# Non-Image-Forming Effects of Light

## Implications for the Design of Living and Working Environments

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**DEPARTMENT OF ARCHITECTURE AND BUILT ENVIRONMENT**
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*Faculty opponent*
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Eindhoven University of Technology, The Netherlands

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# Abstract

Seasonal variation in mood and subjective well-being are common at geographical locations further away from the equator. The 24-h light-dark cycle is the main time cue for synchronizing the human circadian clock to the external day and night.

Nowadays, people spend more of their waking day indoors, with less exposure to the natural daylight cycle, relying on artificial lighting which differs to daylight in a number of aspects, including intensity, spectral composition and light exposure pattern.

In parallel with the technology development that has been mainly driven by energy-saving reasons, it is important to investigate the non-image-forming effects of different properties of the daily and seasonal light exposure.

The overall aim of the thesis was to identify characteristics of the daily light exposure that are important to support physiological and psychological needs of humans. To achieve this objective a number of research questions were posed concerning daily and seasonal light exposure, seasonal variation in physiological processes and psychological parameters, and evaluation of light exposure with respect to non-image-forming effects. The research questions were investigated in a longitudinal research design with measurements conducted each month during the year at a high latitude with large seasonal variation in day lengths.

Self-report diaries and instruments for ambulatory- and static measurements were used to examine daily and seasonal light exposure in the working and living environments and for investigating the relationship between different parameters that can be used for evaluating light exposure according to non-image-forming effects of light. Seasonal variation in daily light exposure and regarding the pattern of light exposure was observed. Also, the results indicate a seasonal variation concerning the quality (i.e. spectral composition of the visible radiation) of the exposing light.

Two biological markers, melatonin and cortisol, were used for investigating seasonal variation in physiological processes relating to the circadian clock. The results showed higher morning melatonin concentrations and peak level of melatonin during the winter although no seasonal change was observed concerning the phase position of the melatonin rhythm.

Seasonal differences in mood and sleep-activity were studied by means of self-report diaries and questionnaires. Seasonal variations were observed for both parameters. The results showed higher ratings of mood in the summer, particularly in the evening, and a relationship between bedtime and evening light exposure and photoperiod length. Furthermore, longer sleep times was observed in the winter.

Appraisal of lighting conditions in the offices during the year was rated by the use of a questionnaire. The results showed some seasonal differences concerning the perceived qualities of the light and some associations between characteristics of the lit environments and positive affect were found.

Two methods, static- and ambulatory measurements, were used for recording lighting conditions in the working environments. Taken together, the results showed weak associations between the two methods.

Research have demonstrated an increased need for taking non-image-forming effects into consideration when designing working and living environments, especially at geographical locations with large variations in day length where people are exposed to much of the daily light exposure at the workplace. Laboratory research has provided a good understanding of the basic concepts. However, more field research is needed. Also, current research has demonstrated that new methods of measuring and evaluating lighting conditions are needed.

**Keywords:** circadian rhythms, circannual, light exposure, melatonin, cortisol, sleep-wake behavior, perception, mood, spectral composition, measurement

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# List of original papers

The thesis is based on the following papers:

## Paper I

Annual variation in daily light exposure and circadian rhythms of melatonin and cortisol at a northern latitude with large seasonal difference in photoperiod length. (2017). Adamsson, M., Laike, T., & Morita, M. *Journal of Physiological Anthropology*, 36 (1), pp.6. DOI: 10.1186/s40101-016-0103-9

## Paper II

Seasonal Variation in Bright Daylight Exposure, Mood and Behavior among a Group of Office Workers in Sweden. (2018). Adamsson, M., Laike, T., & Morita, T. *Journal of Circadian Rhythms*, 16(1), p.2. DOI: http://doi.org/10.5334/jcr.153

## Paper III

Comparison of Static and Ambulatory Measurements of Illuminance and Spectral Composition That Can be Used for Assessing Light Exposure in Real Working Environments. (2018). Adamsson, M., Laike, T., & Morita, T. *LEUKOS*. DOI: 10.1080/15502724.2017.1391101 (Online before print)

## Paper IV

Lighting for Humans Physiological and Psychological Needs: An Overview of the Research from an Applied Perspective. Adamsson, M. (in manuscript)

# The author's contribution to the appended papers

## Paper I

The author designed and planned the study together with Thorbjörn Laike and Takeshi Morita. The author was responsible as contact person for the study and for the data collection. Analyzes of the biological samples were conducted under supervision of Takeshi Morita. The statistical analysis of the data was performed by the author and he interpreted the results. The author wrote the paper together with Thorbjörn Laike and Takeshi Morita.

## Paper II

The author, Thorbjörn Laike and Takeshi Morita planned and designed the study protocol. The author was contact person regarding information and questions relating to the study. The author was responsible for the data collection. Statistical analyzes of the data and interpretation of the results were completed by the author and he wrote the paper. Thorbjörn Laike and Takeshi Morita commented on the manuscript.

## Paper III

The study was planned and designed by the author, Thorbjörn Laike and Takeshi Morita. The author was responsible for the data collection and he performed the static field measurements of illuminance and irradiance. The author analyzed the data and interpreted the results. The article was written by the author and Thorbjörn Laike and Takeshi Morita commented on the manuscript.

## Paper IV

The author carried out the searches for the scientific literature compiled in the article and wrote the article.

# 1. Introduction

In the fall, the daily duration of natural daylight is becoming shorter at latitudes further away from the equator. Many people, particularly those living at higher latitudes, where the seasonal variation in day length is more prominent, experience seasonal variations in various aspects of physiology, neuroendocrine function and behavior subsequently affecting their subjective well-being (Kasper et al., 1989b; Laakso, Porkka-Heiskanen, Alila, Stenberg & Johansson, 1994; Rastad, Sjödén & Ulfberg, 2005; Kuller, Ballal, Laike, Mikellides & Tonello, 2006; Park, Kripke & Cole, 2007; Persson et al., 2008; Grimaldi, Partonen, Haukka, Aromaa & Lönnqvist, 2009). For some people, these seasonal variations lead to more serious problems, recurring during consecutive years at a particular time period of the year (usually during the fall-winter period) (Rosenthal et al., 1984; Kasper et al., 1989a).

The daily changes in human physiological, neuroendocrine and neurobehavioral processes are mainly regulated by the exposure to light and dark cycles during the day. Nowadays, people are spending more time indoors and are thus less exposed to daylight and more dependent on other time cues such as artificial lighting and alarm clocks for the entrainment of biological rhythms (Scheuermaier, Laffan & Duffy, 2010).

Since the properties of artificial light found in typical indoor working and living environments are very different from daylight with regard to intensity, spectral composition and light exposure pattern this leads to important questions of the how well artificial light can compensate for the possible lack of exposure to the diurnal cycles of daylight. This question was already addressed by the physicist Anders Jonas Ångström (1924) when he wrote:” What quantity of light energy is necessary for an organism or part of an organism?” and “Can the natural light irradiation be superseded by other means, and in that case how should the artificial irradiation be composed and how should it be applied?”. For example, are the relatively low light levels that people commonly are exposed to during the day time enough and are exposures during the evening too high. Moreover, today there is an increased evening use of screens using solid state light sources emitting light with a spectral composition different from light sources traditionally used in the home environment.

The awareness of the importance of light for physiological and mental health can be found in historical accounts emphasizing exposure to daylight as an important part of treatment of physical as well as psychological diseases (Aretaeus, 1956;

Nobel Media Ab, 2018). Subsequent research, particularly work conducted during the last century, has increased our understanding of circadian biology and circadian phototransduction (Brainard, & Hanifin, 2006; Golombek & Rosenstein, 2010).

Until the 1980s relatively little was known about the process of circadian photo transduction and the non-image-forming effects of light. The classical photoreceptors (rods and cones) were considered to, in addition to having a function for vision, also mediate information for regulating the circadian system. In the early 1980s, Ebihara & Tsuji (1980) and Takahashi, DeCoursey, Baumann & Menaker M (1984) reported findings indicating the existence of a third type of photoreceptor mediating input about environmental irradiance for circadian phototransduction. Furthermore, in the 1980s, Lewy, Wehr, Goodwin, Newsome & Markey (1980) showed that bright light could suppress melatonin in humans, a discovery that subsequently was developed into a method for treatment of seasonally occurring depression and other types of depression.

In the 1990s, additional findings (Czeisler et al., 1995; Lockley et al., 1997; Freedman et al., 1999; Lucas, Freedman, Munoz & Foster, 1999; Provencio, Jiang, De Grip, Hayes & Rollaq, 1998; Provencio et al., 2000) were reported showing support of a novel photoreceptor in the retina and in the early 2000s conclusive results were reported demonstrating intrinsically photo sensitive retinal ganglion cells in the inner retina which integrate information from the classical photoreceptors and project neural input to the hypothalamic suprachiamatic nucleus (SCN) via the retino-hypothalamic tract (RHT)(Berson, Dunn & Takao M, 2002; Hattar, Liao, Takao, Berson & Yau, 2002; Hannibal, 2002).

Today, we also have a good understanding of clock genes and regulation of circadian clocks, for example the master clock in the SCN and its connection to peripheral clocks located in tissues outside of the brain (Cermakian & Sassone-Corsi, 2000; Reppert & Weaver, 2002).

Concurrent with the development of knowledge of the non-image-forming effects of light there has been a development in lighting technology. Mainly driven by energy-saving reasons, new light sources and advanced control systems have been developed. However, this also calls for taking results from investigations of the effects of different properties of light into consideration to avoid negative impact on our health. Furthermore, current lighting technology also entails increased possibilities of adjusting and fine tuning different characteristics of the artificial lighting, for example intensity and spectral composition. Moreover, there has also been a considerable development in solutions for increasing the use of available daylight.

An important question relating to current design of lighting is how light is measured and assessed. Present codes and recommendations are based on requirements for vision using the photopic luminous function, $V_\lambda$, for weighting the energy in different wavelengths of the visible spectrum. How applicable is this sensitivity function when assessing lighting conditions from a perspective of the resulting non-image-forming effects which also involves a third receptor class? Another question relating to lighting design is how representative static calculations and measurements are of the actual retinal light exposure experienced in daily life?

Much research underlying the basic theoretical models used for explaining the non-image-forming effects of light have been carried out in highly controlled laboratory settings with lighting conditions different than those normally experienced in real-life settings (Duffy & Wright, 2005; Dumont & Beaulieu, 2007). Therefore, field data is needed to complement the findings from laboratory research.

