Human lighting demands : healthy lighting in an office environment

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Human Lighting Demands

Healthy Lighting in an Office Environment

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PROEFSCHRIFT

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Table of contents

Summary

Light influences the daily rhythm and well-being of humans in a physiological, psychological and biological way. Light not only enables humans to see. Beside visual photoreceptors, the human eye also contains (recently discovered) non-visual photoreceptors. Supported by light perception, the human biological clock system tells the human body when to regulate multiple body functions such as body temperature, sleep patterns, cognitive performance, mood, well-being and the release and production of hormones.

Current recommendations for office lighting are purely based on visual criteria. The horizontal illuminance on the working plane is the dominant lighting design parameter in offices. This parameter is not relevant for non-visual stimulation where the vertical illuminance (at the eye) is important. It can be expected that current offices will not provide sufficient lighting for adequate non-visual stimulation. Furthermore, lighting concepts for office rooms that meet both the human visual and non-visual demands are not available. Lighting that meets both the human visual and non-visual demands without causing visual discomfort is called ‘healthy lighting’.
Closer investigation will show which ‘stimulation specifications’ healthy lighting concepts have to satisfy. Examples of specifications are intensity, timing, dynamics, direction and spectral composition of (ocular) light exposure. Exact values are not yet known but literature shows that a high lighting level is the prime requirement for a healthy work environment. These high light levels are not demanded all day. Daylight, including high intensities and natural dynamics, is an important light source for healthy lighting. However, no building can be lit by daylight alone because daylight is not ‘reliable’ according to the weather, the time of day or the time of year. Generally, it does not even reach all areas in a building and sometimes the intensity is too low. Higher demands for task lighting lead to the use of the combination of daylight and electric lighting.

The objectives of this research were to characterize lighting conditions in current office types with regard to current standards and non-visual variables and to develop (conditions for) lighting concepts and system solutions that meet both visual and non-visual demands of humans.

A specially developed, mobile experimental set-up is used to characterize the actual lighting conditions in ten office buildings in the Netherlands. The experimental set-up holds both vertical sensors and retinal exposure detectors and is, in advance of the field study, validated in laboratory experiments. In April 2003, field tests started in offices by measuring lighting at workstations and distributing questionnaires among the employees. The questions were about visual and non-visual items. The outcome of the physical measurements at 87 workstations and 333 subjective questionnaires shows the various influences of light on humans. The measurements show that almost all offices visited meet the visual criteria. The users are satisfied with their lighting. Current lighting does

not satisfy the assumed non-visual lighting criteria. The field study shows significant correlations between the vertical illuminance at eye level and the parameters ‘fatigue’ and ‘sleep quality’. High levels of vertical illuminance were associated with less fatigue and better sleep quality.

Lighting concepts were designed, visualized and realized to improve the situation. New concepts were developed with daylight as primary light source. Furthermore a good general lighting was applied and the concepts were supplemented with ‘special’ electric lighting. To evaluate the visual acceptance of these new concepts, special test offices were used in which test persons spent one shift. The test people’s responses on the new lighting concepts were investigated at different illuminance levels, with different systems and in different seasons. The test results show that, to employee’s satisfaction, it is possible to realize healthy lighting concepts with higher illuminance levels than commonly used in office environments.
The variance in satisfaction ratings between the tested illuminance levels is mainly explained by luminance related variables (nuisance, reflection and ambiance). The results of performed light sensitivity tests were used to understand the acceptation of the variants. The chance for complete satisfaction increases if the luminance level of bright light sources is kept below 1500cd/m². The laboratory study also showed that both light sensitivity and season sensitivity are very important inter-individual parameters. Both must be taken into account in (assessments of) lighting design. Particularly season sensitivity must be investigated in follow-up research.

Samenvatting

Licht beïnvloedt het dagelijkse ritme en het welzijn van mensen op een fysiologische, psychologische en biologische wijze. Licht zorgt er niet alleen voor dat de mens kan zien want naast visuele receptoren zitten er ook (recentelijk ontdekte) niet-visuele fotoreceptorcellen in het oog. Licht dat op deze cellen valt, stuurt signalen naar de biologische klok. Deze interne klok regelt dagelijkse, maandelijkse en jaarlijkse ritmes van vele lichaamsprocessen, zoals lichaamstemperatuur, slaap patronen, cognitieve prestaties, stemming en de aanmaak of onderdrukking van diverse hormonen.

De huidige normen en aanbevelingen voor kantoorverlichting zijn voornamelijk gebaseerd op visuele criteria. Bij het ontwerpen van kantoorverlichting is de horizontale verlichtingssterkte op het bureaublad momenteel de belangrijkste parameter. Deze parameter is echter voor de niet-visuele stimulatie – waarbij de verticale verlichtingsterkte (op het oog) belangrijk is - niet relevant. Het is daarom aannemelijk dat in de huidige kantoren de verlichting voor adequate niet-visuele stimulatie onvoldoende is. Er zijn nog geen verlichtingsconcepten voor kantoorruimten beschikbaar die voldoen aan zowel de visuele als niet-visuele eisen van de mens. Verlichting, die zowel aan de visuele als de niet-visuele eisen van de mens beantwoordt en waarbij geen visueel discomfort ontstaat, wordt ‘gezonde verlichting’ genoemd.
Nader onderzoek zal moeten uitwijzen aan welke ‘stimulatie-specificaties’ gezonde verlichtingsconcepten zullen moeten voldoen. Te denken valt aan de intensiteit, timing, dynamiek, richting en spectrale samenstelling van het (oculair) licht. Exacte waarden zijn nog niet bekend maar literatuuronderzoek wijst uit dat een hoog lichtniveau een eerste vereiste is voor een gezonde werkomgeving. Deze hoge verlichtingssterkten worden niet de hele dag gevraagd. Het daglicht is, onder andere vanwege de hoge intensiteiten en de natuurlijke dynamiek, een belangrijke lichtbron voor gezonde verlichting. Echter, geen enkel gebouw kan door alleen daglicht verlicht worden en op bepaalde momenten (in de avond of in de winter) is de intensiteit te laag. De ‘onbetrouwbaarheid’ van het daglicht en de strengere eisen die aan (taak)verlichting gesteld worden, leiden tot het gebruik van de combinatie van daglicht en kunstverlichting.

De doelstelling van dit onderzoek was tweeledig. De eerste doelstelling was het karakteriseren van de huidige verlichtingscondities in verschillende kantoren met betrekking tot normen en niet-visuele variabelen. De tweede doelstelling was het ontwikkelen en uittesten van (voorwaarden voor) lichtconcepten en systeemoplossingen die aan zowel visuele, niet-visuele als comfort eisen van mensen voldoen.

Een speciaal ontworpen, mobiele experimentele opstelling is gebruikt om de verlichting in tien kantoorgebouwen in Nederland in kaart te brengen. De experimentele opstelling bevat onder andere verticale sensoren en detectoren die de hoeveelheid licht op het netvlies registreren en is, voorafgaand aan de veldstudie, in laboratorium experimenten gevalideerd. In april 2003 is het praktijkonderzoek begonnen met verlichtingsmetingen

op werkplekken en het verspreiden van vragenlijsten onder de werknemers. De kantoormedewerkers zijn zowel over visuele als over niet-visuele onderwerpen ondervraagd. De resultaten van de fysische metingen op 87 werkplekken en 333 subjectieve vragenlijsten laten de verschillende invloeden van licht op mensen zien. De metingen laten zien dat bijna alle bezochte kantoren voldoen aan de visuele criteria. De gebruikers zijn tevreden met hun verlichting. De huidige verlichting voldoet over het algemeen niet aan de veronderstelde niet-visuele verlichtingscriteria. De veldstudie laat significante correlaties tussen de verticale verlichtingsterkte op het oog en de parameters 'vermoeidheid' en 'slaapkwaliteit' zien. Hoge verticale verlichtingssterkten worden daarbij geassocieerd met minder vermoeidheid en betere slaapkwaliteit.

