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LIGHTING FOR HEALTH AND WELL-BEING IN EDUCATION, WORK PLACES, NURSING HOMES, DOMESTIC APPLICATIONS, AND SMART CITIES

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SUMMARY

Summary situation analysis on lighting for health and well-being

Light affects our well-being and health much more than most people realize. Light sets our body clock, thus regulating our sleep-wake cycle, immune responses, appetite and many more of our functions and behaviors. Next to this, light has acute effects on mood, alertness and attention that do not run via the body clock and its 24 hour (circadian) rhythmicity. All these so called non-image forming effects of light are largely overlooked in the current lighting practice, which is dominated by visual aspects. Although our current understanding of the non-visual effects of light is far from complete, continuing to neglect these non-visual effects of light in lighting-standards, -recommendations, -designs, and –installations is potentially more harmful then including them.

The non-visual effects of light depend critically on the intensity, the duration and the spectral composition of the light. Also the prior light exposure and the timing of the exposure determine the kind and size of the non-visual effects that can be achieved. Not only the absolute light level, but also the relative light level in comparison to prior light exposure and/or the concurrent ambient light determine the extent of non-visual effects. A person coming from dimmer light may be expected to show stronger responses to subsequent light exposure than a person that had a brighter preceding light exposure.

Interior lighting designs have to provide optimal illumination to support image as well as non-image forming functions. In order to fulfill this, light conditions will have to be changed across the day using dynamic approaches to control and adapt the spectral content, intensity, duration and timing of the light during day and nighttime. Outdoor lighting can encourage physical outdoor activity, social life and recreation and can be used as an instrument to promote well-being, safety and a pleasant atmosphere in cities.

At present, the most relevant non-visual effects of light across the different time points of our daily life include:

1. During the early morning hours, dawn-simulating light helps to wake-up with less somnolence and has beneficial effects on sleep inertia, and may potentially support individuals' well-being and cognitive performance during the day.
2. During daytime, light exposure of sufficient intensity and blue content can improve alertness, activity, performance, and mood.
3. Daytime light patterns can affect sleep during the subsequent night. Sufficient daytime light exposure is supportive for nocturnal sleep; the same applies for sufficient nocturnal darkness.
4. Healthcare patients and elderly need higher quantity and quality of light, as their body has to cope with immobility, injuries, pathologies and age-related degeneration. The right light can act as an antidepressant for inpatients in hospital wards, and for the elderly it can enhance adaptation of the circadian rhythm of the body clock to the natural day-night cycle.
5. During daytime, but also at night, exposure to more intense and blue-rich light can boost people's feelings of alertness and vitality.

6. Bright and blue rich light exposure in the last two hours prior to bedtime is disruptive for sleep and delays falling asleep. Low intensity light and warmer blue-deprived tints of light (like red & orange) are less disruptive for sleep (onset).
7. Bright and blue-rich light in the evening can phase delay circadian rhythm, leading to delayed activity patterns on the next day. In opposite such light in the very late night and early morning is able to advance the circadian clock, with the consequence of earlier tiredness in the following evening and earlier wake up time on the next day. These phase-shifting effects can be restricted by reducing blue spectral content in the light at relevant times.
8. During the night, exposure to light can reduce the natural secretion of the sleep-associated hormone melatonin and increase the time needed to (re) enter sleep. Longer wavelengths (like red vs blue) and lower brightness help to reduce the impact of nocturnal light on sleep.
9. Exposure to bright and blue-rich light during daytime is probably reducing the sensitivity of the human biological system towards disruptions by nocturnal light. Moreover, a sufficient contrast in light levels between day and nighttime helps to stabilize the circadian rhythm system.

Lighting is considered an attractive opportunity for global energy conservation. This opportunity is largely driven by the global transition towards energy efficient solid state lighting (SSL) solutions. However, the financial savings associated with an efficiently designed and operated lighting system remain small as compared to the huge financial benefits that can result from a seemingly modest improvement in the well-being, performance or health of people working or living under these lighting systems. There is sufficient evidence in the scientific literature that non-visual effects of light are able to achieve such improvements. The current SSL technology enables for unprecedented temporal, spatial and spectral control of light in our indoor environment, and provides a great opportunity to powerfully realize non-visual benefits and simultaneously enhance visual comfort by means of highly innovative solutions.

The capitalization of light's powerful influence on human well-being, performance and health within novel **Human Centric Lighting** solutions will accelerate the deployment of high quality Solid State Lighting systems. The following steps are recommended to achieve this goal:

1) Make use of daylight as much as possible, and design indoor environments accordingly;
2) Use electrical lighting to resemble daylight properties, especially intensity and blue content, as much as possible, especially on places where daylight is insufficiently available;
3) Target light strategies towards those times during which humans are most sensitive to light – this is during the first 1-2 hours either prior to bedtime in the evening, or after waking up in the morning;
4) Use intelligent and programmable dynamic interior lighting installations that allow to tune light setting in intensity, distribution and spectral composition over time, thus enabling for the right trade-off between visual and non-visual effects of light and energy efficiency. Moreover, SSL lighting systems enable an advanced personalization of light settings, so that lighting conditions can be optimized on an individual level to accommodate for personal factors like age, prior light exposure, sleep-wake patterns, activities at hand, and personal preferences of the user.

INTRODUCTION

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1 | INTRODUCTION

This report constitutes the deliverables D3.2 and D3.4 of the SSL-erate FP7 project, "Situation analysis report on lighting for health and well-being" in education, workplaces, healthcare/nursing homes, domestic applications respectively lighting for smart cities.

Light contributes enormously to human functioning and the regulation of our alertness and sleepiness. Via its influence on our body clock but also via acute responses, light has a strong impact on our well-being, performance and health. The photoreceptor and neuronal underpinnings of light's repercussions on the body clock and the brain's sleep and wake-promoting regions is far more complex than initially thought. However, scientific insight in this area is rapidly progressing. Together with the recent advances in solid-state LED technology, this will help to design and implement potentially successful novel light devices and indoor and outdoor light strategies that consider both image-forming and non-image forming effects.

A review of published scientific insights has been executed in order to gather validated knowledge on the non-image forming effects of light on human well-being, performance and health in different application domains: education, workplaces, healthcare/nursing homes, domestic applications, and Smart Cities. The most important scientific insights have been listed and recommendations are made to foster implementation in novel Human Centric Lighting solutions. Suggestions for application, utilisation and implementation of this knowledge are given.

The report highlights the most important general insights and application opportunities around the non-visual, biological effects of light, and provides the information that is needed for further uptake by different stakeholders like producers, installers, designers, architects, and others. Moreover, the report also contains information that can be used to disseminate the topic to the general public and policy makers. To achieve this goal, three different levels of information are discriminated in the report. Level 1 targets the general public, level 2 aims at the various stakeholders and level 3 provides in depth stakeholder information along with the most relevant references/sources in scientific literature. Various applications domains are considered: (i) education (ii) workplaces, (iii) healthcare/ nursing homes, (iv) domestic applications and (v) smart cities, each in an own section of the report.

LIGHTING FOR HEALTH AND WELL-BEING IN EDUCATION

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2 | LIGHTING FOR HEALTH AND WELL-BEING IN EDUCATION

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Level 1 information: Summary of literature retrievals

The right light in the morning, that means sufficient brightness and with higher components of blue, can help to get you ready for the day. Especially in education, a conscious mind is important for a good concentration during the lessons. It doesn't matter if the person is an elementary scholar or a student. Both can benefit from an optimized lighting environment in a direct or indirect way.

Effects of light in educational environments:
- During the early morning hours, the right light can help to wake up with less somnolence.
- A better light environment can improve alertness and concentration during lessons.
- Higher light intensities and color temperature can help to improve duration of sleep and quality of sleep and thus improve learning effects.
- Lighting systems that enhance daytime light exposure can help to improve duration of sleep and quality of sleep and thus improve learning effects.

With biologically optimized lighting systems in educational environments, natural lighting conditions can be achieved more effectively. Simply said it is possible to imitate natural lighting inside the classroom.

Level 2 information: Stakeholder/value-chain information

Stress isn't something that is limited to adults anymore. The requirement and performance pressure on pupils and students is increasing. Pupils and students aren't really awake in the morning, considering the early starting time of school and often bad lighting conditions. However, the right light in the morning is important to activate the human body and mind.

The current situation in most educational environments is that the lighting levels and the quality of light are not sufficient to allow a good learning situation. Intensity levels and light quality have a substantial impact on academic performance. Thus, it is important to know the biological impact of light at certain times with certain spectral distributions.

BENEFITS OF OPTIMIZED LIGHTING SOLUTIONS

First order effects of light in educational environments

An optimized light environment for example in classrooms can have a direct influence on academic performance:

- Studies have shown that a higher color temperature can increase visual acuity.
- In studies, higher light levels and higher color temperatures have been shown to improve concentration levels and errors during various tests.
- Optimized light levels and color temperature can cause a higher oral reading fluency, reading speed, and reading comprehension.
- Bright light in the morning helps to reduce sleepiness and aggressive behavior while it can influence mood in a positive way.
- Exposing adolescents to higher illumination levels and color temperatures during lessons has shown to reduce agitation.

Second order effects of light in educational environments

The effect of the right light at the right time can last even after school. It is well investigated that important learning related processes occur during the sleep period of humans. Disturbed sleep or insufficient sleep can cause a reduction in learning efficiency and compromise academic performance.

- Different studies have linked the length and quality of sleep with academic performance. While a sufficient amount of sleep and good sleeping quality resulted in good grades, an insufficient sleep duration and interrupted sleep caused pupils and students to perform worse.
- Higher sleep quality and sleep duration have a positive effect on memory.
- Improved sleep helps to reduce daytime sleepiness and to achieve a higher concentration and attention level during lectures.
- It is reported that bad sleep quality can result in mood disorders.

Another pathway how optimized lighting solutions can help to improve academic performance depends on the morning or evening preference of children and adolescents. Morning types have fewer difficulties to get ready for the early school start, the late types need longer to start the day. Such late types (so called late chronotypes) experience more difficulties with the early lectures at the start of the day as compared to early types. As the effect of light on the body clock and its circadian (24hr) rhythm has become more and more known, specialized lighting can help children and adolescents with late chronotypes to realize an easier and more comfortable start in the morning.

- Late types will probably benefit from reducing their light exposure, and its blue content, in the evening while enhancing their light exposure, and its blue content, during the first hours of the morning. An optimized lighting solution can support late types in the early awakening on workdays. It also prevents their bedtimes from drifting too late, thus increasing the duration of the sleep opportunity before the alarm clock goes off.

Third order effects of light in educational environments

Above all the mentioned positive effects on children and adolescents there is a further indirect positive effect pupils and students can benefit from. An increased attention and reduced agitation in an educational environment causes a reduced disturbance of the ongoing lecture. Children can concentrate better on the lesson and are less distracted by other children. Teachers, on the other hand, can conduct their lessons in a more sound and concentrated atmosphere.

Just a few scientific studies investigated on the influence of disturbances through pupil on the academic performance of their classmates. Their findings indicate an increase of academic performance if the source of disruption is eliminated. Therefore, it has to be assumed that if with light, the agitation level can be lowered and attention level can be increased academic performance can profit by these measures.

Individuality of educational environment

One difficulty for installing an advanced lighting system is the individuality of the educational environment. Therefore, it is difficult to establish a "one fits all" lighting solution, and the possible benefits of more elaborated lighting systems can differ from school to school and from one classroom to another one. Nevertheless, it is possible to give general recommendations for the lighting solutions that apply to all. The individual requirements should be then discussed with local partners.

General recommendations:

- Enhanced light levels and a higher blue portion in the spectral distribution during the morning hours
- Presets for different activities for example concentrated working (higher light intensity, more bluish) or relaxed working / supporting relaxation (lower light intensity, warmer light tones).
- Possibility for personalization or adaptation to the situation in a limited framework.
- Automated adaptation to outside lighting to either ensure sufficient amount of light inside the classroom or reduce inside lighting to save energy

With the application of the current scientific knowledge on light and its effects on the brain, body clock and mood an ergonomic lighting environment can be a useful instrument to achieve a good academic performance.

A very important implementation in educational lighting systems would be a dynamic regulation of the light characteristic during the day. This would be a regulation of intensity and color temperature to support teachers', students', and pupils' activities regarding the requested requirements. Since schools and higher educational buildings have access to a limited budget for the building and the buildings itself are sometimes very unique a "plug & play" solution for dynamic SSL-lighting might be an opportunity to save production costs for the manufacturer as also implementation costs for the buyer in this case schools, universities, and other educational institutions.

Level 3 information: Literature overview

Abstract

Electrical light can have beneficial effects on health and wellbeing in classrooms. Also for academic elements like mental performance, activity, alertness, and cognitive functions, (artificial) light can have positive effects. This is especially feasible in classrooms where there is little natural light due to architectural restrictions, or during days with low levels of natural light. Especially lighting in morning hours with higher illumination levels and higher color temperature can have positive effects on academic performance, social behavior, and on physical and mental health. It can also help to maintain a stable circadian rhythm and thus, an improved sleep behavior. Sleep is an important factor for many learning processes and with enough uninterrupted sleep, attention and concentration levels during school hours are increased. Therefore, lighting systems that can support the educational environment with dynamic lighting have beneficial short and long-term effects on academic performance.

2.1 EFFECT ORDER OF LIGHT IN EDUCATIONAL ENVIRONMENTS

2.1.1 First order effects

The effects of light used in educational environment can be classified in different orders. First order effects would be of the type like the following effects in paragraph *First order example,* which are for example an increased attention level or a higher oral reading fluency. By switching on the light and exposing humans to an optimized light environment, immediate effects are measureable and refer to a single individual. These effects might also occur after longer exposure periods.

2.1.2 Second order effects

Second order effects are not directly measurable while receiving a certain light dose, but have an influence on longer-term parameters. Academic performance for example is one of the factors that is influenced indirectly through advanced lighting systems, as well as sleep quantity and sleep quality. With the right light at the right time, the circadian hormone system is stabilized and this helps to improve sleep duration and sleep quality. Second order effects will be addressed mainly in paragraph *Second order example.* Second order effects will have its best effect after a longer exposure period, in the sense of proper, non-disrupted light and dark cycles.