## 1.1. Aim of the thesis

The aim of the thesis is to identify characteristics of the daily light exposure that are important to support physiological and psychological needs of humans. This will be discussed in relation to lighting design of environments for human users.

## 1.2. Research questions and specific objectives

To achieve the aim of the thesis, a set of research questions were posed, relating to four main themes dealing with light exposure in daily life, daily and seasonal variation in physiological processes and psychological parameters and evaluating lighting conditions with respect to non-image-forming effects.

### A. Research question concerning light exposure in daily life

A1. How are office working people in Sweden generally exposed to visible radiation in the working and living environments?

### B. Research question concerning daily and seasonal variation of physiological processes

B1. Is there any seasonal variation in the circadian rhythms of melatonin and cortisol for a group of healthy office workers living at a northern latitude, with large seasonal differences in photoperiod length throughout the year?

### C. Research questions concerning psychological parameters

C1. Is there any seasonal variation in psychological well-being for a group of healthy office workers?

C2. Is there any seasonal variation regarding sleep-activity patterns during the year?

C3. How is the light in the working environments perceived under the course of the year?

### D. Research questions concerning evaluation of lighting conditions with respect to non-image-forming effects of light

D1. Is there any seasonal variation regarding the quality of light in the offices, recorded with instruments for static measurements?

D2. How should the exposing optical radiation be measured and evaluated for estimating the resulting non-image-forming effects?

## 1.3. Outline of the thesis

The thesis is divided into five sections. The first section provides a theoretical framework. Next follows a section presenting previous research in the field. The following section presents the research approach and methods in the thesis. The fourth section contains the main results from the studies. The last section contains a general discussion where the results from the studies are discussed in relation to the research questions. Also, implications for research and practice are discussed in the final section. The thesis is based on four original articles.

# 2. Theoretical framework

This chapter presents the theoretical framework and describes key characteristics of the light-dark cycle and its influence on the endogenous circadian clock and other physiological-, endocrine-, and neurophysiological processes. The research building-up the theoretical framework suggest that exposure patterns to light and darkness have a large impact on human health and well-being. This implies that it has become increasingly important for lighting designers to integrate exposure patterns in the design of lit environments (DiLaura, Houser, Mistrick & Steffy, 2011).

## 2.1. Non-image-forming effects of light and light sensitive receptors on the retina

The eyes not only function as a sense organ for vision but have been shown to have important non-image-forming functions. Light has a crucial impact on a wide range of physiological-, endocrine-, and neurobehavioral processes in humans (Gooley, Lu, Saper & Fisher, 2003). For example, daily exposures to light and darkness synchronize the master endogenous circadian pacemaker (ECP) to the daily changes in environmental illumination, which in turn synchronizes peripheral clocks located throughout the human body. As a result, exposure to light affects the circadian rhythms of core body temperature (CBT), melatonin and cortisol (Boivin, Duffy, Kronauer & Czeisler, 1996; Boivin & Czeisler, 1998). Furthermore, light radiation can induce various acute effects, for example suppression of pineal melatonin production, increase of alertness and expression of clock genes (Cajochen et al., 2005a; Lockley et al., 2006; Cajochen, 2007). Moreover, light influences the circadian rhythm of sleep and wakefulness and the size of the pupil is regulated according to environmental irradiance (Åkerstedt & Folkard, 1997; Dijk, Duffy & Czeisler, 2000; Hankins & Lucas, 2002; Dacey et al., 2005).

Also, other metabolic, hormonal and physiological processes are influenced by exposure to optical radiation, amongst others heart rate and blood pressure, blood sugar, water balance, ACTH, thyrotropin, insulin, and levels of cathecolamines (noradrenalin, dopamine, adrenalin and serotonin) and calcium. Additionally, light has an impact on the regulation of carbohydrates and influence metabolism in the liver as well as metabolism of proteins, cholesterol, D-vitamin and bilirubin (Hollwich, 1979; Cajochen, et al., 2005b; DiLaura et al., 2011).

In addition to the classical photoreceptors rods and cones, a third category of photoreceptors have been identified in the inner retina of the human eye. These photoreceptors are a subset of retinal ganglion cells (RGCs) that express the photopigment melanopsin and are intrinsically photosensitive (Berson et al., 2002; Hattar et al., 2002; Ruby et al., 2002; Provencio et al., 2000). Laboratory work in animal models and in humans have found several types of intrinsically photosensitive retinal ganglion cells (ipRGCs), projecting to different areas of the brain (Ecker et al., 2010; Schmidt et al., 2011; Dacey et al., 2005; Hannibal et al., 2017). The response of the ipRGCs is moderated by synaptic input from the classical photoreceptors. Via bipolar and amacrine cells, the ipRGCs receive excitatory and inhibitory input from rods and cones (Belenky et al., 2003; Dkissi-Benhyaha et al., 2007; Droyer, Riuex, Hut, & Cooper, 2007; Østergaard, Hannibal & Fahrenkrug, 2007; Altimus, et al., 2008; Lall et al., 2010). Together with the ipRGCs, the classical photoreceptors form a system that can register irradiance over a wide range of intensities and accurately convey the daily changes of irradiance, from the low light levels experienced at dawn and sunset to the high intensities during the daytime, to the master clock in the SCN (Gooley et al. 2003; Altimus et al., 2010).

The ipRGCs sensitivity to energy in the different wavelengths in the visible spectrum differs from that of rods and cones. Laboratory work, using monochromatic light pulses as well as polychromatic light enriched in the short-wavelength part of the visible spectrum show that short-wavelength light elicits larger responses of various physiological and psychological output measures (Warman, Dijk, Warman, Arendt & Skene, 2003; Lockley, Brainard, & Czeisler, 2003; Cajochen et al. 2005b; Lockley et al., 2006; Münch et al., 2006; Vandwalle et al., 2007; Zaidi et al., 2007; West et al., 2011; Brainard et al., 2015). Furthermore, polychromatic and analytical action spectra for the melatonin suppressing response and pupillary light reflex show that the peak sensitivity of the circadian system is within the range 459-483 nanometer (nm) (Brainard et al., 2001; Thapan, Arendt & Skene, 2001; Hankins & Lucas, 2002).

## 2.2. Entrainment of biological rhythms

Physiological and behavioural rhythms are generated by the master circadian clock, located in the SCN. The SCN is a twin nucleus in the hypothalamic region of the brain containing 10000-15000 neurons (Moore, Speh & Leak, 2002).

The daily 24-h rhythm of the endogenous circadian clock is produced by a transcription-translation feedback loop containing four main phases: transcription, translation, inhibition and decay. In the SCN, the clock genes Clock, BMAL1, NPAS2 and Rorα serve as positive regulators and induce transcription of clock-controlled genes, Period, Chryptochrome and Rev-Erba, which in turn feed-back on the positive regulators in a negative feedback loop (Sahar & Sassone-Corsi, 2010).

Most tissue in the body contain clock genes and display daily rhythms. Clocks outside of the brain are called peripheral clocks and are synchronized by the master clock in the SCN (Cermakian & Sassone-Corsi, 2000; Reppert & Weaver, 2002).

The human circadian clock oscillates with a period close to, but not exactly 24 hours. Many people show a slightly delayed ECP while some display an advanced rhythm (Czeisler et al., 1999; Wright, Hughes, Kronauer, Dijk, Czeisler, 2001). This means that the endogenous circadian clock needs daily resetting to be in an appropriate phase with the solar day and night. The period of the circadian pacemaker is entrained to the external day and night cycle mainly by photic but also non-photic (e.g. social cues, feeding times, exercise, sound and the sleep-wake cycle) time cues, or zeitgebers (Honma, Honma & Nakamura, 1995; Duffy, Kronauer & Czeisler, 1996; Roenneberg & Foster, 1997; Goichot et al., 1998; Danilenko, Wirz-Justice, Kräuchi, Weber & Terman, 2000; Mistleberger & Skene, 2004; Goel, 2005).

Phase angle of entrainment is a principal concept that describes the phase relationship between circadian rhythms of different parameters, for example the endogenous circadian clock, the daily rhythm of sleep and wakefulness and environmental time, a phase relationship which is important for attaining wakefulness during the day and an uninterrupted sleep during the night (Dijk& Czeisler, 1994; Duffy & Wright, 2005;). Furthermore, an incorrect phase relationship between circadian rhythms of various physiological, neuroendocrine and neurobehavioral processes and local time has been associated with serious implications for human health and a number of disorders, for example obesity, depression, diabetes, different sleep disorders and cardiovascular disease (Rajaratnam & Arendt, 2001; Delezie & Challet, 2011; Roenneberg, Allebrandt, Merrow & Vetter, 2012; Buxton et al., 2012).

## 2.3. Characteristics of the light exposure influencing non-image-forming effects

This section provides an overview of main properties of the light exposure that influence the non-image-forming responses.

### 2.3.1. Light intensity

The physiological and behavioral responses of a light exposure depend on the intensity of the light stimuli. Dose-response curves for suppression of melatonin, phase shifts of the circadian rhythms of melatonin and cortisol and acute alerting effects show a non-linear dose-response that best can be described by a logistic model (Boivin & Czeisler, 1996; Cajochen et al., 2000; Zeitzer et al., 2000).

In comparison to a light pulse with an intensity of 9100 lux, ordinary room intensities in the range 50-160 lux elicit approximately half of the maximum melatonin suppressing response, phase shifting response of the daily melatonin rhythm and acute alerting response (Cajochen et al., 2000; Zeitzer et al., 2000). A saturating effect is observed at approximately 550 lux, producing a response amounting to 90 % of the maximal response of a bright light pulse (Zeitzer et al., 2000).

### 2.3.2. Timing and duration of light exposure

The effect of a light exposure is time dependent which can be illustrated by a phase response curve (PRC). Light exposures at early night result in phase delays of the circadian clock and a light exposure late at night elicits a phase advance (Czeisler et al., 1989; Minors, Waterhouse, & Wirz-Justice, 1991; Khalsa, Jewett, Cajochen & Czeisler, 2003; Kripke, Elliot, Youngstedt & Rex, 2007; Revell, Molina & Eastman, 2012; St. Hilaire et al., 2012; Rüger et al., 2013).

Although contradictory results have been reported, most findings show that the circadian system respond to light during the whole day and therefore suggest that the clock is entrained by light exposures throughout the day (Dumont and Carrier, 1997; Jewett et al., 1997; Kripke et al., 2007).