Om de lichtsituatie te verbeteren, zijn er concepten ontworpen, gesimuleerd en gerealiseerd. De nieuwe concepten zijn ontwikkeld met daglicht als primaire lichtbron. Daarnaast is een goede algemene kunstverlichting toegepast en zijn de concepten aangevuld met 'speciale' kunstverlichting. Om de visuele acceptatie van deze nieuwe concepten te evalueren, zijn speciale testkantoren gebruikt waarin testpersonen een dagdeel hebben doorgebracht. De reacties van de testpersonen op de nieuwe verlichtingsconcepten zijn onderzocht bij verschillende verlichtingsniveaus, met verschillende combinaties van systemen en in verschillende seizoenen. De testresultaten laten zien dat het mogelijk is om, naar tevredenheid van medewerkers, gezonde verlichtingsconcepten voor kantoorruimten te realiseren waarbij de verlichtingssterkten hoger zijn dan de waarden die in huidige kantoren voorkomen.
Verschillen in tevredenheid tussen de onderzochte verlichtingsvarianten wordt hoofdzakelijk verklaard door variabelen die gerelateerd zijn aan luminantie (hinder, reflecties en ambiance). De resultaten van een uitgevoerde lichtgevoeligheidstest zijn gebruikt om de verschillen tussen de varianten te begrijpen. De kans op volledige tevredenheid groeit als de luminantie van heldere lichtbronnen lager is dan 1500cd/m². De laboratoriumstudie laat eveneens zien dat zowel de lichtgevoeligheid als de seizoensgevoeligheid zeer belangrijke individuele parameters zijn die beide in (de beoordeling van) een verlichtingsontwerp in acht genomen moeten worden. In het bijzonder de seizoensgevoeligheid zal in vervolgonderzoek verder moeten worden bekeken.

1 Introduction

1.1 Human lighting demands

Since the introduction of electric lighting, a large part of the population is spending time inside buildings during daytime. The consequences of the move from a dynamic outside to a static indoor environment are incalculable. Light controls the human biological clock and is therefore an important regulator of the human physiology and performance. The biological clock is an internal clock which exists in many organisms. This clock is independent of the outside clock or the change from day to night. Internal timing of this biological clock is called the circadian rhythm (Latin: circa = about; dies = day). With absence of (long-term) light simulation, humans go through a sleep-wake cycle of 24,5 hours. Because the light-dark cycle is dictated by the rotation of earth, the human internal clock is adjusted daily to the natural 24-hour cycle of earth rotation. The natural light-dark cycle is the major synchronizing regulator for the biological clock. Homo sapiens evolved from primates and just like their ancestors, these mammals timed their body clocks to the rising sun and the dark of night for millions of years.

1.1.1 Human photoreception

Photoreception is defined as 'the biological responses of organisms to stimulation by light'. In humans, there are two modes of ocular photoreception: visual and non-visual. Both types require ocular (retinal) light perception (Koorengevel, 2001) and the mammalian eye contains both visual and non-visual photoreceptors, situated in the retina of the eyes. The visual photoreception enables humans to see and visual photoreceptors consist of rods and cones. Rods serve vision in dim light (scotopic vision) and cones serve high-resolution color vision in (day)light (photopic vision).

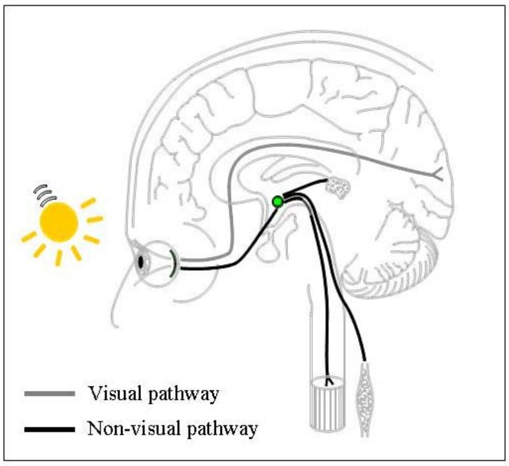


Figure 1.1 Visual and non-visual pathway of light from the eye, via the retina through the human brain (afterVan den Beld, 2003)

Non-visual photoreception affects the circadian rhythm and directly stimulates parts of the brain that influence e.g. the cognitive functions and operating capacity. The biological clock or the suprachiasmatic nucleus (SCN) is located within the hypothalamus at the base of the brain. Supported by light perception, this biological clock system tells the human body when to regulate multiple body functions such as body temperature, sleep patterns and the release and production of hormones, like e.g. melatonin and cortisol. Particularly melatonin ('the sleep hormone') and, to a lesser extent, cortisol ('the stress hormone') are important for human health, mood, well-being and performance.

In 2001, two research groups (Brainard *et al*., 2001; Thapan *et al*., 2001) almost simultaneously found that human melatonin levels were reduced most during exposure to monochromatic blue light at λ=464/459nm. Both groups proposed a 'novel' non-rod, non-cone photoreceptive system in humans with a non-visual photoreceptor that was later identified as melanopsin (Hattar *et al.,* 2003). The observed action spectrum for melatonin suppression shows short-wavelength sensitivity that is very different from the known spectral sensitivity of the scotopic and photopic response curves (see Figure 1.2). In 2002, Berson (2002) discovered a previously unknown function of retinal ganglion cells (RGC). He demonstrated that RGC axons connect to the SCN. The 'retinal-circadian' light transmission system is also coupled to the visual system of rods and cones (Foster and Hankins, 2002; Berson, 2003).

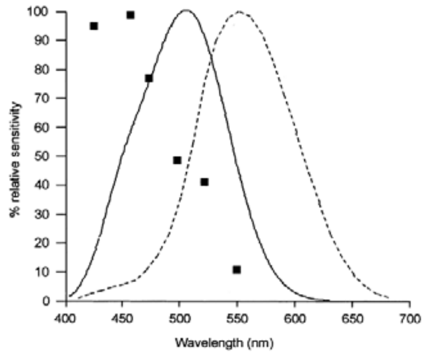


Figure 1.2 Action spectrum for melatonin suppression physiologically derived (■) compared to scotopic (max 505 nm, continuous line) and photopic (max 555 nm, dashed line) vision curves (graph according to Thapan et al., 2001)

The biological clock controls the timing of the release of the pineal hormone melatonin. This hormone is important for sleep and body temperature regulation and is able to influence cognitive performance (Reiter, 1991). In humans, melatonin concentrations exhibit a clear circadian rhythm, with low values during daytime and high values at night. Nocturnal stimulation of the receptors leads to melatonin suppression, which causes reduced sleepiness.

Researchers at mainly medical institutes have investigated the intensity that is necessary to suppress melatonin. In the study of McIntyre *et al.* (1989), five intensities of artificial light were examined for the effect on nocturnal melatonin concentrations. Figure 1.3 shows the relative melatonin suppression as a function of the investigated illuminance levels. The light of ~1000lux intensity was sufficient to suppress melatonin to nearly daytime levels. Nathan *et al.* (2000) found no gender differences in melatonin suppression for light at five tested light intensities. They concluded that the mean melatonin suppression by light in both males and females was only intensity dependent.