2.1.3 Third order effects

The benefits of first (and second) order effects cannot only be applied to an individual but also to its environment in a certain extent. This can be defined as a third order effect. For example, there is one child in a classroom disturbing a lesson. If, with the help of an advanced lighting system, this child can easier calm down and raise its attention level, not only this child has an effect, but the whole class and teacher benefits, because they can concentrate better on the lesson. More examples on third order effects will be addressed in paragraph *Third order example.*

It cannot be excluded that in some cases the different examples might also apply to different orders.

2.2 FIRST ORDER EXAMPLE – IN EDUCATIONAL ENVIRONMENTS OPTIMIZED LIGHTING CAN HAVE POSITIVE EFFECTS ON PERFORMANCE, SOCIAL BEHAVIOR, AND ALSO ON PHYSICAL HEALTH AND WELLBEING

While several investigations have shown that with higher illuminance levels and higher color temperatures, academic performance (for example the level of concentration) increased compared to standard lighting[1, 2, 13, 26, 30, 33, 35, 38], few studies also report that with a reduction of light levels and lower color temperature a decrease in agitation and disturbance during lessons can be achieved[14, 37, 38]. It also seems that light can affect the social behavior of children in a positive way[12, 13, 37, 38] and light might have an effect on physical health (some studies indicated that light might have an influence on parameters like blood pressure or body growth[21] and is able to shift the circadian rhythm[11]).

2.2.1 The effects of optimized light environments on concentration

In a summary of three Dutch studies[33], the findings about the effect of light demonstrate beneficial effects of optimized light settings in educational environment. All three studies used the same light system for their experimental groups, which consisted of 1000lx illuminance level and 6500K (cold white) color temperature. For the study controls there had been (1) 600lx and 4000K, (2) 380lx and 3000K, and (3) 300lx and 3000K to 4000K. In total 197 (98, 44, and 55) pupil participated in these studies. While the second and third study report better performance in concentration or at least a positive trend for concentration and fewer errors compared to their controls, findings of the first study report a better performance in concentration test of the control group. Nevertheless, the first study also reports an increased performance growth in the experimental group compared to the control group.

2.2.2 Lighting with higher illumination levels and higher color temperature shows positive effects on the level of concentration and/or oral reading fluency (ORF)

In a study[26] with 84 pupils (grade 3, age 7 to 8) separated to four classrooms, the oral reading fluency was measured for two kinds of light conditions. Standard lighting which consisted of 500lx illuminance level and 3500K (warm white) color temperature compared to an lighting optimized for focus tasks which consisted of 1000lx illuminance level and 6500K (cold white) color temperature. The influence of daylight was reduced due to small or blocked windows and drawn blinds. The score for ORF was assessed at the beginning (September), the middle (January) and the completion (May) of the study. The intervention in the experimental groups took place during all focus tasks where the pupil had to read something. Children in the experimental group, the optimized lighting, started with a lower score (assessed before the intervention) and ended with a significant higher score (assessed after the intervention) in ORF compared to the children within the control group. The assessment itself took place under standard lighting for all children. Furthermore, the motivation was evaluated. Even though, there have been no significant findings for motivation, there is a positive upwards trend for motivation under the optimized lighting, while the trend for motivation under standard lighting declined during the school year.

2.2.3 Insufficient blue light in the morning can delay the circadian clock and a delayed clock can lead to health and performance problems

Beside the effects on performance, the lack of light with short wavelength causes a delay in the circadian system.

A field study[11] has investigated the effect of light with different blue-content on circadian rhythmicity. Eleven adolescent teenagers (grade 8, age 13 to 14) have been examined regarding their change in dim light melatonin onset (DLMO) during a five-day school week. For this purpose, students had to wear orange glasses during this period of time in school to filter all blue spectral components from the environmental light. DLMO was examined before and after the intervention. To determine DLMO, a number of saliva samples were taken in the evening between 07:30 pm and 11:00 pm every 30 minutes. A significant delay in DLMO of about 30 minutes occurred in the participants after wearing the orange glasses that indicates that a lack of short-wavelength light may lead to a change in circadian rhythmicity. These findings correlate with other findings from laboratory settings[36]. A delayed circadian clock (eveningness) can lead to disadvantages in exams and poorer academic performance. A study with 132 university students graded from 20 to 22 years, showed a highly significant positive correlation between early chronotype and better grades36. Even further, recent studies showed that eveningness could be a risk factor for mental health (higher possibility of depression) and physical health or health-impairing behaviors[22, 29].

2.3 SECOND ORDER EXAMPLE – HOW LONGER EXPOSURE TIMES OF SUPPORTIVE LIGHTING-SYSTEMS CAN INCREASE ACADEMIC PERFORMANCE

2.3.1 Long-term effects of light on concentration and inaccuracy

Beside the short-term effects of light on different academic tasks, also a long-term effect is measureable that shows how blue enriched light during the morning hours in school improve different academic requirements. In a study[19] with 58 High school students, the difference of standard lighting (control) versus blue enriched lightings (test group) was measured for short and long-term effects. Vertical illuminance levels where measured for the control with 300 lx and 3000 K / 3500 K color temperature and for the test group with 300 lx and 5500 K color temperature. The study design consisted of a pre/post measurement with an intervention phase in-between the measurements with standard or blue enriched lighting. Speed of cognitive processing, concentration performance, and inaccuracy has been measured. Pre test took place for all groups under standard lighting. Post test was under standard or acute blue enriched lighting respectively for the intervention phase with standard or blue enriched lighting period. Outcome of this study was, that long-term and acute blue enriched lighting showed significant differences for speed of cognitive performance compared to standard and acute blue enriched lighting. In respect to concentration performance acute blue enriched lighting after long-term standard lighting as also long-term blue enriched lighting and standard and acute blue enriched lighting showed significant differences compared to standard lighting. For inaccuracy, long-term blue enriched lightings showed significant differences compared to standard lighting. Memory effects have not been measured, but it has to be assumed that due to higher concentration levels there might be a positive effect on memory. Nevertheless, this study has shown that there are already beneficial long-term effects due to improved lighting solutions.

2.3.2 A good sleep for good grades – Advanced lighting technology can help to improve sleep quality and quantity

Learning is a process that is also done during sleep at night. Good sleep is therefore essential for a good academic performance. Scientific investigations have linked academic performance with sleep quality and quantity. Students and pupil having not enough sleep often fail in exams or receive bad marks compared to the ones obtaining a higher amount of sleep[4-6, 15, 17, 18, 20, 24, 34, 40]. Furthermore, less sleep can lead to daytime sleepiness and a lack of attention which might also have an adversely effect on academic performance[8, 10, 16, 27, 28, 32, 39]. Beside the direct impact on academic performance, less sleep and poor sleep quality can induce depressive mood and emotional instability[25, 31].

Another difficulty for adolescents is the early start in school. As children age they undergo a change in their chronotype from early type in Kindergarten age to late type in their teens. So they tend to go to bed later with constant early school starting time. This is one reason for reduced amount of sleep[3, 7, 9].

Thus, as second order effects of light, the right amount of light during the day can improve sleep quality and sleep duration and can help to reduce sleepiness during the day. A biologic effective lighting system can help adolescents with late chronotypes, to get a better start into the day.

2.4 THIRD ORDER EXAMPLE – HOW CLASSROOM DISRUPTIONS AFFECT ACADEMIC PERFORMANCE

The third order effects of light on children, adolescents and students are trivial but therefore also very important. Even if there is not much scientific confirmation, there is a common agreement, that disturbance during phases of concentration have negative effects on learning. It's either the disturbance of agitated children to the teacher or other children. Either one or the other can interrupt the lesson and reduce children's concentration or teaching time.

2.4.1 Increased concentration with a quiet classmate – even with a fellow pupil with Hyperactivity Syndrome

Challenging to teachers and fellow pupils are children with Attentional Deficit (and Hyperactivity) Disorder (ADD/ADHD). A recently published case study[23] described an 11-year-old boy, which received drug therapy from 2003 to 2005 for ADHD. He showed some improvement, but still suffered from increased sleep problems and daytime sleepiness. Since 2005 medication was taken off and he was administered to bright light therapy (BLT) with a full-spectrum lamp and 10.000 lx illuminance level. He had to take half an hour of BLT in the morning for one week. Before and after the intervention with BLT, the boy was tested by two types of clinical assessments that both enhanced positively after the intervention. His sleep onset also advanced by two hours. It has to be highlighted that this is just a single case study and more valid data have to be gathered, but bright light in the morning not only improves sleep performance in humans, but also can help to prevent ADHD Symptoms in adolescents. This might be a chance to cope with pupils with ADD/ADHD and should not be underestimated.

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LIGHTING FOR HEALTH
AND WELL-BEING IN WORKPLACES

3

3 | LIGHTING FOR HEALTH AND WELL-BEING IN WORKPLACES

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Level 1 information: Summary of literature retrievals

Workplace lighting can, in addition to providing sufficient light to conduct work-related visual tasks, affect employees' alertness, mood, cognition, sleep-wake pattern and health. The timing, duration and spectral composition The timing, duration and spectral composition of the light exposure all play important roles in these non-image forming effects. Moreover, research has shown that these effects may depend on the environmental context, type of activity, person characteristics and employees' momentary level of fatigue.

Important insights:

- Exposure to more intense light may boost employees' feelings of alertness and vitality during daytime and at night
- Light intensity and spectrum may influence individuals' ability to sustain attention and cognitive performance during daytime and at night
- Employees' experienced light patterns during the daytime may affect their sleep during the subsequent night
- The light settings can influence employees' appraisals of the lighting and working environment, while individuals' preferred light settings show also substantial variations
- Exposure to light during night shifts can reduce melatonin secretion and affect the timing of sleep

Level 2 information: Stakeholder/value-chain information

Light enables vision, but plays also an important role in human everyday functioning via non-image forming processes. Numerous studies have shown that light is an important time cue for the biological clock and may phase-shift the sleep-wake cycle. In addition, a large body of research has shown that light can also induce instantaneous changes in alertness, mood, cognition and behavior.

Where do current solutions fall short? What consequences can this have?

To date, lighting conditions in workplaces are often designed to optimally support visual performance and minimize visual discomfort. The non-image forming effects of light are generally not considered nor implemented in current workplace lighting solutions. Optimal lighting solutions may, therefore require different light settings. This can have the consequence that current lighting systems render lighting conditions that are suboptimal to support non-image forming functions, e.g.., they do not optimally accommodate employees' ability to concentrate and engage in cognitive and mentally demanding tasks during the workday.

What needs to be addressed? How can Human Centric Lighting help?

The non-image forming aspects of light need to be addressed. The intensity, spectrum, timing, duration, and pattern of the lighting are relevant factors for lighting designs and their effects on human functioning. There is a need for flexible and person-tailored lighting solutions to provide the right amount of light at the right time for the user.

Current Solid State Lighting and control systems can provide any spectral composition of the light in a wide range of intensities at any moment of the day. This offers adequate possibilities for flexible and dynamic human-centered lighting, which can be optimally tuned to support users' image-forming and non-image forming functioning.

What boundary conditions need to be considered?

Most studies have been performed under very well-controlled conditions in the laboratory, providing important insights about the significant influence of specific light characteristics on human functioning. This knowledge needs to be extended to real-life working situations. This is particularly relevant as the effects of light have been shown to depend on the context, type of activity and person's light history.

Important tradeoffs?

Potential trade-offs between image-forming and non-image forming effects should be considered. For instance, exposure to bright light can induce feelings of increased alertness and vitality among employees, but at the same time the light settings may be experienced as less pleasant and potentially cause glare if not properly designed. In addition, there may be trade-offs between acute activating effects of light and circadian effects of light. Research has, for instance, shown that non-image forming effects of light not only occur during the actual light exposure, but may also influence employees' alertness, behavior and sleep at a later time.

What are the best application opportunities to start with in this segment?

Research has shown that it is important to also consider the non-image forming effects of light when designing workplace lighting. Moreover, current insights support the use of human centric lighting applications which provide light settings adapted to the user and the context. We recommend the installation of dynamic SSL equipment for flexible adjustment of spectral composition and intensity throughout the workday. Software needs to be installed to promote alertness at times when this is needed, for example at the beginning of the shift or during the so-called post lunch dip. As soon as new insights are available, they should be implemented in the software. In the course of time, this probably will include differences between subjects, and variation with time of year, type of task, etcetera.

Level 3 information: Literature overview

In the next sections, we will discuss potential effects of various light characteristics (intensity, spectrum, timing, duration and pattern of light exposure) on employees' experiences, behavior, cognition and health. In this overview, we will focus on the effects of lighting on human functioning during working hours, but also briefly mention the potential effect of light exposure before and after the workday on employees' alertness, behavior and sleep. Moreover, we will discuss potential inter- and intra-individual differences in employees' sensitivity to light.

3.1 INTENSITY

Good visibility is often a prerequisite to engage in many work-related tasks. In addition to providing sufficient light to conduct work-related visual tasks, the light intensity can also affect employees' appraisals of the lighting and atmosphere perception of the workplace. Research has shown that the atmosphere of a space with a higher intensity level may be perceived as more lively, less tense, more formal (Vogels & Bronkers, 2009) and more pleasant (David & Ginther, 1990). Yet, results by Smolders and colleagues (2012; 2014) suggested that persons may evaluate commonly experienced intensity levels in indoor workplaces as more pleasant as compared to bright light settings (provided by artificial lighting only) after one hour of exposure during daytime. In addition to measuring individuals' appraisals of the lighting, multiple studies have investigated individuals' preferences for artificial light settings during daytime. These preference studies have revealed substantial inter- and intra-personal differences in preferred illuminance levels (e.g., Begemann, van den Beld & Tenner, 1997; Boyce, Eklund & Simpson, 2000; Butler & Biner, 1987; Logadóttir & Christoffersen, 2008; Newsham, Aries, Mancini & Faye, 2008; Smolders, 2013), suggesting that whether a certain intensity level is experienced as pleasant or attractive may vary as a function of person characteristics, time and/or context.