Similar to the dose-response, the duration-response of a light exposure is non-linear showing that light pulses of shorter duration are more effective per minute of exposure than longer durations (Chang et al., 2012). Furthermore, intermittent bright light pulses, which are commonly found in natural settings, cause significant responses (Savides et al., 1986; Hebért et al., 1998; Rimmer et al., 2000; Gronfier, Wright, Kronauer, Jewett & Czeisler, 2004). Due to adaptive responses of the circadian system, increasing the duration of a light exposure is more effective than increasing the intensity of the light stimulus (Dewan et al., 2011).

### 2.3.3. Light exposure patterns and light history

Previous light exposure has been shown to affect the response of a light exposure suggesting that light history has an adapting effect on the circadian system and that the pattern of light and darkness exposure is fundamental. A nocturnal light exposure after a preceding time period spent in dimmer light results in significantly more suppression of melatonin secretion and increased alertness in comparison with after a previous exposure to light conditions with higher intensities (Owen & Arendt, 1992; Hébert, Martin, Lee & Eastman, 2002; Rufiange, Lachapelle & Dumont, M, 2003; Smith, Schoen & Czeisler, 2004; Jasser, Hanifin, Rollaq & Brainard, 2006; Higushi, Motohashi, Ishibashi & Maeda, 2007; Chang, Sheer, & Czeisler, 2011; Chang, Scheer, Czeisler & Aeschbach, 2013; Kozaki, Kubokawa, Taketomi & Hatae, 2015). Moreover, spectral composition of the daytime light exposure also influences the effect of a nocturnal light exposure (Kozaki, Koga, Toda, Nogushi & Yasukoushi, 2008; Kozaki, Kubokawa, Taketomi & Hatae, 2016).

To summarize this section, daily exposures to light and darkness have a crucial impact on human physiological, neuroendocrine and neurobehavioral processes. The main properties influencing the non-image-forming responses to light are spectral composition, intensity, timing and duration, and previous light exposure.

# 3. Previous research

This chapter provides a summary of previous research which include topics relevant for the present research.

## 3.1. Field research on daily and seasonal light exposure in real-life settings

To investigate typical light-dark cycles and the quality of the visible radiation that people of today are exposed to in their real working and living environment, field research has used prototype and commercial portable instruments and diaries for recording daily light exposure in various contexts (Okudaira, Kripke, & Webster, 1983; Eastman, 1990; Espiritu, et al., 1994; Oren et al., 1994; Cole et al., 1995; Ueno-Towatari, Norimatsu, Blazejczyk, Tokura, & Morita, 2007; Thorne, Jones, Peters, Archer, & Dijk, 2009; Figueiro & Rea, 2010; Hubalek, Brink & Schierz, 2010; Smolders, deKort & van den Berg, 2013).

Research carried out in real-life settings also give an opportunity to examine the ecological validity of theoretical models based on results obtained in highly controlled laboratory settings. In their review, Dumont and Beaulieu (2007) points out that there are important differences regarding light conditions tested in laboratory and those experienced in natural settings and consequently data from field research can provide valuable information that can complement findings from laboratory research.

Field studies have been conducted to investigate in what way various factors, including age, type of work, chronotype, geographic location and season influence typical daily light exposure (Okudaira, Kripke, & Webster, 1983; Cambell, Kripke, Gillin & Hrubovcak, 1988; Cole et al., 1995; Hébert, Dumont, & Paquet, 1998; Girardin et al., 2000; Dumont, Benhaberou-Brun & Paquet, 2001; Kawinska, Dumont, Selmaoui, Paquet & Carrier, 2005; Grandner, Kripke & Langer, 2006; Goulet, Mongrain, Desrosiers, Paquet, & Dumont, 2007; Park, Kripke & Cole, 2007; Staples, Archer, Arber & Skene, 2009; Thorne et al., 2009; Figueiro & Rea, 2010; Hubalek, Brink & Schierz, 2010; Miller, Bierman, Figueiro, Schernhammer & Rea, 2010; Scheuermaier et al., 2010; Crowley, Molina & Burgess, 2015; Figueiro & Rea, 2016).

To further inform of what kind of lighting conditions that are needed with regard to psychological well-being and physiological health, others have examined possible differences in light exposure between healthy subjects and people experiencing seasonal problems (Guillemette, Hébert, Paquet, & Dumont, 1998; Graw, Recker, Sand, Kräuchi & Wirz-Justice, 1999).

Based on the prevailing theoretical models used for explaining the impact of light on entrainment of biological rhythms, early field research focused on daily exposure to bright light (Okudaira et al. 1983, Savides et al., 1986; Cambell et al., 1988). Concurrent with increased knowledge about human photictransduction and how different characteristic of the light exposure influence responses of the circadian system, subsequent studies in real working and living environments also have recognized the spectral composition of the 24-h light exposure (Thorne et al., 2009; Hubalek et al., 2010; Figueiro et al., 2010; Smolders et al., 2013).

Taken together, previous field research show that people of today spend much of their waking day indoors, exposed to ordinary room intensities, which generally are between 260-870 lux on the workplace in office environments (measured as horizontal illuminance) (Küller et al., 2006). Prior findings report that, on latitudes between 30° and 50° on the northern hemisphere, people usually are exposed to bright light (i.e. >1000 lux) for 1.5-2.6 hours during the summer (Savides et al., 1983; Cole et al., 1995; Hebért et al.,1998; Guillemette et al., 1998; Aan Het Rot, Moskowitz & Young, 2008) and many spend half of the waking day in lighting conditions less than 100 lux also during the summer. Moreover, the 24-h total and mean light exposure as well as exposures to bright light pulses change with seasons and those variations are greater at higher latitudes (Cole et al. 1995; Higushi et al. 2007; Park et al. 2007). During the winter, many people living at higher latitudes are exposed to bright light, exceeding 1000 lux for less than 30 minutes per day (Cole et al. 1995; Hebért et al., 1998).

Studies focusing on light exposure pattern show that daily exposure to bright light normally comprise brief light pulses distributed throughout the day and seasonal variations have been observed during different time periods of the day. Furthermore, durations of light exposures exceeding various intensity thresholds and amount within different intensity ranges varies during the course of the day. However, there are inconsistencies regarding seasonal variations of daily exposure to various indoor illuminance levels. Hebért et al. (1998) found no seasonal differences which previously have been reported by Cole et al. (1995).

Relating to seasonal changes in photoperiod length, Eastman (1990) demonstrated that, in the summer the time period between the first and last exposure to daylight outdoors was longer in the summer in comparison to the winter and the seasonal difference was larger in the evening. Similar findings were reported by Figueiro and Rea (2010), showing a larger evening exposure to circadian light (i.e. light exposure measured according to the sensitivity of the circadian system) in spring than in winter as a result of exposure to more natural daylight rather than seasonal variations in the use of artificial light. Wehr, Giesen, Moul, Turner & Schwarts (1995) reported findings showing that the use of artificial light results in unvarying photoperiods during the seasons, unlike the seasonal changes of the natural photoperiod. The results are in line with later findings reported by Hebért et al. (1998) and Crowley et al. (2013).

Several field studies have observed exposures to low levels of light in the morning, which then increase during the day reaching maximum levels during the afternoon (between 12.00-16.00) after which the levels decline and reaching low levels in the evening (Thorne et al., 2009; Goulet et al., 2007).

Field research conducted to this date show inconsistencies regarding effects of age. Some studies report no age-differences concerning duration of bright light or duration of light exposures within certain ranges, at least for people living in urban settings at a latitude of 44°-45° N. Others report higher as well as lower daily bright light exposure in older people (Scheuermaier et al., 2010; Cambell, 1988).

There appear to be considerable variations in light exposure from day to day, both within an individual and between individuals. The 24-h light exposure has been found to be different during regular workdays and weekends (Hubalek et al. 2010; Crowley et al., 2015). Hubalek et al. (2010) displayed results showing similar daily light exposures during workdays although the daily light exposure varies considerably during free days on weekends. Furthermore, Crowley et al. (2015), found higher light exposures during workdays in comparison to week-end days, especially during the mornings, both in winter and in summer. Also, timing of sleep and activity in relation to external time (i.e. chronotype) have been shown to influence the 24-h light-dark exposure pattern (Goulet et al. 2007; Staples et al. 2009).

The importance of recognizing the whole 24-h light-dark cycle has clearly been demonstrated in field studies focusing on shift-work and physiological effects of seasonal changes in daily light exposure patterns (Dumont et al., 2001; Morita et al., 2002; Kawinska et al., 2005).

In addition to diurnal and seasonal variations in intensity, also the spectral composition of the light exposure displays changes across the day and during different seasons at higher latitudes. In the summer, the contribution of the short-wavelength part to the overall light exposure is larger than during the winter, especially during the evenings (Thorne et al. 2009).

## 3.2. Seasonal variation in physiology

The circadian rhythm of melatonin secretion is mainly regulated by the photoperiod and has often been used to define biological night and day. Melatonin levels are high during the nighttime and are normally low during the day (Arendt, 2005). In seasonal animals, duration of nocturnal secretion of melatonin represents a seasonal signal regulating physiological and behavioral changes (Arendt, Middleton, Stone & Skene, 1999).

Melatonin is primarily synthesized in the hypothalamic pineal gland. The SCN controls the circadian rhythm of melatonin by neural projections via the paraventricular nucleus (PVN), which then are transmitted along the intermediolateral cell column and the input reach the pineal gland via cervical ganglion (Moore, 1996). Moreover, light can also influence the secretion of melatonin downstream of the SCN (i.e. masking) by acutely suppressing the synthesis.

Different types of melatonin receptors have been observed in a wide variety of tissue. For example, in addition to the SCN, melatonin receptors have been found in the retina, heart, kidneys, pancreatic islets, adrenal glands, stomach and gonads. This suggests that melatonin affects the rhythms of many physiological processes including phase resetting of the endogenous circadian clock (Brown, Pandi-Perumal, Traht & Cardinali, 2010).

Laboratory research have demonstrated that humans can adjust physiological and behavioral processes according to the length of the photoperiod (Wehr, 1991; Buresová, Dvorákova & Illnerová, 1992; Wehr, Moul & Barbato, 1993; Vondrasová-Jelínkova, Hájek & Illnerová, 1999). However, field research by Wehr et al. (1995) showed no seasonal differences regarding nocturnal secretion of melatonin in modern, real-life situations probably as a result of the use of artificial lighting.