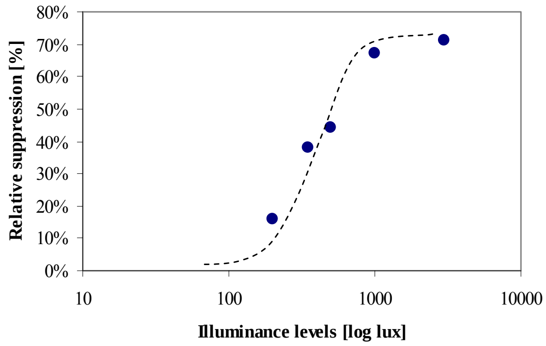


Figure 1.3 Melatonin suppression is light intensity dependent (after McIntre et al., 1989)

In 1997, Brainaird *et al.* (1997) explained that it was initially thought that only very bright photic stimuli (greater than or equal to 2500lux) could suppress nocturnal melatonin secretion and induce other circadian responses. They showed that lower illuminances (less than or equal to 200lux) can suppress melatonin or entrain and phase shift melatonin rhythms when exposure conditions are optimized. Indeed, in 2004, Smith *et al.* (2004) found a significant increase in melatonin suppression during the stimulus after a prior photic history of approximately 0.5lux compared to approximately 200lux, revealing that humans exhibit adaptation to circadian photoreception. However, Rüger *et al.* (2005) explored, in addition to their retinal area research, that 100lux of bright white light is strong enough to affect the photoreceptors responsible for the suppression of melatonin but not strong enough to have a significant effect on sleepiness and core body temperature. Cajochen *et al.* (2000) concluded that nighttime exposure to typical room light (90–180lux) can exert an alerting effect in humans, as assessed by subjective ratings, slow eye movements (SEMs) and electro-encenphalogram (EEG) activity in the theta and alpha range. The magnitude of this alerting response to light depends on the intensity of the light stimulus.

However, several research groups showed that not only intensity of light stimulus is important; the direction of light at the retina plays also an import role in non-visual effects of lighting. Visser *et al.* (1999) investigated whether sensitivity of the nocturnal melatonin suppression response to light depends on the area of the retina exposed (500lux between 1h30 and 3h30). A significant difference in sensitivity was found between the exposure of the lateral and nasal parts of the retinas, showing that melatonin suppression is maximum on exposure of the nasal part of the retina. The results imply that artificial manipulation of the circadian pacemaker to alleviate jet lag, improve alertness in shift workers and possibly treat patients, suffering from seasonal affective disorder, should encompass light exposure of the nasal retina. The results of Glickman *et al.* (2003) indicate that the inferior retina contributes more to the light-induced suppression of melatonin than the superior retina at the light intensities (100 and 200lux) tested in this study. Findings suggest that a greater sensitivity or denser distribution of photoreceptors in the inferior retina is involved in light detection of the retinohypothalamic tract of humans. Rüger *et al.* (2005) explored whether phase shifts and melatonin suppression is due to the same photoreceptors or depends on the same retinal area. Nasal illumination (100lux) resulted in an immediate suppression of melatonin but had no effect on subjective sleepiness or core body temperature (CBT). Temporal illumination suppressed melatonin less than the nasal illumination and had no effect on subjective sleepiness and CBT.

While the results of nighttime studies may be relevant to night-shift work situations, the potential for bright light to be used to improve alertness and performance levels during **daytime** is also studied. In the study of Badia *et al*., (1991) the immediate psychophysiological and behavioral effects of photic stimulation on humans were investigated under four different conditions with bright light of 5000lux and dim light of 50lux. In the first, third and fourth condition, the test persons received light during the night. In the second condition, the male subjects (*N*=8) received photic stimulation during daytime hours. They received alternating 90-minute blocks of bright and dim light. There were no differential effects between bright and dim light on any measurements during daytime.
A few years later, in a study to investigate the bright light effects on alertness and performance rhythms, eight subjects were exposed to either bright light (1000-1500lux) or dim light (50lux) during a 24-hours constant routine (Daurat *et al.,* 1993). During the day (08h00-18h00), all subjects were exposed to bright light (1500-2000lux; daylight and electric lighting); this only improved the mood and motivation levels. In contrast with night exposure, subjective and objective (EEG test) alertness and performances were not improved. In the study of Küller and Wettenberg (1993), two types of fluorescent lamps, 'daylight/full spectrum' (FSFL) and 'warm-white' (WWFL) were compared, each at two different illuminance levels (1700 and 450lux). The researchers focused on the impact of fluorescent light on endocrine, neurophysiological and subjective indices of well-being and stress. EEG-measurements contained less delta rhythm under high illuminance conditions, which indicated decreased sleepiness. Increased beta activity (activity) under high illuminances did not occur. The researchers found no effect of illumination intensity or spectral composition on melatonin or cortisol secretion. In one case, daylight lamps were associated with sleepiness (more theta activity) and in another case with increased activity (greatest afternoon increase in beta activity). In the study of Grünberger *et al.* (1993), healthy young volunteers were exposed to bright light (2500lux) or dim light (500lux) for four hours between 9h00 and 17h00. As compared to the dim-light condition, subjects who were exposed to 'non-visual-active' light showed an improved attention and concentration. Also subjective variables, such as drive, revealed an improvement lasting for the whole investigation period. The authors also reported "that psychophysiological measurements reflected an improvement of central and autonomous activation, which was parallel to the improvement of cognition and of well-being".
Instead of laboratory experiments, Espiritu and colleagues (1994) equipped 106 volunteers with a device that monitors illumination exposures (daylight and electric

lighting) and activity. After data analyses, they found that subjects who were scoring higher on Season Affective Disorder (SAD) mood symptoms spent less time in bright illumination. This suggested that many humans may be receiving insufficient light exposure to maintain an optimal mood. Data of Jewett *et al.* (1997) indicated "that the human circadian pacemaker is sensitive to light at virtually all circadian phases, implying that the entire 24-hour pattern of light exposure contributes to entrainment". They conducted 56 trials during the day on 43 young men, using a three-cycle bright-light (~10,000lux) stimulus against a background of very dim light (10-15lux). Lafrance *et al.* (1998) found that daytime (9h00-13h30) bright light exposure did not affect subjective alertness, sleep latencies or psychomotor vigilance task (PVT) performance. All test persons were fatigued or sleep-deprived by two nights of sleep restriction. The measured intensities ranged from 9000 tot 13000lux in the bright light condition and in the dim light condition from 50 to 150lux. The only effect they found was on the strategy the subjects used, as shown by faster reaction times and an increased percentage of errors in the bright light group. They concluded that if daytime bright light exposure had stimulating effects on vigilance, these effects were not strong enough to compensate for two nights of 4-hour sleep restriction. However, it is reported (Cajochen *et al*., 2000) that half of the alerting effect of a bright light condition (e.g. 9100lux) occurred at approximately 100lux (ordinary room lighting). This may explain why a direct effect of light was not observed in some previous experiments where the effects of 'bright light' were compared to 'dim light' conditions that were of sufficient intensity to elicit near maximal effects. This was the reason that Phipps-Nelson and colleagues (2003) compared a bright light condition of ~1000lux vertically to a dim light condition of <5lux. They also reduced the period of sleep restriction, so the participants were exposed to two nights of five hours of sleep per night. In this research, the authors concluded that daytime bright light decreases sleepiness and improves performance as soon as they were exposed to bright light. This is consistent with the study of Górnicka *et al.* (2004), where 23 subjects were examined under laboratory conditions during two separate 9-hour days (9h00-17h00). They performed psycho-technical tests and answered questionnaires under bright and dim light conditions of respectively ~1100 and ~100lux (vertically). When participants entered the test room, electrodes were applied to continuously record EEG, ECG (electro-cardiogram) and EOG (electro-oculogram) activity. Górnicka reported that employees, working at approximately 100lux at the eye during normal office hours, showed changes in brain activity which did not appear in persons who work at a high, non-visual stimulating lighting levels during the entire day. In bright light conditions, the percentage of sleepiness periods hardly varied, whereas in dim light conditions the number of sleepiness periods increased during the day (~ factor 50). Phipps-Nelson *et al.* (2003) and Rüger *et al.* (2005) concluded that these reduced sleepiness effects appear to be mediated by mechanisms that are separate from direct melatonin suppression. According to Cajochen *et al.* (2004) "it is more likely to be the ventromedial preoptic area (abbreviated as VLPO), which innervates all of the major nuclei of the ascending monoaminergic and in particular the histaminergic system and plays a key role in wakefulness and EEG arousal".