Insights in the non-image forming effects of light have shown that the effect of light on a persons' affective, cognitive and physiological functioning is dependent on the intensity level. Multiple studies have demonstrated acute activating effects of exposure to brighter light at night on subjective and objective indicators of alertness and arousal. For instance, results showed that exposure to more intense light during the biological night can counteract subjective feelings of sleepiness, result in faster responses on attention tasks, suppress melatonin secretion, increase heart rate and core body temperature, and modulate brain activity (e.g., Badia, Myers, Boecker, & Culpepper, 1991; Boyce, Beckstead, Eklund, Strobel & Rea, 1997; Cajochen, Zeitzer, Czeisler & Dijk, 2000; Campbell & Dawson, 1990; Daurat et al., 1993; Figueiro, Bullough, Bierman, Fay & Rea, 2007; Lewy, Wehr, Goodwin, Newsome & Markey, 1980; McIntyre, Norman, Burrows & Armstrong, 1989; Myers & Badia, 1993; Rüger, Gordijn, Beersma, De Vries & Daan, 2006; Yokio, Aoki, Shiomuar, Iwanaga, & Katsuura, 2003; Zeitzer et al., 2000).

Exposure to light at night may, in addition to its acute effects on melatonin secretion, also shift the timing of melatonin onset after the light exposure, which can be accompanied by changes in the timing of sleep and wakefulness during the next day. Research has shown that the intensity of the light exposure at night affects the magnitude of the phase-shift in individuals' circadian rhythm induced by the lighting (e.g., Zeitzer et al., 2000). Zeitzer and colleagues (2000) showed a larger phase delay in the melatonin rhythm after exposure to more intense light during the subjective early night.

A major output of the biological clock system is the production of the hormone melatonin. This production in the pineal gland shows systematic variations with time of day and is under the control of the biological clock. Melatonin is secreted at night and has minimal levels during daytime, even if persons during one day are not exposed to light. A larger melatonin suppression during the light exposure often coincides with increased feelings of alertness and higher sustained attention. However, there are also indications that melatonin suppression at night can have adverse health effects in the long term (Blask, 2009; Davis, Mirick, & Stevens, 2001; Haus, & Smolensky, 2013; Schernhammer, & Hankinson, 2005; Schernhammer, & Schulmeister, 2004; Stevens, Brainard, Blask, Lockley, & Motta, 2013; Stevens, 2009; Stevens, & Davis, 1996; Straif et al., 2007). It is thus important to not only consider the effects of the intensity of workplace lighting on employees' state of alertness and performance at night, but also its potential disturbing effect on their sleep-wake cycle and long term health.

As discussed above, acute alerting effects and phase-shifts of light are larger with increasing illuminance level at night. Several studies have shown that these relationships can be best described by a logistic function (Boivin, Duffy, Kronauer, & Czeisler, 1996; Cajochen et al., 2000; Zeitzer, et al., 2000). These latter studies also suggested that, at least under very controlled conditions, relatively low illuminance levels (~150 lx at the eye) are sufficient to induce alertness and shift a free-running circadian rhythm. The acute as well as phase-shifting effects shown at night are particularly relevant for night shift workers.

Although most studies to the acute alerting effects of light intensity among healthy persons are performed at night, several studies have provided indications that light can also induce alertness during daytime. For example, a few laboratory studies have shown alertness-enhancing effects of exposure to a high illuminance level (>1000 lx at the eye) as compared to dim light (<10 lx) during daytime under high sleep pressure due to sleep loss (Phipps-Nelson, Redman, Dijk & Rajaratman, 2003) or after prior exposure to very low intensity levels (Rüger et al., 2006; Vandewalle et al., 2006). Complementary to these results in the laboratory, a field study by Partonen and Lönnqvist (2000) revealed improved feelings of vitality and reduced depressive symptoms among office workers after four weeks of exposure to bright light (2500 lx at eye level, 6500 K) for at least one hour per workday during the dark winter months in Finland. In addition, two very recent laboratory studies revealed that daytime exposure to bright light (1000 lx at the eye) can also induce alertness and vitality during regular office hours, even in the absence of the deprivation of sleep and light (Smolders et al., 2012; Smolders & de Kort, 2014) and when compared to an illuminance level which is commonly experienced in indoor work environments during daytime (i.e., 200 lx at the eye; Smolders, de Kort & van den Berg, 2013). Extending these results under controlled conditions in the laboratory to everyday situations, a recent field study confirmed a significant relationship between experienced light intensity and feelings of vitality during daytime in everyday life (Smolders et al., 2013). Their results suggested that when persons are exposed to more light, they feel more energetic immediately afterwards. Together, these studies suggest that exposure to a higher intensity level can also benefit employees working during daytime. It should be noted, however, that daytime effects of illuminance level were most consistent for the subjective measures of alertness and vitality as compared to objective indicators for performance and physiological arousal. This suggests that among office employees bright light exposure during daytime may particularly support mental wellbeing.

In addition to the acute effects of exposure to more intense light on human daytime functioning, a few studies have provided indications that the light intensity experienced during daytime office hours may also affect employees' alertness, performance and sleep later in the evening or at night. Hubalek et al. (2010), for example, showed that office employees reported a better sleep quality when they had experienced more light during the day. Figueiro and colleagues (2013) revealed some improvements in performance in the early morning after extended wakefulness when participants were exposed to daylight as compared to darkness between 7 am and 5 pm. In addition, results by Münch and colleagues (2012) suggest that bright light exposure (~1000 lx at the eye; daylight, sometimes combined with artificial lighting) in the afternoon may affect alertness and performance in the early and late evening.

3.2 SPECTRUM

The spectrum of the lighting may also play an important role in employees' appraisals of the lighting and the environment. The spectral composition of the light can influence the appearance of colors of objects in the environment, and may influence performance on visual tasks requiring color detection and discrimination. Moreover, the spectrum of a light source has an influence on the appearance of the lighting and the perceived ambience of the environment. Research has shown that lighting with a low correlated color temperature (CCT) is often experienced as warmer, more relaxing and less tense (Boyce & Cuttle, 1990; Davis & Ginther, 1990; Fleischer, Krueger & Schierz, 2001; Manav, 2007; Viénot, Durand & Mahler, 2009; Vogels & Bronckers, 2009). In addition, exposure to blue-enriched light as compared to a lower CCT with the same illuminance level may also be experienced as more bright (Chellappa et al., 2011; Iskra-Golec & Smith, 2011; Iskra-Golec et al., 2012; Wei et al., 2014). However, some studies showed no significant differences in individuals' lighting appraisals between white light conditions varying in CCT (Boray et al., 1989; Davis & Ginther, 1990; Knez, 1995; Knez & Kers, 2000) nor between narrowband light conditions differing in wavelength (Chellappa et al., 2014). Moreover, results by Logadóttir and Christoffersen (2008) revealed substantial inter-individual differences in preferred CCT levels.

Research has shown that exposure to light in the blue part of the spectrum resulted in lower melatonin secretion at night (Brainard et al., 2001; Thapan et al., 2001). Moreover, several studies have shown that exposure to blue light may not only suppress melatonin secretion, but could also result in a higher subjective alertness, core body temperature and heart rate as compared to exposure to green light in the late evening (Cajochen et al., 2005) and at night (Lockley et al., 2006). In line with these studies employing monochromatic or narrow-band blue light, studies investigating the effect of nocturnal exposure to blue-enriched white light on human physiology have also revealed larger melatonin suppression (Figueiro, Rea & Bullough, 2006; Kozaki, Koga, Toda, Noguchi & Yasukouchi, 2008) and higher alertness as assessed with EEG at night (Katsuura, Jin, Baba, Shimomura & Iwanaga, 2005). Similarly, several laboratory studies have shown that exposure to polychromatic white light with a high CCT at relatively low intensity levels can suppress employees' level of melatonin secretion and induce alertness in the late evening (Chellappa et al., 2011; Cajochen et al., 2011; Santhi et al., 2012; Wood, Rea, Plitnick & Figueiro, 2013). Note that the CCT of a polychromatic light source increases when it contains relatively more power in the blue part of the spectrum. In addition to these acute effects of blue light or blue-enriched white light on melatonin secretion and alertness, phase-shifting effects are also suggested to be more sensitive to light in the blue part of the spectrum (e.g., Lockley, 2008; Rüger et al., 2013; Warman, Dijk, Warman, Arendt, & Skene, 2003).

There are some indications that the effect of blue-enriched light on persons' circadian phase may saturate at high intensity levels (Smith, Revell & Eastman, 2009; Smith & Eastman, 2009). Similarly, Figueiro and colleagues (2006) showed that exposure to a higher CCT level resulted only in a significantly larger melatonin suppression at a relatively low intensity level (~100 lx). In addition to potential moderation of the acute effects of CCT by the intensity level employed, there are also some indications that the effect of blue light on melatonin secretion is not always accompanied with increased task performance and alertness. A laboratory study by Van de Werken and colleagues (2013) revealed that although nocturnal exposure to full-spectrum fluorescent lighting (at ~250 lx at the eye) resulted in significantly higher melatonin suppression and lower distal-to-proximal skin temperature gradient as compared to short-wavelength attenuated polychromatic lighting (at ~200 lx at the eye), there was a significant improvement in performance on an addition task under exposure to full-spectrum light as well as short-wavelength attenuated polychromatic light exposure as compared to dim light exposure (<5 lx). Subjective vitality was higher under the full-spectrum light, but subjective sleepiness did not significantly differ between the three conditions in this study. Results of a laboratory study employing narrow-band lighting instead of polychromatic lighting suggested alertness-enhancing effects of both red and blue light at relatively low intensity levels during nighttime, while melatonin was only significantly suppressed under blue light (Figueiro, Bierman, Plitnick & Rea, 2009).

In addition to the laboratory studies performed to investigate acute activating effects of blue or blue-enriched light in the late evening or at night, several studies have investigated these non-image forming effects during daytime. Results of a study by Revell and colleagues (2006) revealed that exposure to monochromatic blue vs. red light can increase subjective alertness in the early morning. In addition, Vandewalle and colleagues (2007a; 2007b) showed that daytime exposure to dim blue light induced stronger activity modulations in brain areas associated with arousal and cognition as compared to dim green or violet light. A laboratory study by Rahman and colleagues (2014) revealed faster responses and fewer lapses on a sustained attention task as well as a lower EEG power in theta/low alpha range under exposure to dim blue vs. green light at equal photon density for 6.5 hours in the afternoon. In contrast to their earlier results at night (Lockley et al., 2006), these improvements in alertness during daytime were not accompanied with lower feelings of sleepiness.

Extending these results of monochromatic or narrow-band blue light under well-controlled conditions to everyday situations in workplaces, a few studies investigated the effect of exposure to blue-enriched white light during the work hours on employees' alertness, mood, performance and sleep in the field. Results of two field studies among office employees revealed beneficial effects of exposure to blue-enriched white light in office environments for several weeks on subjective alertness, mood, sleep quality and self-reported performance compared to lighting with a lower (commonly used) CCT (Mills, Tomkins & Schlangen, 2007; Viola, James, Schlangen & Dijk, 2008). Iskra and colleagues (2012) also showed beneficial effects of exposure to blue-enriched white light in an office environment for three weeks on employees' subjective vitality. This effect on vitality was, however, only shown in the morning, and results revealed no significant differences in subjective sleepiness and mood after three weeks of exposure to light with a higher CCT. In addition to these effects on employees' experiences during working hours, results of a field study by Vetter and colleagues (2011) showed that exposure to a high CCT during the workday in the office may affect the timing of employees' rest-activity pattern during days off. Their results suggested that exposure to blue-enriched light in the office may entrain employees' circadian rhythm to the start of the workday instead of adapt to seasonal variations in the timing of dawn. It is yet unknown whether this is beneficial or not for employees' wellbeing, health and performance in the long term. Nevertheless, these results suggest to adapt the timing of artificial lighting not only to average daylight conditions but also to seasonal changes of natural daylight.

Laboratory studies to the acute effects of the spectral composition of the lighting during daytime have revealed mixed results. Although some laboratory studies revealed activating effects of daytime exposure to blue-enriched white light on physiological arousal (Noguchi & Sakaguchi, 1999; Sato, Sakaguchi & Morita, 2005; Shi, Katsuura, Shimomura, & Iwanaga, 2009) and on cognitive performance (Ferlazzo, Piccardi, Burattini, Barbalace & Bisegna, 2014), other laboratory studies reported no alertness-enhancing effects of exposure to a higher CCT on sleepiness, mood and performance during daytime (e.g., Boray, Gifford & Rosenblood, 1989; Gornica, 2006; Santhi et al., 2013) or revealed complex interaction effects with gender and/or age (Knez, 1995; Knez & Kers, 2000). Moreover, a very recent study by Sahin and Figueiro (2013) provided indications that exposure to dim red light, instead of dim blue light (both at 40 lx), for 48 minutes in the afternoon induced higher alertness as assessed with EEG power in the theta and alpha range compared to darkness (<.01 lx). Thus, the current literature concerning the effects of exposure to blue light or blue-enriched white light during daytime on individuals' alertness, behavior and physiology is still inconclusive.

3.3 TIMING

The development of artificial lighting has enabled us to provide sufficient light to engage in visual work-related tasks at any moment during the 24-hour day. However, as discussed in previous sections, artificial lighting not only enables vision, but may also affect employees' feelings, cognition and physiology throughout the 24-hour day. Several studies have shown that the non-image forming effects of light are influenced by time of day. For instance, research has shown that the size and direction of the phase-shifting effect of light on the human circadian rhythm are dependent on the timing of the light exposure. Phase-response curves have demonstrated that light exposure in the evening and early night (before core body temperature minimum) can result in a phase delay, while exposure to light in the early morning (after core body temperature minimum) can phase advance the circadian rhythm (e.g., Czeisler et al., 1989; Jewett et al., 2005; Khalsa, Jewett, Cajochen & Czeisler, 2003; Minors, Waterhouse & Wirz-Justice, 1991; Rüger et al., 2013).

Rüger and colleagues (2006) investigated effects of bright light exposure on persons' state of alertness and physiological arousal both during daytime and at night. While acute effects of bright light exposure on subjective alertness, fatigue and vitality were independent on time of day (daytime: noon – 4 pm vs. nighttime: midnight – 4 am), results revealed only a significant increase in heart rate and core body temperature under bright light exposure at night and not in the afternoon. In addition, a few studies provided indications that the effects of light intensity during daytime office hours also depend on the timing of the light exposure. Results by Smolders and colleagues (2012) showed that the effect of bright light exposure on sustained attention were only significant in the morning, and not in the afternoon. Moreover, recent results provided indications for a more pronounced relationship between the amount of light experienced and feelings of vitality in the morning than in the afternoon (Smolders et al., 2013). Together, these studies show that it is also important to take into account the time at which employees will be present in the workplace (e.g., day vs. night shift) when designing lighting scenarios to support well-being and performance at work.