Other research carried out at different latitudes, investigating seasonal differences in various features of the melatonin rhythm, for example melatonin peak amplitude, daily and nocturnal concentrations and phase position of the circadian rhythm have reported inconsistent findings. Some authors have reported seasonal variations of the phase position of the rhythm, showing an advanced phase in the summer and the autumn in comparison to the spring and the winter (Illnerová, Hoffman & Vanecek, 1985; Laakso, Porkka-Heiskanen, Alila, Stenberg & Johansson, 1994). On the other hand, others have not observed any seasonal changes or found a delayed phase position in the summer and spring when compared to the winter (Stockan & Reiter, 1994; Van Dongen & Dinges, 2005; Figueiro & Rea, 2010; Crowley et al., 2015).

Furthermore, longer durations of melatonin secretion during the winter have been shown in some studies while other researchers did not observe any seasonal variations (Kauppila, Kivelä, Pakarinen, A & Vakkuri, 1987; Wehr et al., 1995; Wehr et al., 2001). Higher concentrations of melatonin, both during the day and the night have been reported at high latitudes in the winter (Martikainen, Tapanainen, Vakkuri, Leppälouta & Huhtaniemi, 1985; Kivelä, Kauppila, Ylöstalo, Vakkuri & Leppälouto, 1988; Stokkan & Reiter, 1994; Morera & Abreu, 2006). Moreover, a seasonal variation has been observed showing higher peak melatonin amplitude in the winter in comparison to the summer (Morera & Abreu, 2006).

There are several hypotheses connecting the rhythm of melatonin to the problems experienced by people suffering from SAD and its non-clinical form subsyndromal seasonal affective disorder (S-SAD) (Lam & Levitan, 2000; Roecklin et al., 2013). This has contributed to investigations comparing melatonin rhythms in healthy subjects and patients. According to the phase shift hypothesis the symptoms associated with SAD and S-SAD occur as a result of a seasonal phase shift in the relationship between the circadian rhythms generated by the endogenous circadian pacemaker (e.g. melatonin, cortisol and core body temperature) and the sleep-wake cycle (Lewy, Sack, Singer & White, 1987; Lewy, Lefler, Emens & Bauer, 2006).

In support of the phase shift hypothesis, some researchers have observed a phase delay or advance in the rhythm of melatonin and other endocrine rhythms during the depressive state in SAD-patients (Dahl et al., 1993; Avery et al., 1997; Lewy et al., 2006). On the other hand, there are examples of studies where the authors have not found any differences concerning the melatonin rhythm in SAD-patients in comparison to healthy controls (Checkley et al., 1993).

Similar to the circadian rhythm of melatonin, the rhythm of cortisol shows a diurnal pattern with higher levels during the day and lower values during the night (Jung et al., 2010). A distinct peak (i.e. awakening cortisol response) is displayed shortly after time of wake-up (Clow, Thorn & Evans, 2004).

Cortisol is a stress hormone that is influenced by a variety of factors and is regulated depending on the demand for mobilizing the organism. It has an effect on many physiological processes including metabolic-, immune and muscle functions (Küller & Wetterberg, 1996; Jung et al., 2010).

Exposure to light has been shown to increase morning levels of cortisol (Leproult, Coleccia, L´Hermite-Balériaux & Van Cauter, 2001; Scheer & Buijs, 2009). However, other results show that exposure to light have a reducing effect on the level of cortisol (Kostoglou-Athanassiou, Trecher, Wheeler & Forsling, 1998; Jung et al., 2010). Field research carried out at high latitudes have shown low levels of cortisol in the summer and higher levels in the spring, autumn and winter (Hansen, Garde, Skovgrad & Cristenson, 2001; Persson, Garde, Hansen, Larsson, Orbaek & Karlsson, 2008). Other researchers have shown a relationship between lighting in the school environment and seasonal variation in morning cortisol concentrations (Küller & Lindsten 1992).

## 3.3. Seasonal variations in psychological and neurobehavioral parameters

Previous findings reported in the literature show an agreement on light having an acute alerting effect during the nighttime which have been associated to its suppressing effect on nocturnal secretion of melatonin (Badia, Myers, Boecker &

Culpepper, 1991; Myers & Badia, 1993; Lowden, Åkerstedt, & Wibom, 2004). However, a number of studies carried out in the laboratory and in the field have found similar alerting effects also during the daytime when melatonin levels are low (Phipps-Nelson, Redman, Dijk & Rajaratnam, 2003; Rüger et al., 2006; Kaida, Takahashi, Haratani, Otsuka, Fukasawa, & Nakata, 2007a; Smolders, de Kort & Cluitmans, 2012). Furthermore, beneficial effects of bright light and exposure to blue-enriched light, with a higher content of short-wavelength light, have been observed for other psychological measures, including cognitive performance, vitality, concentration and irritability (Mills, Tomkins & Schlangen, 2007; Viola, James, Schlangen & Dijk, 2008; Vandwalle et al., 2007; Corbett, Middleton & Arendt, 2012)

Bright light and light enriched in the short-wavelength part of the visible spectrum have been demonstrated to have a positive influence on mood and social interaction in people suffering from SAD and S-SAD and healthy, non-depressed subjects (Sack et al., 1990; Partonen & Lönnqvist, 2000; Goel & Etwaroo, 2006; Kaida, Takashi & Otsuka, 2007b; Aan Het Rot, Moskowitz & Young, 2008; Meesters, Decker, Schlangen, Bos & Ruiter, 2011). However, there are some contradictory results (Rosenthal, Rotter, Jacobsen & Skwerer, 1987; Kasper, Rogers, Madden, Joseph-Vanderpool & Rosenthal, 1990; Bauer, Kurtz, Rubin & Marcus, 1994; Genhart, Kelly, Coursey, Datiles & Rosenthal, 1993; Daurat, Foret, Touitou & Benoit, 1996). Moreover, field studies have shown a relationship between daily light exposure and light exposure during the morning and feelings of vitality, social and emotional functioning and quality of life (Grandner et al., 2006; Smolders et al, 2013).

Most studies examining seasonal variation in various measures of sleep, including bedtime, time of awakening, sleep onset, and sleep duration have been reporting seasonal effects (Kohsaka, Fukuda, Honma & Morita, 1992; Anderson, Rosen & Mendelson, 1994; Hebért et al, 1998; Figueiro & Rea, 2010; Friborg, Bjørvatn, Amponsah, & Pallesen, 2012; Garde et al., 2014). However, there are also contrasting findings, showing no seasonal variations in sleep (Park et al., 2007; Crowley et al., 2015).

Also, perception of light in the indoor environment might be affected by season. The perceived qualities of the lighting conditions have a major impact on mood, work performance and work satisfaction (Küller et al., 2006; Grimaldi, Partonen, Haukka, Aromaa & Lönnqvist, 2008; Veitch, Newsham, Boyce, & Jones, 2008). Therefore, it is important to understand the relation between perception of lighting conditions in working environments and season.

# 4. Methodological considerations

This chapter gives a description of the methodology used in the studies included in the thesis.

## 4.1. Research approach

Lighting design is a complex field of research, where physiological, psychological as well as technical aspects need to be considered together (DiLaura et al., 2011). An extensive overview of previous research reported in the scientific literature was undertaken to compile existing knowledge in research fields relevant for the present research and to identify appropriate methods and instruments, with high validity and reliability.

The research questions were investigated by studying human adaptation to regional lighting conditions during one year. Data was collected in a longitudinal field study with a mixed-method design considering physiological functioning, emotion and technical and physical properties. Moreover, a perceptional dimension exploring seasonal experience of lighting conditions in the working environments was incorporated in the holistic design.

To answer the questions concerning diurnal and seasonal variations (A1, B1, C 1-3, D1) in the studied parameters a longitudinal, within subject's design was chosen. This research design is a strong design that controls for individual differences concerning physiological and psychological effects of the daily and seasonal light exposure (Shaughnessy & Zechmeister, 1990). The design had to include methods for assessing daily and seasonal differences in physiological processes connected the biological clock to answer the question in theme B (B1). Moreover, the instruments used in the studies needed to permit measurements of diurnal and seasonal variation in psychological well-being and sleep (C1-C2) during daily life. Also, the questions relating to daily and seasonal perception of the light in the office environments required instruments for evaluation of different aspects of lighting, such as the perceived quality and strength of the light (C3). To answer the research questions concerning light exposure and measurement of light with respect to non-image-forming effects of light, instruments for measuring intensity as well as spectral composition were needed (A1, D1, D2).

Furthermore, the geographical location, at high latitude with large seasonal variations in the natural photoperiod was selected as it provides a variation of available daylight and need for additional artificial lighting.

## 4.2. Subjects and settings

The final sample for the studies consisted of 30 healthy participants, 20 women (mean age = 42.6 years, SD = 9.98 years, range 24 - 61 years) and 10 men (mean age = 45.2 years, SD = 14.7 years, range 21 - 64 years). Two subjects withdrew at an early stage and are not included in the data analysis. The sampling criteria included male and female office employees, working at least 75 % of full time during daytime. A normal workweek consisted of 40 h of work during weekdays.

Different types of offices were included in the study representing office settings regularly found in Sweden. All workplaces except one had access to daylight through at least one side window. Most subjects were seated relatively close to a window (mean distance = 1.7 m, SD = 1.1 m, range = 1.1 - 6.8 m). Localized lighting from fixtures, suspended from the ceiling was used in the majority of the offices. The fixtures were mostly equipped with fluorescent light sources with a correlated color temperature between 3000 Kelvin (K) and 3500 K. In some cases, the subjects had access to task light delivered by fixtures placed on the desk. Additional artificial lighting in the office environments was provided by wall luminaires and downlights equipped with compact fluorescent light sources.

## 4.3. Procedure

The collection of data for the studies was conducted between February 2008 and January 2009. The participants were recruited from four work sites. Before the start of the study, appropriate persons with a leading position within the organizations were contacted and received a letter describing the purpose and general procedure of the study. The contact persons were asked to distribute an invitation to a meeting with the researchers among the staff. During this meeting, the audience was informed about the purpose of the study and a description of the procedure. Those who were interested in taking part in the study were then given time for consideration before giving informed consent and deciding to participate.

Prior to the start of the study, the subjects were contacted regarding preliminary dates for data collections and concerning a visit to the workplace by a member of the research team. During the visit, the workplace was visually inspected and suitable points for physical measurements in the office environments, including lighting conditions and temperature were documented. A sketch of the room was also made marking window placement, luminaires, seating position and desk.