1.1.2 Current recommendations

During the day, it is important for humans to receive enough light at the eye for entrainment of the biological clock. Insufficient light levels could cause lower concentration, reduced performance and decreased well-being and the chance increases that humans doze off as tiredness increases and alertness decreases. Triggering occurs through recently discovered receptors in the human eye. The vertical illuminance at the eye is therefore a key factor. Currently, there are no criteria for this vertical illuminance. Lighting recommendations for office lighting are based on visual criteria. The standards are based on the traditional paperwork offices with desks and tables to work at and put paper on. This makes the 'horizontal illuminance on the working plane' the dominant lighting installation design parameter.
In 2003, the Light and Health committee of the Dutch Lighting Society (NSVV) defined the first lighting recommendations where both visual and non-visual demands were taken into account (NSVV, 2003). With regard to the visual criteria, these recommendations maintain the standard NEN-EN 12464-1 and the IES Lighting Handbook (1993) that prescribe horizontal illuminance levels from 200 to 700lux. For normal office work, a horizontal illuminance of 500lux with a minimum color index $\underline{R}_a$ of 80 is required (ISO/CIE standard, NEN-EN 12464-1), although an amount of $\underline{E}_{hor\ desk}$>800lux is preferred (Begemann *et al.*, 1997, Tenner *et al.*, 1997). Building occupants place a premium on natural light and a view to the exterior. In the Netherlands, it is compulsory to have a daylight opening in an office room with a surface of at least 5% of the floor surface (NEN-EN 12464-1). A view is important for the occupants' sense of well-being, since it provides cues on orientation, time of day and weather. Both the ISO (2000) and the CIBSE standards (2001) recommend limiting the average luminance of lighting fixtures, windows or surfaces which can be reflected in the computer screen to a maximum of 1000cd/m². The current recommendations for maximum luminances are (mainly) based on office work with visual display terminals (VDT's). With regard to non-visual light effects the Light and Health committee recommends light intensities on the vertical plane that are on the order of 1000-1500lux (NSVV, 2003). These high light levels are not demanded all day. A dynamic light dosage means a high level in the morning to support wake-up, then a decrease to the standard level, a high level after lunch to compensate the post-lunch-dip and (especially in winter) after ±15h00 the level will rise to decrease tiredness (van den Beld, 2003), see Figure 1.4.

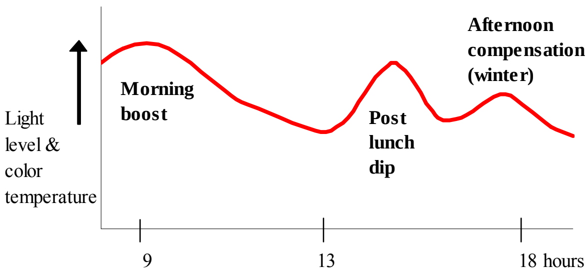


Figure 1.4 Dynamic light dosage (after Van den Beld, 2001): a high level in the morning to wake-up, followed by a decrease to the standard level, a high level after lunch to compensate the post-lunch-dip. After ±15h00, the level will rise to decrease tiredness (especially in winter)

The available two light sources in the office environment are daylight and electric lighting. Daylight is a good and preferred source of energy-efficient, flicker-free light that can reveal subtle color differences with dynamic intensities. Geerts (2003) concluded that the effects of daylight are more positive than electric lighting. People feel more satisfied working under daylight illuminance than working under electric lighting illuminance only. Mainly vertical daylight openings are used to allow daylight. Vertical openings not only allow daylight to enter the room, they also provide information about for example the weather condition and outdoor activities. Until now, view is inextricably related to daylight entrance and therefore strongly influences the difference in perception. However, no building can be lit by daylight alone because daylight is not reliable according to the weather, the time of day or the time of year. Generally, it does not even reach all areas in a building and sometimes the intensity is too low. Higher demands for task lighting lead to the use of the combination of daylight and electric lighting. Begemann *et al.* (1997) showed that people always add extra electric lighting to the daylight level on the desk for all daylight situations in all seasons.

Boyce (2003) investigated three possible causes of why people prefer daylight to electric lighting: for physical, physiological or psychological reasons. Physically, there is no unique characteristic of daylight which separates it from all other light sources. For example, full spectrum lamps are designed to mimic the daylight. The two distinct psycho-physiological systems in humans that respond primarily to light are the visual and the circadian system. The visual system does not respond very sensitively to an exact spectral content of the light and should function equally well by using light consisting of many different wavelengths. Although the human biological clock can be influenced by light of different wavelengths and all types of light with high illuminance levels can manipulate the phase of the circadian rhythm, it is not proved that it should be done specifically by daylight. On the other hand, in experiments conducted in 1993-1994 (Begemann *et al.,* 1994), the average group behavior during the day showed that people prefer to follow the daylight cycle instead of a constant level scenario. Morning, midday and afternoon effects were also distinguished. According to these researchers, visual effects only could not explain this phenomenon and they provided the first subjective clues for non-visual effects of light.

Although electric lighting can be used at every hour of the day and at every location, it needs energy. In a world concerned about carbon dioxide emissions, global warming and sustainable building design, the planned use of natural light has become an important strategy to improve energy efficiency by minimizing lighting, heating and cooling (IEA task 21, 2000). Energy saving has been studied intensively since the energy crisis of 1973. Due to energy savings, the illuminance levels in particularly office buildings were fixed. On the other hand, environmentalism stimulated the development of high-efficiency luminaries, dimming ballasts and improved light fixtures. With recently developed electric lighting solutions, it is possible to change the color temperature and the intensity of the light during the day. Along with smart electric lighting systems, researchers and lighting designers invented and proved a lot of simple and complex daylight control devices to arrange a well-balanced light climate (e.g. Fontoynont, 1999; IEA task 21, 2000). Slanting window sides are the simplest way to reduce contrast (see Figure 1.5 – picture on the left). The illuminated side provides a smooth entrance of daylight. An example of a very complex daylight control system is shown at the picture in the middle of Figure 1.5. This heliostat system leads the daylight to a subterranean room with the help of an extensive mirror system. Venetian blinds are examples of an adjustable daylight control device. Lighting has to become adaptable to personal preferences, which differ widely between individuals. The slides can be turned in a way that they both reduce the direct daylight on sunny days and allow a view outside (see also Figure 1.5 – picture on the right).

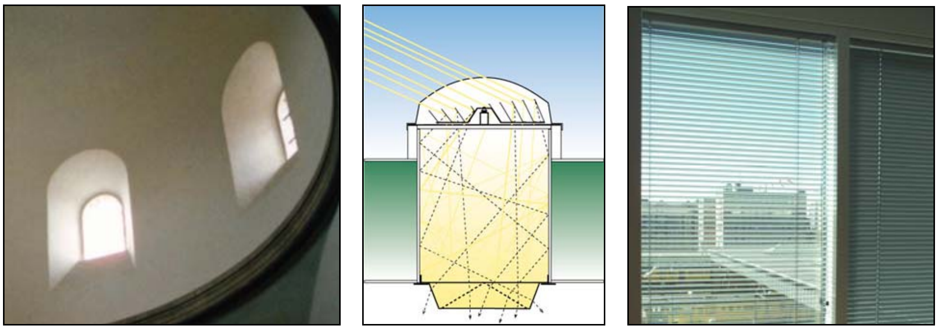


Figure 1.5 Different daylight control devices; from left to right: slanting window sides (simple), heliostat (complex) and Venetian blinds (adjustable)

Well-balanced daylight entrance makes this light source attractive and important in the architectural environment. However, there are two main reasons why daylight should be ‘well-balanced’:

- When daylight falls on glass and other partially transparent materials, some of the incident energy is reflected, some is absorbed by the material and the rest is transmitted to the inside of the building. A part of the transmitted radiation acts to increase the cooling load and this costs energy.
- Large differences in luminances between the daylight opening and the walls can cause disability or discomfort glare. A way to decrease this discomfort is to illuminate the walls with electric lighting.

1.1.3 Concluding remarks

Since the introduction of electric lighting, many people spend time inside buildings during daytime. The consequences of the move from a dynamic outside to a static indoor environment are incalculable. Light is an important regulator of the human physiology and performance. Visual photoreception enables humans to see, while non-visual photoreception affects the circadian rhythm and directly stimulates parts of the brain.