In addition to potential time-dependent effects of light on employees' feelings of alertness, performance and physiology, a few studies have shown that preferred light settings may vary with time of day. Begemann et al. (1997) and Newsham et al. (2008) revealed time-dependent variations in office employees' preferences for light settings (combination of natural and artificial light exposure). Results showed that employees did not prefer constant light settings in terms of intensity and CCT during the workday. In these studies, artificial lighting was generally added to the daylight levels throughout the day, resulting in – on average - higher intensity and CCT levels around noon than in the early morning and late afternoon. A field study by Juslén et al. (2005) showed also variations in light preferences over time among employees working in an industrial work environment without daylight contribution. However, their results suggested that employees preferred a higher illuminance level especially in the morning, at the start of their working day. Although current insights on time-dependent variations in individuals' preferred light setting are still inconclusive, these studies provide indications that light preferences can differ over time.

3.4 DURATION

Research performed in the evening and at night has shown that phase responses to bright light are dependent on the duration of the light exposure, with larger phase-shifts with increasing exposure durations (Chang et al., 2012; Dewan, Benloucif, Reid, Wolfe, & Zee, 2011). Yet, recent insights demonstrated that short durations of bright light exposure can also induce phase-shifts in individuals' circadian rhythm, and may result in even larger shifts than longer pulses when expressed per minute of exposure (Chang et al., 2012; St Hilaire et al., 2012). Moreover, research has shown that (repeated) exposure to intermittent bright light at night or in the early morning can induce phase-shifts (delay and advance, respectively) in human circadian rhythms of a similar magnitude as consolidated exposure to bight light (Gronfier et al, 2004; Rimmer et al., 2000). In fact, results by St Hilaire et al. (2012) and Rimmer et al. (2000) revealed a non-linear relationship between the duration of exposure to bright light and the size of the phase-shift, suggesting that persons are particularly sensitive to light in the first part of the light exposure.

Several studies have provided indications that the acute effects of light are moderated by the duration of exposure. Instead of employing various durations, these studies have mainly studied the onset of such effects during the light exposure. Results revealed that the onset of lighting effects on alertness and arousal vary depending on the type of indicator (e.g. Cajochen et al., 2005; Smolders et al., 2012; Smolders & de Kort, 2014). For instance, Smolders and colleagues (2012; 2014) showed that effects of bright light on subjective alertness and vitality were not dependent on the duration of exposure, while effects on participants' response times on a sustained attention task occurred with a delay (i.e., after about 20-30 minutes of exposure). In addition, Cajochen and colleagues (2005) showed quite direct effects of blue light on melatonin secretion and subjective alertness, but more delayed effects on core body temperature and heart rate. Moreover, an overview paper by Vandewalle, Maquet and Dijk (2009) reported duration-dependent dynamics in brain activity by light, with initial activation in subcortical structures related to the regulation of alertness and emotion within several minutes and modulations in activity in various cortical areas after about 20 minutes of exposure. Like this activation process takes about 20 minutes to establish, the activation is only maintained for a time period of 20 minutes after end of light exposure. This suggests that continuous or repeated exposure is required when activation is its intention.

3.5 EXPOSURE PATTERN

A few studies have investigated the effect of dynamic light exposure patterns on individuals' affective and cognitive functioning. Results of a laboratory study by Hoffman and colleagues (2008) revealed some subtle improvements in subjective vitality and fatigue under exposure to a variable lighting regime with gradual changes in illuminance level (500-1800 lx at 6000 K) in the morning and early afternoon as compared to constant office lighting at 500 lx with a lower CCT (4000 K) during daytime office work. Results showed, however, no significant activating effects of the dynamic light exposure on performance or physiological arousal (Hoffmann, Griesmacher, Bartenbach & Schobersberger. 2010). Iskra-Golec and Smith (2008) revealed some trends for beneficial effects of intermittent exposure to bright light pulses (4000 lx) during the day on cognitive performance and feelings of vitality as compared to a constant exposure to 300 lx. However, their results also suggested that the bright light pulses were experienced as less pleasant. A field study by de Kort and Smolders (2010) revealed no activating effects of exposure to artificial lighting with gradual variations in illuminance level (500 lx - 700 lx) and CCT (3000 K - 4700 K) in the morning and early afternoon for several weeks on individuals' mental wellbeing, health and performance during the winter period. However, employees were more satisfied with the dynamic lighting scenario providing subtle changes over time as compared to the constant lighting condition (500 lx and 3000 K). Thus, insights in the potential beneficial effects of temporal modulations in the artificial light settings on employees' experiences, task performance and physiology are still inconclusive.

In addition to temporal changes in the lighting settings during working hours, several studies have investigated the effect of gradual increasing intensity levels in the early morning. Results of these studies showed that exposure to artificial dawn simulation light as compared to darkness prior to awakening may reduce sleep inertia and improve persons' wellbeing and cognitive functioning during the day. A laboratory study by Van de Werken et al. (2010) showed that exposure to artificial dawn light can reduce experienced sleepiness and increase vitality after awakening among persons experiencing difficulties to wake up in the early morning. Similar results were found in the field (Gimenez et al., 2010). In addition, results by Gabel and colleagues (2013) suggested some improvements in subjective well-being, mood and cognitive performance under dim light exposure during the waking period after prior exposure to artificial dawn simulation light (0-250 lx) vs. dim light (<8 lx) during waking up among persons with mild sleep deprivation.

Research has also provided indications that employees' experienced light patterns prior to their office hours may affect their sensitivity to lighting conditions at work. Several laboratory studies have shown that individuals' responses to light in terms of melatonin suppression (Jasser, Hanifin, Rollag & Brainard, 2006; Smith, Schoen & Czeisler, 2004) and phase-shifts in the circadian rhythm (Chang, Scheer & Czeisler, 2011) are dependent on their light history. Moreover, a very recent laboratory study by Chellappa and colleagues (2014) showed more pronounced modulations in executive brain functions during daytime exposure to green light with gradual changes in intensity over time after prior exposure to dim orange as compared to dim blue light, suggesting that the effect of light on executive functioning may depend on the spectral composition of a person's prior light exposure. In addition to these results obtained under well-controlled conditions in the laboratory, results in the field also suggested that exposure to more intense light during the day may result in less pronounced effects of light on melatonin secretion at night (Hébert, Martin, Lee & Eastman, 2002; Owen & Arendt, 1992). Hébert and colleagues (2002) showed that exposure to bright light for several hours during the waking period for one week during participants' daily routine as compared to no bright light during the day resulted in reduced melatonin suppression by relatively bright light (500 lx) for three hours at night at the end of the week. These results suggest that exposure to bright light during daytime may protect the biological system from distortion by moderate light levels in the night. Results by Owen and Arendt (1992) also showed some differences in individuals' responses to light at night in terms melatonin suppression during the summer period as compared to the dark winter months in Antarctica. In addition to these potential moderations by prior light history in the effect of light on melatonin suppression at night, results of a field study by Smolders et al. (2013) showed that persons' light exposure was only significantly related to their feelings of vitality during the darker months of the year, providing some first indications that prior light history may also play a role in the effect of light intensity on vitality during daytime.

3.6 INTRA- AND INTER-INDIVIDUAL VARIATIONS IN SENSITIVITY TO LIGHTEXPOSURE

Responses to light can vary between individuals as well as within individuals. The current literature has shown that the effects of light may depend on a person's momentary state and type of activity as well as individuals' characteristics (e.g., chronotype and level of chronic fatigue).

Type of activity. Several studies have provided indications that the effect of light on performance depends on the type of task employed (Chellappa et al., 2011; Boyce et al., 1997; Kretschmer, Schmidt, & Griefahn, 2012; Rüger et al., 2005; Smolders et al., 2012; Smolders & de Kort, 2014). For instance, studies have shown increments in performance on cognitive performance tasks but not on sustained attention tasks when exposed to bright light during daytime after hours of exposure to dim light (Rüger et al., 2005) or at night (Boyce et al., 1997; Kretschmer, Schmidt, & Griefahn, 2012). In contrast, exposure to a higher CCT in the evening enhanced speed on an auditory sustained attention and visual response inhibition task, while it did not significantly affect performance on a visual executive functioning task (Chellappa et al., 2011). In addition, Smolders and de Kort (2014) reported faster responses on a sustained attention task under bright light, but also some performance-undermining effects of exposure to more intense white light during daytime on tasks requiring inhibitory control and working memory. Together, these studies suggest that some tasks may benefit more from bright or blue-enriched light exposure than others. Yet, more research is necessary to determine the optimal light settings for different types of activities.

Mental state. Most studies investigating non-image forming effects of light on human functioning have been performed at night and/or after sleep deprivation, suggesting that light can benefit persons under conditions of relatively high fatigue and sleep pressure. Although circadian and homeostatic sleep pressure are often relatively low during the subjective day, workers may also experience increased feelings of sleepiness, a lack of energy, and decrements in motivation and task performance during daytime office hours due to mental or physical exertion. Recent research has provided some indications that persons' responses to the ambient light settings during daytime are dependent on their momentary level of fatigue, with more pronounced effects when persons suffer from mental fatigue and experience a lack of energy. A laboratory study by Smolders and de Kort (2014) revealed that the effect of bright light exposure on subjective sleepiness was only significant when persons suffered from fatigue due to mental exertion, and not when they felt more rested and had mainly engaged in relaxing activities prior to the light treatment. In addition, their findings suggested that persons' appraisals concerning the lighting may also depend on their momentary level of fatigue. Participants evaluated the bright light condition as less pleasant and less adequate when rested, but had a more positive attitude towards working in a comparable environment under 1000 lx when fatigued. In contrast, effects of daytime bright light exposure on the indicators for task performance and physiology were not moderated by participants' prior mental state. Moreover, the high illuminance condition was experienced as brighter and more activating regardless of individuals' mental state (Smolders & de Kort, 2014). In line with the results on subjective alertness in the laboratory, Smolders and colleagues (2013) showed that the relationship between light intensity and feelings of vitality in everyday situations was most pronounced when participants' felt relatively less energetic during the previous hour.

Chronic fatigue. When persons do not sufficiently recuperate from work-related fatigue and the effort spent during the workday on a regular basis (e.g., due to too high work demands, limited time to relax and sleep debt), this may eventually lead to a more chronic level of fatigue. In addition to potential intra-individual variations in light exposure patterns and sensitivity to light as a function of a person's momentary state, there are some indications that persons who experience relatively high general levels of fatigue are exposed to lower light levels during the day (Martin et al., 2012; Smolders et al., 2013) and feel less energetic throughout the day than persons with a low level of chronic fatigue (Smolders et al., 2014).

Chronotype. As discussed in section 3.3, research has shown that the effects of light intensity on subjective vitality, sustained attention and physiological arousal may depend on the timing of the light exposure. Recent research has provided evidence that individuals' light exposure patterns as well as their sensitivity to acute alerting effects of light may not only depend on local time (i.e., clock time), but also on a person's internal time (Chellappa et al., 2012; Martin et al., 2012; Smolders et al., 2014; Vandewalle et al., 2011). Field studies by Martin et al. (2012) and Smolders et al. (2014) demonstrated differences in light exposure patterns throughout the day between persons as a function of chronotype. Chronotype is based on individual's timing of sleep and wakefulness, and quantifies an individual's phase of entrainment (Roenneberg et al., 2003).

Controlled laboratory studies demonstrated inter-individual differences in responsiveness to acute effects of blue or blue-enriched light exposure on alertness as a function of individuals' clock gene polymorphisms (Chellappa et al, 2012; Vandewalle et al., 2011). A fMRI study by Vandewalle et al. (2011) showed that the effect of exposure to 1 minute of blue vs. green light on brain activity in the early morning were moderated by a person's clock gene polymorphism and level of sleep pressure. In the morning after a 7.5 hour sleep episode, modulations in brain areas associated with alertness and executive functioning due to brief exposure to blue light as compared to green light were only significant in PER$3^{4/4}$ individuals. In contrast, only PER$3^{5/5}$ individuals showed significant increments in brain activity under short exposure to blue vs. green light in the morning after sleep deprivation. Note that PER35/5 has been related to increased morning preference (Archer et al., 2003), suggesting that morning types showed more pronounced brain modulation after exposure to blue light in the morning after sleep restriction, while late types showed responses to blue light in the morning after a night of sleep. Vandewalle et al. (2011) reported no significant effects of a 1-minute light exposure to monochromatic blue vs. green light on brain functioning in the evening in either genotype. Employing a longer exposure duration, Chellappa and colleagues (2012) demonstrated stronger acute effects of exposure to relatively dim light with a high vs. low correlated color temperature (CCT) on subjective alertness, EEG power in the theta range and melatonin suppression in the late evening among PER35/5 individuals as compared to PER$3^{4/4}$ individuals, independent of differences in circadian phase and homeostatic sleep pressure. These results suggest that persons with increased morning preference are more sensitive to the acute activating effects of blue-enriched light in the evening as compared to persons with increased evening preference.

Complementing these results under controlled conditions in the early morning and late evening, a recent study by Smolders et al. (2014) showed that the relationship between light exposure and feelings of vitality during daytime (between 8 am and 8 pm) was moderated by chronotype. Their results showed that late chronotypes felt more energetic when they were exposed to more light during the previous hour during their daily routine, while light intensity was not significantly related to subjective vitality in early chronotypes.

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LIGHTING FOR HEALTH AND WELL-BEING IN HEALTHCARE AND NURSING HOMES

4 |

4 | LIGHTING FOR HEALTH AND WELL-BEING IN HEALTHCARE AND NURSING HOMES

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Level 1 information: Summary of literature retrieval

The healing properties of sunlight have been known thousands of years ago, the ancient Egyptians had sun-gardens, but with the invention of electrical light and the industrial revolution, the predominant focus became sufficient illumination for vision. Electrical light replaced daylight and allowed to in increase windowless indoor space. That the quality of artificial light sources, its intensity and spectral composition, could matter for well-being beyond visual comfort was not known until very recently, although experiments using bright white light boxes to treat depression has been tested since the 1980ies (Terman & Terman 1989neuropsychopharmacol). Research has discovered that the eye – just like the ear – is a dual sense organ that not only links light and vison but also light and non-image forming functions, notably alertness, emotions and biological timing. By doing so, light contributes to the regulating of body functions as diverse as appetite, sleep and body temperature. Current artificial light sources in hospitals and care homes do not live up to the growing responsibilities incumbent on the European public healthcare sector. However, research provides accumulated evidence that there is great potential for engineering and architecture to develop non-image forming lighting solutions for future application in healthcare.

