)) is converted into the different light quantities required by the models – photopic illuminance (lx), melanopic illuminance (lx) and effective irradiance (W/m^2) for models 1, 2 and 3 respectively – is presented in Figure 7.6.



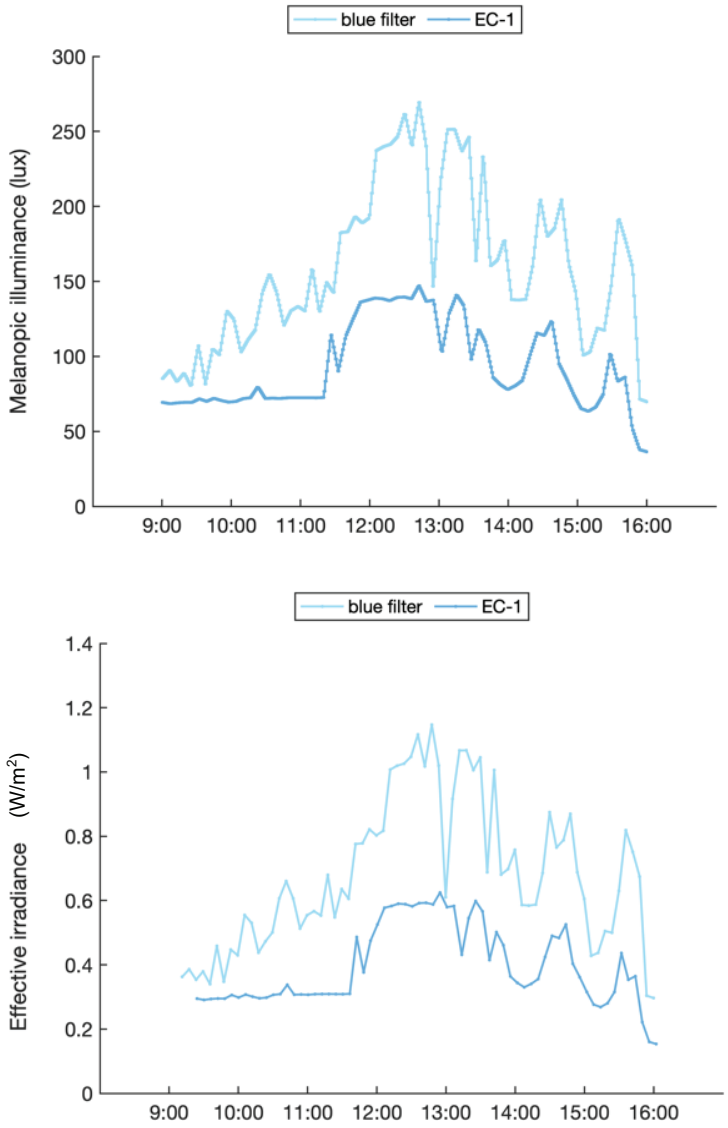


Figure 7.6 Average light values over time measured at the eye level during day 1 in study B. From top to bottom, original measured data (spectral irradiance), derived photopic illuminance (model 1), melanopic illuminance (model 2) and effective irrdiance (model 3).

It is important to highlight that, since models 1 and 2 required information about sleep schedules and light data for at least 24 hours, arbitrary values (as realistic as possible) had to be set outside experimental hours (9:00 a.m. – 4:00 p.m.): first, a consistent sleep schedule from 12:00 am to 8:00 a.m. was assumed; in addition, a constant vertical illuminance at the eye of 150 lux during the day (from 8:00 to 9:00 a.m. and from 4:00 p.m. to 8:00 p.m.) and of 15 lux during the night (from 8:00 p.m. to 8:00 a.m.) was assumed for the purposes of this analysis.

In addition, and although long-term light data can be used as an input to models 1 and 2 to predict phase-shifting effects, model 3 is limited instead to 24-hour evaluations (as it assumes constant, entrained conditions). In this case, since we are also mostly interested in daytime alertness responses, experimental days were simulated independently so as to have a fair comparison between the three models.

7.2.2 Alertness data and analyses

As introduced in Chapter 3, self-reports of subjective levels of alertness were collected every hour and every experimental day, since the beginning of the exposure at 9 a.m. until the end at 4 p.m. Two scales were used for this purpose: the Karolinska Sleepiness Scale (KSS) and the Stanford Sleepiness Scale (SSS). For this particular investigation, we will limit the comparisons only to the more commonly used KSS values.

Since the three investigated models use different scales to show alertness predictions, experimental data will be rescaled accordingly, and all values will be normalized so that they can be fairly compared. Elaborating on this, models 1 and 3 offer a scale that goes from 0 to 1 (where higher scores indicate more alertness), while model 2 offers scores directly based on the KSS scale (from 1 to 9, where lower scores correspond to higher alertness levels).

To investigate the performance of models describing self-reports of alertness, Spearman correlation analyses were conducted. This method, selected due to the nature of our data (i.e., ordinal), was used to test the relationship between observed and simulated data (i.e., paired variables). Unlike the Pearson correlation, where paired values are compared to one another to depict linear relationships – with potentially misleading, results when outliers are present –, the Spearman correlation applies a ranking system to both variables and compares the ranks of each observation instead based on a monotonous, non-linear relationship. The correlation coefficient, which ranges between -1 and +1, indicates both the magnitude of shared variance between both variables and the direction of their relationship: 1 represents the strongest agreement between the variables, while 0 represents the strongest disagreement; a positive value represents a prediction in the same direction (i.e., alertness increases in both variables), whereas a negative one indicates predictions in opposite directions (i.e., while one variable predicts increases in alertness, the other one predicts decreases in alertness of the same magnitude).

The interpretation of such values in our case will be based on thresholds established by Ferguson (2009), as it represents a rather strict method (unlike Cohen, for example) and has been used in lighting research before (Chamilothori, 2019). He suggests a recommended minimum r value of 0.2, thereby representing a practically significant effect. Note that r values of 0.5 and 0.8 will correspond to moderate and strong effects, respectively.

On the other hand, the difference between measured and simulated values was evaluated as the root mean square error (RMSE) and the normalized root mean square error (NRMSE). The choice of these related error metrics was based on the fact that we are investigating the accuracy of different models for different studies while focusing on a common output, namely subjective alertness, which is, however, measured using different scales. And as the RMSE allows for comparisons of results between studies within the same model (since it provides the same unit as the response variable), while the NRMSE (which is not scale dependent) allows for comparisons of results within the same study but across models, it was decided that we needed to rely on the evaluation of both. Indeed, we are interested, on the one hand, in analysing the internal consistency of the model, for which we compare outcomes of different studies and identify which model has a lower error across studies. On the other hand, we want to look at differences between models per lighting condition and study, to determine which model has a lower error per daylighting condition and/or study.

The interpretation of results in this case is somehow more challenging than in correlation analyses, since no established thresholds exist to evaluate the magnitude of error metrics. It is of course generally agreed that the best fit corresponds to the point where the prediction error between the model and the measured data is lowest. However, the fact that our models produce outputs based on different scales (i.e., models 1 and 3 use a 0 to 1 scale, where higher is better, while model 2 relies on a 1 to 9 reversed scale, meaning that lower is better in that case), adds another level of complexity to the evaluation. RMSE can be interpreted as the standard deviation of the unexplained variance in the data, and since it is scale-dependent, the RMSE in models 1 and 3 will vary between 0 and 1, while in model 2 can go up to 9. Still, for both cases, lower values indicate a better fit of the data. The NRMSE represents instead a percentage of variation (as it is non-scale dependent), where lower values also indicate less residual variance. For this last one, values <10% are generally considered as acceptable.

7.3 RESULTS

A total of 6 daylighting conditions (two per study, A, B and C) and 12 datasets including both light data and subjective responses, were tested in models 1, 2 and 3 regarding their abilities to predict observed daylight alertness during as evaluated during studies A, B and C and applicable to routinely working hours.

7.3.1 Model 1

As illustrated in Figures 7.7 to 7.9 and further detailed in Table 7.2, the Spearman rank correlation showed moderate, occasionally significant associations only for certain days and conditions in studies B and C between observed and predicted values of

subjective alertness. When studies are analysed as a whole and not individually per day, we can observe that only study A has a small correlation for both conditions ($\rho <$ 0.50), whereas for study B and C the correlation was on average moderate ($\rho > 0.50$) for both conditions. In general, the overall correlation of the model can be considered as moderate and of positive direction (average $\rho = 0.51$). Figures 7.7–7.10 show that, while subjective reports tend to increase throughout the day (i.e., participants feel more alert), model predictions also increased, resulting in a decrease in subjective sleepiness.

Table 7.2 Spearman rank correlation coefficient ρ, associated p-values, and error metrics (RMSE and NRMSE) for the different datasets (per study and lighting condition). Correlations approaching moderate or large effect sizes (ρ>0.5) and statistical significance (p<0.10) are represented in bold.

		(neutral / blue filter / bright)				*(blue / EC-1 / dim)*			
Study	Day	ρ	*p-value*	*RMSE*	*NRMSE*	ρ	*p-value*	*RMSE*	*NRMSE*
A	*Day 1*	0.21	0.66	0.19	0,91	0.43	0.35	0.10	0,46
B	*Day 1*	**0.71**	0.06	0.15	0.61	**0.50**	0.21	0.08	0.33
	Day 2	0.49	0.22	0.06	0.25	0.12	0.78	0.12	0.48
C	*Day 1*	**0.52**	0.20	0.14	0.56	**0.70**	0.06	0.11	0.43
	Day 2	**0.64**	0.10	0.07	0.31	**0.88**	**0.01**	0.09	0.38
	Day 3	**0.67**	0.08	0.15	0.62	0.24	0.56	0.18	0.71
		0.54				0.48			

Furthermore, the accuracy of this model at predicting alertness scores was not very good since NRMSE values were always above 0.31 (i.e., equivalent to a 31% error) for all studies and conditions but reaching up to 91 % error for study A. This indicates a rather large fluctuation between measured and predicted values and can be thus considered a rather poor reliability of the model to anticipate human responses in the specific conditions experienced in our studies (at least based on our analysis of the data collected). In general, data from study A led to higher prediction errors in the model under both conditions compared to studies B and C. In addition, the model presented deviations of the variance that ranged from 0.06 to 0.19, with the lowest values corresponding to day 2 of study B and day 2 of study C. Although the model does not account for spectral sensitivity, in study C (where both conditions are spectrally neutral) both the deviation of the variance and the error percentage were considerably large (RMSE between 0.07 and 0.18 on a scale of 0 to 1, NRMSE > 31 %).

STUDY A

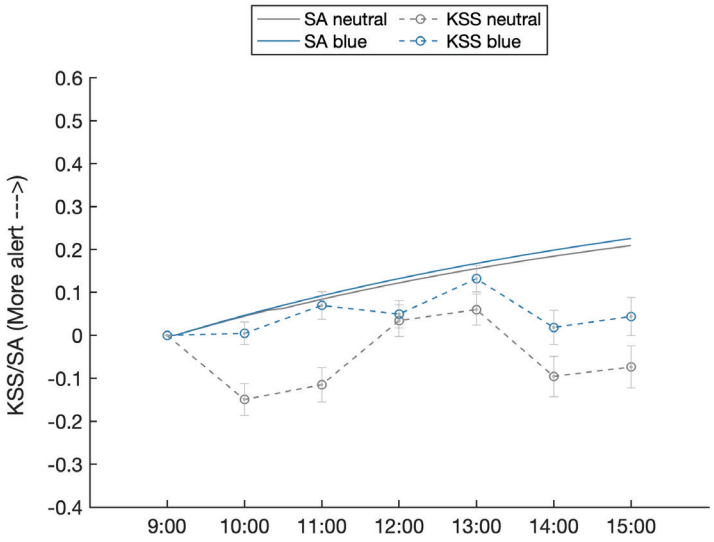
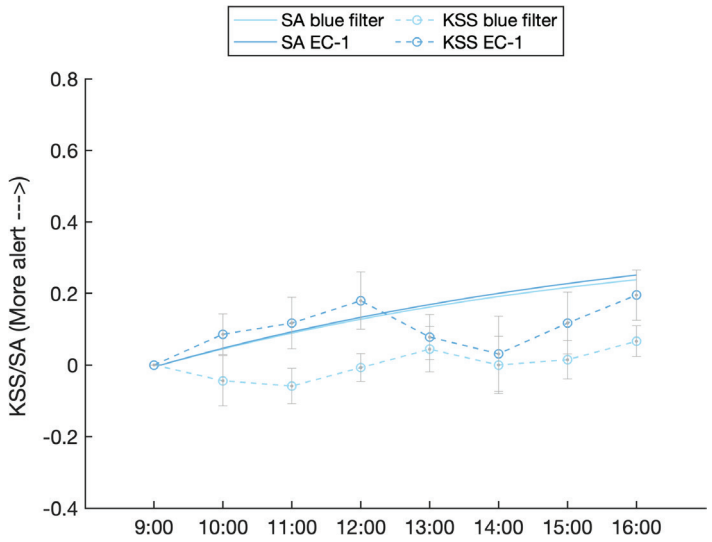


Figure 7.7 SA model prediction vs KSS subjective data under dim neutral vs. dim blue daylighting conditions (day 1).

STUDY B



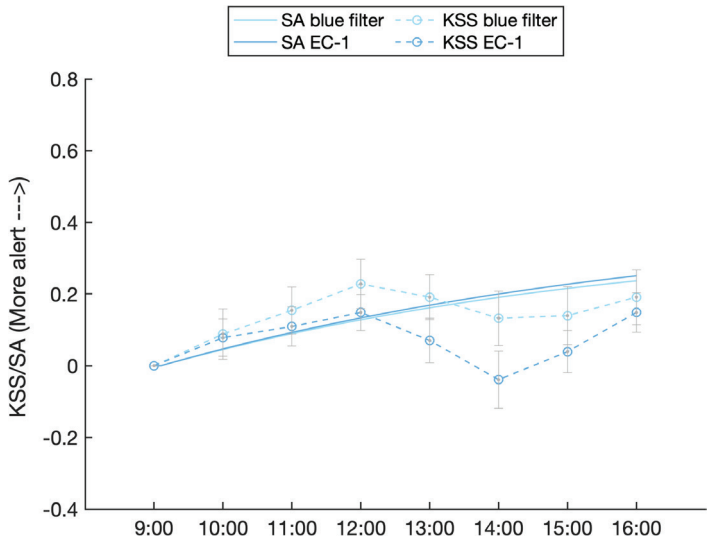
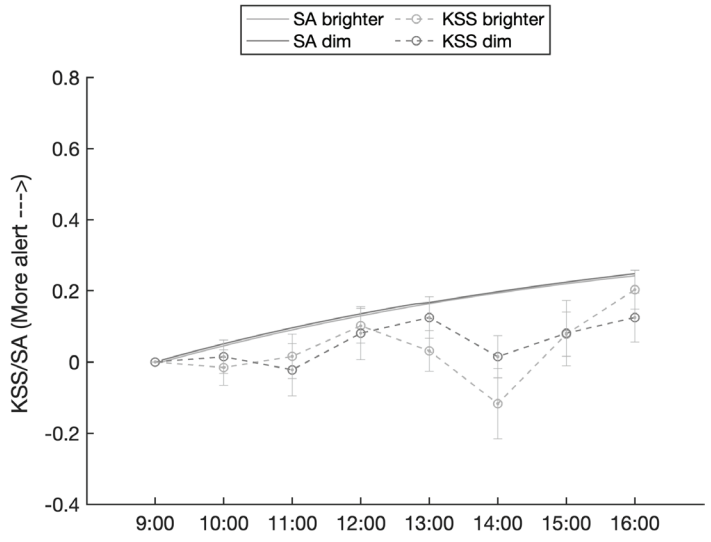


Figure 7.8 SA model prediction vs KSS subjective data under bright blue (blue filter) vs. dim blue (EC-1) daylighting conditions (days 1 and 2).