The effects of light on humans both during day and night were investigated by many research institutes. Exposure to (bright) light during the night suppresses the synthesis and secretion of the pineal ‘sleep’ hormone melatonin. The strength of melatonin suppression is dependent on the intensity, wavelength and direction of light. Bright white light levels of 100lux are strong enough to affect the photoreceptors but not strong

enough to have a significant effect on sleepiness and core body temperature. 'Novel' non-rod, non-cone photoreceptors (ganglion cells) in the retina are most sensitive to blue light (λ=~460nm). These special photoreceptors have a greater sensitivity in the inferior retina or are denser distributed. Nasal illumination is more effective than temporal illumination. The non-visual light transmission system is coupled to the visual system of rods and cones.
During the day, bright light (1000-2000lux) in a combination of daylight and electric lighting improves mood and motivation levels. Humans must receive sufficient light exposure to maintain an optimal mood. Different types of electric lighting at high illuminance levels (1700-2500lux) cause decreased sleepiness and increased attention, concentration, cognition and well-being. A dim light condition (~100lux) increases the number of sleepiness periods during the day compared to a bright light condition (1100lux). The fact that half of the alerting effects of a bright light condition occurred at approximately 100lux, might be the explanation of the fact that some studies did not find differences between bright and dim light conditions. The results of bright light exposure must not be overestimated (to compensate for two nights of 4-hour sleep restriction) and 90-minute blocks of bright light and dim light might be not enough to see the difference between the two conditions. All these effects appear to be mediated by mechanisms that are separate from melatonin suppression, but it is more likely to be the ventromedial preoptic area.
Light dosage not only means a determination of intensity, but also of timing and positioning; light should be applied where and when it is demanded. Also, dynamics of lighting in terms of level, spectral composition and direction during the day play an important role.

1.2 Problem statement

Light influences the daily rhythm and well-being of humans in a physiological, psychological and biological way. High lighting levels appear to be necessary to maintain or enhance alertness, performance and health. The horizontal illuminance on the working plane is the dominant lighting design parameter in offices. This is not very relevant for non-visual stimulation where the vertical illuminance (at the eye) is important. It can be expected that current offices will not provide sufficient lighting for adequate non-visual stimulation. It is unknown, however, how bad the situation is in real offices. Furthermore, lighting concepts for office rooms that meet both human visual and non-visual demands are not available. For the purpose of this thesis, *lighting that meets both human visual and non-visual demands without causing visual discomfort* is called 'healthy lighting'.

1.3 Research objectives

This research is restricted to office environments and the objectives are:

- To characterize lighting conditions in current office types with regard to current lighting standards and non-visual variables;
- To develop (conditions for) architectural concepts and system solutions that meet both visual and non-visual lighting demands of humans.

1.4 Hypotheses

The first objective of the research is to characterize lighting conditions in offices with regard to current lighting standards and (non-)visual variables. The following hypotheses can be derived:

- If the visual performance of humans needs a horizontal illuminance of approximately 500lux, then the present-day office lighting does satisfy the visual lighting criteria.
- If the non-visual performance needs a vertical illuminance of approximately 1000lux, then the present-day office lighting does not satisfy the non-visual lighting criteria.

The hypotheses with regard to the relation between the building and the vertical illuminance level are:

- Various inter-architectural parameters (orientation, obstruction, daylight opening and office type) will have a significant influence on the vertical illuminance.
- Various intra-architectural parameters (interior, working place position, daylight control device and electric lighting) will have a significant influence on the vertical illuminance at eye level.

The hypothesis with regard to the relation between the daylight availability and the vertical illuminance level is:

- Various climatic parameters (weather, time and season) will have a significant influence on the vertical illuminance at eye level.

The hypotheses with regard to the relation between the human and the vertical illuminance level are:

- If the intra-individual parameter 'fatigue' is related to the vertical illuminance level at eye level, then the people with a work station with lower levels will indicated more fatigue.
- If the intra-individual parameter 'sleep quality' is related to the vertical illuminance level at eye level, then people with a work station with lower levels will indicate decreased sleep quality.
- If the intra-individual parameter '(physical) health state' is related to the vertical illuminance level at eye level, then people with a work station with lower levels will indicate a decreased (physical) health state.

The second objective of the research is to develop (conditions for) architectural concepts and system solutions that meet both visual and non-visual lighting demands of humans. The following hypotheses can be derived:

- If acceptance is related to vertical illuminance levels of 1000lux that are realized within the human visual comfort limits, then increasing the vertical illuminance to 1000lux will not decrease the acceptance of individuals.
- If acceptance is related to vertical illuminance levels of 2000lux that are realized within the human visual comfort limits, then increasing the vertical illuminance to 2000lux will not decrease the acceptance of individuals.

- Specific lighting conditions with a vertical illuminance of 1000lux will have a significant influence on the acceptance of a vertical illuminance of 1000lux.
- The seasonal period will have a significant influence on the acceptance of a vertical illuminance of 1000lux.

The hypothesis with regard to the relation between the human parameters and the vertical illuminance level is:

- Various inter-individual parameters (gender, age, eye correction, season sensitivity, chronotype and light sensitivity) will have a significant influence on the acceptance of a vertical illuminance of 1000lux.

1.5 Outline

The thesis opened with an introduction to the problem field and shows recent developments according to relevant medical, biological and technical literature (chapter 1). According to the literature, the total flux of visual radiation on the retina determines the non-visual light exposure. An experimental set-up that holds retinal exposure detectors was developed and used in laboratory experiments. Chapter 2 discusses the validation of the measurement equipment, the contribution of parameters (parameter study) together with the applied methodology.

The mobile experimental set-up was used to characterize the actual lighting conditions in ten office buildings in the Netherlands (field study). The outcome of the physical measurements at 87 workstations and 333 subjective questionnaires confirmed the hypotheses about (non-)visual lighting criteria and describes the state of the art (chapter 3). People with a work station with lower levels indicated more fatigue and decreased sleep quality.

To improve the situation, new lighting concepts were designed, visualized and realized. Daylight is an important light source for healthy lighting. The new concepts were developed with daylight as the primary light source, supplemented with special electric lighting equipment. To evaluate the visual acceptance of these new concepts, special test offices were used in which test persons spent one shift (laboratory study). The test person responded to the new lighting concepts that were investigated at different levels and in different seasons. The results are described in chapter 4.

The results of the present-day lighting situation and the new lighting solutions lead to design elements that are discussed in chapter 5. Chapter 6 contains main conclusions of the research and recommendations for further research.

2 Experimental set-up for a field study

2.1 Introduction

Literature shows that high light levels increase alertness and reduce fatigue. A field study (described in Chapter 3) was conducted in present-day Dutch offices to investigate the effect of current lighting standards. Non-visual aspects (health, well-being, performance, etc) are not taken into account in the standards. New measurement equipment was developed to measure purposefully and rapidly in the office environment.

In the field test, the measurements were performed during working hours with the employees doing their work. To limit disturbances for office workers, only **short-term** measurements were performed. However, a limited data collection at only one time or over a very short period of time, can provide only a brief snapshot of illuminance levels in the offices. Therefore **long-term** measurements in laboratory offices were performed in advance. The measurements were used to control measuring equipment, determine the contribution of influencing parameters (parameter study) and test a methodology for dividing illuminances in a daylight and electric lighting component.

2.2 Measuring equipment

To obtain information about the non-visual aspects of lighting, it is important to know how much light enters the human eye (Koorengevel, 2001). Because it is not possible to measure directly on the retina, a tailor-made measuring instrument, the Retinal Exposure Detector (RED) was used (Van Derlofske *et al.,* 2000). Retinal detectors were mounted at eye-height at a mobile, experimental set-up.