The months of the year were divided into seasons with respect to the solstices. That meant that winter included the months November, December and January, and spring the months February, March and April. Further, May, June and July represented the summer and the autumn season encompassed September, October and November.

Since the purpose was to study the natural pattern of light exposure and sleep-activity pattern during a regular workweek in the four seasons, there were no fixed bedtimes and wake-up times.

The static field measurements of lighting conditions were conducted at five occasions, in February/March, April/May, June, September/October and December/January throughout the year. The measuring periods were determined based on previous data reporting timing of seasonal changes in physiological and psychological parameters (Küller & Lindsten 1992; Küller & Wetterberg 1996).

## 4.4. Instruments

This section presents the instruments used for physical measurement of light exposure, measurements of biological markers and measurement of psychological parameters.

### 4.4.1. Ambulatory measurements of light exposure

The lighting conditions that the subjects were exposed to when conducting their daily activities at the workplace, in the home environment and in places where they spent their leisure time, were continuously recorded with two instruments for ambulatory measurement of light. That made it possible to investigate daily and seasonal patterns of light exposure in terms of intensity, timing and duration, and spectral power distribution (SPD).

The Actiwatch-L monitor (Minimitter/Respironics, Bend, OR) has a sensor for measurements of illuminance and also includes an accelerometer for measurements of activity. The instrument is sensitive to illuminance levels ranging from 0.1 to 150 000 photopic lux and has a peak spectral sensitivity at 580 nm. The device registers optical radiation in a wavelength range between 330 nm (nanometer) and 720 nm. Furthermore, the instrument has a linearity of < 2 % for illuminances between 0.1 – 150 000 lux and an angular response of +- 50 degrees. In the present study, the monitor was worn on the wrist and illuminance data were sampled by logging an illuminance value every minute.

A prototype instrument for ambulatory recordings of irradiance in different wavelength-bands was used to investigate the quality (i.e. SPD) of the radiant energy the subjects were exposed to throughout the day. The instrument had seven channels with bandwidths of 50 nm, ranging from 400-750 nm. It was designed by use of photopic devices (Hamamatsu Photonics K.K., Hamamatsu City, Japan) and a linear variable band pass filter for spectral filtering (Edmund Optics Inc, Barrington, New Jersey, USA). Spectral sensitivity, accuracy and linearity were validated by calculating calibration equations for the seven channels according to simultaneous measurements with a calibrated spectroradiometer (Light Spex:McMahan Research Laboratories, Chapel Hill, North Carolina, USA) in various lighting conditions, including daylight and artificial lighting, which are commonly experienced in real working and living environments.

A logging interval of 1 minute was used for recording the measurements and the collected data was stored in a module carried in a shoulder bag. The sensor was positioned at the chest. Study I, focused on the range between 450 and 500 nm as a measure of light exposure with a particular impact on ipRGCs. In study III, the total exposure was divided into three wavelength ranges, representing short-wavelength radiation (400 - 550 nm), middle-wavelength radiation (550 nm – 650 nm) and long-wavelength radiation (650 nm – 750 nm).

### 4.4.2. Static measurements of lighting conditions in the offices

Field recordings of lighting conditions in the offices, in terms of intensity and spectral composition, were conducted by static measurements of illuminance and irradiance. A calibrated Hagner Universal Photometer S4 (B. Hagner AB, Solna, Sweden), with a detector SD 2 (B. Hagner AB, Solna, Sweden), was used for measurements of illuminance. The spectral composition of the visible radiation in the working environments was recorded using an Avantes Avaspec-2048-USB 2 spectroradiometer (Avantes BV, Apeldoorn, the Netherlands).

### 4.4.3. Measurements and assessments of biological markers

The subjects collected saliva for assessment of two biological markers, melatonin and cortisol, during a 24-hour period, between the second and third day of the measuring period. Saliva sampling was chosen because it is a non-invasive method permitting the subjects to collect saliva at the work place and at home. The hormones melatonin and cortisol display a circadian rhythm and have been used as biological markers in research investigating non-image-forming effects concerning various physiological processes, including phase resetting of the endogenous circadian clock and suppression of nocturnal melatonin secretion. The circadian rhythm of melatonin, is considered an especially stable marker as it is not easily influenced by masking responses due to movement (Duffy and Wright, 2005; Lewy et al., 2006).

Saliva were collected every four hours, using Salivettes cotton swabs (Salivette; Sarstedt, Newton, North Carolina, USA). The samples were immediately stored at < -20 degrees Celsius until the sample was analyzed.

The times of saliva collection permitted estimations of daily and nocturnal levels of melatonin. Moreover, the circadian profile, peak time and peak levels were calculated by spline interpolations of the original points to determine if there were any seasonal variations regarding the phase and amplitude of the expressed rhythm.

The saliva was centrifuged for 5 min at 3000 rpm. The melatonin concentration in the samples was analyzed by using a commercial Elisa kit (Direct Saliva Melatonin Elisa (EK-DSM), Buhlmann Laboratories AG, Switzerland). This is a competitive immunoassay using a capture antibody (Ab) technique. Intra-Assay precision (Within-Run) was 12.6 %. The intraassay precision was calculated from the results of four different saliva samples within the standard range, measured 10 times in duplicate in a single run. Inter-Assay Precision (Run-to-Run) was 22.9 %. The inter-assay precision was calculated from the results of 17 independent runs with 5 samples within the standard range. The detection limit of the assay was 0.5 pg / ml.

Cortisol concentrations were measured using an ELISA KIT (DRG Salivary Cortisol ELISA KIT (SLV-2930), DRG International, Inc., USA) based on the competition principle and the micro plate separation. The intra-assay variation, determined by replicate measurement of four saliva samples and expressed as coefficient variation (C.V.) was between 1.47 % and 4.52 %. The inter-assay (between-run) variation, determined by quadruplicate measurements of commercial control samples in three different day’s runs was between 5.82 % and 7.47 %. The detection limit was 0.0537 μg/dl.

### 4.4.4. Subjective evaluations of psychological well-being

The Positive and Negative Affect Schedule (PANAS) was used for investigating seasonal variations in subjective psychological well-being. The instrument is validated and easy to administer which makes it suitable for self-ratings of mood during daily life. PANAS is a factor-analytically derived instrument that was developed for brief measurements of two broad dimensions of the subjective emotional experience, reflecting affective, physical and cognitive states (Watson et al., 1988).

Twenty adjectives, each describing an emotion were assessed in terms of ‘how do you feel right now’. The form comprises two, ten-item Likert type scales (range 10-50) measuring positive affect, PA ($\alpha$=0.86-0.90) and Negative affect, NA ($\alpha$=0.84-0.87). High PA is characterized by amongst others enthusiasm, energy level, mental alertness, interest, joy and determination and a low positive affect imply lethargy and lassitude. NA is a dimension describing subjective distress. A low NA indicate a state of calmness and relaxation. Results from studies show that PA display a diurnal rhythm related to rhythm of the ECP (Watson et al., 1988; Clark et al., 1989).

### 4.4.5. Assessments of seasonality

Seasonality was retrospectively assessed with a questionnarie for investigating recurring experiences of seasonal variations in subjective well-being and mood (Küller et al., 2006).

### 4.4.6. Recordings of sleep-wake behavior

A 24-h graphic log was developed for determining sleep-wake behavior in the present research. Time of wake-up and time when lights were turned off for sleep were noted in addition to the times when the subjects started and ended working.

### 4.4.7. Subjective ratings of perceived lighting quality in the office settings

An instrument comprising sixteen bipolar seven-grade scales were used for the assessment of the perceived qualities of the lighting in the offices (Küller & Wetterberg, 1993; Küller & Wetterberg, 1996). By means of factor analysis four overarching dimensions, hedonic tone ($\alpha$=0.84), strength ($\alpha$=0.82), variation ($\alpha$=0.52, Cronbach's $\alpha$ based on the data included in the present research), and flicker (only one scale) can be captured from the scales (Johansson, Pedersen, Maleetipwan- Mattsson, Kuhn & Laike, 2014). This instrument has been used for evaluations of lighting conditions by laypersons in a number of studies carried out in the field (Küller & Wetterberg, 1996; Maleetipwan-Mattsson & Laike, 2015; Gentile, Govén, Laike & Sjöberg, 2017).

### 4.4.8. Instrument for determining circadian type

Three scales were used for assessment of circadian type (Küller and Wetterberg 1996). It was determined by the answers to the following statements: I am a typical sort of person that likes to stay up late at night, I am a typical sort of person that likes to get up early in the morning, I usually have difficulty falling asleep in the evening. The three scales were graded as follows: Yes, I agree; I'm not sure; No, I do not agree. Watson et al. (1988). suggest that there is a high correlation between simple self-identification of circadian type and the scores on the complete Morning-Evening Questionnaire (MEQ)(Horne & Östberg, 1976).

### 4.4.9. Photoperiod length and outdoor exposure to bright daylight

The sunrise/sunset calculator (National Research Council Canada) was used to establish the daily exposure to bright daylight during the seasons. In a graphic log that was developed for the purpose of the present research, the subjects registered the time spent outdoors. Regarding resolution of the data, the diurnal graph was divided into ten-minute bins.

### 4.4.10. Questionnaire on home lighting

A questionnaire concerning light sources in the home environment was developed for the study and was used to get information of the light sources used in the home environment. The questionnaire depicted various light sources and the participants were asked to indicate on a 4-point Likert scale if the light sources were used in most luminaires, in some luminaires, in a few luminaires, or not at all. The following light sources were included in the questionnaire: incandescent lamp, halogen lamp, linear fluorescent tube, compact fluorescent tube and compact fluorescent integrated lamp. The participants also had the opportunity to make additional reports of light sources that were used in the home environment, not included in the questionnaire.

## 4.5. Data treatment

The Statistical Program for Social Sciences (SPSS), version 19 for Windows was used for the calculations.

Regarding statistical level of acceptance, a $p$-value $< 0.05$ was considered to be a significant effect.

In study I, ANOVA Repeated Measures were used to examine the daily and seasonal variations of melatonin and cortisol concentrations, peak melatonin concentration and peak time of the melatonin rhythm. Missing values were replaced by the individual seasonal mean for the corresponding time point.

ANOVA Repeated Measures were also used to investigate diurnal and seasonal difference regarding light exposure. The data from the ambulatory recordings of light exposure were divided into 4-h time periods across the day and a seasonal mean for each time period was computed. Missing data were replaced by individual seasonal mean for the corresponding time period. Correlational analysis (Pearson's product-moment correlation coefficient) were used to compute the relationship between the light exposure measured as irradiance (within the wavelength range between 450 nm – 500 nm) and as illuminance.