Important insights:

- Patients and elderly people have higher demands on the quality and quantity of light as their body has to cope with immobility, injuries, pathologies and age-related degeneration of tissue.
- Day-light exposure of sufficient intensity during the day acts as an antidepressant in inpatients on a hospital wards and enhances adaptation of circadian rhythms to the natural day-night cycle in the elderly.
- Energy efficient innovative glass material exists, waiting to be used in architecture of hospitals and care home facilities to increase the areas of natural daylight to come in.
- Interior lighting designs for hospitals and long-term care facilities has to fulfil two roles: providing optimal illumination for image- and non-image forming functions – using dynamic approaches for spectral content, intensity, duration and time of day.
- Two forms of artificial light treatment regimes exist, namely white light of strong intensity (6000 lux and above for old age, 3000 lux for depressive symptom of middle-age, moreover, when selecting intensities, exposure duration also is a relevant parameter) and dawn simulation, either of them applied in the morning, is most effective in abolishing symptoms of depression.
- Enhanced fluorescent indoor light intensity in care homes has shown very limited evidence of improving neuropsychiatric behaviours such as agitation, aggression, irritability, apathy, or nigh-time sleep quality in people with various dementias.

Level 2 information: Stakeholder / value-chain information

With increasing understanding of the morphology of the eye as the receptive organ for light, highly specific photoreceptive retinal structures project not only to the visual cortex for image processing but to a number of brain regions modulating basal physiology, such as to the circadian master pacemaker ('body clock') which adjusts its activity to light and regulates internal timing of hundreds of physiological processes. Many non-image forming effects of light are dependent on the inner retinal photopigment melanopsin that is expressed in subpopulations of retinal ganglion cells. Through these pathways, light information is relayed to many regions throughout the brain, i.e. the amygdala, known to mediate stress and anxiety responses. Abundant evidence is emerging that actions of light extend far beyond that of vision, and both visual and non-visual functions need to be considered for well-being of sick and elderly people in healthcare and nursing homes.

Where do current solutions fall short? What consequences can this have?

To date, the designs of lighting systems in hospitals and nursing homes are primarily made to support visual acuity for staff and secondly to minimise hazards such as staircases. However, to obtain proper visual sharpness and better contrast people of older age require heightened light levels due to age-related failing vision. Furthermore, the hospital and nursing home environments are often purpose-made for hygiene, cleanliness and safety and ignore that light sources produce substantial glare due to shiny floors/surfaces and inappropriate light at night disrupts not only sleep but also the timing of the body clock, with negative consequences for cognition and emotions. Properties of current lighting systems are inflexible and not designed to take non-image forming effects of light into account for patients or older people's wellbeing in hospitals or nursing homes.

What needs to be addressed? How can Human Centric Lighting help?

In addition to meeting the age-related demands in heightened illumination, aspects of light's non-image forming effects on mood, cognition, alertness, sleep and internal rhythms, can and should be implemented in future designs of healthcare buildings, in particular daylight exposure and dynamic lighting systems. Ideally, building and indoor designers need to consider direction of natural light, glass structures and proportions of window surfaces to allow maximising natural light exposure. Special lighting solutions for individual rooms with different purposes (recovery or emergency rooms in a hospital, bed rooms or day-activity rooms in nursing homes), should be programmed to be remotely user-tuneable by staff, patient, resident or carer. Rather than being at a systems' inflexible mercy, being in control of the environment increases independency, confidence and a positive attitude in individuals that is beneficial for the mood and any healing process. Prototypes of such dynamic lighting systems based on current Solid State Lighting control system should implement the option of changing colour temperature and intensity dynamically. Funding is needed to test the output of such systems and to amend and improve systems technically, e.g. requirements on intelligent user-friendly programming to enter the market and applications on a large scale.

What boundary conditions need to be considered?

The healthcare sector has to fulfil special care as inhabitants are either sick or chronically ill, disabled or have age-related problems in basic daily activities with or without visual problems, frailty, movement disorders, sleep disturbances or memory and thinking problems. Light can play a very prominent role in improving the quality of life for these individuals as has been shown for daylight but not as much for artificial lighting, which is due to lack of interdisciplinary working models, i.e. a lot of effort has been put into energy efficient solutions – but the human body has fallen out of the equation. The eye's health (lens transmission, pupil size and reflex) can be measured and assessed. Accurate information is important for vision (glare, acuity) and non-image forming function (sleep-wake timing) and has to be taken into consideration for lighting solutions. The temporal 24-hour light-dark exposure becomes very important for the repair and regeneration of cells, because cell cycles dependent on strong signals from the body clock, whose activity is influenced by light quality, intensity and timing. Therefore, personalised dynamic light settings for each room in hospitals and care homes should be propagated. For example, dynamic light can include a dawn simulation, a cool light colour temperature that fluctuates with warmer colour temperature over the course of the day, and absence of cool colour temperature in the evening. Furthermore, in a hospital a patient should be allowed to adjust light levels in the room by shading daylight to darkness, dimming ceiling light from cool to warm colour temperature and have spot lights for reading or getting up at night. All switches need to be accessible from the bed, therefore a remote console, well labelled for visual impaired and with buttons, which light up when it is dark (e.g. at night).

Important trade-offs?

The eye has evolved a sophisticated neuronal network enabling the use of daylight for signalling light for image-forming but also for non-image forming functions such as entraining the body clock. Exposure to artificial light of inappropriate properties and timing has been shown to affect human health negatively. For example, floor lights and light pulses at night for checking up on patients and residents, may help staff and carers, but interrupt sleep and stimulate the body clock at the wrong time of day with implications for downstream autonomous regulations if improper light settings are used for those functions. Furthermore there will always be a trade-off between the need of the patients and the need of the carers. Light at night, if insufficiently dimmed, will inevitably compromise the body clock, with consequences for the overall regulation of physiological processes, e.g. from disrupted cell cycles, immune function, to the replenishment of the entire nervous system. Light promotes circadian entrainment by phase-shifting the activity of the body clock, with light in the morning phase advancing and light in the evening phase delaying the circadian timing system. Research has provided evidence for morphologically different photoreceptors and nerve cells in the eye, which can be selectively activated by different wavelengths and intensities. Applying this understanding to dynamic light sources will help to separate non-image forming from image forming responses to light without compromising on light quality for either vision or non-visual effects.

What are the best application opportunities to start with this segment?

Overall, research has shown that bright light installations in community rooms of nursing homes do not promote improvement in neuropsychiatric behaviours and sleep as expected. However, fewer studies using natural daylight have documented improvements for these behaviours in the hospital environment and care homes. Therefore, the best strategy for successful application is to 1) make use of daylight, 2) simulate daylight quality (intensity and spectral composition) as much as possible, and 3) target the most sensible times during which humans are most sensitive to light – the morning and the evening. The hospital and nursing home environment, with in-patients and residents is ideal to model dynamic lighting, according to the natural time course of outdoor light – e.g. use a 14:10 hour light-dark cycle, starting dawn simulation from 6:00 o'clock for 20 min. While the change in spectral composition should change automatically, the intensity of day- and evening light should be remotely adjustable according to the individual's choice. These systems should be installed in all rooms and corridors and not only in communal rooms, because individuals need to be given the choice to stay in their rooms while others do different activities. Before systems are being installed permanently, field studies where the systems' output is measured by sensors installed in the rooms and an individual's visual (visual acuity, lens transmission, pupil size and reflex, visual comfort) and non-visual responses (phase/amplitude of circadian marker rhythms, sleep, mood, cognition) to such lighting system need to be carried out, ideally for nursing home residents over a three months period and across different seasons. No such systematic measurements have been published to date, but normative data are urgently needed as guideline for the hospital and nursing home sector.

Level 3 information: Literature overview

4.1 LIGHT AND ITS EFFECT ON HEALTH OF INPATIENTS AND NURSING HOME RESIDENTS

When asked what comes to mind when imagine light, people immediately think of sunlight and positive mood. However, when asked to think of the function of the eye, the immediate answer is vision. These responses seem to be completely separable entities; yet, light evokes both visual and non-visual responses in our brain. The eye plays a central role in light reception, transmission as well as transducing light information to many regions of the brain, not only the visual cortex but notably the hypothalamus that harbours the circadian master pacemaker (body clock). While the pathways and processes in the eye are relatively well understood for vision, the structures and pathways driving non-image forming responses are far less explored. Among those, the pathways involved in the effects of light on the body clock and subsequent peripheral oscillators are better known than those by-passing the body clock and eliciting acute, non-circadian effects on mood, alertness and attention. Below, we describe pathways in the eye and brain responsible for differential responses to light for patients and elderly.

In humans, the eyes are the conduit for light. Just as the ear does two jobs, hearing and telling you which way is up, so the eye is a multiple sense organ that not only links light and vision but also light and time, mood, attention. It receives the input necessary for vision via the rods and cones, but the mammalian retina contains a subclass of photosensitive retinal ganglion cells (pRGCs) containing melanopsin, which integrate rod, cone and melanopsin information about illumination levels and spectral quality and transduce this information through a dedicated pathway to discrete brain structures, including the suprachiasmatic nucleus (SCN, the circadian pacemaker or body clock) for circadian photoentrainment, the olivary pretectal nucleus (OPN) for pupillary light reflex and the dorsal geniculate nucleus (dLGN) for image formation. The different photoreceptors are specialised cells and differentially sensitive to bright or dim light and absorb light of different wavelength within the visual spectrum, with rods responsible for shades of grey (night) vision and cones for colour vision. Rod and cone photoreception operate over brief time spans while pRGCs operate over long time scales. Morphological and physiological classification revealed that pRGCs comprise a complex population with up to 5 distinct cell types (called M1-M5) with distinct dendritic morphology and axonal projections. The relative influence from rod, cone and melanopsin signalling on pRGC subtypes is the origin by which the functional roles of pRGCs in behaviour can be explained (Schmidt, Chen et al. 2011). The influence of any light source (whether natural or artificial) on non-image forming behaviour is dependent on the unique light responses of pRGCs subtypes being activated and the signal processing in specific brain regions innervated.

One recipient of pRGC cell input is the bilateral SCN located in the anterior hypothalamus above the optic chiasm. The SCN is the central pacemaker of our circadian system which includes subsidiary clocks in nearly every body cell. The central clock is synchronized to geophysical time mainly via the changes in light intensity in the blue spectrum at dawn predominantly absorbed by rods and pRGCs in the retina, transmitted by electrical signals to SCN neurons. In turn, the SCN coordinates circadian physiology and behaviour by using neuronal and humoral signals that synchronize local clocks within the cells of most organs and tissues. Thus, some of the SCN output pathways serve as input pathways for peripheral tissues (Dibner, Schibler et al. 2010).

The ability of humans to manipulate their light exposure has an immanent potential to inflict problems with human physiology (as in shift workers) or to augment the ability of synchronisation (as in age-related impaired lens transmission). Before the invention of electrical light, humans lived their lives for thousands of years exposed to different spectra of light in the morning, the late afternoon and evening. As the sun rises and reaches its peak at noon, the spectrum it emits is smooth throughout the visible spectrum with a high intensity in the blue range [400 - 500 nm]. As the sun sets, light intensity is decreasing and blue visible light is preferentially scattered from sunlight, leaving an emission appearing orange-red [600 - 700 nm]. At night, there is darkness with limited visible light emitted from the reflection of sunlight by the moon, with the exception of when there is a full moon (Roberts 2010).

Nowadays we spend little of our lives exposed to natural light. We use artificial light to extend our period of wakefulness and activity into the evening hours, and a short sleep schedule which consolidates sleep efficiently at night. A study in New England found that older people (mean age 66 years) spent on average 38% of their waking day in light levels above 100 lux and 15% in light levels above 1000 lux (likely to be outdoor levels of light), whereas young subjects (mean age 24 years) spent only 27% of their waking day in light exceeding 100 lux and only 9% in light levels above 1000 lux (Scheuermaier, Laffan et al. 2010). The older people also woke up and went to bed an hour earlier than younger people and it is important to note that habitual patterns of light exposure could mask underlying circadian phases or affect entrainment of the body clock directly. The greatest sensitivity to light occurs during the habitual night time, when there is typically little light exposure (Chang, Santhi et al. 2012; St Hilaire, Gooley et al. 2012).

Another level of reduced light input relates to age-related changes in the eye. In order to obtain proper visual sharpness, the average 60-year-old person needs two to three times the light of a 20-year-old, and an 86-year-old person may require five times the lighting levels. These lighting level differences are due to age-related lens yellowing, opaque cataract or pupil narrowing (Winn, Whitaker et al. 1994; van de Kraats and van Norren 2007; Cuthbertson, Peirson et al. 2009), Van de Kraas, Winn,), creating a decline in retinal illumination, which makes the effective adaptation luminance lower for older adults (Veitch 2001). Therefore, older adults generally require better contrast and higher task luminance to obtain the same visibility level as a younger person.

Indirect evidence of the effect of the level and timing of light on mood comes from randomised trials under controlled conditions in people with Seasonal Affective Disorder (SAD) and unipolar depression. The diagnosis of SAD is based on the patient having episodes of depression which have occurred at least two years running during months of short photoperiod (winter) and with no symptoms during long photoperiod (summer). While mood changes are similar to those of non-seasonal depression, SAD is atypical in that symptoms are more likely to include craving sweet things, increased appetite, weight gain, and increased sleepiness. Reports show a dose-response relationship for morning light in SAD patients for typical but not atypical symptoms, with strong light (6000 lux and more) being more effective than medium light (1700-3500 lux) or dim light (600 lux and less) (Lee and Chan 1999). Time of day evaluation of bright light therapy for non-seasonal depression showed that morning exposure was more effective than at any other time of day, and this was equal between groups with and without concomitant drug therapy (Tuunainen, Kripke et al. 2004). This indicates that light intensity applied in the morning has different therapeutic effects on typical mood symptoms. Bright light therapy (10000 lux) in comparison to medium (4000 lux) or dim light (50 lux), applied in the morning as adjunct treatment, increases the antidepressant effects of SSRIs such as sertraline and citalopram in patients treated for depression (Martiny, Lunde et al. 2005; Sondergaard, Jarden et al. 2006). Light therapy in form of a dawn simulation in non-seasonal depression showed similar effect sizes but here no dose-response relationship was carried out (Golden, Gaynes et al. 2005). The effect sizes for light therapy are equivalent to those in antidepressant pharmacotherapy trials.