STUDY C



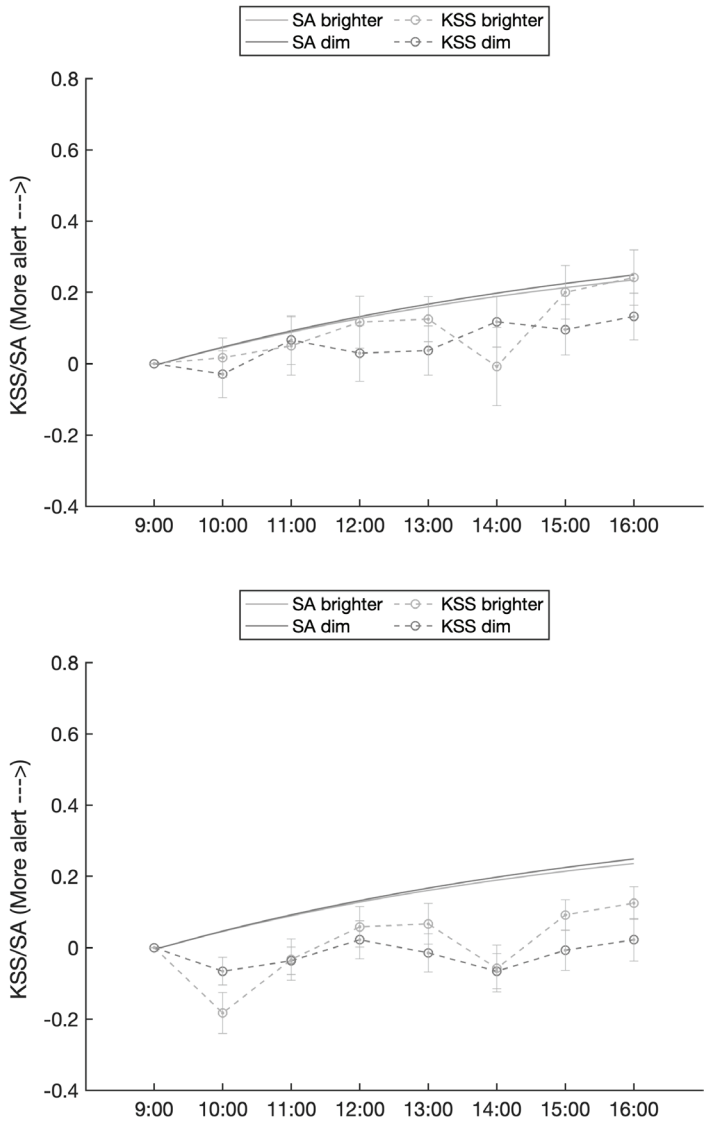


Figure 7.9 SA model prediction vs KSS subjective data under bright neutral vs. dim neutral daylighting conditions (days 1, 2 and 3).

7.3.2 Model 2

For model 2, the Spearman rank correlation showed several moderate to high associations, with again occasional significance, for different days and under both conditions between observed and predicted values of subjective alertness in studies B and C (Table 7.3). When analysing results for studies A through C, we can first observe that, unlike in model 1, no negligible correlations can be observed. While in studies A and B the average correlation was small ($\rho < 0.50$), in study C a moderate correlation was instead discovered ($\rho < 0.80$). This led to an overall correlation of the model that is still considered as small, although already higher than the one in the previous model, and again of negative direction (average ρ = -0.45). This can be seen in Figures 7.10 to 7.12, where while subjective reports tend to decrease throughout the day (i.e., participants feel more alert), model predictions go up, anticipating an increase in subjective sleepiness instead.

Table 7.3 Spearman rank correlation coefficient ρ, associated p-values, and error metrics (RMSE and NRMSE) for the different datasets (per study and lighting condition). Correlations approaching moderate or large effect sizes (ρ>0.5) and statistical significance (p<0.10) are represented in bold.

		(neutral / blue filter / bright)				*(blue / EC-1 / dim)*			
Study	Day	ρ	*p-value*	*RMSE*	*NRMSE*	ρ	*p-value*	*RMSE*	*NRMSE*
A	*Day 1*	-0.21	0.66	1.21	0.66	-0.21	0.66	1.59	0.96
B	*Day 1*	-0.32	0.43	0.55	0.55	-0.47	0.25	1.65	1.19
	Day 2	-0.49	0.22	1.33	1.29	-0.12	0.78	1.45	1.02
C	*Day 1*	**-0.52**	0.20	1.16	1.29	**-0.70**	0.06	2.02	1.01
	Day 2	**-0.52**	0.20	1.97	1.42	**-0.88**	**0.01**	2.30	1.01
	Day 3	**-0.64**	0.10	1.48	1.04	-0.24	0.56	1.60	0.71
		-0.45				-0.44			

The accuracy of this model at predicting alertness scores was, in general, worse than the previous model since NRMSE errors were always above 0.55 (i.e., equivalent to a 55 % error) for all studies and conditions but reaching up to 142 % error between observed and predicted values for Day 2 in study C. This particular value corresponds to a deviation of 1.97 points, which translated to the KSS scale (i.e., on a scale from 1 to 9), could represent the difference between feeling “rather alert” or instead, with “some signs of sleepiness”. Thus, the reliability of the model for our given dataset could be considered as rather poor overall. In this case, data from study A rendered overall lower prediction errors in the model than studies B and C, as well as higher error in the blue room than in the neutral one. In addition, the model was better at predicting dimmer conditions (either neutral or blue-shifted) in studies B and C.

STUDY A

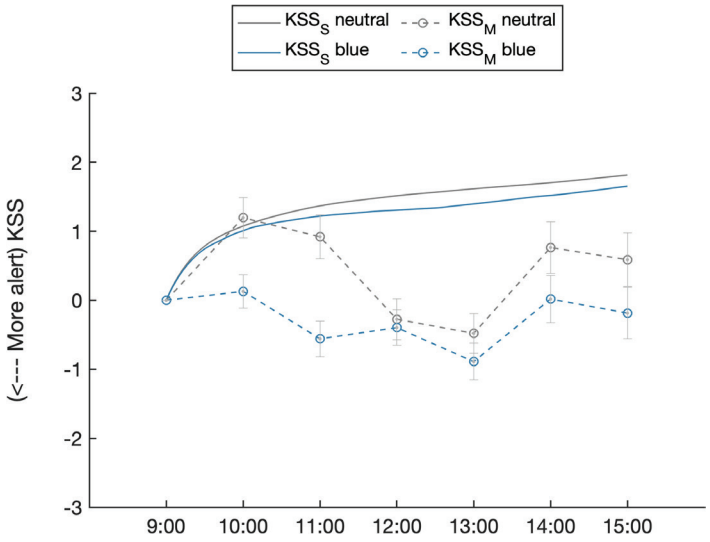
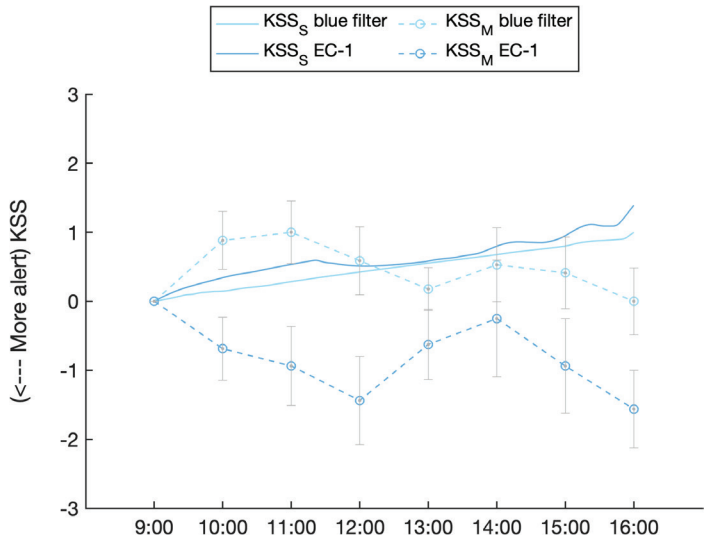


Figure 7.10 KSS model prediction vs KSS subjective data under dim neutral vs dim blue daylighting conditions (day 1).

STUDY B



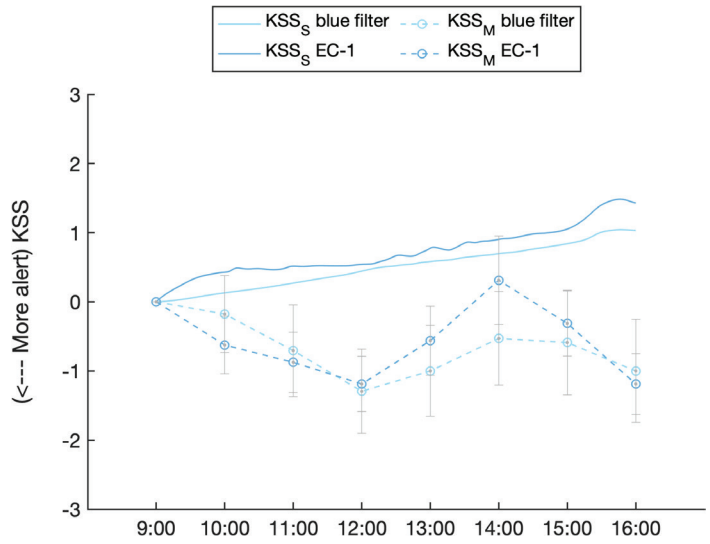
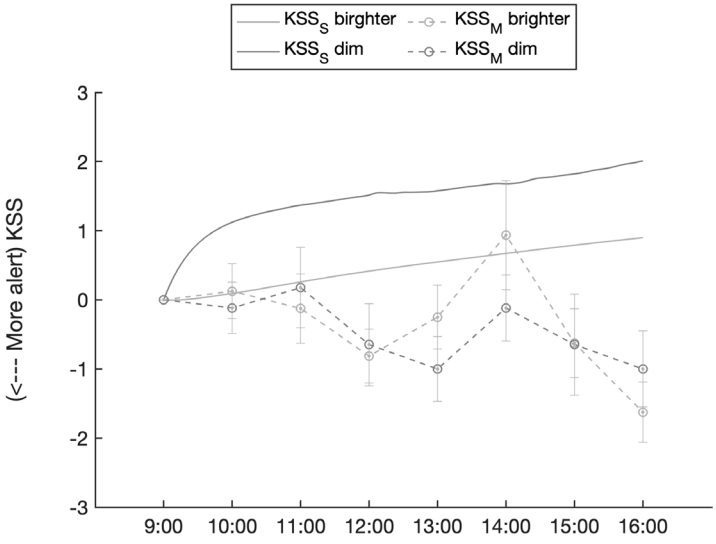


Figure 7.11 KSS model prediction vs KSS subjective data under bright blue vs dim blue daylighting conditions (day 1 and 2).

STUDY C



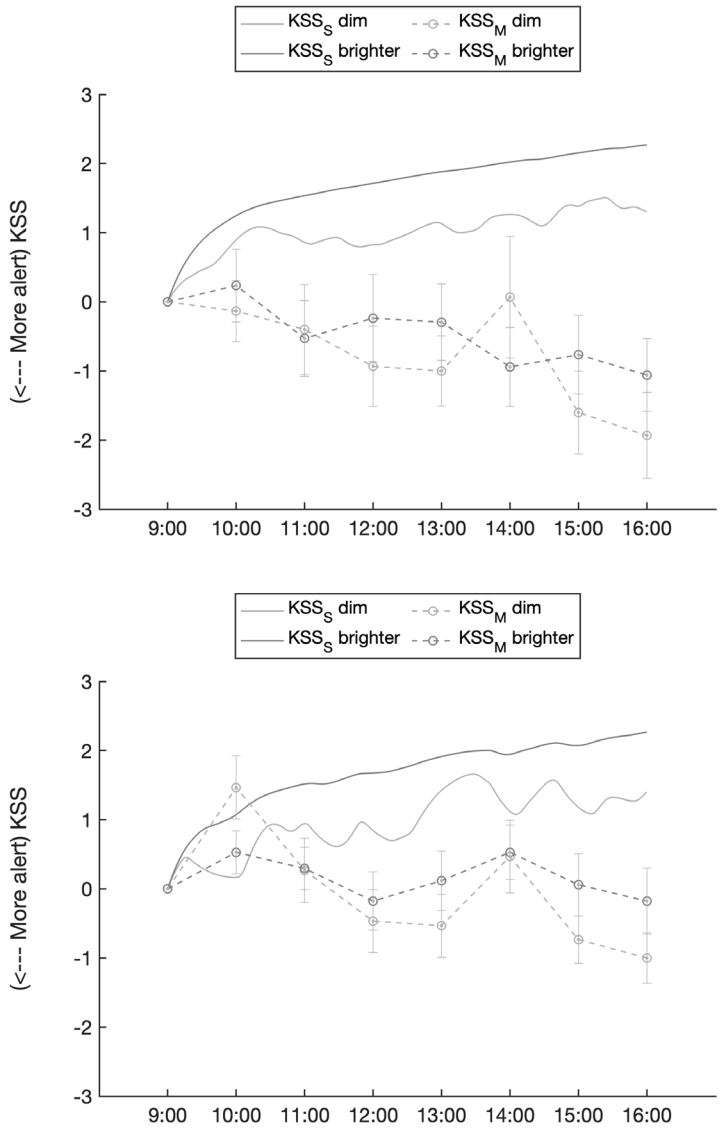


Figure 7.12 KSS model prediction vs KSS subjective data under bright neutral vs dim neutral daylighting conditions (days 1, 2 and 3).

7.3.3 Model 3

For model 3, the Spearman rank correlation showed moderate to strong associations, with occasional significance, for most of the days and for both pairs of conditions in studies B and C between observed and predicted values of subjective alertness, as shown in Table 7.4 and Figures 7.13 to 7.15. Like for models 1 and 2, however, these associations were not revealed in study A, especially for the neutral condition (Figure

7.13, upper graph), which showed a rather small correlation. This was the case also for day 2, study B (Figure 7.14, middle graph) and day 3, study C (Figure 7.15, bottom), where a negligible in the former and a small correlation in the latter were found in EC-1 or dim condition, respectively. The improved correlation for model 3 compared to the model 2 between simulated and observed responses can be observed when looking at day 1, study B and days 1 and 2, study C, and comparing to Figures 7.14 (upper graph) and 7.15 (upper and middle graphs) respectively. It is for instance very interesting to note that the highest correlation was achieved from the data in the dim (neutral) condition from study C during day 2, as described in Figure 7.15 (middle). More generally speaking, the overall correlation of the model can be considered as moderate and, unlike the previous model, of positive direction (average $\rho = 0.51$). This means that when subjective responses increase, predicted responses tend to increase as well, which is what one would expect from a model.