Moreover, effect sizes (*r*) of seasonal variations in daily light exposure and concerning the two biological markers were computed.

In study II, seasonal variations concerning mood, exposure to bright daylight outdoors, sleep-activity behavior and subjective evaluations of the light in the offices were examined by ANOVA Repeated Measures. To investigate if a previous history of experiencing seasonal variations in subjective well-being and mood had an influence, the statistical analysis also included seasonality as a between group factor. Interrelationships between the different physical and psychological measures were explored by the use of correlational analysis (Pearson correlation coefficients). The seasonal mean duration of bright daylight exposure outdoors during six four-hour time periods were computed. Missing values were replaced by individual seasonal mean for the corresponding time point or time period.

In study III, the association between ambulatory and static measurements of spectral composition and illuminance were determined by calculations of Pearson's product-moment correlation coefficient and through the use of dependent means *t*-tests. The data from the ambulatory measurements were treated to allow comparisons with the static measurements. Missing values in the ambulatory recordings were replaced by individual seasonal mean. Missing data concerning the static measurements were replaced by annual mean as a result of the lower resolution not permitting a seasonal mean to be calculated.

## 4.6. Ethical considerations

The research carried out in the studies included in this thesis entailed important ethical implications regarding informed consent, confidentiality and intrusion in daily life that needed to be carefully considered.

Measures were undertaken to ensure that the data collection was confidential. The method of data treatment secured that no individual persons could be identified. Furthermore, the study was designed to minimize the interference on the participant's daily activities by limiting the number of assessments.

Before the start of the study informed consent was obtained from responsible persons in the organizations where the subjects were employed. The purpose and procedure of the study were explained to personnel that were interested to participate in order for them to be able to give an informed consent. Furthermore, it was emphasized that participation was voluntary and that they could withdraw from the study without stating any reason for the decision.

The study design was approved by the ethics committee at Fukuoka Women's University.

# 5. Results

## 5.1. Main results from study I

One part of the overall aim of the study, was to investigate daily and seasonal illuminance exposure and exposure to short-wavelength light in a group of healthy Swedish office workers (13 women, 2 men, mean age = 46.1 years, SD = 9.8 years, range = 28-61 years). The results were used as a part for answering the research question in theme A, concerning how office working people in Sweden generally are exposed to visible radiation in the working and living environments. Furthermore, to answer the question in theme B, regarding seasonal changes in physiological processes, the study examined seasonal changes in two biological markers.

The specific objectives were to a.) investigate if there are any seasonal variations in daily light exposure patterns in terms of illuminance and SPD in the wavelength range between 450-500 nm and b.) to examine if there are any seasonal differences in daily and nocturnal levels of melatonin and cortisol. Also, to investigate if there are any seasonal variations regarding the phase and peak level of the expressed circadian rhythm of melatonin.

### 5.1.1. Natural patterns of diurnal and seasonal light exposure

There was a significant seasonal variation in total daily light exposure, both when measured as illuminance exposure ($F(3, 42) = 46.07$, $p < .001$) and concerning exposure to irradiance in the short-wavelength part of the spectrum between 450 nm and 500 nm ($F(3, 39) = 12.58$, $p < .001$). Throughout the summer, the subjects were exposed to approximately 15 times more illuminance than during the winter, and 3 - 4 times more than during the autumn and spring. Furthermore, seasonal differences in light exposure were found during all time periods of the day except during nighttime, between 00.00 - 04.00. Daily light exposure during the different time periods across the year is shown in figures 1 - 3 and tables 1 - 3 (see appended paper I).

A seasonal difference was also observed regarding the relative light exposure throughout the day. In the winter, the subjects were exposed to more of the daily light exposure during the day and to a lesser extent in the evening. However, during the summer they were exposed to more of the daily light exposure during the evening. Figure 4 (see appended paper I) display the relative light exposure during the day for the four seasons.

### 5.1.2. Circadian change of melatonin and cortisol concentrations during the year

The results showed a significant seasonal variation in peak level of melatonin (F(3, 42)= 5.67, $p$ =.002. Significant contrasts were observed with higher levels in the winter in comparison to the spring, F (1, 14) = 6.87, $r$ = .57, summer, F (1, 14) = 7.07, $r$ = .57 and autumn, F (1,14) = 7.07, $r$ = .057. Moreover, during the winter, higher levels of melatonin were found in the morning at 07.00 (F (3,39) = 5.59, $p$ = .003). Daily and nocturnal levels of melatonin during the four seasons are shown in table 4 in appended paper I.

No seasonal variation was observed regarding the phase of the circadian rhythm of melatonin in terms of the timing of maximum concentration.

Regarding daily and nocturnal cortisol concentrations, no seasonal changes were found.

## 5.2. Main results from study II

The aim of the study was to investigate mood, sleep-activity patterns, experience of the light in the offices and daily patterns of exposure to bright daylight outdoors in a group of healthy Swedish office workers (20 women (mean age = 42.6 years, SD = 9.98 years, range = 24 - 61 years) and 10 men (mean age 45.2 years, SD = 14.7 years, range = 21 - 64 years)) during the course of the year. The results from the study were used to answer the research questions in theme C, which relates to seasonal variation concerning psychological aspects. Information regarding daily outdoor exposure to bright daylight during spring, summer, autumn and winter was used for partly answer the question in theme A relating to daily lighting conditions commonly experienced throughout the year. The study had the following six specific objectives:

- To examine if there was a seasonal variation in emotions.

- To investigate to what extent the subjects usually experienced seasonal changes in subjective well-being and mood during the year (seasonality).

- To investigate if there was a seasonal variation concerning the sleep-activity pattern throughout the year.

- To study possible seasonal differences in how the lighting conditions in the workplace generally were perceived.

- To investigate if there was any seasonal variation in the daily pattern of exposure to bright daylight outdoors during the course of the year.

- To explore potential relationships between the physical and psychological measures that were investigated.

### 5.2.1. Diurnal and seasonal patterns regarding mood

First, the daily profile of PA showed an increase from morning to midday and lower values from afternoon to the evening, demonstrating a diurnal course (F (3, 87) = 16.999, *p* <.001).

The subjects reported a significant seasonal variation in mean daily PA ((F = 3, 87) = 4.054, *p* = .010). Comparison of contrasts revealed that, during the spring the subjects experienced a significantly lower PA in comparison to the autumn, F (1, 29) = 7.651, *r* = .46, *p* =.01, and the summer, F (1, 29) = 6.995, *r* = .44, *p* = .013. However, no seasonal differences in mean daily PA were observed when comparing summer and winter, summer and autumn or between spring and winter.

Furthermore, a significant main effect of season was found regarding the subjective assessments of positive affect (PA) in the evening, at 20.00 (F (3, 87) = 4.609, *p* = .005). Comparison between the seasons showed that the subjects reported a significantly higher PA in the evening during the summer compared with the winter, (F1, 29) = 7.78, *r* = .45, *p* = .009, spring, F (1, 29) = 10.76, *r* = .52, *p* = .003, and autumn, F (1, 29) = 4.94, *r* =.38, *p* = .034). No seasonal differences were found when comparing the ratings of positive affect in the evening during the spring, autumn and winter. The subjects reported low ratings of negative affect (NA) and the analysis showed no diurnal nor seasonal variation concerning this parameter.

Results from the analyses of the data collected by the use of the PANAS forms are given in figure 1 and tables 4 and 5 (see appended paper II).

### 5.2.2. Retrospective assessments of seasonality

The findings from the questionnaires investigating frequency of seasonality imply that a majority of the subjects usually experienced a seasonal variation in subjective well-being during consecutive years and nearly half, 46 %, reported a noticeable or rather strong lowering of mood during some months of the year.

### 5.2.3. Sleep-activity behavior across the seasons

There was a significant seasonal variation in bed times and time in bed, but not in wake-up time (F (3, 87) = 3.127, $p$ = .030). Comparisons between the seasons revealed that during the winter the subjects reported significantly longer time in bed in comparison to the summer, F (1, 29) = 8.011, $r$ = .47, $p$ = .008, and autumn, F (1, 29) = 4.983, $r$ = .38, $p$ = .033. Also, there were tendencies indicating shorter bedtimes in the summer in comparison to the spring, F (1, 29) = 3.610, $r$ = .33, $p$ = .067, and autumn, F (1, 29) = 3.986, $r$ = .35, $p$ = .055. However, no significant seasonal differences were found between spring and autumn nor between spring and winter. Table 6 in appended paper II, show the sleep and activity patterns across the year.

### 5.2.4. Seasonal appraisal of the lighting conditions in the working environments

In general, the subjects reported that they experienced the lighting conditions in the offices as fairly pleasant (with a mean score of 4.9 on the index scale 1 - 7), fairly strong (with a mean score of 4.8 on the index scale 1 - 7), and rather varied (with a mean score of 3.9 on the index scale 1 - 7). Furthermore, the lighting in the offices was experienced to support the visual needs of the users (with a mean score of 5.5 on the index scale 1 - 7) and low scores concerning flicker (with a mean score of 2.1 on the index scale 1 - 7) were reported. Means medians and standard deviations for the five variables, by season and by time of the day are given in table 7 (see appended paper II).

The analysis showed seasonal and diurnal differences concerning some of characteristics of the light environments in the offices. First, significant seasonal variations in hedonic tone, or pleasantness, were found in the morning assessments (F (4, 116) = 2.909, $p$ = .025). On average, the ratings were higher in April and September in comparison to February, June and December. Furthermore, the analysis showed a seasonal variation in how varied the light in the offices were perceived by the subjects. Highest average ratings were observed in December and lowest average ratings were reported in February. Finally, there was a tendency for a diurnal variation (F (1, 31) = 4.048, $p$ = 0.53) displaying that the visibility, or how well the lighting supported vision, was higher in the morning than in the afternoon.

### 5.2.5. Duration of time spent outdoors and daily exposure to bright daylight across the year

The analysis showed a seasonal variation regarding how much time the subjects spent outdoors ($F (3, 87) = 29.6$, $p < .001$). Table 8 in appended paper II display the duration of time spent outdoors throughout the four seasons.

Regarding the daily pattern of exposure to bright daylight outdoors, significant seasonal differences were found during all time periods, except during the night time between 00.00 - 04.00. Furthermore, during the winter, bright daylight exposure outdoors was received during the time period between wake-up time and 16.00. On the other hand, during the summer, more than two-thirds of the bright daylight exposure was received during the evening, between 16.00 and 24.00. Daily patterns of bright daylight exposure during spring, summer, autumn and winter are reported in table 9 and Figure 3 in appended paper II.