Assuming reduced light appears to be key factor in seasonal affective disorder, reduced levels of light experienced by elderly individuals should result in depression and concomitant SAD symptoms.
When studying a group of senior individuals with good physical and mental health, there was negligible seasonal variation in mood and behaviour and very little depressed feeling. Moreover, when exposed to additional bright light, the intervention tended to make these healthy elderly individuals more irritable, anxious, and agitated whilst sleep was not affected, suggesting that bright light is not beneficial for healthy elderly individuals unaffected by mood (Genhart, Kelly et al. 1993). Good quality trial evidence for effective light therapy in treating sleep disturbances (no comorbidities) in the healthy population over 60 years has been very scare and as a result recommendation were not provided (Montgomery et al, 2002, 2004). However, in a recent laboratory study comparing young versus older people, time patterns of melatonin showed an earlier melatonin phase and lower melatonin amplitude but no age-related difference in the magnitude or direction in their acute phase-shifting response to moderate- (2000 lux) or high-intensity (8000 lux) broad spectrum light stimuli administered before and after core body temperature minimum (Kim, Benloucif et al. 2014). The results indicate that there are age-related differences in internal circadian timing but not in the circadian response to light.

The effectiveness of enhanced indoor light intensity in care homes of elderly people as a treatment for neuropsychiatric behaviours, including agitation, dysphoria or apathy show a similar negative outcome as in healthy elderly, at a magnitude opposite to what is expected, clinically not relevant (Barrick, Sloane et al. 2010) and not decreasing caregiver burden (Dowling, Graf et al. 2007). A recent meta-analysis evaluating light therapy reported no evidence that light therapy decreases the decline in cognition or decreases agitation and psychiatric symptoms, including depression (Forbes, Blake et al. 2014). The individual trials varied in the modalities of the light therapy but numbers were too small to allow for subgroup analyses that would determine, which modality, (type, intensity, duration, time-of-day) might be beneficial for specific types and severity of dementia. Increased indoor light intensity in care homes as a treatment for sleep problems, including sleep onset latency, sleep efficiency and night-time awakenings showed a similar trend of low efficacy and considerable variability between studies (Forbes et al. (2014). However, the double-blind, long-term study by Riemersma et al., (2008) included in Forbes (2014) meta-analysis has shown a modest benefit of bright light therapy in improving day-time activity and some cognitive and non-cognitive symptoms of dementia. Other comparative studies and clinical trials showed that increased light levels reduced day-time sleepiness (Salami, Lyketsos et al. 2011). Furthermore, increased natural light caused an increase in nocturnal melatonin secretion in elderly people as indexed by a 13% increase in night-time urinary 6-sulfatoxymelatonin excretion, leading to a strengthening of the internal biological timing signal (Obayashi, Saeki et al. 2012).

4.2 CONCLUDING REMARKS

Understanding the effects of light on human physiology and behaviour in patients and elderly requires systematic elucidation of complex neuronal systems in the eye and the brain, related to their functional roles in vision, affect, sleep and the body clock. The pRGC population in the eye consists of several subtypes, each with unique responses to light, suggesting possible specific functional roles for each subtype in image-forming and non-image forming behaviour, such as sleep and mood. Progressive and often irreversible age-related impairments in the eye and brain may be in part responsible for the inefficient behavioural responses of artificial light installations compared to the much stronger natural daylight. However, innovative approaches in the lighting industry targeting pRGC requirements or adapt solid-state LED technology to spectral daylight composition (e.g. mimicking dawn, the sun, clouds and dusk) can potentially create successful lighting systems with application for individuals in hospitals and elderly people in care homes.

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LIGHTING FOR HEALTH AND WELL-BEING IN DOMESTIC APPLICATIONS

5 |

5 | LIGHTING FOR HEALTH AND WELL-BEING IN DOMESTIC APPLICATIONS

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Level 1 information: Summary of literature retrievals

The non-image forming effects of light in domestic applications have not yet entered the scope in the design of homes. Based on results from studies in the laboratory, light in domestic applications can potentially modulate sleep, well-being and in turn health in general. These typical room light effects at home depend on intensity, prior light exposure, the duration and the spectral composition of the light. There has been an increased domestic exposure to light from large TV screens, computers and tablets, which are frequently used at homes during times when the circadian timing system is particularly sensitive to the non-image forming effects lights (e.g. evening). Thus, besides fixed light sources at home also "mobile" light sources need to be taken into account for optimizing light solutions at home. Since most of us spent time in the evenings and mornings at home, two particularly important time windows for circadian and alerting effects of light, there is a great potential to implement so-called non-image forming light solutions for domestic applications in the future.

Important insights:

- Blue-enriched light from TV sets, computers and tablets in the evening and early night at home elicits an alerting response and can phase delay the circadian clock.
- Light levels above 100 lux when blue-enriched in the late evening can delay the time to fall asleep, and decrease initial deep sleep and sleep quality.
- Dawn simulating light during the (early) morning in the bedroom at home has beneficial effects on sleep inertia, well-being and cognitive performance during the day.
- Exposure to moderate light (i.e. 250 lux) in the morning can affect circadian physiology as indexed by the timing of melatonin secretion levels and sleep-wake timing. It can increase alertness, activity and cognitive performance during the day.
- Older residents exposing themselves to higher light levels in the evening have a higher risk for insomnia.

Level 2 information: Stakeholder/value-chain information

Besides the well-known „Zeitgeber" effects of light for entraining endogenous circadian rhythms to the environmental 24-light dark cycle, light exerts direct non-visual responses in a number of physiological and neuropsychological measures ranging from clock gene expression, hormonal secretion, brain wave activity, to human cognitive function. These effects can outlast the duration of light exposure without necessarily affecting circadian phase and show a clear dose- and wavelength dependency with stronger effects for light that is "blue-rich". The ocular photopigment melanopsin is crucially involved as a mediator of both the "Zeitgeber" and the direct effects of light in humans. Thus, there is accumulating and compelling evidence that light is "more than just vision". This should increase our awareness of the importance of both natural and artificial light for human health and well-being also in domestic settings.

Where do current solutions fall short? What consequences can this have?

To date, the designs of lighting systems at home are geared towards aesthetical demands of customers and to support visual performance. Light as a potential tool to impact on well-being at home has only recently reached the market with new LED products offering ambient lighting solutions which allow changing color temperature and intensity by the customer. However, these new smart light devices are considered life-style products not related to health issues. Thus, the non-image forming effects of light are not at all considered nor implemented in current lighting solutions for domestic applications. There is great potential to support circadian physiology, cognitive performance and sleep quality via cleverly designed lighting systems at home, which consider non-imaging forming effects of light in future lighting solutions.

What needs to be addressed? How can Human Centric Lighting help?

Besides, the aesthetical and visual aspects of lighting systems at home, the non-image forming aspects of light need to be addressed. Special light solutions for different rooms (bathroom, bedroom, living rooms etc.) could potentially help accommodating the biological effects of light on people's well-being, concentration, circadian physiology and sleep. Thus, more flexible lights solutions at home are required, which are not too complicated for the customer, but allow individual solutions based on scientific evidence. Technically, this can already be achieved by the current Solid State Lighting and control systems which dynamically offer many different spectral light compositions and intensities . Similarly as one chooses the optimal bed, and the quietest part in the building or of the apartment for the bedroom etc., one should also choose the ideal light solution for each room at home which respects visual and non-visual demands in combination with the outside natural light entering the rooms. Human Centric Lighting should develop light control systems based on solid scientific evidence, which help supporting the customer's non-image forming light demands beyond just a "life-style requirement".

What boundary conditions need to be considered?

Age, gender, light exposure history and sleep-activity patterns of a certain individual seem to play an important role in the non-image effects of light. It is the relative light level, rather than the absolute level, in comparison to prior light exposure and/or the concurrent ambient light that strongly influences the extent of non-visual effects. A person coming from dimmer light will usually have stronger responses to subsequent light exposure than a person coming from brighter light. The non-visual effects of light also depend critically on the timing of the light exposure. Furthermore, women prefer warmer light colors than men in the evening, and older people need, in general, higher light levels or biological effects, due to age-related changes in pupil size and lens quality.

Most of the evidence for biological effects of light in general stem from controlled laboratory experiments and urgently need to be translated into real-life scenarios. Besides individual differences in the response to light, the temporal 24-h hour aspects of light's action are very relevant for its domestic use in order to design appropriate dynamic light settings for use at home.

Important tradeoffs?

Light in the domestic use can face tradeoffs between the visual and non-visual (i.e. non imaging forming) effects of light. For instance less light in the evening at home with warmer color temperature in order to promote sleepiness, particularly in the younger population or people with sleep onset problems, can compromise visual acuity. Furthermore, there is always a tradeoff within the non-image forming action of light which targets the circadian system and the one which targets the acute non-circadian action of light. For instance, too much light in the morning at home, has beneficial effects on alertness and mood and potentially phase advances the circadian timing system. This may be preferential in young people and/or adults, who are usually circadian phase delayed (i.e. late chronotype), but not in older, who are usually more alert in the morning and of earlier chronotype than the young. Mobile light sources emanating from smart devices, tablets and portable computers will always interfere with lighting solutions at home. For instance it is useless to use warmer color temperature fixed light sources in the evening at home, while surfing on a tablet with high blue-content LED light. Thus, there will be an important tradeoff between fixed and mobile intelligent human centric lighting applications at home.

What are the best application opportunities to start with in this segment?

The best application opportunities to start implementing the biological effects of light at home is to target the most sensible times during which humans are most sensitive to light. The domestic environment is ideal to apply light in the late evening and early morning, since most people are at home during these times of the day and the biological effects of light greatest. Thus, these time slots should be targeted for an intelligent human centric lighting application at home. We recommend installing intelligent light solutions which simulate the natural time course of outdoor light at dawn and dusk for an average day with a photoperiod of about 12 hours light (preferably with sufficient brightness) and 12 hours of reduced light (relatively dim light, blue-deprived light or darkness). For the times in between dawn and dusk, light at home needs to promote alertness and should be of sufficient intensity and of cooler color temperature in rooms where natural light cannot appropriately enter because of small windows or if neighboring buildings are responsible for shadows' being cast on the façade.

Level 3 information: Literature overview

5.1 LIGHT EFFECTS ON HUMAN ALERTNESS AND SLEEP

The role of light as the major Zeitgeber (i.e. synchronizer) for human circadian entrainment has been firmly established over the past 40 years (1, 2). From early on, it was noticed that besides circadian photoentrainment, light also evokes non-circadian 'masking' effects on behavior and physiology (3). In human sleep and circadian research, the term 'masking' is scarcely used and is often substituted by expressions such as 'acute', 'direct' or 'non-circadian' effects of light, particularly for alertness. Badia et al. (4) were among the first to show that light can evoke acute alerting responses in humans, as indexed by increased core body temperature, electroencephalographic (EEG) waking beta-activity, alertness and performance during bright light exposure. Thereafter, non-circadian effects of light have been implemented in shift work environments, where elevated light levels made night-shift workers more alert when they had their breaks in well-lit rooms (5). Likewise, bright light but also blue-enriched light at moderate (100 lx) to low levels (40 lx) promoted alertness during prolonged nighttime performance testing during a simulated night shift (6, 7). These results were corroborated in non-shift workers during daytime such that a four week exposure to blue-enriched light during office hours improved well-being, alertness, and sleep quality in comparison to a non-blue enriched light solution in the office (8). Whether light changed circadian parameters, such as the diurnal profile of melatonin secretion, is not clear, since circadian profiles were not assessed in studies (5-8). Thus, it could still be that light acted via its Zeitgeber properties and in turn ameliorated worker's well-being, alertness and sleep. Also considering the long-term application of light, the described effects were probably rather of circadian than acute nature. Thus, in our view, acute effects of light should only describe short-term effects, which minimally last for minutes up to some hours and do not exceed 24 hour (i.e. one circadian cycle maximally).

The discovery of the new photoreceptor system, the intrinsic photosensitive retinal ganglion cells (ipRGCs) containing the photopigment melanopsin (9-11), maximally sensitive to 460-480 nm (10, 12-14), highlighted the importance of light's wavelength , blue light in particular, and has received substantial scientific interest (15) and media attention (16). We and others performed multiple investigations on the acute effects of short-wavelength light and in unison found that light evokes alerting responses that crucially depend on time-of-day, light's intensity, duration, and wavelength composition, and more recently also on prior light-dark light history (6, 17-24). If light is of sufficient intensity and applied during the biological night, when the circadian controlled release of melatonin is active, the alerting response typically occurs within 10 to 20 minutes after lights on (22). If the lights levels are lower and of a monochromatic nature and as short as 50 seconds, no significant behavioral changes in alertness and cognitive performance were reported [for a review see (25)]. However, light evoked significant cognitive task-related responses in subcortical and cortical brain structures, during functional imaging scans (25). Thus, light may affect brain regions before any behavioral sing of this effect emerges and can be noticed, probably anticipating and promoting changes in behavior. However, one can reliably measure non-image-forming behavioral light effects for light exposure levels below 500 lux and for exposure durations shorter than 30 minutes. We have current evidence that evening light levels as low as 40 lux evoke alerting responses and increase cognitive performance when blue-enriched or monochromatic at 460 nm in comparison to non-blue enriched and monochromatic light at 550 nm when the volunteers were dark-adapted before they were exposed to the corresponding light sources (18, 19). Interestingly, when we controlled for light intensity by performing two simulated evenings, one with light emitting diodes (LED) computer screen and another one with a non-LED screen, we detected significant alerting effects of the LED screen, and better performance in higher cognitive tasks than to the non-LED condition, most likely due to the two third higher irradiance level measured for the LED screen compared to the non-LED screen (26). It is rather the relative than the absolute light level in comparison to prior light exposure and/or the concurrent ambient light that determines the extent of non-visual effects. In other words, it is the 'extra light' that makes the difference- a fact, which has been recently proved in a controlled laboratory setting (24). If humans are particularly sensitive to 'extra light' coming from LED screens and other artificial light sources in the environment, this poses the question, whether the decreasing trend in habitual sleep duration and the concomitant prevalence of sleep disorders in our modern societies can also be attributed to too much 'extra light', particularly in the late evening hours. Light in the evening can make you acutely "bright", but has the potential to delay circadian rhythms and in turn negatively impacts the circadian entrainment of sleep-wake and natural light-dark cycle, which can lead to delayed sleep-onset, daytime sleepiness and cognitive performance decrements- and thus makes you "dim" in the long run. Very recently, we showed that evening light exposure significantly decreased sleep pressure in the following sleep episode, as indexed by less NREM slow-wave activity, for blue-enriched light than non-blue enriched light (27). However, the extent to which this light exposure will impact on the next sleep episode is still unknown. Furthermore, it is not yet clear whether this reflects a carry-over effect of the alerting action of evening light onto the first sleep cycle or rather an induction of a circadian phase delay. Thus, there is an urgent need to further investigate these potential interrelations, since there is epidemiological evidence that circadian disruptions and light at night (LAN) may negatively impact human health (28). This explains the WHO's decision to declare shift work that involves circadian disruption (rotating night shift work schedules in particular), as potentially carcinogenic (29). Besides LAN, inter-individual differences in the non-image forming light responses should be accounted for in further studies. Recent evidence indicates that the alerting responses to light depend on a specific clock gene polymorphism (30), gender (own data in preparation) and age (31, 32), even when carefully controlled for prior light history, the amount of prior wakefulness and circadian phase.