2.2.1 Theory

Retinal illuminance is the amount of light falling on the retina (Wyszecki and Stiles, 1982). An interesting quality of retinal illuminance is that it remains constant for any object distance. According to Wyxzecki and Stiles, the actual retinal illuminance in visual investigations, produced by an external stimulus, cannot be determined directly. Instead, the conventional retinal illuminance of a particular retinal area is defined by taking the product of the (photopic) luminance $\underline{L}$ [cd/m²] - in the corresponding direction of the external field - and the apparent area $\underline{A}_p$ of the pupil, seen from that direction. For actual eyes, the simple product $\underline{L} \cdot \underline{A}_p$ is useful as a measure of the internal stimulus from which the main effects of pupil variations are eliminated. In practice, the unit adopted for this product is always the ‘Troland’. A Troland is defined as *the (conventional) retinal illuminance when a surface with luminance of one candela per square meter is viewed through a pupil at the eye with an area of one square millimeter*:

$$e_r = L_{scene} \cdot A_p$$

with $\underline{e}_r$ = Troland value [td], $\underline{L}_{scene}$ = scene luminance [cd/m²] and $\underline{A}_p$ = pupil area [mm²].

The term 'Troland value' is preferred to 'retinal illuminance', particularly when the actual retinal illuminance is also under consideration. Troland values are related to illuminance at the retina by the following function (Nillson, 1983):

$$E_{retinal} = e_r \cdot \frac{1}{d_{eye}^{\;2}}$$

with $\underline{E}_{\text{retinal}}$ = retinal illuminance [lux], $\underline{e}_{\text{r}}$ = Troland value [td] and $\underline{d}_{\text{eye}}$ =diameter of the human eye (=22.6mm) [mm]. Illuminance that is measured in front of the eye and which is not restricted by the human anatomy is called vertical illuminance ($\underline{E}_{\text{vert}}$ [lux]). A schematic overview of the different quantities is shown in Figure 2.1.

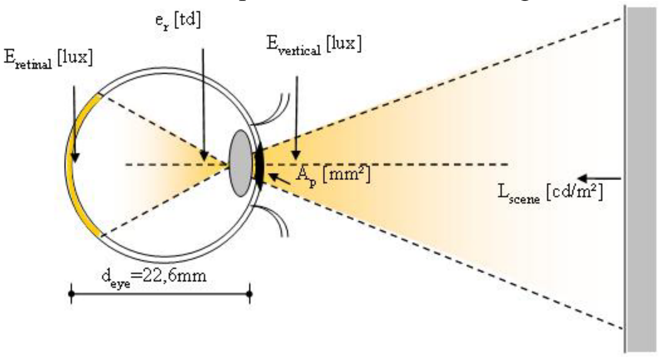


Figure 2.1 Schematic overview of different variables which are necessary to calculate the light in the eye with regard to the troland value [td] and the retinal illuminance [lux]

Boff and Lincoln (1988) described the relationship between photopic troland value and scene luminance as follows:

$$e_r = R \cdot L_{scene} \cdot A_p$$

with $\underline{e}_{\text{r}}$ = Troland value [td], $\underline{R}$ = the effectivity ratio [-], $\underline{L}_{\text{scene}}$ = scene luminance [cd/m²] and $\underline{A}_{\text{p}}$ = pupil area [mm²]. The effective pupil area is less than the actual pupil area because the relative contribution to the brightness perception decreases as the light enters the pupil at an increasing distance of the pupil centre (see Figure 2.2). This effect is called the Stiles-Crawford-effect and may be considered as an optical property of the cone receptor cells. The effectivity ratio, $\underline{R}$, allows the Stiles-Crawford effect and is defined as follows:

$$R = 1 - 0.0106 \cdot d_p^{\,2} + 0.0000416 \cdot d_p^{\,4}$$

where, $\underline{d}_{\text{p}}$ = the eye's pupil diameter [mm]. According to Nilsson (1983), some researchers argued that the Stiles-Crawford effects make the troland ambiguous unless the pupil size is also specified.

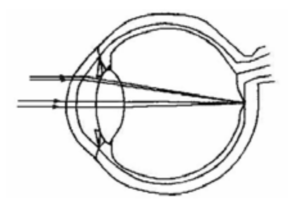


Figure 2.2 Schematic representation of the eye and pathways of axial and non-axial light beams

The pupil is the adjustable opening at the centre of the iris that allows the varying amounts of light to enter the eye. It changes in size in response to ambient light levels. The pupil's horizontal diameter ranges from about 2 to 8mm. In 1952, De Groot and Gebhard (1952) wrote an empirical equation describing the pupil diameter, $\underline{d}_p$, as a function of luminance level:

$$d_p = 10^{(0.8558-0.000401(\log(L)+8.6)^3}$$

2.2.2 Retinal Exposure Detector

As mentioned above, the retinal exposure was measured with Retinal Exposure Detectors. These REDs measure the total amount of light that enters the human eye. The exposure device was designed by determining the spatial efficiency function of the human eye system. This was accomplished by combining the spatial response function of the average human eye with a standard facial cut-off function. The response of the retinal exposure detector device design was shown to match that of the theoretical eye response within three percent. The total flux on the retina is influenced by two factors: the cut-off angle of the eye as a result of anatomic restrictions, and the eye's spatial response function. A facial shield around the detector produces appropriate cut-off angles for the eyes. Developing the instrument, the data was obtained from the eyes of an average person of 45 years old and the pupil was assumed to be representative for the luminance range in the current office environment (see Figure 2.3). The RED is a prototype and measures 'Troland' units. Results of this device are indicated as 'Troland value'.

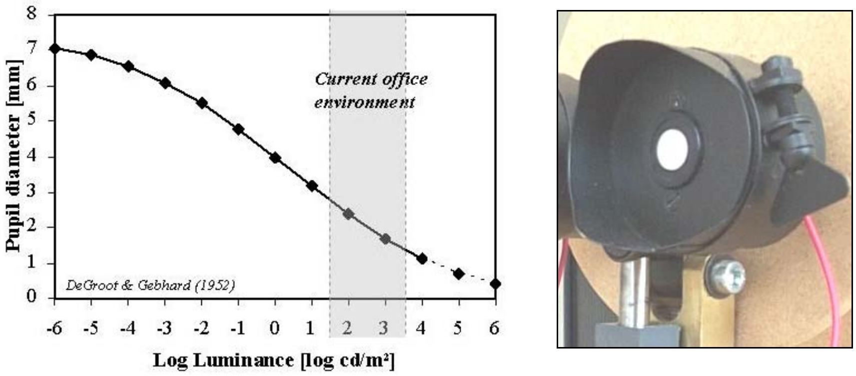


Figure 2.3 Left: calculation of the pupil diameter; right: close-up of the Retinal Exposure Detector

The relationships between several quantities relating to the light at the eye and retina were measured in a test room with homogenous luminance distribution. Daylight was not available in this experimental room. The electric lighting had three presets. The horizontal illuminance levels at the desk were set to ~1700lux (P1), ~550lux (P2) and ~100lux (P3). In current offices, an electric lighting preset of 500lux at the desk is common and therefore preset 2 can be compared with a present-day situation. The other presets were chosen above and below that level. The scene luminance (the wall), the horizontal and vertical illuminances were measured for the three lighting levels. The REDs, a vertical detector and a luminance camera (LMK 96-2) were positioned at eye level ($\underline{h}$=1.25m), at three meters from a white, illuminated side wall. Besides the measurements, the retinal illuminance ($E_{retinal}$) and the Troland value (e_r) were calculated for the preset conditions. Both values including the Stiles-Crawford effect were calculated. The pupil diameter was unadjusted for the calculations (d_p=1.99mm as L_{scene}=365cd/m²; preset 1). The deviations between the measurements and calculation results were little (expressed as percentages: 1 to 4%). The results are presented in Table 2.1. With these results, the influence of anatomic restrictions, taken along in the design of the RED, are calculated for a homogeneous illuminated environment. The 'facial shield' reduced the ordinary vertical illuminance with a factor 0.24 (difference between E_{vert} and e_r). The table shows that the illuminance at the retina, $E_{retinal}$, is approximately 2lux for a vertical illuminance of 1000lux and decreases to 0.6lux for E_{vert}=400lux.