In terms of accuracy, this model performed worse than the other two models at predicting alertness scores, since NRMSE values fluctuated between 31 – 818% of error among studies and lighting conditions. This suggests once again, a relatively large difference between measured and predicted values and, as a result, a rather low reliability of the model to predict human responses in the special circumstances encountered in our experiments. In addition, the model presented deviations of the variance that ranged from 0.06 to 0.36, with the lowest values corresponding to days 1 and 2 of study C.

Table 7.4 Spearman rank correlation coefficient ρ, associated p-values, and error metrics (RMSE and NRMSE) for the different datasets (per study and lighting condition). Correlations approaching moderate or large effect sizes (ρ>0.5) and statistical significance (p<0.10) are represented in bold.

		(neutral / blue filter / bright)				*(blue / EC-1 / dim)*			
Study	Day	ρ	*p-value*	*RMSE*	*NRMSE*	ρ	*p-value*	*RMSE*	*NRMSE*
A	*Day 1*	0.21	0.66	0.18	4.62	0.43	0.35	0.22	1.04
B	*Day 1*	**0.71**	**0.06**	0.34	0.57	**0.50**	0.21	0.13	0.37
	Day 2	0.49	0.22	0.20	0.38	0.12	0.78	0.13	0.50
C	*Day 1*	**0.52**	0.20	0.36	0.51	**0.70**	0.06	0.06	3.68
	Day 2	**0.64**	0.10	0.07	0.49	**0.88**	**0.01**	0.07	8.18
	Day 3	**0.67**	0.08	0.16	0.60	0.24	0.56	0.17	1.96
		0.54				0.48			

STUDY A

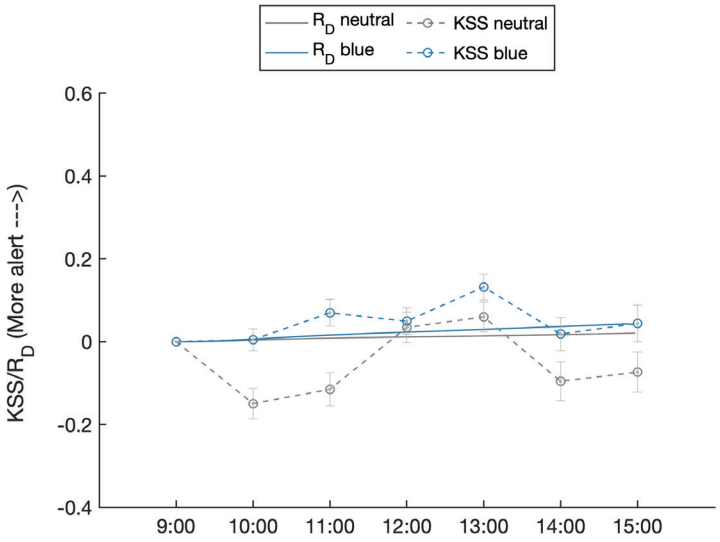
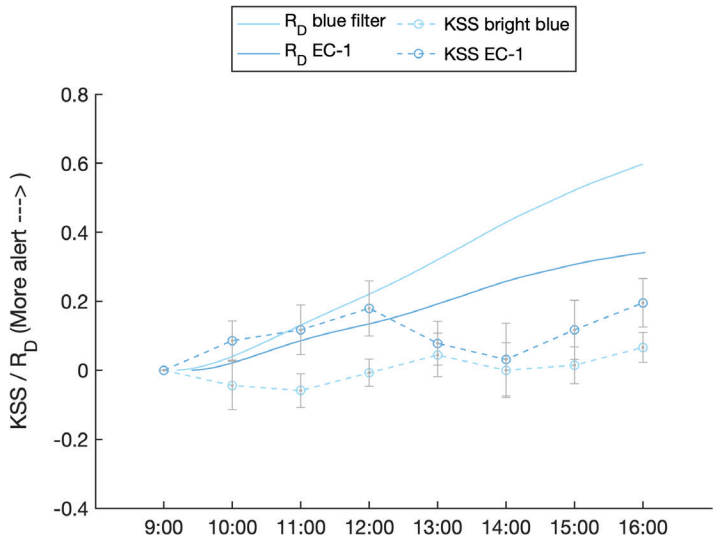


Figure 7.13 RD model prediction vs. KSS subjective data under dim neutral vs. dim blue daylighting conditions (day 1).

STUDY B



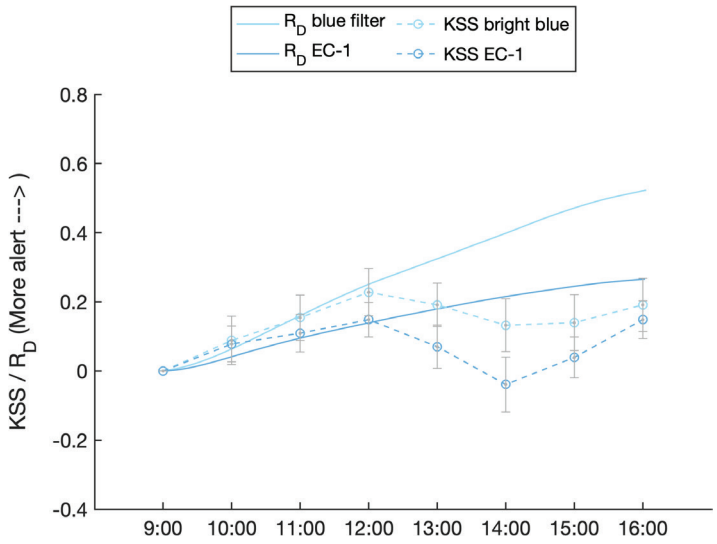
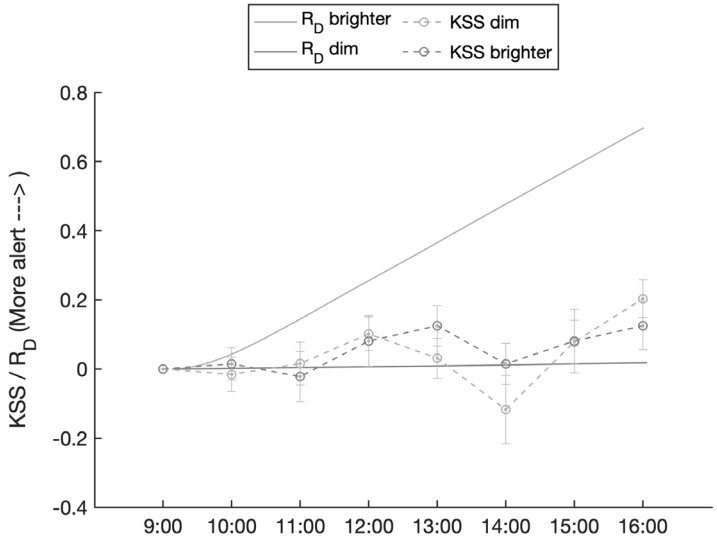


Figure 7.14 RD model prediction vs. KSS subjective data under bright blue vs. dim blue daylighting conditions (days 1 and 2).

STUDY C



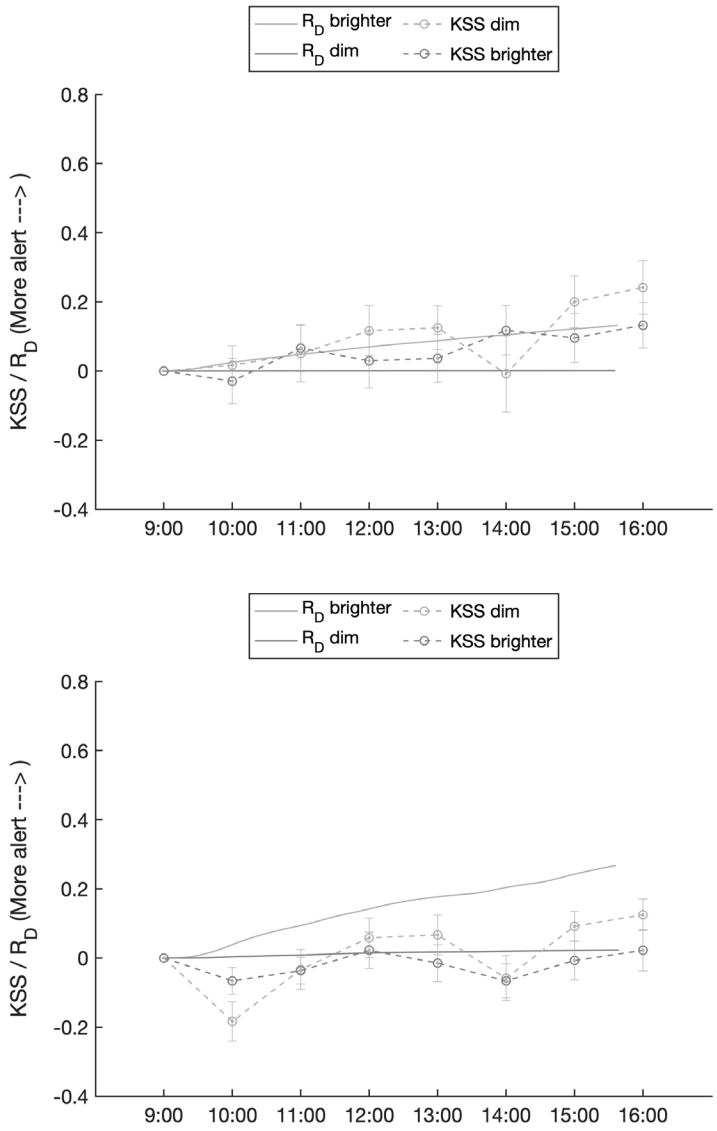


Figure 7.15 RD model prediction vs. KSS subjective data under bright neutral vs. dim neutral daylighting conditions (days 1, 2 and 3).

7.4 MAIN OUTCOMES

A model that accounts for the effects of light on circadian resetting and alertness would be a useful tool for tailored light interventions in occupational settings. Towards this end, three existing computational models, that offer different possibilities in terms of prediction of non-visual responses, have been tested. For the first time, the models have been examined with daylight measurements, and

compared against subjective responses collected during working hours and in near-realistic conditions. The goal was first to get a better understanding of their individual accuracy and performance, then to compare them to one another.

Results from our investigation show that, overall, models 1 and 3 (mean ρ = 0.54 and 0.48, cf. Tables 7.2 and 7.4) performed better than model 2 (ρ = -0.45 and -0.44, Table 7.3): a positive moderate correlation was indeed found between measured and simulated data in models 1 and 3, under any two pairs of lighting conditions, while model 2 reported negative small correlations.

However, when looking at the accuracy of the models, errors between measured and simulated data (NRMSE in %) remain very high for all three: overall, they were typically between 31 - 818% for model 3, between 55 - 142% for model 2, and between 41 – 91% for model 1. These results are particularly interesting in the sense that, while some models (especially 1 and 3) show promise at anticipating trends of results (correlation analyses), none of them managed to acceptably predict specific values of alertness, as the prediction error was in general rather large (> 10%). In other words, this means that, while the underlying mechanisms of the cause-effect relationship in models 1 and 3 proved to be a valid approximation of patterns to daytime alerting responses, further adjustment and recalibration is warranted in their components so as to improve the accuracy of their alertness scores prediction. Such an outcome could be explained by the fact that none of the models was developed with either daytime data or daylight conditions, whereas in this investigation they were confronted to responses collected both during daytime and under exclusive use of daylight. It is therefore not surprising to see that they failed at predicting exact results and it is still positive to see that trends were anticipated to some extent, especially for models 1 and 3.

Also promising is the fact that when comparing the consistency of models individually across studies (RMSE), the deviation of results was lowest in model 1 (RMSE between 0.06 and 0.19 on a scale from 0 to 1), while model 2 (RMSE between 0.55 and 2.30 on a scale from 1 to 9) and model 3 (RMSE between 0.06 and 0.36 on a scale from 0 to 1) performed similarly.

On the other hand, it is important to note that model 1 (St Hilaire et al., 2007) and model 2 (Tekieh et al., 2020) both offer the possibility to predict alertness based on potential phase-shifting circadian dynamics due to light exposure and irregular sleep-wake cycles. As model 3 assumes instead a regular occupant behaviour (i.e., normal working hours and sleep-wake cycles), it can only predict alertness variations induced from light exposure patterns that are based on “normal” circadian timing (i.e., entrained conditions). Thus, models 1 and 2 might actually turn out to be better suited for spaces with an irregular occupation such as that of shift workers, whereas model 3 is likely to align better with habitual work environments were regular schedules are imposed (i.e., classrooms or offices), as was indeed the case in our studies.

Unlike model 3, which assumes a static circadian oscillator (i.e., no phase-shifting capacity), models 1 and 2 consider a dynamic oscillator that allows for circadian phase-shifts. The need for a feedback mechanism in the latter does make them more realistic – our biological processes are dynamic – but also computationally less efficient, which can become an issue for annual evaluations, for example. In addition, the presence of a non-photic component in models 1 and 2 (i.e., a sleep schedule) position them as more challenging than model 3 from a design integration perspective, as no personal information is required in the latter and is typically difficult to get or hypothesize in a design process. In general, it could be said that the approach proposed by model 3, by means of a simpler, linear cause-effect structure (light being the cause and the neurophysiological response being the effect), makes it ultimately more suitable for analyzing daylighting strategies in the built environment compared to the other two models, but its lack of accuracy at predicting daytime alertness still remains as a huge constraint. Its potential for design applications has in fact already been further developed, both conceptually (Amundadottir et al., 2017) and as an integral part of decision support tools (Rockcastle et al., 2018, 2017).

7.5 APPLICABILITY OF FINDINGS IN A DESIGN DECISION SUPPORT PROCESS

Architecture is arguably the most important factor when it comes to supplying building occupants with access to daylight, as it mediates the boundary between the outside world and the indoor environment. A lot of effort has been put in the development of daylighting simulation tools to assess visual specifications and comfort by means of evaluating light intensity values at the horizontal plane with static threshold values. This is not the case, however, for the integration of non-vision-related psycho-physiological responses. Moreover, considering that, on the one hand, non-visual responses are evaluated based on dynamic light values (unlike static visual thresholds), and on the other hand, that the non-visual system is slower in responding to changes in light when compared to the visual system, traditional light metrics and simulation platforms are limited in their capacity to anticipate non-visual responses in the built environment (Amundadottir, 2016).