5.2 CONCLUSION

The circadian timing system and light via the non-image forming system contribute enormously to human alertness-sleepiness regulation. The discovery of the multifaceted neuronal underpinnings of the central circadian clock's outputs as well as light's repercussions on the brain's sleep and wake-promoting regions is far more complex than initially thought. However, these discoveries along with the recent advances in solid-state LED technology, will help to design and implement novel light devices and light exposure schedules for at home and in the work place environment to promote beneficial non-visual effects of light beyond vision.

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LIGHTING IN SMART CITIES

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6 | LIGHTING IN SMART CITIES

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Level 1 information: Summary of literature retrievals

The effect of light on wellbeing, performance and health in urban environments is dependent both on the objective lighting environment and how it is perceived and interpreted in a given context. Research has shown that urban lighting at night may have numerous positive and negative effects on the biological well-being of humans and animals. It enables safe passage on the routes by ensuring sufficient visibility. There is mounting evidence connecting lighting to higher perceived safety and pedestrian and cyclist outdoor activity. Lighting may also reduce criminal activity. Lighting environment may thus encourage physical outdoor activity, social life and recreation and promote the well-being in cities. However, exposure to light at night must be handled with care, as depending on lighting intensity, exposure duration and spectrum light can contribute to biological effects that are disruptive for sleep and health.

Due to the potential of light to simultaneously elicit positive as well as undesirable effects lighting paradigms for lighting in cities and other outdoor regions have to be reassessed and improved by incorporating the new and emerging potentials of LED lighting on intelligence, controllability, tenability, and energy saving. The negative effects of the urban light at night can be minimized by appropriate luminaire and lighting design, e.g., by carefully choosing the spectra, determining the timing and defining the light intensity range (min and max) of the lighting system.

Outdoor lighting can encourage physical outdoor activity, social life and recreation and thus can be used to promote well-being, safety and a pleasant atmosphere in cities. However, the light use has to be sustainable and the biological effects of light, such as the effects on the circadian rhythm including sleep-wake rhythm, and alertness, need to be taken into account:

- Avoid high light intensity and reduce blue light content
- Focus light where it is needed
- Use lighting control to adjust lighting (intensity, color, time) according to demand, such as individual needs

Level 2 information: Stakeholder/value chain information

Possible effects of outdoor lighting

Street lighting affects pedestrian outdoor activity and route choices (Alfonso, 2005; Bernhof & Carstensen, 2008; Larco et al. 2012; van Loon&Frank, 2011)
Current street lighting practice is based on the foveal vision of car drivers whereas the needs of pedestrians have received less attention. Mobility, recreation and social life after dark can be encouraged through the creation of attractive outdoor spaces. Furthermore, the needs of senior citizens should be taken into account as Europe, together with the rest of the world, is facing a demographic change into aged society.

There is research evidence indicating that preference, restorativeness and feeling of safety may be enhanced when light is aimed towards pedestrian and natural elements of the environment whereas aiming light towards parking lots may have adverse effects. Preference is also related to appropriate luminance and spatial distribution and good colour quality.

Besides appropriate luminance aged pedestrians might benefit from clear visual cues improving their postural control. Provision of visual cues is feasible with LED lighting. Elderly might also appreciate if lighting would clearly indicate possibilities to rest and points of irregularities in the walking surface. As LED lighting is easy to integrate into street furnishing lighting enhancing surface structure is easier to implement with LEDs than with traditional light sources. In terms of spectra elderly would benefit from limitations in blue emission at night. Research points out that blue-rich light results in the aggravation of night-time driving conditions for elderly people due to the yellowing of the lenses of the eye with age.

Blue rich light and high intensity light at night may disrupt circadian system (Falchi et al., 2011; Lockley 2009; Brainard et al., 2001; Thapan et al., 2001).
Discharge lamps that are currently widely used for outdoor lighting are difficult to control electronically and the power range is limited. This may lead to unnecessary ‘over lighting’. Furthermore, the choice of light source spectra is limited. However, with proper lighting design, the positive effects of light can be achieved without inducing the potentially negative impacts on the circadian rhythm.

Circadian sensitive lighting provides a healthy living environment at night. The circadian system of humans can be disturbed by light exposure interfering with the hormone secretion, such as melatonin. The changes in the hormone levels can further affect the alertness, sleepiness, mood and stress levels. In circadian sensitive lighting intensity is adjusted according to expectations and task demand and blue emission is limited. LED-based light sources with low circadian action are feasible. It must be noted that the light history, i.e. the prior light exposure of an individual and the level of adaptation, may affect the impact the light has on the circadian rhythm.

Spatial pattern of illuminance is important for feeling of safety of pedestrians (Haans & de Kort, 2012; Viliunas et al., 2014; Atici et al., 2011)
Discharge lamps are difficult to control electronically. Furthermore, in outdoor lighting they offer fewer possibilities for a precise control of spatial distribution of light as common discharge luminaries do not include lenses whereas LED light sources have built in optics.

Research points that lighting in the immediate surroundings is important for feelings of safety and that pedestrians want to walk in a spotlight. In shared traffic spaces pedestrians want to be clearly visible to the other space users.

Limitations

As the possible lighting effects are context dependent no absolute values of the possible effects can be given. Only direction of the likely effect can be stated.

Application opportunities

Greener lights

Light sources limiting blue wavelength emission and having strong green wavelength emission should be developed for outdoor lighting. According to current scientific knowledge this type of spectral content would be circadian sensitive, enhance mesopic vision and limit discomfort glare. It would also produce less sky glow and attract fewer insects as compared with blue rich light sources.

Separate lighting for car traffic and pedestrians

The development of car technology may bring big changes for lighting industry. What is the future of road lighting in areas where there is no pedestrian traffic or cyclists? What kind of assistance if any do robot cars need? Is the future of road lighting in the provision of visual cues? These issues should be studied together with the car manufacturers. The needs of pedestrians and especially elderly pedestrians should be taken into account in night time lighting environments. For example, it has been indicated that horizontal and vertical visual cues affect positively the postural control, which may improve the safety of the elderly. However, more research is needed to verify whether it applies also in outdoor environments. Research also suggests that focusing light on natural objects, such as the greenery, may improve the safety, restorativeness and preference of the pedestrians.

Level 3 information: Literature overview

6.1 INTRODUCTION

Since its introduction electric light has been essential part of urban nightscape. Within a century light use has increased rapidly transforming the way of life after dark. Climate change brings now new challenges to urban lighting. Cloud coverage may increase and snow coverage decrease in the future decades leading to increased artificial lighting demand. As carbon emissions should be reduced, energy efficient light sources together with careful design should be adopted.

Europe is facing a demographic change into an aged society. Cities should be prepared to provide accessible outdoor spaces for senior citizens. Mobility, recreation and social life after dark should be encouraged through the creation of attractive outdoor spaces. Lighting is a major factor in the formation of the visual image of urban nightscapes and the visual forces of light and darkness should be used for the benefit of all citizens. However, recent research has pointed that the illuminated environment is also a biological environment that affects circadian system of humans and animals. Thus also biological effects should be taken into consideration when designing outdoor lighting environments.

So far a large amount of urban lighting has been devoted to fulfil the needs of car drivers. When the vehicle light technology together with automatic detection and response technologies is advancing it may be possible to give more emphasis to the needs of the pedestrians and cyclists and encourage their mobility. Street lighting becomes redundant and thus can be completely avoided in areas where there is no pedestrian or cyclist mobility. This would have considerable impact on the visual image of urban nightscapes.

LED lighting enables better control possibilities than the old lighting technologies. It is also possible to produce light sources with different spectra. Lighting may thus be adjusted according to the human needs without wasting resources. It is also possible to incorporate lighting into structures and devices enabling a new kind of approach to urban lighting.

6.2 EXPOSURE TO LIGHT AT NIGHT NEEDS CAREFUL DESIGN TO PREVENT DISRUPTION OF HEALTH AND WELL-BEING

The effect of light on circadian rhythms was discovered in the 1960s [1, 97, 98], and at the beginning of the new millennium a new retinal photoreceptor, which is responsible for non-imaging vision functions like circadian regulation, was discovered [2, 3]. Over the last decades, there has been a growing concern with the effects of light exposure during night-time [4]. As the day-night pattern of natural light is now modified by our 24hr 7/7 economy and the availability of artificial light, human circadian rhythms may become disrupted. This disruption may affect health — such as contributing to tumor growth [5], cardiac disease [6] and metabolic syndrome [7]. The impacts on circadian rhythm alerting effect and melatonin suppression have been found to depend on the light history [97-103], but dependence may vary for individuals [101]. Nocturnal light may also harm other animals by affecting processes like primary productivity, partitioning of the temporal niche, repair and recovery of physiological function, measurement of time through interference with the detection of circadian, lunar and seasonal cycles, detection of resources and natural enemies and navigation [8].

Thus, it may be that as our knowledge of the biological effects of light increases, it will also be taken into account in lighting recommendations and standards [9, 104, 105].

At the moment neurophysiological light-responses are not fully comprehended. However, there seems to be agreement that the human circadian system has peak sensitivity in the blue region, around 460-490 nm, and that besides spectra also timing, exposure duration and intensity affect human circadian responses [2, 10-12]. Furthermore, preliminary models evaluating the circadian effects of light sources have been developed [13] and first steps in the development of circadian sensitive LEDs have been taken [14, 15]. All these actions are essential in the way of adopting circadian sensitive urban lighting as it has been suggested that blue rich light sources may potentially increase sky glow [16, 17]. Further research is needed to study the effects of light at night at population and ecosystem levels [8].

The potential negative (circadian, non-visual) effects of urban lighting at night can be minimized by appropriate lighting design. To reduce the amount of blue component in the light source spectrum is one suggested design option, but other effective recommendations can be given. The light sources themselves need to be designed and installed so that there is no upward light component (upward light output ratio ULOR 0%) or that the light is emitted only on the surface to be illuminated. Attention must be paid to the placing and orientation of the luminaires to avoid 'light trespassing'. The lighting control system can, depending on the users' needs, optimize the time when the lighting is on, and it also enables dimming of the light, providing the minimum needed light level.

6.3 NIGHT TIME LIGHTING IMPROVES PERFORMANCE AT NIGHT

Studies have shown that brighter lighting at night induces higher alertness and improves performance as compared with dimmer lighting [10, 18-20]. Recent research has suggested that both long- and short wavelength lighting reduces sleepiness and increases positive affect and alertness at night [18, 19] thus indicating that alertness and mood may be affected without stimulating the melatonin pathway.

In urban nightscapes high performance is required in traffic environment in order to ensure safe passage. Road lighting may improve both visual and cognitive performance at night and it is connected with decreased amount of accidents at night [21]. It has been presented that the safety effect of road lighting is highest with pedestrian, cyclist and moped accidents [22]. Along with intensity also the spectral quality affects safety by improving brightness, facial recognition and response time [23, 24]. Research suggest that pedestrians prefer walking in light making them clearly visible to other road users [25] and that visibility of pedestrians is also important for drivers [26].

Although road lighting improves visual conditions of drivers [22] and it is generally expected to decrease accidents [21, 22], it may also result in increased driving confidence, lower performance [27], higher speed [28] and thus higher traffic noise level. The safety effect of road lighting with automobile accidents may decrease further in the future along with the emergence of automatic detection and response technologies. Technological advances may also enable more altruistic approach to vehicle lighting in the future. Lighting systems of different vehicles would co-operate and provide good visual conditions for all road users.

6.4 LIGHTING AFFECTS POSITIVELY PEDESTRIAN OUTDOOR ACTIVITY

Research evidence points to the direction that lighting affects people’s willingness to use urban spaces after dark [29, 30]. Lighting may also affect the way in which these spaces are used, e.g. route choices [31], and how frequent they are used. Increased amounts of walking and cycling, instead of motorised mobility, has environmental benefits, such as lower levels of fine particles in the air. It also has a positive effect on mental and physiological health [32]. An increased use of outdoor spaces by women, elderly and families also affects the nature of social environment at night.

Besides fear of crime also fear of falling may lead to diminished outdoor activities among elderly. At winter evenings low ambient light levels complicating postural control together with slippery pavements create challenging environment for senior citizens. There is research evidence indicating that lighting system providing horizontal and vertical visual cues affects positively postural control [33-34]. Further research is needed to clarify whether outdoor lighting could also promote the postural control of the elderly through visual cues as LED technology enables incorporation of light sources into street structures. This kind of approach might be more energy efficient than general brightness increase. However, practical applications should carefully study possible eye heights and view angles in order to avoid glare.