Table 2.1 Results of the measurements and calculation for light at the retina and in the eye (three different electric lighting presets (P))

	Measurement			Calculation			Dev.**
	L [cd/m²]	e_r* [td]	E_{vert} [lux]	d_p [mm]	e_r [td]	$E_{retinal}$ [lux]	
P 1	365 ± 53	915 ± 0	1196 ± 1	1.99	951	1.90	0.04
P 2	117 ± 18	307 ± 3	414 ± 4	1.99	305	0.61	0.01
P 3	23 ± 4	62 ± 2	81 ± 3	1.99	60	0.12	0.03

*Right RED **Deviation measurement and calculation

In the RED, the pupil diameter did not change and the calculation was made for an unadjusted pupil diameter. In reality, the pupil will accommodate and the calculation was repeated for an adjusted pupil diameter (see Table 2.2). The results showed that measured values of luminances around 100cd/m² may be a factor 0.22 too low. This difference increased to a factor 0.40 for very low luminances (20cd/m²). The measuring instrument is suitable for luminances between 200 and 750cd/m² (maximum deviation=0.10). REDs with adjusted pupil diameters are recommended for environments with higher or lower luminances. In this research, only one RED was available.

Table 2.2 Calculation of the light quantities at the retina for unadjusted and adjusted pupil diameter (three different electric lighting presets (P))

	Pupil	d_p [mm]	e_r [td]	$E_{retinal}$ [lux]	Deviation
P 1	unadjusted	1.99	951	1.90	0.00
	adjusted	1.99	951	1.90	
P 2	unadjusted	1.99	305	0.61	0.22
	adjusted	2.34	392	0.78	
P 3	unadjusted	1.99	60	0.12	0.40
	adjusted	2.88	100	0.20	

2.2.3 Experimental set-up

A mobile, experimental set-up was used (see images in Figure 2.5) to measure the Troland value and the vertical illuminance in offices. This experimental set-up simulated a person sitting at a desk. Detectors were mounted at eye-height (h=1.25m). When a person is reading or writing, the head is inclined forwardly circa 25° (Navvab *et al.*, 1997), expressed with γ=25°. The 'head' of the set-up was able to make the inclined angle (see Figure 2.4). When a person is facing straight ahead, the angle γ=0°.

Figure 2.4 Different positions of the experimental set-up according to different positions of humans

A vertical detector (standard, cosine correct Hagner SD2) was located close to the REDs. It was placed at $\underline{h}$=1.35m to have an unobstructed measuring field. Behind the REDs, a board was placed that screened the light like the human body would do. The horizontal illuminance was measured in front of the set-up at the desk. The detector was placed on a sheet of white paper.

Figure 2.5 Mobile, experimental set-up (outside, inside and on duty)

Besides the mobile measuring equipment, two stands with both a horizontal ($\underline{h}$=0.75m) and vertical ($\underline{h}$=1.25m) light detector were used to characterize the room. The stands were distributed over the room(s) and at least one stand was located in the back zone. Two detectors at the window registered the daylight entrance during the measuring period (horizontally and vertically). At each location, the illuminance was measured both horizontally (eye height) and vertically (desk height). A receiver (Hanwell radiologger CR-1), located in the mobile set-up, received the information radiographically, via transmitters, of all detectors in the room. The collected data was stored directly on a laptop that was positioned in a drawer of the mobile set-up. An overview of the measuring equipment used and the specifications can be found in Appendix A.

2.2.4 Concluding remarks

Because it is not possible to measure directly on the retina, a tailor-made measuring instrument was used: the Retinal Exposure Detector (RED). Results of this device are indicated as 'Troland values'. The deviations between measurements and calculation of the Troland value were small. Expressed as percentages, the differences between calculation and measurement were 1 to 4% and therefore negligible. With homogeneous conditions, the RED reduced the ordinary vertical illuminance with a factor 0.24. Illuminance that is measured in front of the eye and which is not restricted by the human anatomy is called vertical illuminance. A vertical illuminance of 1000lux means an illuminance at the retina of approximately 2lux. The calculations of Troland values and retinal illuminances showed that pupil size has a large influence. The RED was developed for measurements in environments with luminances between 200 and 750cd/m². Within this range, the influence of an unadjusted pupil diameter is below a deviation of 0.10. For studies with luminances far above or underneath the indicated range, extra RED's with adjusted pupil diameters are recommended to restrict too large deviations. In this research, only one RED (prototype) was available. Retinal detectors were mounted at eye-height at a mobile, experimental set-up. This experimental set-up simulated a person sitting at a desk. Besides the mobile measuring equipment, two stands with horizontal and vertical detectors and daylight detectors were used to characterize lighting conditions.

2.3 Parameter study

A parameter study was performed to determine the contribution of different parameters in the room. The set-up was therefore placed in test rooms. Information about the light at eye level was obtained by systematically varying the aspects in the rooms. Two test rooms were used for the parameter study. A description of the rooms is given in the next section.

Conditional differences between office buildings are the result of **inter-architectural** parameters. The majority of these parameters is chosen (often by the architect) and appointed during the development of a building and they cannot be changed. Examples of these parameters are:

- Orientation
- Obstructions
- Daylight opening
- Office type

Differences between **intra-architectural** parameters result in differences inside buildings. These parameters are mainly chosen by the owners of the building and can easily be changed by users/owners or during e.g. renovations. Examples of these parameters are:

- Interior
- Workplace position
- Daylight control device
- Electric lighting type and position

In this parameter study, the inter-architectural parameters 'orientation' and 'daylight opening' and the intra-architectural parameters 'workplace position', 'daylight control device, and 'position electric lighting' were investigated separately. Also, the related variable 'weather condition' was taken into account. For each variable, the vertical illuminance and the Troland value (for the right eye) were measured (see Figure 2.6). In daylight situations, both values were divided by the daylight contribution on the window to correct the changing daylight contributions. Per variant, the difference (or correspondence) between these values is shown. As mentioned above, there were two test rooms. The test room that was actually used, was chosen dependent of the investigated variable and mentioned separately at each discussion. The parameter study shows a first selection of variables and can probably be improved or supplemented by future research.

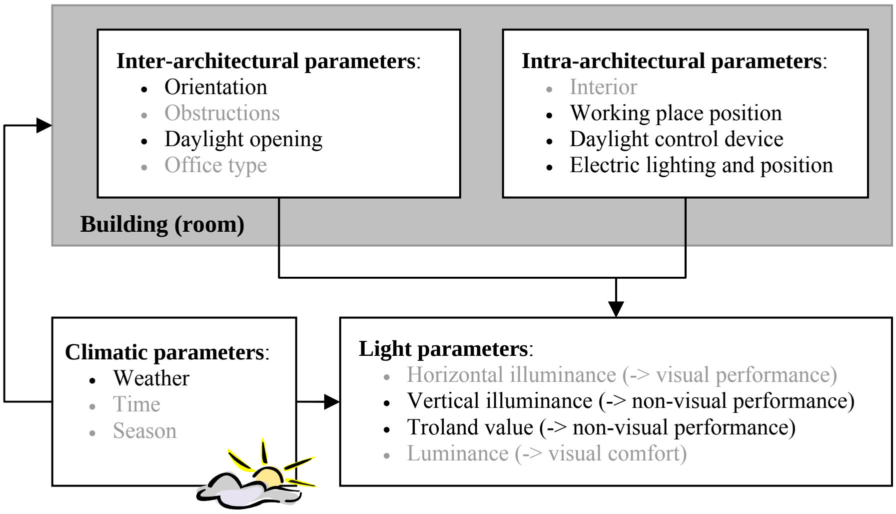


Figure 2.6 Schematic structure of the procedure that was used for the parameter study. The influence of all architectural parameters on both light parameters was investigated separately (dotted paths and variables in grey text were not investigated).