7.5.1 Potential of spectral simulations

To become relevant to light-induced neurophysiological responses, lighting simulation must offer a way to overcome the limitations inherent to a 'universal' weighing according to the photopic sensitivity curve V(λ) as the photoreceptors that matter in these responses (notably the melanopsin photopigment) have different sensitivities. One way to overcome this limitation is to enhance information embedded in lighting simulations by integrating a complete spectral definition of the luminous environment at any given moment of time, which requires to have access to the spectral characteristics of all light source(s) and all surfaces and materials in

contact with light, or in other words, to their respective spectral power distribution (SPD) properties. An SPD allows to formally describe colour and intensity variations in emitted or received light, including of course natural light. Since the human eye's spectral sensitivity spans the wavelength range from about 380 nm to 780 nm, calculating spectral information at, say, 5 nm intervals would require around 80 samples to be stored and analysed for each rendered pixel. To date, one of the key obstacles to incorporating non-visual effects of light into the design process has been the additional computational effort that this represents. While in our case recorded light data was available so as to properly characterise the experimental set-up and thus investigate the non-visual potential of different lighting strategies through investigated models, this information is often unavailable in practice.

Resorting to the three-dimensional RGB colour space is the most common and frequently used way to approximate spectral resolution and is in fact present in nearly all light simulation platforms. This kind of information, however, is not sufficient to characterize the spectral sensitivity of the non-visual system, as the key issue of converting RGB triplets into spectral information is the infinite number of different spectral distributions that can be derived. To address these limitations (i.e., of RGB triplets inaccuracy and of computational cost of spectral simulations), two user friendly, non-RGB based spectral simulation tools (ALFA, by Solemma LLC and Alertness CRC (2018) and Lark, by Inanici et al. (2015)) were recently reviewed and validated against indoor daylight measurements by Pierson et al. (2021).

In a nutshell, they concluded that, while Lark provided the most accurate results in terms of % error between measured and simulated data, ALFA was a more user-friendly tool. The former statement might be because Lark's simulation inputs are less predefined than in ALFA's, thus requiring more specific information (i.e., while a simulation in ALFA requires only the sky type, location, and time, a simulation in Lark also includes the irradiance and sky SPD) and hence providing more accurate results. The latter might because, as a consequence of the former, ALFA requires less previous knowledge of lighting simulation (i.e., Radiance) and of design software (i.e., Grasshopper), and does not rely on a user's coding skills (i.e., Phython). For this reason, ALFA might be in the end better suited to integrate a design process, but necessarily comes at a cost in terms of limitations in the accuracy of the outcomes.

7.5.2 Alertness potential in daylit architecture

Attempts at integrating findings about non-visual effects of light in the built environment through the design process are not new (Acosta et al., 2017; M. Amundadottir et al., 2017; Amundadottir et al., 2013; Andersen et al., 2012; Borisuit et al., 2016; Konis, 2017; Pechacek et al., 2008). However, no agreement has been reached to this end as the complexity of the topic is two-folded: on the one hand, there is a fundamental lack of understanding about the mechanisms behind psycho-physiological light-induced responses, as the field is still on its infancy; on the other

hand, there is a technical barrier as to be more faithful to reality, especially with regards to simulation of ocular light exposure.

Research conducted in this thesis has primarily focused on the former, with the goal of expanding current understanding of non-visual effects of light (which is rapidly evolving) to daylight integrated exposures in our daily working routines. Without this kind of more fundamental knowledge advances, the debate regarding what really matters (and to what extent) in the field of architecture, will remain open. In this section, however, we will focus on the technical aspects instead. Now that simulation platforms like Lark and ALFA are made available to facilitate the exploration of daylighting spectral-dependent strategies, new possibilities open up, to some extent, for the optimization of daylighting performance as an added value for health and well-being promotion (Figure 7.16). Yet, considering that the best performing model (i.e., models 1 and 3) obtained an error accuracy that ranged between 31 to 818% for our experimental data (i.e., exposures to daylight), one should be careful and use light-driven models more as an informative, orientation tool in the design process than as a design decision support tool.

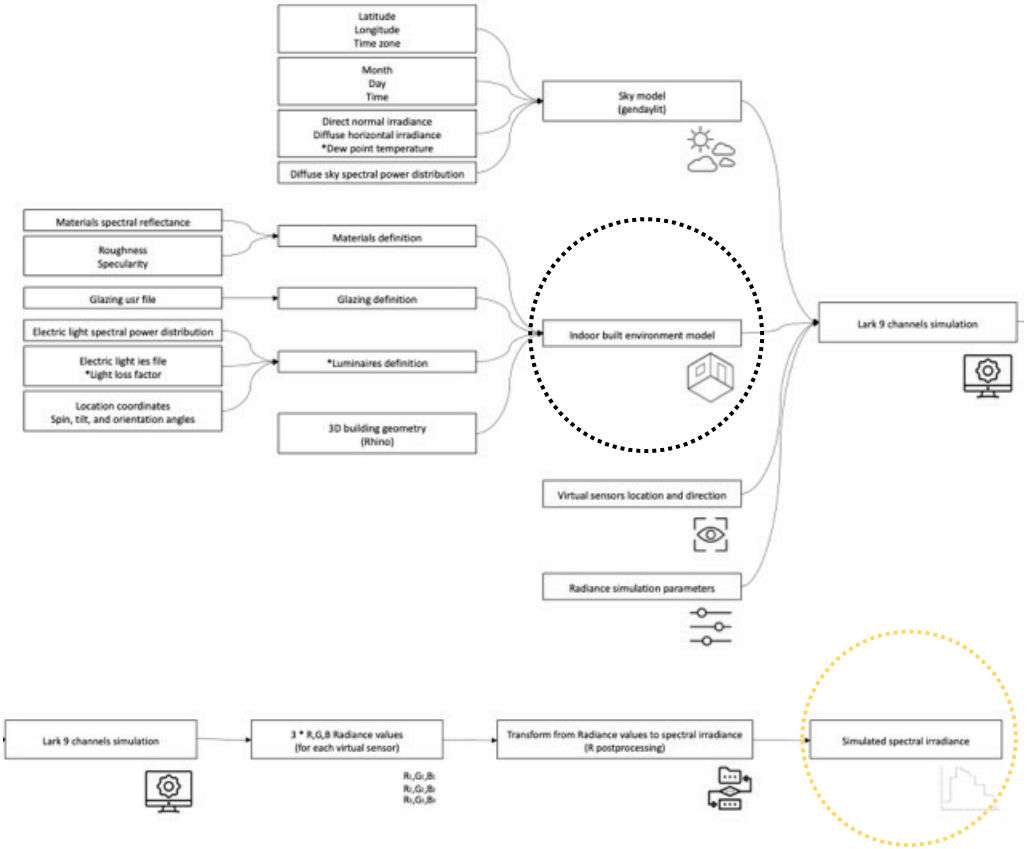


Figure 7.16 Diagram of the spectral simulation workflow required for Lark

Based on findings presented in this chapter, which at the same time build upon insights gained from analyzing the effects of daylight exposure on alertness in specific conditions (Chapters 4 to 6), and on advances regarding spectral characterization of the indoor environment, a simulation workflow could potentially be proposed for the assessment of alertness potential in daylit architecture (Figure 7.17).

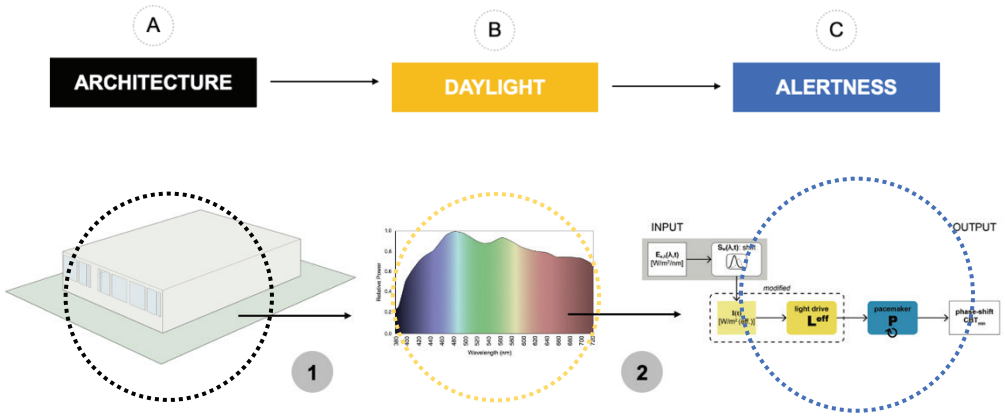


Figure 7.17 Diagram of the simulation workflow to integrate the study of alertness within the design process

The workflow might consist of three main parts:

- (A) the definition of architectural spaces by means of design features such as glazing, indoor materials or shading systems, important due to their potential impact on the spectral irradiance received at the eye (Arsenault et al., 2012).

- (B) the characterisation of the luminous environment by means of spectral content, important due to its potential to stimulate the non-visual system (CIE, 2018).

- (C) the transformation of light, wavelength-dependent information into expected neurophysiological responses by means of prediction models.

Addressing the concerns raised regarding the accuracy of such methods (C), it is important to remind that performing such computations would not yield data of practical utility per se, other than a mere trend or results direction. In this conceptual workflow, note that model outputs other than alertness could be also explored, such as cognitive throughput, circadian disturbance, etc., with the same three-part structure.

7.5.3 Challenges ahead

Given the proposed methodology, in an effort to increase interactions and motivation for knowledge exchange across multiple disciplines (i.e., from chronobiology and photobiology to neuroscience and architecture), the question remains as to also define the extent of the following issues:

- how daylighting strategies of various types, from contextual interventions such as building orientation or urban canyon, to building features such as geometry, materials or windows, might affect the sensitivity of spectral content in the built environment;

- more importantly, how non-visual response models' sensitivity might be affected by other type of lighting conditions, distinct from the ones that have been already tested in this thesis, and as suggested in sections 4.6.3, 5.6.3 and 6.6.3.

To address these limitations, and to verify the adequacy of the proposed simulation workflow (Figure 7.17) in informing non-visual responses during the design process, a follow up investigation should be conducted. To this end, variations in architectural features and design strategies (i.e., such as glazing characteristics or finishing materials, among others) should be tested (workflow part A) for their influence on indoor spectral conditions (workflow part B) and consequently, in occupants' alertness by means of prediction models (workflow part C). The interpretation of simulation results, both in terms of light characterisation (phase 1) and alertness prediction (phase 2), will allow to highlight what learnings are to be expected from such a workflow. Ultimately, these insights will help improve the design of buildings while accounting for occupant's well-being due to the integration of daylight exposure in our daily routines.

In addition, performance criteria assess how well buildings achieve specific goals such as energy efficiency or comfort. These objectives are often interacting with one another and in some cases, their relationship is conflictive. In such situations, compromises have to be made when looking for the best design solutions. Integrating non-visual light effects in the built environment implies a yet unexplored dialog with visual comfort and other visual performance indicators, which is likely to involve new challenges. In other words, what is good for the visual system might not be good enough for the non-image-forming pathway. Therefore, future studies should start addressing this confrontation.

8 [CONCLUSIONS]

The research driving this thesis was conducted at the intersection of architectural design, lighting theory and neurobehavioural science, and incorporates non-visual system discoveries that mediate the light effects on human functioning into a workflow for design simulation.

The idea that light mediates a sequence of non-visual, non-image-forming responses that are essential to our biological processing was discovered just two decades ago. Via a novel photoreceptor in the human retina (ipRGCs), light can generate acute reactions in the brain while our body adjusts over 24-hour periods to the light-dark cycles, thus controlling major body functions over time.

The circadian rhythm in alertness is probably the most powerful and replicable of all the rhythms in the so-called non-visual processes. The measured circadian rhythm in alertness reflects the combined influences of the endogenous body clock and exogenous factors. These include, but are not limited to, our habitual sleep schedule, activity or meals, but also, environmental factors. In that sense, light is considered a key stimulus for the synchronization of circadian rhythms, and daylight as the equivalent natural zeitgeber. This underlying dual nature of measured rhythms has long been recognized by experts in different fields but complicates the interpretation of results in many studies. In most investigations, it is difficult to elucidate whether results are measuring an actual inner biological process (circadian rhythm), or rather a response that changes due to the influence of external factors.

In addition, most of the studies on acute alerting effects have been conducted in well-controlled laboratory settings, where somewhat extreme and narrowly defined lighting conditions were tested. Very limited attempts have been made towards the integration of daylight in such investigations, but no study exists to date that has explored alerting effects of daylight in isolation from electric light. Moreover, owing to weather conditions or automatic controls, the indoor luminous environment is continuously changing, even in terms of daylight. Light will have both positive and detrimental effects on human health and well-being in the course of the day based on temporal and qualitative characteristics.

Our work explored cause-effect relationships of indoor daylight exposure and correlates of daytime alertness, to gain a better understanding of the role of architectural design in daylight provision from a psycho-physiological perspective. The goal was to help elucidate whether responses already observed in a laboratory setting could also be noticeable in a more realistic scenario, during working routines. A conceptual simulation workflow, which resulted from insights gained from conducted user studies and the application of this same experimental data to light-driven models, was proposed for the study of alertness in the context of architectural design.

Before this new knowledge becomes a reality, further validation is needed from future works. In the next sections, an overview of the main findings and contributions of the thesis is provided, while potential research prospects will be identified in the outlook.

8.1 FINDINGS AND CONTRIBUTION

Alertness has been widely studied both as a psychological and a physiological construct, and as a result, has been subject of many interpretations and definitions. In this thesis, we have explored the potential of daylight to elicit alerting responses in individuals during daytime working routines. The term alertness was investigated in this thesis from three different perspectives: as an indicator of subjective alertness, to measure the opposite of sleepiness or the desire to sleep, as an output of cognitive functioning, to measure the ability of an individual to sustain attention, and as a marker of physiological arousal, to measure changes in the autonomous nervous system activity. Furthermore, several mathematical models exist for the prediction of alertness as a response to light stimuli. By confronting experimental data from user studies with computational approaches, we evaluated their potential for moving forward in the consolidation of non-visual responses as a design criterion.

This section summarizes the work discussed in this thesis, with an emphasis on significant contributions and key findings from Chapters 3 to 7, including methodological constraints, insights from user studies and learnings from computational methods on the evaluation of alertness in the built environment.

8.1.1 Methodology to investigate alerting effects of daylight

In this thesis, we investigated the effect of variations on indoor daylight exposure through a series of user studies that employed a mixed experimental design (Chapter 3). We suggested a novel approach for conducting user studies in realistic, semi-controlled conditions outside the laboratory confinement based on an assessment of current alertness quantification strategies and lessons learned from similar investigations.

On the one hand, we designed a between-subjects exposure so as to test two daylight conditions simultaneously, while experiencing the same dynamics and temporal variations that are inherent in daylight's nature. The goal was to assess the effect of the exogenous component of interest (i.e., daylight) on alertness, by comparing participants responses (both psychological and physiological) from both groups. This was studied as the "main effect of daylighting condition".

Although most related examples in the literature employed instead a within-subject exposure, we wanted to prevent bias on participants in terms of expectations or result associations (as these can particularly affect subjective measure of alertness), which are difficult to avoid in such cases since it is not possible to keep participants blind to light manipulations.