6.5 STREET LIGHTING AFFECTS POSITIVELY FEAR OF CRIME

Street lighting affects positively fear of crime. Fear at night may stem from several reasons. Besides the reasons related to the social environment, or so-called 'social night' [35], and individual factors, such as gender and environmental trust [36], an obstructed field of view has also been connected with feelings of discomfort and fear [37]. The obstruction may be physical, but it may also be caused by insufficient lighting. There is mounting research evidence pointing that lighting positively affects a fear of crime [36, 38-42]. Even still, there are studies showing that lighting only has minor effects [43] or no effects [44] on fear of crime. The factors that might help explain the inconsistency include variations in the preliminary lighting conditions, the follow-up times, the characteristics of the residents, halo effects and the complex nature of reactions that cannot be reached by practical interventions with only a limited amount of control [45].

Visual performance at night is reduced by limited or scattered luminance distribution, low luminance levels, very high or low luminance contrasts and glare [46]. Also, weak colour contrast or a colour appearance that deviates from what is normal may harm the performance of visual tasks. When outdoor lighting provides an environment where photopic luminances vary between 0.01 and 3 cd/m^2, the human visual system relies on more peripheral mesopic vision than the photopic vision used during daytime lighting conditions [46]. Mesopic vision is less able to discriminate between colours. However, it detects movement more readily than photopic vision, but with less sharpness in terms of the images produced. This higher degree of sensitivity to movement and lower quality images sets high demands for recognition processes.

Urban nightscapes are also environments where shadows have a strong role. Very often there is hardly any scattered light leading to high-luminance-contrast lighting environments with strong shadows. Thus, the visual image of three-dimensional objects, like faces, differs significantly at night from the daytime image, making the recognition process challenging. Furthermore, the multiplicity of light sources, and thereby the directions of light, generates an environment where even an observer's own shadow makes sudden movements when passing between the various light sources. Also, when branches are close to the light source, a small movement caused by the wind stirring the branches of trees is multiplied in the movement of shadows cast upon the ground. These shadow movements, together with the higher movement sensitivity of mesopic vision, may further induce experiences of fear. Therefore, an urban electric lighting environment may also be a source of disinformation and fear.

The lighting environments of early humans with a single dominant far off light source, sun or moon, provided a more stable light-shadow environment. Thus, at that time strong shadow movements during night may well have been produced by a predator and fear was a beneficial reaction supporting survival in such a situation.

For modern humans, fear at night is more likely a damaging rather than a beneficial reaction. Besides being an unpleasant feeling, fear is related to stress and harmful psychophysiological conditions [47-48]. Furthermore, fear limits the use of outdoor spaces during night-time [49], which negatively affects human well-being. However, there is evidence indicating that making changes to environmental conditions can reduce the fear of crime [39-40, 43, 50]. It is thus important to find those lighting characteristics that promote a perceived sense of safety and increase pleasurable stimuli, thereby helping to combat uncertainty and confusion in nightscapes. However, practical lighting interventions to diminish the fear of crime have often encompassed changes in various lighting attributes, e.g. in terms of photometric attributes, the spectral power distribution, mean surface luminance and luminance distribution may have been changed [39]. Because of the large number of attributes, it is difficult to identify which lighting attributes may have caused the possible positive effects.

Traditionally, lighting has been seen as a matter of visual performance and visual access, providing reassurance for those who are fearful in public places. Lighting allows people to see what is around them so that they can easily recognise potential escape routes and notice that there are no places for offenders to hide [37, 51]. Furthermore, lighting makes it possible to evaluate the expressions, gestures and appearances of other people, enabling a person to make risk evaluations and change their route if necessary [46, 52]. Lighting also makes it possible for a person to be seen so that, in the case of an attack, others may perceive and react to the situation [40].

Lighting is also related to the concepts of territorial functioning and physical incivility [50, 53]. Fully operating and aesthetical lighting may lead to a reduced fear of crime, since it alerts a person that they are in a well-off environment that is taken care of, whereas dull lighting with broken luminaries sends a signal of indifference and disarray. There is also empirical evidence that perceiving the lighting environment as pleasant is more important for feelings of safety than merely perceiving the brightness of an environment [36].

Lighting provides visual access (prospect) for pedestrians and enables them to observe escape opportunities. Haans and de Kort (2012) [54] indicate that pedestrians especially appreciate near-field prospects and escape opportunities. In their study, prospect, escape and concealment (assailant's refuge) were manipulated through the way in which lighting was distributed. The study demonstrated that in terms of feeling safe, pedestrians value more lighting in their immediate surroundings than further away in the street, thus indicating that an extensive 360 degree prospect in the near field is more important than a far field but very narrow prospect.

However, although prospect is fundamental to feeling safe, there is also research evidence suggesting that some spatial limitation is needed for a feeling of safety during daytime [55] and that the perception of enclosure created by lighting may be connected with feelings of safety [56]. Therefore, people may feel that a large, open, illuminated space is unsafe even though it provides a large prospect. Kaplans [57] and Ulrich [58] suggest that this kind of an open space would also be less liked than more defined and closed space. Thus, more research is needed on the near/far field prospect and escape and feelings of safety.

When standing in a pool of light that provides a prospect, a pedestrian can also be seen by a potential assailant. The pool of light also limits both the prospect and the escape possibilities if there are strong and sharp luminance differences. Appleton's prospect-refuge theory [51] would thus suggest that pedestrians would like to be located within a dimmer spot (not seen) in the illuminated environment (being able to see). This is the ideal refuge provided by daytime environments, which is quite hard to achieve in urban nightscapes. However, new light sources with intelligent lighting control would facilitate some aspects of this kind of environment. The study by Haans and de Kort (2012) [54] indicated that people prefer to walk in a spotlight rather than to walk in a dark spot. Thus, the study gives some indications that 'not being seen' is not very important for feeling safety during night-time.

Since the actual lighting interventions have included changes in various lighting attributes and failed to fully characterise the lighting, it is difficult to say which factors in the lighting environment decrease the fear of crime. In terms of photometry, luminance, and thereby illuminance, is considered central. Horizontal illuminance is considered to describe how well lighting facilitates surveillance in general, whereas semi-cylindrical and vertical illuminances describe more the possibilities that lighting provides for facial recognition. It has further been suggested that illuminance uniformity, glare and spectral power distribution may also affect fear of crime [46].

The importance of illuminance in determining people's perceptions of safety at night is supported by Boyce et al. [59]. They suggest that the relationship between perceived safety and illuminance is not linear; rather, it weakens after a certain level of illuminance is reached. Furthermore, their study indicates that women require higher illuminance levels before they feel that the illuminated environment has a good amount of security lighting. They also note that lower illuminance is needed in suburban areas than in urban areas for people to feel that the illuminated environment has a good amount of security lighting. If the risk of social threat is higher, then more light is appreciated. Furthermore, the surrounding luminance levels are higher in urban areas, which affect people's perceptions of the lighting in the neighbouring areas as well.

Also, Stamps has found in his studies that safety is strongly correlated with the lightness of the scene [60] and that the impression of safety is more strongly influenced by locomotive than by visual permeability, highlighting the importance of escape possibilities [61]. Blöbaum and Hunecke [38] reached similar conclusions. Lighting, prospect, opportunities to escape and a person's gender were all relevant factors affecting perceived danger in an area. However, the opportunity to escape seemed to be the strongest factor.

Increasing the illuminance levels may also have negative effects. More intense lighting may increase fear if it makes the unpleasant things more visible [39]. It is also possible that lighting may create a feeling of being watched by an assailant lurking in the darkness [44]. This feeling may be created by a 'barrier of light' formed either by glare or by strong luminance differences, thereby making it difficult to control the environment visually. The spectral power distribution may also affect people's perceptions of safety [46]. There is evidence that spectral power distribution has an effect on brightness perceptions [62-64] and that people's perceptions of greater levels of brightness may well have an effect on their fear of crime, as stated earlier. This suggestion is also supported by Fotios et al. [65]. Likewise, the research conducted by Rea et al. [66] indicates that people feel that the lighting provided by metal halide lamps (with fairly good CIE CRI and a higher colour temperature) is brighter and safer than the lighting provided by high-pressure sodium lamps (with moderate CIE CRI and a relatively low colour temperature). In terms of its acceptability for social interaction, facial recognition and many aspects of eyewitness identification, there were no clear differences between the types of lighting. However, a study conducted by Knight [67] suggested that spectral composition also affects perceptions of comfort.

Previous studies have mainly compared metal halide and high-pressure sodium light sources. Therefore, it is difficult to clarify how well the results can be generalised to other light sources and the extent to which researchers should distinguish between the effects of colour-rendering properties and the effects of colour temperature. If spectral power distribution affects perceived safety due to mesopic vision, adapting the mesopic photometry would restrain the effect. However, it is also possible that the spectral power distribution affects people's perceived safety when it is mediated by some factor other than brightness perception. Possible candidates could include mood [68] or pleasantness [36], or a combination of different factors.

6.6 LIGHTING MAY PROMOTE RESTORATION

Restoration is the counterpoint to stress and attentional fatigue. It covers various processes involving renewing or recovering diminished functional resources and capabilities [69-70]. In the restoration research field, two processes have received much attention — one focuses on attention restoration and the other on psychophysiological stress recovery.

While urban planning strategies often refer to the benefits of urban greenery in general terms as promoting the well-being, some cities state more specific benefits and acknowledge the importance of attention restoration. Furthermore, the importance of near home restoration opportunities is increasing due to the aging process facing the world's population. However, the possibility to gain restorative experiences during darker hours is rarely considered although restoration during the evening may be very important, as recreational time is often limited to these hours. The need for restoration may also be considerable in the evening due to the mental effort needed during the workday [71]. Public lighting should promote people's near-home opportunities for restoration, enabling them to distance themselves from their everyday concerns and regain their attentional capabilities. Limited access to restorative environments may have negative consequences on attentional capabilities, health, and well-being [72-75]. Attractive environments may also promote walking and cycling as people may choose their desired footpaths or means of travelling because of the perceived potential for restoration [76-78].

There is preliminary research evidence indicating that focusing light to urban greenery instead of parking lots and roads results in higher perceived restorativeness and preference ratings and lower fear [79-80]. There are also some indications that besides focus of light also other lighting factors e.g. brightness may be connected to restorative potential [81]. Thus lighting provides visual access to restorative environments but the quality of light may also be important for restorative experiences. However, further research is needed to clarify the preliminary indications.

6.7 DISCOMFORT GLARE AND PHOTOPHOBIA DEPEND SPECTRA

Lighting may also have distracting and distressing nature. Flickering light, bright light and glare have been identified as common triggers of headaches [82-83]. Vehicle lights have been associated with discomfort, pain, seeing double and flickering [84] posing a potentially dangerous scenario for all road users. Recent research has related discomfort glare to photophobia and suggested increasing sensitivity with low wavelengths and secondary peak in red area [85-90]. As discomfort glare harms well-being and performance in urban nightscapes there is a need for further research.

6.8 LIGHTING AFFECTS SOCIAL BEHAVIOR

Several studies within the field of social psychology have indicated that lighting is an environmental factor that may affect social behavior. Brighter environments have been connected with less selfish behavior and higher volunteerism, reflective self-regulation and honesty than dimmer environments [91-93]. It has been suggested that darkness may induce a psychological feeling of illusory anonymity that may further disinhibit dishonest and self-interested behavior [93]. However, also prosocial behavior in dim environments has been reported [94] thus leading to suggestion that most salient response in any given situation is expressed, regardless of whether it has prosocial or antisocial consequences. Furthermore, it has to be pointed out that these studies have been conducted in laboratory conditions that differ considerably from public outdoor spaces after dark. It also has to be acknowledged that e.g. bullying may raise status within certain groups and bullying may include recordings of violent acts which are later put into internet. Brighter lighting may thus also contribute violation of the victim. Thus, there is a need for a research studying the possible effects of outdoor lighting on social behavior. These effects are likely to be context dependent.

6.9 LIGHTING REDUCES CRIMES

There are contradictory views on the effect lighting has on actual crimes [41-43, 46, 95]. However, a recent meta-analysis by Welsh & Farrington [96] concludes that lighting significantly reduces crimes. The crime reduction effect has mainly been explained on the basis of two theories [96]. One suggests that improved lighting increases surveillance and deterrence, whereas the other focuses on the role of lighting improvements in increasing community pride and informal social control. The Welsh & Farrington meta-analysis [96] indicates that the night-time crimes did not decrease any more than daytime crimes. Thus, a theory focusing on community pride and informal social control was regarded as more plausible than a theory focusing on increased surveillance and deterrence. Also, Pease [42] has assessed the effect of lighting on crime during daytime hours. However, although the effect of lighting on crime may be regarded as commonplace, it is also conditional. An untargeted general increase is presented to be less effective than a targeted increase [42].

It has also been pointed out that lighting may promote criminal activity by increasing social activity outside home, thus bringing a greater number of potential victims and offenders into the same environment. Lighting also makes it possible to observe suitable targets and people that may intervene in crimes [42, 96]. Furthermore, most of crimes, including those that take place at night, are committed in well-lit areas with plenty of people — such as areas that are close to stations and restaurants. Also, very few criminals say that they look for dark or poorly lit areas [39].

6.10 CONCLUSIONS

Night time lighting is a part of modern urban living environment. Lighting creates a scene for various outdoor activities including romantic walks, car drives, a space for kids to play, jogging and relaxation. Lighting provides access and enhances feeling of safety. It may be a source of fascination and pleasure. However, research has also shown that light exposure at night may have disruptive effects on circadian rhythms and human health. Furthermore, lighting and light sources cause environmental concerns also because of their energy consumption. Energy production causes carbon and fine particle emissions harming the well-being of humans, other animals, and the man-made and natural environment. It is thus important to carefully consider the light use in our night time environment from both the point of view of the impacts of light and the life cycle impacts of lighting equipment.

Due to biological effects research has suggested limitations in intensity, exposure duration and spectra of the outdoor lighting, and new lighting technologies offer good possibilities for adopting lighting control in extensive use. Furthermore, light sources with lower circadian impact have also been developed. However, further efforts are needed in order to develop circadian sensitive urban lighting environment. It has been presented that besides the circadian effect also discomfort glare, photophobia and sky glow may be sensitive to blue rich light sources. This gives further support to the light source development taking all these possible effects into account within the outdoor lighting context of mesopic vision.

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