### 5.2.6. Relationships between the studied parameters

Correlational analysis showed a positive association between bright daylight exposure outside during the evening and bedtime ($r = .211$, $p = .010$, 1-tailed). A significant positive relationship was also found between the length of the natural photoperiod and bedtime ($r = .154$, $p = .046$, 1-tailed).

Furthermore, the analysis revealed a positive correlation between the length of the natural photoperiod and daily amount of bright daylight exposure outdoors ($r = .606$, $p < .001$, 1-tailed) and exposure to bright daylight outdoors during the time period between 20.00 and 24.00 ($r = 0.628$, $p < .001$, 1-tailed).

### 5.2.7. Lighting in the home environments

The subjects mainly used incandescent and halogen lamps in the home environments. In some lighting fixtures integrated compact fluorescent lamps and fluorescent tubes were used.

## 5.3. Main results from study III

The main objective in the study was to investigate the relationship between ambulatory and static field measurements of parameters that can be used for describing lighting quality in real working environments with respect to non-image -forming effects of light. This aim relates to the research question D1 in theme D which deals with the question of how light should be measured with respect to non-image-forming effects of light. The results from the study also contribute to the answer to the research question in theme A (A1) and research question D2 concerning the quality of the light exposure at the work place.

The study had two specific objectives. First, to investigate the relationship between static field measurements of horizontal illuminance at the normal working position, average horizontal illuminance in the room and vertical illuminance at the position of the eye, in the normal angle of gaze and ambulatory measurements of illuminance. Secondly, to examine if there was any association between static field measurements of spectral composition, measured horizontally at the normal working position at the normal working position and vertically at a position of the eye, in the normal angle of gaze and ambulatory measurements of irradiance.

The sample included 20 women (mean age = 42.6 years, SD = 9.98 years, range = 24 - 61 years) and 10 men (mean age 45.2 years, SD = 14.7 years, range = 21 - 64 years). Some of the analyses include a part of the total sample as a result of access to ambulatory data for 15 subjects.

### 5.3.1. Static and ambulatory measurements of light exposure in the working environment

The results from the static measurements of vertical illuminance at the position of the eye, in the normal angle of gaze, showed that illuminances exceeding 1000 lux (i.e. illuminances defined as bright light in several studies found in the literature) were only recorded during 7.3 % of the measurements. On the other hand, vertical illuminances at the position of the eye, in the normal angle of gaze, less than 200 lux were recorded during approximately one third of the measurements. Furthermore, the ambulatory measurements showed an annual average illuminance of 380 lux in the offices during the morning and early afternoon. The results from the static and ambulatory measurements of illuminance are given in table 2 (see appended paper III).

The results from the correlations using Pearson's correlation coefficient showed a strong relationship between the static measurements of horizontal illuminance at the normal working position, vertical illuminance at the position of the eye in normal angle of gaze, and average illuminance in the room for the settings used in the study.

The comparisons of the ambulatory and static measurements using Pearson's coefficient and t-tests showed inconsistencies regarding the relationship between the two methods. The results from the *t*-tests suggest a relationship between static and ambulatory measurements of illuminance for the group but the correlations show a weak association for the individual measurements. The results from the correlational analyses comparing the parameters included in the static measurements of illuminance are reported in table 4 (see appended paper III). Table 5 in appended paper III show the relationship between the parameters included in the static measurements of illuminance and the ambulatory measurements.

Some discrepancies between the static and ambulatory measurements were found regarding the measurements of spectral composition of the light in the offices. On average, the static measurements showed a higher relative content of short (50 %)- and middle wavelength visible light radiation (35 %) and a lower content of long - wavelength visible radiation (14 %) than the measurements recorded by the ambulatory instruments which showed that the light in the offices were comprised of 34 % short wavelength light, 22 % middle wavelength radiation and 44 % long wavelength radiation. Table 3 in appended paper III show results for the static and ambulatory measurements of spectral composition.

There was a strong relationship between the static measurements of spectral composition recorded horizontally at the normal working position and the spectral composition measured vertically at the position of the eye, in the normal angle of gaze. However, the comparison between static and ambulatory measurement of spectral composition showed a weak relationship between the two methods, both assessed by *t*-tests and by the use of Pearson’s correlation coefficient.

# 6. General discussion

This chapter contains a discussion of the main findings in relation to the general aim of the thesis and the research questions connecting to the four themes. The work in this thesis has contributed to the research field by adding information on characteristics of the daily light exposure in real-life settings together with seasonal variations regarding psychological and physiological aspects. Moreover, the results of the research that have been carried out have further informed about relationships between different methods of investigating and evaluating lighting conditions in real environments.

## 6.1. Diurnal and seasonal light exposure in daily life

In this work, diaries, ambulatory instruments and instruments for static field measurements were used to record typical lighting conditions to which office working people in Sweden normally are exposed in their real working and living environments throughout the year.

Taken together the results showed daily and seasonal variation concerning various aspects of the daily light exposure. In line with previous findings from field research, the results showed that nowadays are people, living on this high latitude, exposed to substantially less visible light radiation during the winter in comparison to the summer, spring and autumn both when measured as total illuminance exposure and as daily exposure to visible light radiation in the wavelength range between 450 - 500 nm (Cole et al., 1995; Hebért et al., 1998; Park et al., 2007; Thorne et al., 2009; Figueiro and Rea, 2010).

Similar to the majority of other studies, office-working people in Sweden spend most of their time in indoor environments during all seasons. When comparing with results from studies carried out on the north hemisphere they seem to be exposed to less light in the winter, relying on artificial lighting to an even greater extent (Oren et al., 1994; Hebért et al., 1998; Guillemette et al., 1998; Aan Het Rot et., 2008) They spend significantly less time outdoors in bright daylight, on average only 10 minutes, during the winter probably both as a consequence of climatic conditions such as temperature and the photoperiod that together with the work schedule lead to commutes to and from work before and after sunrise and sunset respectively.

Seasonal differences in light exposure were observed during all time periods of the day except during the night. Largest differences between the seasons were displayed during the afternoon and evening, confirming earlier results. Comparisons of relative light exposure showed that many office workers, especially during the winter but also during spring and autumn, receive most or in any case a substantial part of the daily light exposure at their workplace high-lighting the significance of the lighting conditions in the working environment.

The results from the ambulatory measurements and the static field measurement of illuminance and irradiance showed intensities typically found in office settings, within illuminance ranges suggested that should be maintained according to recommendations (Swedish Standards Institute, 2011).

Different types of offices were included in the studies. Most subjects were seated relatively close to a window permitting exposure to daylight through the window. The measures of spectral composition showed that the light in the offices were mainly comprised of short- and middle-wavelength light and suggested seasonal differences with a larger relative contribution of longer wavelength light in the winter. Previous findings reported by Thorne et al. (2009) similarly demonstrated a relatively larger contribution of short-wavelength light in the summer.

## 6.2. Daily and seasonal variation in physiological processes

The two hormones melatonin and cortisol were used as biological markers to investigate possible seasonal variations in physiological processes relating to the daily light-dark exposure and its effect on the endogenous circadian clock.

A delyed circadian rhythm was anticipated to be observed during the winter. Also, as a consequence of less exposure to natural daylight in the evening and thus less exposure to short-wavelength light and more exposure to light from incandescent light sources, which include most of the visible light radiation in the middle- and long wave part of the visible spectrum, a higher peak level of melatonin was expected in the winter.

Similar to results from a field study by Küller & Lindsten (1992) and laboratory research showing an increase of cortisol in morning after previous exposure to higher intensities of light (Scheer & Buijs, 2009; Leproult et al., 2009), a seasonal change in cortisol was expected with increasing morning levels in the spring.

The results from the analysis of the data revealed higher peak values of the expressed melatonin rhythm in the winter. However, no seasonal variation was observed regarding the phase position of the rhythm. These findings, which partly confirm the hypotheses, are in line with results reported from earlier field studies but contrasts from other findings showing an advanced phase position in the summer because of a larger exposure to visible light in the phase-advancing part of the PRC for a day-active person (Ilnerova et al., 1985; Laakso et al., 1994; Morera & Abreu, 2006; Higushi et al., 2007; Crowley et al., 2015).

In this study, the analysis of the relative light exposure showed that in the summer, the office workers were exposed to a relatively large proportion of the daily light exposure, especially concerning bright daylight, during the phase delaying part of the PRC (Minors et al., 1991; Kripke et al., 2007; Rüger et al., 2013). However, laboratory work and research carried out in the field have demonstrated the effects of the circadian system's adaption to previous light exposures and the importance of recognizing relative light exposure patterns rather than absolute levels (Dumont et al., 2001; Hebért et al al., 2002, Chang et al., 2011; 2013; Kozaki et al., 2015). The higher intensities to which the subjects were exposed during the daytime in the summer may have compensated for the increased exposure during the evening when light pulses have a phase delaying effect on the clock. Moreover, although the total daily light exposure was nearly fifteen times lower in the winter, the light exposure pattern, displaying a large proportion of the daily light exposure between 04.00 and 16.00, may explain why no seasonal variations in the timing of melatonin peak levels were observed.

Previous reports of an increase in morning cortisol concentrations during the spring were not corroborated in this field study (Küller & Lindsten, 1992).

## 6.3. Seasonal variations in psychological well-being and sleep-wake behavior

In accordance with most findings, the results from the present research showed that a majority of the subjects experienced a seasonal variation concerning mood (Kasper et al., 1989b; Küller et al., 2006; Park et al., 2007; Grimaldi et al., 2008). When comparing the seasons, higher ratings were reported during the summer and autumn. Also, higher ratings of positive affect were found in the evening during the summer.

However, unlike previous results showing associations between light exposure and various psychological measures, including mood, alertness, feelings of vitality, social interaction, and quality of life, no relationship was found between positive affect and exposure to bright levels of daylight outdoors (Espiritu et al., 1994; Aan het Rot et al., 2008; Grandner et al., 2006; Smolders et al., 2013).