On the other hand, we established a within-subjects "long-term" routine, so as to replicate habitual work patterns. The goal was for participants to experience

circumstances closer to real life, including natural dynamics of daylight over prolonged exposures, to ultimately assess the influence of the endogenous circadian rhythmicity. This was studied in the thesis as the "effects of duration and timing of exposure".

A problem that aroused at the beginning of this thesis was the lack of definition as to what specific procedures for investigating the effect of light are to be employed in an investigation of this kind. Moreover, the need for a more consolidated methodological guideline for the evaluation of non-visual responses was noticed while reviewing the literature, since the comparison of results between existing studies and different experiments was in most cases not possible (i.e., either due to inconsistencies in the documentation of light exposures or because of the use of very distinct protocols).

In addition, the vast majority of reviewed investigations in Chapter 2 consisted of laboratory studies, thus imposing an extra challenge in the thesis as to what directions should be followed for interventions in field instead. While the traditional, most frequently used approach removes environmental noise in the data as a proxy for consistency, lacks direct application to the real world and thus, of practical consequences for the purpose of this thesis (i.e., the anticipation of alertness in the built environment).

In general, the assessment of alertness state during daytime is particularly challenging as our body functioning is often in sync with task demands, at least under normal circumstances. The proposed methodology in this thesis is expected to guide future work pertaining to alerting effects in non-laboratory settings, and to assist further research that could help elucidate the fundamental mechanisms behind this psycho-physiological response.

8.1.2 Outcomes from user studies

A wide range of experiments have already been conducted on alerting effects of light, mainly with static and electric lighting conditions. In an effort to widen the current research panorama, the work presented in this thesis investigated, for the first time, daytime effects of dynamic and prolonged exposures to daylight as the source of illumination in the room, on subjective feelings of alertness and well-being, sustained attention and arousal. More specifically, studies presented in Chapter 4, 5 and 6 explored whether findings from previous studies about spectral manipulations or intensity variations of white light (whether monochromatic or polychromatic) could be replicated in a purely daylit environment, and under conditions which would be closer to those found in our daily routines (i.e., allowing both temporal and dynamic variations in participants' exposure, and imposing no pre-treatment requirements as opposed to laboratory controlled routines). In addition, the circadian rhythmicity of alertness state was explored with longer exposures (i.e., over several days and for multiple consecutive hours).

In particular, study A investigated the consequences of variations in daylight's spectrum by contrasting conditions with a blue shift to neutral conditions while keeping the related photopic illuminance constant. By resorting to filtering approaches, two daylighting scenarios were created: one with a red-impoverished spectrum that looks "blue", and the other one with neutral filters that would allow to maintain a similar photopic illuminance without manipulating the spectrum of transmitted daylight. Results suggested that blue conditions are more effective for promotion of alertness, vigour and attention than neutral ones at low illuminances, and that the effects are able to persist over time (i.e., since neither duration nor timing of exposure interfered in this findings).

Study B examined the impacts of changes in the daylight spectrum and intensity levels by comparing the effects of spectral shifts in the blue range of visible daylight (and related confounded intensity variations). To accomplish the lighting scenarios for this study, two filtering methods based on blue-shifts and related illuminance variations were used, namely blue vs brighter blue. These combinations produced a red-depleted spectrum that appears "blue," though the amount of blue content in each room varied, and thus intensity levels (which were confounded with spectral shifts). Results indicated that, under blue-shifted conditions, manipulations in the amount of content of blue in the spectrum are not an effective measure to improve correlates of alertness, but illuminance variations are, since they resulted in significant differences between responses to different blue conditions.

Study C studied the consequences of varying daylight intensity levels by comparing conditions in which brightness was modified while retaining a steady, neutral spectrum. Two optically neutral, non-spectrally changed conditions were used in this study, corresponding to a brighter vs. dim (neutral) daylit scenario. Results highlighted the importance of blue-enriched/red-impoverished conditions by showing no significant differences in alertness profiles when varying intensity levels under non-filtered (i.e., neutral) conditions. In this last case, whether results were driven by the possibility that daylight intensity variations were not extreme enough, remains unknow.

The effects of light on circadian rhythms have been extensively researched. This is the indirect pathway by which light will shift the timing of circadian rhythms and, as a result, indirectly lead to changes in psycho-physiological responses that may not be immediately apparent after exposure. Light has been shown to induce direct effects, which can be observed almost immediately in healthy individuals and do not necessarily affect the circadian system. By means of duration and timing of exposure, circadian vs acute alerting effects were explored in this thesis.

Our second hypothesis (H2) questioned whether longer exposures could elicit stronger alerting effects. Duration of exposure led to observable significant differences between days of experiment on correlates of alertness in studies A and B, with higher levels towards the end of the experience and independently of the daylight condition itself, despite slightly decreasing illuminance levels over the duration of the experiments.

Moreover, the time of day at which light is administered (i.e., whether during the morning or during the afternoon) was proved to play a key role on determining the magnitude of evaluated responses, thus confirming our third and final hypothesis (H3). However, as the dynamics of daylight were accepted as part of the experimental design (and experienced simultaneously in both rooms) but were not quantified or analyzed, it remains difficult to determine whether the main effect of timing of exposure may be due to the hypothesized underlying circadian rhythmicity or whether, instead, it should be attributed to a systematic variation in illuminance levels between morning and afternoon sessions within classrooms. Afternoon exposures were consistently more effective for subjective indicators whereas morning sessions showed stronger physiological effects across studies, suggesting again a non-photic effect that might correspond to a phase-alignment throughout the day.

These series of user studies gave us new insights regarding the effects of indoor daylight exposure on daytime alertness, while allowing to demonstrate that not only intensity or spectrum are important qualities of daylight driving non-visual responses. Endogenous circadian rhythmicity, as explored in this thesis by means of duration and timing of exposure, is also an important consideration to account for when evaluating alertness state, even during daytime. Thus, investigations that are conducted over longer periods of time (as opposed to just a few hours) are recommended so as to be able to differentiate between acute and circadian alerting effects of light.

8.1.3 Adequacy of light-driven models

The ultimate goal of this thesis was to explore the role of architectural design on daylight provision from a psycho-physiological perspective. In other words, to advance knowledge in the field of daylight integration in the built environment to support occupants' health and well-being, evidence-based lighting criteria needs to be determined. To this end, several physiology-based, light-driven models exist that were trained with laboratory data to predict subjective alertness. Three of these approaches were selected and investigated, for the first time, on their role in the prediction of daytime, daylight-derived alertness.

While model 1 proposed the transformation of the light signal (i.e., photopic illuminance) and sleep-wake information (i.e., bedrest timing) into direct driving forces on the circadian pacemaker to predict non-visual responses, model 2 suggested, similarly to model 1, the prediction of non-visual responses through an interaction between the sleep-wake cycle and light (i.e., melanopic illuminace), and the dynamic circadian oscillator. However, unlike model 1, the non-photic component of this model is further refined by the activity of two wake-active neural populations that account for physiological arousal. Model 3, instead, presented a linear structure to predict various non-visual effects in response to different light exposures, but from a typical subject who has no recollection of previous exposure. The model suggests converting the light signal into a relative response (which can be

understood as the direct driving force of light on the circadian pacemaker), and then this response function into a cumulative one. The latter can then be understood as light's ability to have an effect over time, and it may be linked to alertness levels during the day or melatonin suppression at night.

Since all three models predict alertness based on different scales, results were not easy to read. For this reason, the “validation” of the models was done on a relative basis (i.e., by comparing accuracy on the anticipation of patterns of results), rather than in absolute terms. Overall, correlation analyses suggested that models 1 and 3 performed better, while error metrics indicated that model 1 was best at anticipating daytime alerting responses to daylight exposure when confronted to experimental data collected during our user studies. Also, due to its computationally efficient structure, model 3 appeared to be better suited for analysing daylighting strategies in the built environment, as it does not require knowledge from prior individual light exposures. This last finding was one of the main drivers of the investigation, as it opens the possibility to work in a more efficient integration of non-visual effects in the design process.

To further explore the potential of these models for anticipating the impact of varying lighting conditions in a space and on informing design decisions, an accurate characterisation of the luminous environment is required, especially with regards to its spectral content. Thus, traditional static methods of daylight simulation are not valid. With such properties integrated into a holistic simulation workflow that includes both spectral tools and a predictive model, the effect of this dynamic light-response relationship can be anticipated. To this end, a conceptual simulation workflow is proposed for the study of alertness indoors, with the aim to raise awareness among architects and other stakeholders towards considering daylight performance not only as an added value for visual acuity or energy savings, but also for its potential as a source of health and well-being. Although further validation and refinement is needed for both the proposed workflow and prediction models, future work is expected to move forward in this direction.

8.2 IMPACT AND OUTLOOK

In this thesis, a methodology was developed to examine the alerting effects of daylight in the hope of enabling other researchers to reliably track more responses to a broader variety of daylight conditions. By following a common protocol in this kind of studies will inexcusably increase not only our current understanding of the topic, but also the comparability of findings that are still required in the field to draw more rigorous conclusions. Future work is expected towards the consolidation of such methodology, in combination with similar, recent guidelines from international standards.

Also, the evaluation of daylight is much more complicated and less controllable in the field than laboratory research on pure electricity, and so experimental techniques and instruments need to be improved and consolidated to make daylight research widely

available and studies comparable. Building reliable and commercially available instruments to track daylight spectral emission (representing light exposure at eye level in a vertical direction) is also crucial and remains as one of the biggest gaps in daylight research.

In recognizing the importance of daylight for human health and well-being, future work should continue to incorporate analysis of finer temporal dimensions of psycho-physiological interactions. Exogenous factors such as metabolism, sleep or physical activity have been investigated for their implications in daytime alertness. Future studies should try to further define the contribution of other neural processes that may have an effect on alertness, including tension, motivation or novelty. Stress-related neural networks are clinically relevant. In light of the implications that individual monitoring might represent in laboratory-controlled studies, stress appears like an important masking factor when assessing non-visual responses. Also, for its implications in performance for work-related activities, it seems like understanding alertness control can be especially useful in a context such as the one investigated in this thesis.

Moreover, some inconsistencies in research results to date are likely to lead to inadequate monitoring of individual differences. Further investigations about the effect of gender, age, genetic or cultural and behavioural differences would be beneficial to the field, and so future work is expected to continue also in this direction.

In general, very little can be found in the literature about the potential dependency of alerting daytime effects with exposure duration or time of day. However, the ability of the circadian pacemaker to incorporate light input over time allows potential advantages when designing light-oriented buildings. An adequate exposure at the right time (as analysed in this thesis by means of morning of afternoon exposures) might be enough to entrain our biological functions to the 24-hour light-dark cycle, and thus, to keep us awake and alert during our working routines.

In view of the uncontrolled, extended and rather dynamic environments (i.e., closer to real-life) experienced by participants in the above-mentioned studies, our results on prediction models could represent a move forward in predicting the effect of daylighting strategies. Interdisciplinary sharing of (day)light information (i.e., in the form of open access databases) might represent the gateway for further validations of these models and thus, of the incorporation of results into practice.

A bigger umbrella of light interventions should be compared during daytime, and not only electric light or daylight as independent observations, but rather a dynamic combination of both since this is the standard. A few existing studies have already made some attempts in this direction, but no strong conclusions were drawn from these investigations. In addition, there is extensive literature on the role of daylight for visual comfort and glare evaluations, but little is understood about their interaction with non-visual functions such as alertness. Furthermore, environmental, contextual and design factors that influence the quantity and quality of daylight in the built

environment (especially with regards to spectral content), need to be further investigated.

More than six decades ago, Richard Neutra anticipated in his book *Survival Through Design* that "designers will recognize that gradually but surely, they must underbuilt their proposals and compositions with more solid physiological foundations rather than with mere speculative conversation or sales talk…new instruments and obligations have come to us from research penetrating into life's performance. Physiology is a pursuit and a science which opens the door to broad and intensive application. We begin to wield tools which will enable us to do the patient spade-work which must be done. It will be fascinating, because it is so novel"] (Braham, 2006; 1954-Richard Neutra *Survival through design* (pages 111-113))

APPENDIX A

BASELINE QUESTIONNAIRE

[BACKGROUND INFORMATION]

- AGE _____

- GENDER [M] [F]

- WEIGHT _____

- HEIGHT _____

- ACTIVITY LEVEL (display)

- Have you travelled to a different time zone in the last month?
[YES] [NO]

If YES, where? _____

- Are you taking prescribed medication that could be affecting your sleep?
[YES] [NO]

- How many cups of coffee do you normally have on a daily basis? [_____]

In general, in your life…How likely are you to doze off or fall asleep in the following situations, in contrast to feeling just tired? (use the following scale to choose the most appropriate number for each situation)

would never doze	slight chance of dozing	moderate chance of dozing	high chance of dozing
0	*1*	*2*	*3*

(chances of dozing) (situation)

____1. Sitting and Reading

____2. Watching TV

____3. Sitting, inactive in a public place (e.g., a theatre or a meeting)

____4. As a passenger in a car for an hour without a break

____5. Lying down to rest in the afternoon when circumstances permit

____6. Sitting and talking to someone

____7. Sitting quietly after a lunch without alcohol

____8. In a car, while stopped for a few minutes in the traffic

In recent weeks… (for each question, please select the answer that best describes you)

1. *Approximately* what time would you get up if you were entirely free to plan your day?

[5] 5:00 AM–6:30 AM *(05:00–06:30 h)*
[4] 6:30 AM–7:45 AM *(06:30–07:45 h)*
[3] 7:45 AM–9:45 AM *(07:45–09:45 h)*
[2] 9:45 AM–11:00 AM *(09:45–11:00 h)*
[1] 11:00 AM–12:00 PM *(11:00–12:00 h)*

2. *Approximately* what time would you go to bed if you were entirely free to plan your evening?

[5] 8:00 PM–9:00 PM *(20:00–21:00 h)*
[4] 9:00 PM–10:15 PM *(21:00–22:15 h)*
[3] 10:15 PM–12:30 AM *(22:15–00:30 h)*
[2] 12:30 AM–1:45 AM *(00:30–01:45 h)*
[1] 1:45 AM–3:00 AM *(01:45–03:00 h)*

3. If you usually have to get up at a specific time in the morning, how much do you depend on an alarm clock?

[4] Not at all
[3] Slightly
[2] Somewhat
[1] Very much

4. How easy do you find it to get up in the morning (when you are not awakened unexpectedly)?

[1] Very difficult
[2] Somewhat difficult
[3] Fairly easy
[4] Very easy

5. How alert do you feel during the first half hour after you wake up in the morning?

[1] Not at all alert
[2] Slightly alert
[3] Fairly alert
[4] Very alert

6. How hungry do you feel during the first half hour after you wake up?

[1] Not at all hungry
[2] Slightly hungry
[3] Fairly hungry
[4] Very hungry

7. During the first half hour after you wake up in the morning, how do you feel?

[1] Very tired
[2] Fairly tired
[3] Fairly refreshed
[4] Very refreshed

8. If you had no commitments the next day, what time would you go to bed compared to your usual bedtime?

[4] Seldom or never later
[3] Less than 1 hour later
[2] 1-2 hours later
[1] More than 2 hours later

9. You have decided to do physical exercise. A friend suggests that you do this for one hour twice a week, and the best time for him is between 7-8 AM *(07-08 h)*. Bearing in mind nothing but your own internal "clock," how do you think you would perform?

[4] Would be in good form
[3] Would be in reasonable form
[2] Would find it difficult
[1] Would find it very difficult

10. At *approximately* what time in the evening do you feel tired, and, as a result, in need of sleep?

[5] 8:00 PM–9:00 PM *(20:00–21:00 h)*
[4] 9:00 PM–10:15 PM *(21:00–22:15 h)*
[3] 10:15 PM–12:45 AM *(22:15–00:45 h)*
[2] 12:45 AM–2:00 AM *(00:45–02:00 h)*
[1] 2:00 AM–3:00 AM *(02:00–03:00 h)*

11. You want to be at your peak performance for a test that you know is going to be mentally exhausting and will last two hours. You are entirely free to plan your day. Considering only your "internal clock," which one of the four testing times would you choose?

[6] 8 AM–10 AM *(08–10 h)*
[4] 11 AM–1 PM *(11–13 h)*
[2] 3 PM–5 PM *(15–17 h)*
[0] 7 PM–9 PM *(19–21 h)*

12. If you got into bed at 11 PM *(23 h),* how tired would you be?

[0] Not at all tired
[2] A little tired
[3] Fairly tired
[5] Very tired

13. For some reason you have gone to bed several hours later than usual, but there is no need to get up at any particular time the next morning. Which one of the following are you most likely to do?

[4] Will wake up at usual time, but will not fall back asleep
[3] Will wake up at usual time and will doze thereafter
[2] Will wake up at usual time, but will fall asleep again
[1] Will not wake up until later than usual

14. One night you have to remain awake between 4-6 AM *(04-06 h)* in order to carry out a
night watch. You have no time commitments the next day. Which one of the alternatives would suit you best?

[1] Would not go to bed until the watch is over
[2] Would take a nap before and sleep after
[3] Would take a good sleep before and nap after
[4] Would sleep only before the watch

15. You have two hours of hard physical work. You are entirely free to plan your day. Considering only your internal "clock," which of the following times would you choose?

[4] 8 AM–10 AM *(08–10 h)*
[3] 11 AM–1 PM *(11–13 h)*
[2] 3 PM–5 PM *(15–17 h)*
[1] 7 PM–9 PM *(19–21 h)*

16. You have decided to do physical exercise. A friend suggests that you do this for one hour twice a week. The best time for her is between 10-11 PM *(22-23 h).* Bearing in mind only your internal "clock," how well do you think you would perform?

[1] Would be in good form
[2] Would be in reasonable form
[3] Would find it difficult
[4] Would find it very difficult

17. Suppose you can choose your own work hours. Assume that you work a five-hour day (including breaks), your job is interesting, and you are paid based on your performance. At *approximately* what time would you choose to begin?

[5] 5 hours starting between 4–8 AM *(05–08 h)*
[4] 5 hours starting between 8–9 AM *(08–09 h)*
[3] 5 hours starting between 9 AM–2 PM *(09–14 h)*
[2] 5 hours starting between 2–5 PM *(14–17 h)*
[1] 5 hours starting between 5 PM–4 AM *(17–04 h)*

18. At *approximately* what time of day do you usually feel your best?

[5] 5–8 AM *(05–08 h)*
[4] 8–10 AM *(08–10 h)*
[3] 10 AM–5 PM *(10–17 h)*
[2] 5–10 PM *(17–22 h)*
[1] 10 PM–5 AM *(22–05 h)*

19. One hears about "morning types" and "evening types." Which one of these types do
you consider yourself to be?

[6] Definitely a morning type
[4] Rather more a morning type than an evening type
[2] Rather more an evening type than a morning type
[1] Definitely an evening type

[___ Total points for all 19 questions] (to be filled by the RESEARCHER)

During the past month…(the following questions relate to your usual sleep habits; your answers should indicate the most accurate reply for the majority of days and nights in the past month)

1. What time have you usually gone to bed at night? _____

2. How long (in minutes) has it usually taken you to fall asleep each night? _____

3. What time have you usually gotten up in the morning? _____

4. How many hours of actual sleep have you gotten at night? (This may be different than the number of hours you have spent in bed) _____

5. How often have you had trouble sleeping because you...

	Not during the past month	Less than once a week	Once or twice a week	Three or More times a week
a. Cannot get to sleep within 30 minutes	[0]	[1]	[2]	[3]
b. Wake up in the middle of the night or early morning	[0]	[1]	[2]	[3]
c. Have to get up to use the bathroom	[0]	[1]	[2]	[3]
d. Cannot breathe comfortably	[0]	[1]	[2]	[3]
e. Cough or snore loudly	[0]	[1]	[2]	[3]
f. Feel too cold	[0]	[1]	[2]	[3]
g. Feel too hot	[0]	[1]	[2]	[3]
h. Have bad dreams	[0]	[1]	[2]	[3]
i. Have pain	[0]	[1]	[2]	[3]
j. Other reason(s), please describe _____ (including how often you have had trouble sleeping because of this reason(s)	[0]	[1]	[2]	[3]

6. How often have you taken medicine (prescribed or “over the counter”) to help you sleep?

[0] [1] [2] [3]

7. How often have you had trouble staying awake while driving, eating meals, or engaging in social activities?

[0] [1] [2] [3]

8. How much of a problem has it been for you to keep up enthusiasm to get things done?

[0] [1] [2] [3]

9. How would you rate your sleep quality overall?

Very good	Fairly good	Fairly bad	Very bad
[0]	[1]	[2]	[3]

[___ Total points for all 9 questions] (to be filled by the RESEARCHER)

During the past two weeks…how often have you been bothered by any of the following problems?

	Not at all	Several days	More than half the days	Nearly every day
1. Little interest or pleasure in doing things	[0]	[1]	[2]	[3]
2. Feeling down, depressed or hopeless	[0]	[1]	[2]	[3]
3. Trouble falling asleep, staying asleep or sleeping too much	[0]	[1]	[2]	[3]
4. Feeling tired or having little energy	[0]	[1]	[2]	[3]
5. Poor appetite or overeating	[0]	[1]	[2]	[3]
6. Feeling bad about yourself – or that you are a failure or have let yourself or your family down	[0]	[1]	[2]	[3]
7. Trouble concentrating on things, such as reading the newspaper or watching television	[0]	[1]	[2]	[3]
8. Moving or speaking so slowly that other people could have noticed. Or the opposite, being so fidgety or restless that	[0]	[1]	[2]	[3]

you have been moving around a lot more than usual			
9. Thoughts that you would be better off dead or of hurting yourself in some way	[0]	[1]	[2]	[3]

[___ Total points for all 9 questions] (to be filled by the RESEARCHER)

... And also, how true have the following feelings been for you over that period?

1. Feeling tired (R / 7-1)

Yes, that is true ☐ ☐ ☐ ☐ ☐ ☐ ☐ *No, that is not true*

2. Feeling very active

Yes, that is true ☐ ☐ ☐ ☐ ☐ ☐ ☐ *No, that is not true*

3. Thinking requires effort (R / 7-1)

Yes, that is true ☐ ☐ ☐ ☐ ☐ ☐ ☐ *No, that is not true*

4. Feeling physically exhausted (R / 7-1)

Yes, that is true ☐ ☐ ☐ ☐ ☐ ☐ ☐ *No, that is not true*

5. Feeling like doing all kinds of nice things

Yes, that is true ☐ ☐ ☐ ☐ ☐ ☐ ☐ *No, that is not true*

6. Feeling fit

Yes, that is true ☐ ☐ ☐ ☐ ☐ ☐ ☐ *No, that is not true*

7. Doing quite a lot within a day

Yes, that is true ☐ ☐ ☐ ☐ ☐ ☐ ☐ *No, that is not true*

8. Concentrating quite well when doing something

Yes, that is true ☐ ☐ ☐ ☐ ☐ ☐ ☐ *No, that is not true*

9. Feeling weak (R / 7-1)

Yes, that is true ☐ ☐ ☐ ☐ ☐ ☐ ☐ *No, that is not true*

10. Not doing much during the day (R / 7-1)

Yes, that is true ☐ ☐ ☐ ☐ ☐ ☐ ☐ *No, that is not true*

11. Concentrating well

Yes, that is true ☐ ☐ ☐ ☐ ☐ ☐ ☐ *No, that is not true*

12. Feeling rested

Yes, that is true ☐ ☐ ☐ ☐ ☐ ☐ ☐ *No, that is not true*

13. Trouble concentrating (R / 7-1)

Yes, that is true ☐ ☐ ☐ ☐ ☐ ☐ ☐ *No, that is not true*

14. Physically feeling in a bad condition (R / 7-1)

Yes, that is true ☐ ☐ ☐ ☐ ☐ ☐ ☐ *No, that is not true*

15. Being full of plans

Yes, that is true ☐ ☐ ☐ ☐ ☐ ☐ ☐ *No, that is not true*

16. Getting tired very quickly (R / 7-1)

Yes, that is true ☐ ☐ ☐ ☐ ☐ ☐ ☐ *No, that is not true*

17. Having a low output (R / 7-1)

Yes, that is true ☐ ☐ ☐ ☐ ☐ ☐ ☐ *No, that is not true*

18. Feeling no desire to do anything (R / 7-1)

Yes, that is true ☐ ☐ ☐ ☐ ☐ ☐ ☐ *No, that is not true*

19. Thoughts easily wandering (R / 7-1)

Yes, that is true ☐ ☐ ☐ ☐ ☐ ☐ ☐ *No, that is not true*

20. Physically feeling in a good shape

Yes, that is true ☐ ☐ ☐ ☐ ☐ ☐ ☐ *No, that is not true*

Here are a number of characteristics that may or may not apply to you. For example, do you agree that you are someone who likes to spend time with others? Please write a number next to each statement to indicate how much you agree.

disagree	*slightly disagree*	*neutral*	*slightly agree*	*agree*
1	*2*	*3*	*4*	*5*

I see myself as someone who...

____ 1. Gets stressed out easily

____ 2. Am relaxed most of the time

____ 3. Worry about things

____ 4. Seldom feel blue

____ 5. Am easily disturbed

____ 6. Get upset easily

____ 7. Change my mood a lot

____ 8. Have frequent mood swings

____ 9. Gets irritated easily

____ 10. Often feel blue

HOURLY QUESTIONNAIRE

[HOURLY MONITORING]

1. Right now, on a scale from 0 to 100, where 0 is very little and 100 very much…

- How **alert** do you feel?

Very little (0) _____ (100) Very much

- How **sad** do you feel?

Very little (0) _____ (100) Very much

- How **tense** do you feel?

Very little (0) _____ (100) Very much

- How **much of an effort** is it to do anything?

Very little (0) _____ (100) Very much

- How **happy** do you feel?

Very little (0) _____ (100) Very much

- How **weary** do you feel?

Very little (0) _____ (100) Very much

- How **calm** do you feel?

Very little (0) _____ (100) Very much

- How **sleepy** do you feel?

Very little (0) _____ (100)
Very much

2. Using the scale below, pick what best represents how you are **feeling right now**:

Feeling active, vital, alert, or wide awake	1
Functioning at high levels, but not fully alert	2
Awake, but relaxed; responsive, but not fully alert	3
Somewhat foggy, let down	4
Foggy, losing interest in remaining awake; slowed down	5
Sleepy, woozy, fighting sleep; prefer to lie down	6
No longer fighting sleep, sleep onset soon; having dream-like thoughts	7

3. Indicate how true each statement is for you **at this moment**:

- I feel alive and vital

Not at all true	☐	☐	☐	Somewhat true	☐	☐	☐	*Very true*
	1	*2*	*3*	*4*	*5*	*6*	*7*	

- I feel so alive I just want to burst

Not at all true	☐	☐	☐	Somewhat true	☐	☐	☐	*Very true*
	1	*2*	*3*	*4*	*5*	*6*	*7*	

- I have energy and spirit

Not at all true	☐	☐	☐	Somewhat true	☐	☐	☐	*Very true*
	1	*2*	*3*	*4*	*5*	*6*	*7*	

- I look forward to each new day

Not at all true	☐	☐	☐	Somewhat true	☐	☐	☐	*Very true*
	1	*2*	*3*	*4*	*5*	*6*	*7*	

- I feel alert and awake

Not at all true	☐	☐	☐	Somewhat true	☐	☐	☐	*Very true*
	1	*2*	*3*	*4*	*5*	*6*	*7*	

- I feel energized

Not at all true	☐	☐	☐	Somewhat true	☐	☐	☐	*Very true*
	1	*2*	*3*	*4*	*5*	*6*	*7*	

4. In a scale from 1 to 9, how **alert or sleepy** do you feel **right now**?

Extremely sleepy	9
Very sleepy	8
Sleepy	7
Some signs of sleepiness	6
Neither sleepy nor alert	5
Rather alert	4
Alert	3
Very alert	2
Extremely alert	1

APPENDIX B

EFFECT OF (DAY)LIGHTING CONDITION

Table 1. Results of the Mann-Whitney test for evaluations of (day)lighting condition per dependent variable. **Study A** (spectral shifts) (CM4-A, dim neutral vs CM5-A, dim red-impoverished).

Scale	Mean CM4	SD CM4	Mean CM5	SD CM5	N	Z-score	*p*-value (two-tailed)	Effect size (r)
Sleepiness (KSS)	4,84	1,86	4,07	1,78	831	6,05	**1,45E-09*** **	**0,21**
Sleepiness (SSS)	3,56	1,67	2,96	1,45	832	5,59	**2,32E-08*** **	0,19
Vigour (GV)	51,61	20,67	60,06	20,38	832	-5,85	**4,79E-09*** **	**-0,20**
Affect (GA)	71,24	18,33	73,06	14,56	832	-0,98	0,33	-0,03
Vitality (VS)	3,82	1,31	3,92	1,16	831	-0,98	0,33	-0,03
Reaction time (PVT)	390,63	84,28	353,35	72,18	579	7,04	**1,93E-12*** **	**0,29**

SD: standard deviation; N: sample size. Significance of p values: α≤0.001***, α≤0.01**, α≤0.05*. Effect size: r < 0.20 = negligible; 0.20 ≤ r ≤ 0.50 = small; 0.50 ≤ r ≤ 0.80 = moderate; r ≥ 0.80 = large.

Table 2. Results of the Mann-Whitney test for evaluations of (day)lighting condition per dependent variable. **Study B** (intensity changes) (CM4-B, acceptable neutral vs CM5-B, dim neutral).