Previous findings from research investigating seasonal variation in different aspects of sleep have shown contradictive results probably due to methodological differences (Park et al., 2007; Figueiro & Rea, 2010; Friborg et al., 2012; Garde et al., 2014). The self-report diaries used in this study revealed seasonal variations in the sleep-activity pattern as a consequence of seasonal differences in bedtimes although the time of wake-up did not differ. Therefore, the results indicated that the subjects experienced longer sleep durations during the winter in comparison to spring, summer and autumn. Furthermore, the bedtimes were associated with amount of evening exposure to bright daylight outdoors and to the length of the photoperiod.

## 6.4. Seasonal differences in appraisal of lighting conditions in the working environments

The perception of lighting conditions has been found to have a significant influence on psychological well-being (Küller et al., 2006). In the present study, seasonal variations were observed concerning the quality of the light in addition to how varied the light in the room was perceived.

Based on previous findings, the light in the offices was expected to be experienced as stronger and more pleasant during the summer in comparison to the other seasons. This hypothesis was not confirmed by the results. The contradictions may be explained by window placements in the offices which possibly influenced the use of blinds and the balance between daylight and artificial light. Perceived contrast between the brightness of the surfaces outside and the room surfaces may also be influenced by effects of adaption as previously have been found regarding non-image-forming responses of the circadian system (Owen & Arendt, 1992; Morita et al., 2002; Higushi et al., 2007; Rufiange et al., 2007).

Regarding associations between positive affect and perception of certain characteristics of the office lighting, a number of correlations were found during some of seasons.

## 6.5. Measuring light exposure in real environments with respect to non-image-forming effects

In the present research, static- and ambulatory measurements of illuminance and irradiance were compared to investigate the relationship between methods that can be used in research and in practice of lighting design to evaluate lighting conditions with respect to non-image-forming effects of the exposing visible radiation.

Overall, the results showed weak associations between the static measurements and the light exposure continuously recorded by the means of portable instruments indicating limitations of using static measurements as an estimate of personal light exposure during daily life. However, there are several important differences between the two methods that were used, including resolution of the collected data, influence of weather conditions and subsequent manual control of shading devices and artificial lighting and natural changes of body position.

## 6.6. Limitations

The field studies in this thesis were conducted in real-life settings. This ecological research approach means that it is difficult to isolate and control external factors that may influence the parameters under investigation and thus affect the validity of the outcomes.

The ambulatory measurements of daily and seasonal light exposure and measurements of daily and seasonal concentrations of the two biological markers that were used included a relatively small sample size which has an effect the reliability of the measurements. The longitudinal-, within-subjects, design of the investigation, with a relatively high resolution of the recorded data was selected in an effort to increase the validity of the results. Also, effect sizes were determined to assess the influence of the independent measures on the various dependent variables.

A sample including men and women in a wide range of ages was selected leading to both advantages and disadvantages. In the same time as it offers an opportunity to generalize the results, it makes it more difficult to relate the outcomes to different age groups due to few individuals representing each group.

Seasonal variations in sleep- and wake-activity were investigated by the use of self-report diaries. Ambulatory measurements offering higher resolution of the sleep and activity data possibly would have increased the reliability.

The studies included measurements during regular workdays and can therefore not be inferred to diurnal light exposure during free weekend days.

Saliva sampling for measurement of endocrine markers were conducted in the subjects' natural settings which influence the lighting conditions at the times of saliva collection. Moreover, the measurements are influenced by behavioral stimuli. Consequently, the measurements display the expressed rhythm of melatonin and daily and nocturnal concentrations of melatonin and cortisol.

Regarding the instruments used for ambulatory measurements, there are some limitations concerning spectral and spatial sensitivities.

## 6.7. Implications for research

As a result of extensive laboratory research, today we have relatively much knowledge about the basic concepts. However, more field studies and data from real-life settings are necessary to further validate the applicability of the current theoretical models in natural settings.

As discussed by Lucas et al. (2014), it is important to measure light exposure with a high resolution. This permits calculation of effects on different photoreceptor systems and offer larger possibilities to compare data from different studies and perform meta-analyses. The influence of the different receptors to the resulting signal from the ipRGCs to the SCN depends on the context. Findings suggest that rods and cones contribute to phase shifts of daily rhythm of the master clock at lower intensities and at the beginning of the light exposure and the melanopsin-containing retinal ganglion cells register light radiation at higher intensities and are responsible for the sustained response (Gooley et al., 2010; 2012).

## 6.8. Implications for practise

The current knowledge about non-image-forming effects show the importance for lighting designers to take non-image-forming effects of light into consideration when choosing lighting solutions, especially in the working environments where people living at high latitudes receive much of their daily light exposure during the winter but also during parts of spring and autumn.

It is also important to develop an appropriate lighting technology to be used in the home environments. Furthermore, lighting controls have an important role to support the need of daily variation concerning light intensity and spectral composition.

Concurrently with the development of knowledge in the field codes and standards recommendations needs to include this knowledge.

# Sammanfattning

Våra ögon är viktiga, inte bara för vårt seende, utan också för att synkronisera vår inre biologiska klocka med dygnets 24 timmar. Den biologiska klockan som styr människors dygnsrytm regleras främst av det mönster av ljus och mörker som vi utsätts för under dygnet.

Tidigare trodde man att de klassiska fotoreceptorerna, tapparna och stavarna, var de enda ljuskänsliga cellerna i ögat. På 1980-talet publicerades de första forskningsresultaten som tydde på att det fanns ytterligare en typ av receptor. I början av 2000-talet genomfördes forskningsstudier som tydligt visade att det finns en tredje typ av fotoreceptor som har en viktig roll i att förmedla information om den omgivande ljusmiljön från ögat till ett område i hjärnan som styr den biologiska klockan. Dessa receptorer har en större känslighet för energi i det kortvågiga området av den del av det elektromagnetiska våglängdsområdet som definieras som ljus (380 nanometer - 780 nanometer).

Idag tillbringar människor alltmer tid inomhus och vistas mindre ute i dagsljus. Det innebär att vi exponeras för det naturliga dagsljusets dygnsrytm i lägre utsträckning än tidigare. Det artificiella ljuset på dagens arbetsplatser, i våra hemmiljöer och i andra inomhusmiljöer som vi vanligtvis vistas i under dagen skiljer sig på många sätt från det naturliga dagsljuset utomhus. Belysningsstyrkan är lägre och ljusstrålningen har ett annat spektrum, d.v.s. en annan fördelning av energi vid olika våglängder. Dessutom varierar dagsljuset kraftigt över dagen medan det artificiella ljuset normalt är mer statiskt. Detta leder till viktiga frågor om vilken typ av artificiellt ljus som människor bör vistas i för att få en väl fungerande dygnsrytm och ett välbefinnande.

En snabb och omfattande teknikutveckling har gjort att vi idag har tillgång till energieffektiva ljuskällor och avancerad teknik för styrning av artificiell belysning och dagsljus i våra byggnader. Detta har gjort det möjligt att i hög grad anpassa belysningen. Med hjälp av kunskap om hur olika aspekter av den dagliga ljusexponeringen påverkar människor kan vi utforma belysningen utifrån människors fysiologiska och psykologiska behov.

Syftet med den här avhandlingen har varit att identifiera faktorer i den dagliga ljusexponeringen som har en avgörande påverkan på människors hälsa och psykologiska välbefinnande. Frågorna i avhandlingen handlade om vilka ljusförhållanden kontorsarbetande människor normalt vistas i under dagen och över året. Vidare undersöktes om det finns en årstidsvariation i den dagliga utsöndringen av två hormon som påverkas av ljus samt när det gäller psykologiskt välbefinnande och sömn. Dessutom studerades hur människor upplevde ljusmiljön på arbetsplatserna vid olika tidpunkter under året.

Dagens krav och rekommendationer på inomhusbelysning baseras huvudsakligen på förutsättningarna för att vi skall kunna se. Eftersom de s.k. icke-visuella effekterna av ljus till stor del bestäms av den tredje receptortypen, som har en annan känslighet för ljusstrålning, handlade andra frågeställningar om hur ljuset i ett rum bör utvärderas med avseende på de icke-visuella effekterna av ljusexponeringen.

Den dagliga ljusexponeringen under de olika årstiderna mättes genom att deltagarna under två-tre dagar varje månad bar två olika mätinstrument. Ett av instrumenten registrerade belysningsstyrkan och det andra instrumentet registrerade mängden strålningsenergi i olika våglängdsområden. Dessutom fick deltagarna föra dagbok över den tid de vistades utomhus. På arbetsplatserna mättes ljusets belysningsstyrka och spektrum på förmiddagen och eftermiddagen vid fem tillfällen under året. Detta innebar också att jämförelser mellan de statiska mätningarna och de kontinuerliga mätningarna med de bärbara instrumenten kunde genomföras.

Resultaten visade stora årstidsskillnader i den dagliga ljusexponeringen, både när det gäller nivåer och exponeringsmönster. Dessutom tydde resultaten på att det förekom en årstidsskillnad i ljusstrålningens energiinnehåll i olika delar av spektrum.

Frågeformulär och dagböcker användes för att ta reda på om det fanns några skillnader under året beträffande välbefinnande och sömn. Resultaten visade ett högre positivt känsloläge under sommaren, speciellt på kvällen. Vidare observerades längre sömn under vintern i jämförelse med sommar, höst och vår.

Vid fem tillfällen under året bedömde deltagarna, med hjälp av ett frågeformulär, hur ljuset i kontorsrummen upplevdes. Resultaten visade att upplevelsen av ljusets skiljde sig under året. Dessutom observerades samband mellan känsloläget och upplevelsen av ljuset.

Jämförelsen mellan de två metoderna att utvärdera ljusförhållandena i kontorsrummen, med hjälp av bärbara instrument och genom statiska mätningar, visade på skillnader mellan metoderna.

Resultaten styrker att det är viktigt att ta hänsyn till de icke-visuella effekterna av ljus vid utformningen av belysningsanläggningar. Detta är speciellt viktigt på platser långt ifrån ekvatorn där det är stora årstidsskillnader i dagsljustillgång. Under stora delar av året sker här en betydande del av den dagliga ljusexponeringen på arbetsplatsen. Baserat på laboratoriestudier har vi idag en god förståelse för de aspekter av den dagliga ljusexponeringen som påverkar icke-visuella effekter av ljus. Det här arbetet har bidragit till att visa hur människor som arbetar i kontorsmiljöer vanligtvis exponeras för ljus i vardagen. Studierna visar också att det finns ett behov att utveckla metoder för att utvärdera ljusförhållandena i verkliga ljusmiljöer med avseende på icke-visuella effekter och att inkludera denna kunskap i krav och rekommendationer för belysning.

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# Appendix

Papers I-IV.

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