Scale	Mean CM4	SD CM4	Mean CM5	SD CM5	N	Z-score	*p*-value (two-tailed)	Effect size (r)
Sleepiness (KSS)	3,48	1,98	4,05	1,87	776	-4,54	**5,71E-06*** **	-0,16
Sleepiness (SSS)	2,70	1,60	2,99	1,66	776	-2,67	**7,61E-03** **	-0,10
Vigour (GV)	63,06	21,17	59,42	19,45	776	2,64	**8,33E-03** **	0,10
Affect (GA)	66,38	18,69	65,04	17,80	776	1,27	0,21	0,05
Vitality (VS)	4,54	1,05	4,29	0,94	776	3,65	**2,64E-04*** **	0,13
Reaction time (PVT)	360,50	74,61	339,15	70,25	563	4,07	**4,64E-05*** **	0,17

SD: standard deviation; N: sample size. Significance of p values: α≤0.001***, α≤0.01**, α≤0.05*. Effect size: r < 0.20 = negligible; 0.20 ≤ r ≤ 0.50 = small; 0.50 ≤ r ≤ 0.80 = moderate; r ≥ 0.80 = large.

EFFECT OF DURATION OF EXPOSURE

Study A

Table 3. Results of the Wilcoxon signed-rank test for the evaluation of duration of exposure per lighting condition and dependent variable. **CM4-A** (dim neutral).

Scale	Day	N	Z-score	*p*-value (two-tailed)	Effect size (r)
Sleepiness (KSS)	1-2	270	1,07	0,28	0,06
	2-3	271	0,93	0,35	0,05
	1-3	270	2,12	**0,03***	0,11
Sleepiness (SSS)	1-2	270	0,22	0,83	0,03
	2-3	271	0,53	0,60	0,02
	1-3	271	0,74	0,46	0,06
Vigour (GV)	1-2	270	-1,45	0,15	-0,03
	2-3	271	-1,52	0,13	-0,07
	1-3	271	-3,67	**2,46E-04*****	-0,11
Affect (GA)	1-2	270	-4,81	**1,53E-06*****	-0,16
	2-3	271	-0,14	0,89	0,00
	1-3	271	-4,74	**2,17E-06*****	-0,17
Vitality (VS)	1-2	270	-1,33	0,18	-0,04
	2-3	271	-2,47	**1,34E-02***	-0,08
	1-3	270	-3,20	**1,37E-03****	-0,11
Reaction time (PVT)	1-2	162	-0,49	0,62	-0,09
	2-3	149	-0,48	0,63	-0,03
	1-3	163	-1,30	0,19	-0,12

SD: standard deviation; N: sample size. Significance of p values: $\alpha \leq 0.001$***, $\alpha \leq 0.01$**, $\alpha \leq 0.05$*. Effect size: $r < 0.20$ = negligible; $0.20 \leq r \leq 0.50$ = small; $0.50 \leq r \leq 0.80$ = moderate; $r \geq 0.80$ = large.

Table 4. Results of the Wilcoxon signed-rank test for the evaluation of duration of exposure per lighting condition and dependent variable. **CM5-A** (dim red-impoverished).

Scale	Day	N	Z-score	*p*-value (two-tailed)	Effect size (r)
Sleepiness (KSS)	1-2	282	4,27	**1,98E-05*** **	**0,24**
	2-3	287	1,34	0,18	0,04
	1-3	283	5,62	**1,89E-08*** **	**0,30**
Sleepiness (SSS)	1-2	282	2,75	**5,96E-03** **	0,19
	2-3	287	1,51	0,13	0,06
	1-3	283	4,08	**4,46E-05*** **	**0,24**
Vigour (GV)	1-2	282	-3,86	**1,14E-04*** **	**-0,22**
	2-3	287	-0,74	0,46	-0,02
	1-3	283	-4,91	**9,18E-07*** **	**-0,23**
Affect (GA)	1-2	282	-1,53	0,13	-0,04
	2-3	287	1,72	0,09	0,06
	1-3	283	-0,87	0,39	0,01
Vitality (VS)	1-2	282	-1,66	0,10	-0,09
	2-3	287	-1,50	0,13	-0,05
	1-3	283	-2,46	**1,38E-02***	-0,14
Reaction time (PVT)	1-2	231	-0,38	0,70	-0,03
	2-3	217	-0,03	0,97	-0,06
	1-3	230	-1,22	0,22	-0,11

SD: standard deviation; N: sample size. Significance of p values: $\alpha \leq 0.001^{***}$, $\alpha \leq 0.01^{**}$, $\alpha \leq 0.05^{*}$. Effect size: $r < 0.20$ = negligible; $0.20 \leq r \leq 0.50$ = small; $0.50 \leq r \leq 0.80$ = moderate; $r \geq 0.80$ = large.

Study B

Table 5. Results of the Wilcoxon signed-rank test for the evaluation of duration of exposure per lighting condition and dependent variable. **CM4-B** (acceptable neutral).

Scale	Day	N	Z-score	*p*-value (two-tailed)	Effect size (r)
Sleepiness (KSS)	1-2	248	1,11	0,27	0,04
	2-3	240	-1,83	0,07	-0,09
	1-3	248	-0,85	0,40	-0,04
Sleepiness (SSS)	1-2	248	1,36	0,17	0,03
	2-3	240	-2,28	**0,02***	-0,11
	1-3	248	-0,86	0,39	-0,07
Vigour (GV)	1-2	248	-1,11	0,27	-0,08
	2-3	240	2,55	**1,07E-02***	0,11
	1-3	248	0,96	0,34	0,03
Affect (GA)	1-2	248	0,94	0,35	0,06
	2-3	240	0,72	0,47	0,06
	1-3	248	1,76	0,08	0,09
Vitality (VS)	1-2	248	0,68	0,49	0,01
	2-3	240	1,70	0,09	0,05
	1-3	248	1,55	0,12	0,06
Reaction time (PVT)	1-2	174	-0,79	0,43	-0,07
	2-3	191	0,13	0,90	-0,03
	1-3	193	-0,07	0,94	-0,09

SD: standard deviation; N: sample size. Significance of p values: $\alpha \leq 0.001^{***}$, $\alpha \leq 0.01^{**}$, $\alpha \leq 0.05^{*}$. Effect size: $r < 0.20$ = negligible; $0.20 \leq r \leq 0.50$ = small; $0.50 \leq r \leq 0.80$ = moderate; $r \geq 0.80$ = large.

Table 6. Results of the Wilcoxon signed-rank test for the evaluation of duration of exposure per lighting condition and dependent variable. **CM5-B** (dim neutral).

Scale	Day	N	Z-score	*p*-value (two-tailed)	Effect size (r)
Sleepiness (KSS)	1-2	272	-1,74	0,08	-0,11
	2-3	272	0,29	0,77	0,05
	1-3	272	-1,08	0,28	-0,05
Sleepiness (SSS)	1-2	272	-3,10	**1,95E-03****	-0,17
	2-3	272	-0,31	0,76	0,04
	1-3	272	-2,93	**3,35E-03****	-0,12
Vigour (GV)	1-2	272	2,26	**0,02***	0,11
	2-3	272	-1,27	0,21	-0,09
	1-3	272	1,03	0,30	0,02
Affect (GA)	1-2	272	-0,35	0,72	-0,01
	2-3	272	-2,71	**6,71E-03****	-0,09
	1-3	272	-2,89	**3,87E-03****	-0,10
Vitality (VS)	1-2	272	2,67	**7,62E-03****	0,16
	2-3	272	-0,95	0,34	-0,02
	1-3	272	1,81	0,07	0,11
Reaction time (PVT)	1-2	196	1,04	0,30	0,03
	2-3	191	1,04	0,30	0,04
	1-3	193	1,25	0,21	0,06

SD: standard deviation; N: sample size. Significance of p values: $\alpha \leq 0.001^{***}$, $\alpha \leq 0.01^{**}$, $\alpha \leq 0.05^{*}$. Effect size: $r < 0.20$ = negligible; $0.20 \leq r \leq 0.50$ = small; $0.50 \leq r \leq 0.80$ = moderate; $r \geq 0.80$ = large.

Interaction effect of light and duration of exposure

Table 7. Results of the Mann-Whitney test for the evaluation of interaction effects between light and duration of exposure. **Study A** (spectral shifts) (CM4-A, dim neutral vs CM5-A, dim red-impoverished).

Scale	Day	Mean CM4	SD CM4	Mean CM5	SD CM5	N	Z-score	*p*-value (two-tailed)	Effect size (r)
Sleepiness (KSS)	1	5,02	1,69	4,71	1,76	274	1,57	0,12	0,09
	2	4,85	1,92	3,85	1,84	277	4,38	**1,20E-05*** **	**0,26**
	3	4,65	1,95	3,65	1,58	280	4,35	**1,35E-05*** **	**0,26**
Sleepiness (SSS)	1	3,59	1,46	3,29	1,38	274	1,75	0,08	0,11
	2	3,59	1,77	2,91	1,57	278	3,58	**3,39E-04*** **	**0,22**
	3	3,51	1,76	2,69	1,33	280	4,14	**3,43E-05*** **	**0,25**
Vigour (GV)	1	49,43	17,08	53,76	19,65	274	-1,88	0,06	-0,11
	2	51,07	22,49	62,19	20,12	278	-4,37	**1,25E-05*** **	**-0,26**
	3	54,30	21,86	64,06	20,02	280	-3,58	**3,50E-04*** **	**-0,21**
Affect (GA)	1	66,94	19,10	72,46	15,44	274	-2,33	**0,02***	-0,14
	2	73,39	17,69	74,32	13,66	278	-0,06	0,95	0,00
	3	73,36	17,53	72,38	14,58	280	0,73	0,46	0,04
Vitality (VS)	1	3,68	1,24	3,73	1,09	274	-0,30	0,77	-0,02
	2	3,81	1,35	3,95	1,18	277	-0,84	0,40	-0,05
	3	3,98	1,31	4,08	1,19	280	-0,47	0,64	-0,03
Reaction time (PVT)	1	382,58	80,30	348,43	65,97	210	3,93	**8,66E-05*** **	**0,27**
	2	396,39	84,51	351,34	68,08	183	4,95	**7,40E-07*** **	**0,37**
	3	394,39	88,89	360,93	82,29	183	3,26	**0,001*** **	**0,24**

SD: standard deviation; N: sample size. Significance of p values: $\alpha \leq 0.001^{***}$, $\alpha \leq 0.01^{**}$, $\alpha \leq 0.05^{*}$. Effect size: $r < 0.20$ = negligible; $0.20 \leq r \leq 0.50$ = small; $0.50 \leq r \leq 0.80$ = moderate; $r \geq 0.80$ = large.

Table 8. Results of the Mann-Whitney test for the evaluation of interaction effects between light and duration of exposure. **Study B** (intensity changes) (CM4-B, bright acceptable vs CM5-B, dim neutral).

Scale	Day	Mean CM4	SD CM4	Mean CM5	SD CM5	N	Z-score	*p*-value (two-tailed)	Effect size (r)
Sleepiness (KSS)	1	3,50	2,09	3,88	1,76	264	-1,85	0,06	-0,12
	2	3,33	1,99	4,14	1,61	256	-4,39	**1,15E-05*** **	**-0,27**
	3	3,60	1,86	4,15	2,19	256	-1,81	0,07	-0,11
Sleepiness (SSS)	1	2,73	1,75	2,67	1,48	264	-0,34	0,73	-0,02
	2	2,53	1,48	3,09	1,42	256	-3,47	**5,28E-04*** **	**-0,22**
	3	2,83	1,54	3,23	1,99	256	-1,05	0,29	-0,07
Vigour (GV)	1	62,13	22,36	61,31	17,42	264	0,61	0,54	0,04
	2	65,67	20,18	57,41	17,78	256	3,72	**2,02E-04*** **	**0,23**
	3	61,40	20,85	59,54	22,65	256	0,39	0,70	0,02
Affect (GA)	1	67,21	20,74	63,79	17,97	264	1,73	0,08	0,11
	2	67,15	16,91	64,03	17,99	256	1,37	0,17	0,09
	3	64,77	18,28	67,32	17,32	256	-1,05	0,30	-0,07
Vitality (VS)	1	4,59	1,05	4,43	0,81	264	1,43	0,15	0,09
	2	4,58	0,99	4,19	0,86	256	3,56	**3,66E-04*** **	**0,22**
	3	4,45	1,11	4,24	1,11	256	1,51	0,13	0,09
Reaction time (PVT)	1	349,06	71,17	337,32	71,25	189	1,52	0,13	0,11
	2	366,86	71,49	339,37	69,29	181	3,11	**1,87E-03****	**0,23**
	3	366,06	80,18	340,85	70,89	183	2,59	**9,61E-03****	0,19

SD: standard deviation; N: sample size. Significance of p values: $\alpha \leq 0.001^{***}$, $\alpha \leq 0.01^{**}$, $\alpha \leq 0.05^{*}$. Effect size: $r < 0.20$ = negligible; $0.20 \leq r \leq 0.50$ = small; $0.50 \leq r \leq 0.80$ = moderate; $r \geq 0.80$ = large.

EFFECT OF TIMING OF EXPOSURE

Interaction effect of light and timing of exposure

Table 9. Results of the Mann-Whitney test for the evaluation of interaction effects between light and timing of exposure. **Study A** (spectral shifts) (CM4-A, dim neutral vs CM5-A, dim red-impoverished).

Scale	Hour	Mean CM4	SD CM4	Mean CM5	SD CM5	N	Z-score	*p*-value (two-tailed)	Effect size (r)
Sleepiness (KSS)	9	4,57	1,64	4,49	1,90	104	0,37	0,71	0,04
	10	5,76	1,96	4,54	1,85	105	3,12	**1,81E-03****	**0,31**
	11	5,46	1,88	3,96	1,80	103	3,92	**8,80E-05*****	**0,39**
	12	4,29	1,45	4,09	1,79	104	0,77	0,44	0,08
	13	4,14	1,43	3,52	1,33	104	2,29	**0,02***	**0,23**
	14	5,33	1,99	4,43	1,98	105	2,19	**0,03***	**0,21**
	15	5,16	1,98	4,22	1,90	105	2,36	**0,02***	**0,23**
	16	4,02	1,67	3,24	1,23	101	2,40	**0,02***	**0,24**
Sleepiness (SSS)	9	2,98	1,22	3,15	1,43	104	-0,41	0,68	-0,04
	10	4,29	1,98	3,26	1,47	105	2,69	**7,10E-03****	**0,26**
	11	4,22	1,82	2,98	1,70	103	3,77	**1,62E-04*****	**0,37**
	12	3,02	1,26	2,87	1,33	104	0,98	0,33	0,10
	13	2,86	1,36	2,56	0,98	104	1,00	0,32	0,10
	14	4,29	1,86	3,30	1,76	105	2,72	**6,56E-03****	**0,27**
	15	3,94	1,59	3,20	1,58	105	2,50	**1,23E-02***	**0,25**
	16	2,90	1,08	2,33	0,89	102	2,65	**8,02E-03****	**0,26**
Vigour (GV)	9	55,98	17,75	57,41	20,63	104	-0,46	0,65	-0,05
	10	43,19	21,07	55,69	20,24	105	-3,08	**2,09E-03****	**-0,30**
	11	47,30	20,92	63,44	19,47	103	-3,54	**3,97E-04*****	**-0,35**
	12	55,29	17,93	60,99	20,48	104	-1,43	0,15	-0,14
	13	57,70	18,34	64,44	18,60	104	-1,89	0,06	-0,19
	14	47,06	20,20	56,76	20,68	105	-2,35	**0,02***	**-0,23**
	15	47,25	22,71	55,51	23,30	105	-2,02	**0,04***	**-0,20**
	16	59,12	20,96	66,67	16,97	102	-2,00	**0,05***	**-0,20**
Affect (GA)	9	68,73	20,79	73,40	16,12	104	-0,95	0,34	-0,09

	10	69,02	19,93	72,59	14,87	105	-0,74	0,46	-0,07
	11	71,05	18,31	75,47	13,53	103	-1,07	0,29	-0,11
	12	71,47	18,30	71,46	14,30	104	0,17	0,87	0,02
	13	73,35	16,18	75,05	14,27	104	-0,51	0,61	-0,05
	14	72,60	16,04	70,79	13,49	105	0,45	0,65	0,04
	15	73,04	17,73	71,34	14,58	105	0,58	0,56	0,06
	16	70,69	19,47	74,46	15,38	102	-0,83	0,41	-0,08
Vitality (VS)	9	4,22	1,17	4,05	1,11	103	0,95	0,34	0,09
	10	3,51	1,28	3,68	1,08	105	-1,02	0,31	-0,10
	11	3,57	1,34	4,10	1,12	103	-1,86	0,06	-0,19
	12	3,97	1,08	3,87	1,14	104	0,61	0,54	0,06
	13	4,09	1,15	4,13	1,09	104	-0,08	0,94	-0,01
	14	3,50	1,39	3,64	1,24	105	-0,55	0,58	-0,05
	15	3,59	1,42	3,67	1,24	105	-0,46	0,65	-0,04
	16	4,14	1,43	4,26	1,15	102	-0,32	0,75	-0,03
Reaction time (PVT)	9	405,73	78,49	380,70	48,10	69	2,71	**6,80E-03*** **	**0,33**
	10	381,22	109,86	347,87	82,33	74	2,13	**3,35E-02*** **	**0,25**
	11	396,70	68,57	345,35	67,91	76	2,90	**3,78E-03*** **	**0,34**
	12	399,16	80,92	344,31	77,80	76	3,39	**6,92E-04*** **	**0,39**
	13	378,70	92,47	351,17	71,47	70	2,03	**4,27E-02*** **	**0,24**
	14	385,30	85,15	362,01	75,39	76	1,65	**9,92E-02*** **	0,19
	15	383,27	91,15	348,07	72,83	68	2,16	**3,10E-02*** **	**0,26**
	16	394,83	66,98	353,30	67,04	67	3,06	**2,24E-03*** **	**0,38**

SD: standard deviation; N: sample size. Significance of p values: $\alpha \leq 0.001^{***}$, $\alpha \leq 0.01^{**}$, $\alpha \leq 0.05^{*}$. Effect size: $r < 0.20$ = negligible; $0.20 \leq r \leq 0.50$ = small; $0.50 \leq r \leq 0.80$ = moderate; $r \geq 0.80$ = large.

Table 10. Results of the Mann-Whitney test for the evaluation of interaction effects between light and timing of exposure. **Study B** (intensity changes) (CM4-B, acceptable neutral vs CM5-B, dim neutral).

Scale	Hour	Mean CM4	SD CM4	Mean CM5	SD CM5	N	Z-score	*p*-value (two-tailed)	Effect size (r)
Sleepiness (KSS)	9	3,82	2,08	4,29	1,93	97	-1,15	0,25	-0,12
	10	4,33	2,40	4,51	1,93	97	-0,49	0,62	-0,05
	11	3,78	2,17	4,27	1,95	97	-1,11	0,27	-0,11
	12	3,11	1,80	3,94	1,82	97	-2,25	**0,02***	-0,23
	13	3,22	1,73	3,90	1,79	97	-1,79	0,07	-0,18
	14	4,36	2,17	4,12	1,85	97	0,52	0,60	0,05
	15	2,84	1,22	3,84	1,79	97	-2,67	**7,49E-03****	-0,27
	16	2,33	1,02	3,55	1,83	97	-3,58	**3,39E-04*****	-0,37
Sleepiness (SSS)	9	3,04	1,57	2,98	1,63	97	0,47	0,64	0,05
	10	3,33	2	3,43	1,76	97	-0,54	0,59	-0,06
	11	2,93	1,62	3,14	1,93	97	0,10	0,92	0,01
	12	2,31	1,12	2,92	1,68	97	-1,52	0,13	-0,16
	13	2,49	1,41	2,88	1,56	97	-1,54	0,12	-0,16
	14	3,49	1,91	3,22	1,64	97	0,56	0,58	0,06
	15	2,27	1,27	2,78	1,47	97	-1,87	0,06	-0,19
	16	1,71	0,79	2,61	1,58	97	-3,33	**8,83E-04*****	-0,34
Vigour (GV)	9	58,94	23,39	58,92	17,74	97	-0,02	0,98	0,00
	10	58,17	24,93	52,99	18,01	97	1,04	0,30	0,11
	11	59,61	23,05	57,60	19,68	97	0,31	0,76	0,03
	12	66,39	18,17	59,56	21,45	97	1,22	0,22	0,13
	13	64,72	18,79	60,49	19,51	97	1,09	0,28	0,11
	14	55,06	23,22	57,99	19,18	97	-0,62	0,54	-0,06
	15	68,06	17,36	62,35	17,86	97	1,78	0,08	0,18
	16	73,56	12,72	65,44	20,72	97	1,87	0,06	0,19
Affect (GA)	9	63,33	18,33	67,06	16,83	97	-0,79	0,43	-0,08
	10	66,44	18,70	64,51	17,39	97	0,69	0,49	0,07
	11	64,50	18,98	64,41	17,20	97	0,13	0,90	0,01
	12	67,11	20,73	63,63	20,32	97	0,85	0,40	0,09
	13	66,61	17,74	65,74	15,73	97	0,27	0,79	0,03
	14	64,44	19,52	65,44	17,29	97	-0,20	0,84	-0,02

	15	67,67	17,61	63,97	19,69	97	0,78	0,43	0,08
	16	70,89	18,16	65,59	18,46	97	1,50	0,13	0,15
Vitality (VS)	9	4,37	1.15	4,37	0,82	97	0,10	0,92	0,01
	10	4,23	1,18	4,10	0,93	97	0,35	0,72	0,04
	11	4,34	1,11	4,26	0,93	97	0,20	0,84	0,02
	12	4,74	0,91	4,35	1,05	97	1,82	0,07	0,19
	13	4,61	0,95	4,38	0,92	97	1,05	0,30	0,11
	14	4,33	1,09	4,21	0,95	97	0,78	0,43	0,08
	15	4,64	0,97	4,21	0,96	97	2,12	**0,03***	0,22
	16	5,04	0,81	4,40	0,94	97	3,35	**8,05E-04*****	0,34
Reaction time (PVT)	9	345,97	62,64	331,48	70,47	74	1,16	0,15	0,14
	10	361,17	85,00	338,08	64,25	61	1,49	**1,35E-01****	0,19
	11	356,83	76,31	336,37	77,48	74	1,28	**0,04***	0,15
	12	359,37	77,01	339,08	69,64	69	1,25	0,07	0,15
	13	361,35	74,40	338,27	67,72	68	1,82	**6,85E-02****	**0,22**
	14	381,58	71,13	328,92	73,99	73	3,39	**0,03***	**0,40**
	15	368,36	72,98	334,67	73,45	69	1,74	**8,26E-02*****	**0,21**
	16	358,09	72,56	372,27	57,01	65	-0,87	0,62	-0,11

SD: standard deviation; N: sample size. Significance of p values: $\alpha \leq 0.001^{***}$, $\alpha \leq 0.01^{**}$, $\alpha \leq 0.05^{*}$. Effect size: $r < 0.20$ = negligible; $0.20 \leq r \leq 0.50$ = small; $0.50 \leq r \leq 0.80$ = moderate; $r \geq 0.80$ = large.

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VICTORIA EUGENIA SOTO MAGÁN

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EDUCATION

[08/2016-05/2021] École Polytechnique Fédérale de Lausanne, Switzerland
PhD Doctor in Science
Doctoral Program in Civil and Environmental Engineering (EDCE), Switzerland
Thesis: Alertness in work environments. On the role of indoor daylight exposure
Supervisor: Prof. Marilyne Andersen

[10/2014-10/2015] **Architectural Association, United Kingdom**
MSc Sustainable Environmental Design
Dissertation: Biological Effects of Daylight on Human Performance; reinterpreting daylighting strategies for research environments
Tutor: Prof. Jorge Rodríguez Álvarez

[10/2013-01/2015] **University of Seville, Spain**
MA Innovation, Technology and Design in Architecture
Dissertation: Evaluation of eco-efficient façade envelopes: proposals for urban dwellings
Tutor: Prof. María del Pilar Mercader Moyano

[09/2017-09/2013] **University of Seville, Spain**
BArch + MArch (ARB/RIBA part III equivalent)
Final project: Toma castaña, eco-efficient refurbishment in the town of Ponte Hermida

ACADEMIC POSITIONS

[06/2021-11/2022] **ETH Zurich, *Postdoctoral Researcher***
The Institute of Landscape and Urban Studies (LUS), Chair of Architecture and Urban Design; ETH CASE Centre for Research on Architecture, Society & the Built Environment; Institute of Technology in Architecture (ITA), Chair of Architecture and Building Systems

[08/2016-05/2021] **École Polytechnique Fédérale de Lausanne, *Doctoral Assistant***
Laboratory of Integrated Performance in Design (LIPID)

(Teaching assistance)

- Comfort and architecture: sustainable strategies, Master level

Participated in the planning of course content, supervised students on the analysis of study projects -from the early-stage conceptualization to design completion- for environmental performance evaluation, and served as jury member for the final oral exam.

- Space and light: the lighting project, Master level

Assisted instruction with Professors Marilyne Andersen and Bernard Paule, and introduced the use of physical models for shadow analyses and daylighting evaluation.

[08/2019] ETH Zurich (International School), *Unit co-leader*
Laboratory of Integrated Performance in Design + Chair of Cognitive Science

(Courses taught)

- Human centric performance simulations in architecture (humARCH'19), Doctoral and Master level

Coordinated, planned and co-organized a summer school for 21 international students. The course integrated state-of-the-art industry and research-based simulation tools and promoted the integration of daylighting and wayfinding as a method to explore human-space interactions. Lectured on daylighting theory, modelling, simulation and visualization, to encourage an iterative design process through dedicated workshops and hands-on design sketches.

[10/2011-09/2014] University of Seville, *Research Assistant*
School of Architecture, Department of Architectural Design and Construction Technologies

(Teaching assistance)

- Design studio VIII, Undergraduate Level

Independently taught 16 undergraduate students about design strategies for building refurbishment to promote the regeneration of abandoned rural areas, integrating structural, constructive and design techniques.

[06-09/2011] **University of Technology and Economics Budapest, *Research Intern***
School of Architecture, Department of History of Architecture and Monuments

PUBLICATIONS

Journal papers

V.E. Soto Magán and M. Andersen (2021). *Daylight exposure and alertness – Part 1: effects of spectrum in dim conditions.* Lighting Research and Technology [submitted].

V.E. Soto Magán, Y.A.W. de Kort, K.C.H.J. Smolders, M. Andersen (2021). *Daylight exposure and alertness – Part 2: effects of brightness under neutral conditions.* Lighting Research and Technology [submitted].

V.E. Soto Magán, M. A. St. Hilaire, T. Tekieh, S. Postnova, M. Andersen (2021). *Use of light-driven models to predict alerting effects of indoor daylight exposure.* [in preparation].

Conference papers

C. Pierson, **V.E. Soto Magán**, M. M. Andersen. *Daylight exposure and alertness indoors: on the role of spectral simulation.* CISBAT 2020: Carbon Neutral Cities – Energy Efficiency & Renewables in the Digital Era, Lausanne, September 8-10, 2021. [accepted]

M. Andersen, **V.E. Soto Magán**, F. S. Webler and C. Pierson. *Light hygiene in the built environment.* ANFA 2020: Sensing Spaces, Perceiving Places, The Academy of Neuroscience for Architecture, Online, September 14-25, 2020.
[https://infoscience.epfl.ch/record/282954]

V.E. Soto Magán and M. Andersen. *How to assess alerting effects of daylight at the workplace? Learnings from semi-controlled studies.* 29th CIE Quadrennial Session, Washington DC, June 20-22, 2019.
[https://doi.org/10.25039/ x46.2019.OP34]

V.E. Soto Magán, F. S. Webler and M. Andersen. *Perceived and yet not seen: non-visual effects in daylit spaces.* ANFA 2018: Neurobehavioural Outcomes, The Academy of Neuroscience for Architecture, Salk Institute La Jolla, California, September 22-22, 2018. [http://infoscience.epfl.ch/record/258110]

F. S. Webler, **V. E. Soto Magán** and M. Andersen. *EPFL smart glass study.* SLTBR 30th Annual Meeting, Groningen, June 21-24, 2018. Neuropsychobiology, Chronobiology - Abstracts 74, 251–252.
[https://doi. org/10.1159/000477426]

V.E. Soto Magán and M. Andersen. *Towards human-centric lighting for office buildings: pilot study on the interactions of visual, perceptual and non-visual effects*

of workplace (day)lighting. SLTBR 29th Annual Meeting, Berlin, June 23-25, 2017. Neuropsychobiology, Chronobiology - Abstracts 76, 37.
[https://doi.org/10.1159/000489584]

P. Mercader Moyano and **V.E. Soto Magán** *Rehabilitación Sostenible en Edificaciones Residenciales*. Workshop on Environmental Impact of Buildings (WEIB 2013) Polytechnical University of Madrid, Spain, September 25-26, 2013. ISBN 978-84-695-8575

Book chapters

V.E. Soto Magán *Hacia el reconocimiento de la mujer arquitecta*, Literatura, cine y prensa: criterios, valores y actitudes. Andavira Editions. Pages 269-278. Santiago de Compostela, 2011. ISBN 978-84-8408-638-3

GRANTS AND AWARDS

[2021] **Daylight Fellowship**, ETH Zurich and VELUX Stiftung
[2019] **ETH International School Grant**, ETH board
[2014] **Graduate School Bursary Award**, Architectural Association
[2014] **First Place Diploma Thesis Prize**, Lafarge-Holcim Foundation
[2012] **First Place ANfhARQ Competition**, FYM-Italcement group
[2011] **Erasmus Internship**, Erasmus Training Program + Budapest University of Technology and Economics

BOARDS AND COMMITTEES

[2020-current] **Peer reviewer**, Lighting Research and Technology (SAGE Journals)
[2019-current] **Scientific committee member**, PLEA Conference
[2019] **Scientific committee member**, Facade Tectonics 2020 World Conference
[2019] **Organizing committee**, humARCH Summer School 2019 ETH Zurich
[2012-2014] **Organizing committee member**, CICSE Conference

LANGUAGES

Spanish Native proficiency
Galician Native proficiency
English Full professional proficiency
Portuguese Advanced competences