2.3.1 Test facilities

Each building and office type has its own arrangement. With respect to the interior, different user positions are possible. Four working positions (A, B, E, F) in the window zone and four working positions in the back of the room (C, D, G, H) were assumed. A working place was called position A when the daylight opening is located at the left of the user. Position E is the opposite of position A. The user at position B faces the daylight opening. At position F, the user's back is turned to the window. Working places further in the room (back zone) were indicated with letters C, D, G and H. An example of the naming, applied to different working locations, is shown schematically in Figure 2.7. This naming is used in the entire research (parameter study, field study and laboratory study).

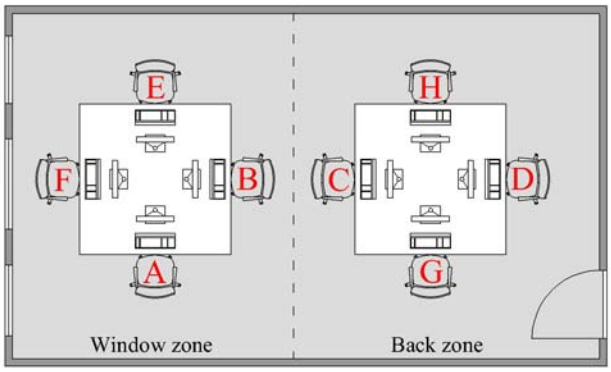


Figure 2.7 Naming of different working locations in an office room (floor section)

To investigate the parameters, two different test offices were used: the 'Swift' room and the 'Etap' room. The Swift room was built for the European Swift-project (Tenner *et al.,* 2001) and the Etap room is a test facility of the lighting company Etap Lighting BV.
The architectural environment of the Swift room is an office space with standard dimensions (6.4 x 3.6 x 2.7m) on the top floor of a two story-high building, facing east. The room is located in Eindhoven (the Netherlands). The façade contains a vertical glazed daylight opening across the total façade width, interrupted twice by steel window posts. The façade is provided with Venetian blinds. The windowsill is at a height of 0.9meters above the floor. The color of the walls and ceiling is white (ρ=0.85) and the carpet on the floor is mixed blue-green (ρ=0.09). The large desk in front of the window and the table at the back both have a light grey desktop (ρ=0.46). Other furniture items in the room are a black and yellow cupboard and blue-seated chairs. The electric lighting in the Swift office exists of three rows with each two recessed 28W twin lamp luminaires (Philips TBS630-2*TL5 28W) with mirror optics, located parallel to the façade. In the Swift room, four positions were available: A, B, C, and D.

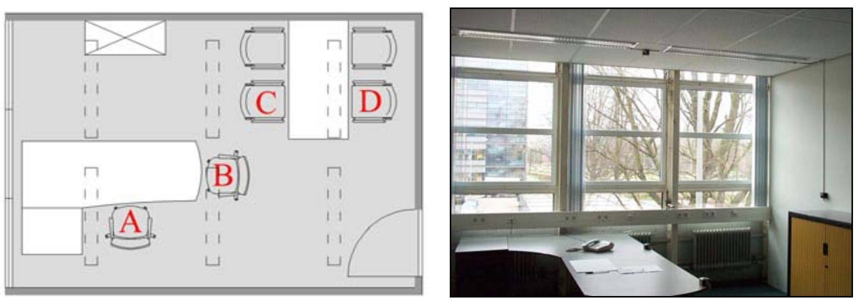


Figure 2.8 Floor section (dotted lines are the luminaire positions) and interior of the Swift test room

The Etap room is a rotating office room with dimensions 5.4 x 5.4 x 2.7m. The room is located in Malle (Belgium) on the top of a two-story building, with an unobstructed view in all directions. To the north, there is a high reflective building (one story). The façade consists of 35% glass (from sill $\underline{h}$=0.8 to ceiling $\underline{h}$=2.7m with two closed parts of 1.35m wide on both sides). The electric lighting in the office room was not used. In the Etap room, three positions were available: A, B and E.

Figure 2.9 Floor section, interior and exterior of the Etap test room

2.3.2 Results and discussion

One condition, per position, was taken as basic position and set as 1.00. Other conditions were compared to this basic condition to show the impact of a parameter. The absolute illuminances or Troland values for the positions were not similar.

Nearly all offices in Western Europe are equipped with vertical daylight openings. When designing daylight openings, one of the main points of interest is to utilize daylight as much as possible. Calculation methods currently used (ISO/CIE, 2002) are based on the horizontal illuminance in the open field with an overcast sky. A daylight opening design is usually based on minimum levels (worst case) that occur when the sky is overcast. In the Netherlands, the sky condition is overcast during approximately 20% of the year (Zonneveldt, 1986). The influence of different **weather conditions** were investigated with a 'sunny sky' and an 'overcast sky' situation in the Swift test room. The room was orientated east and the measurements were taken in the morning (9h00-12h00) on different days in the spring (March/April). The situation for an overcast sky was taken as basic position (set as 1.00) for each position separately (see Figure 2.10).

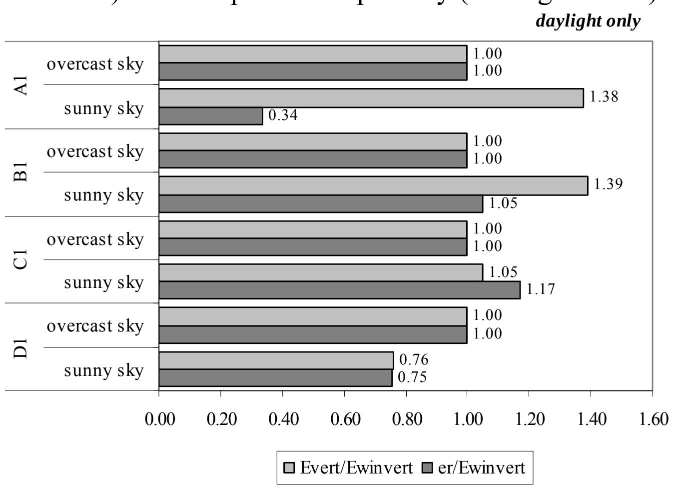


Figure 2.10 Comparison between a sunny sky and an overcast sky situation for the vertical illuminance and Troland value (both corrected by $\underline{E}_{winvert}$ for changing daylight conditions) for positions A and B (south orientation).

Although a 'sunny sky' caused higher absolute illuminance levels, its contribution to $\underline{E}_{vert}$ and $\underline{e}_r$, inside the room was not always efficient. A sunny sky condition is approximately 1.4 times more effective for both positions A and B to receive daylight at a vertical plane. In the back zone, the influence of direct sunlight is hardly noticeable for position C and an overcast sky condition is more effective for position D (factor 0.25). The difference between the vertical illuminance and the Troland value is clearly shown at position A. The facial shield of the RED screened two-third (factor 0.64) of the direct sunlight. The overcast condition was three times more effective with the same amount of vertical illuminance at the window ($\underline{E}_{winvert}$).

On a sunny day, the facade receives a large amount of light but this quantity does not always effectively contribute to the vertical illuminance in the room. Love and Navvab (1994) showed that 'a vertical-horizontal ratio is much more stable over time than the daylight factor for any real sky conditions'. This $\underline{E}_{vert}$ / $\underline{E}_{hor}$ ratio shows that there is only a small difference between the two situations (see Figure 2.11), e.g. $\underline{E}_{vert}/\underline{E}_{hor}$ for position A is 0.83 with sun and 0.78 without sun. Direct sunlight must be present (or absent) on both the vertical and the horizontal detector. Both graphs show the results of the vertical illuminance only.

The ratios $\underline{E}_{vert}/\underline{E}_{hor}$ and $\underline{e}_r/\underline{E}_{hor}$ are suitable for making comparisons between situations with direct sunlight. In the situations with direct sunlight, the ratio $\underline{E}_{vert}/\underline{E}_{hor}$ was used. The graphs have a pattern when this ratio is used.

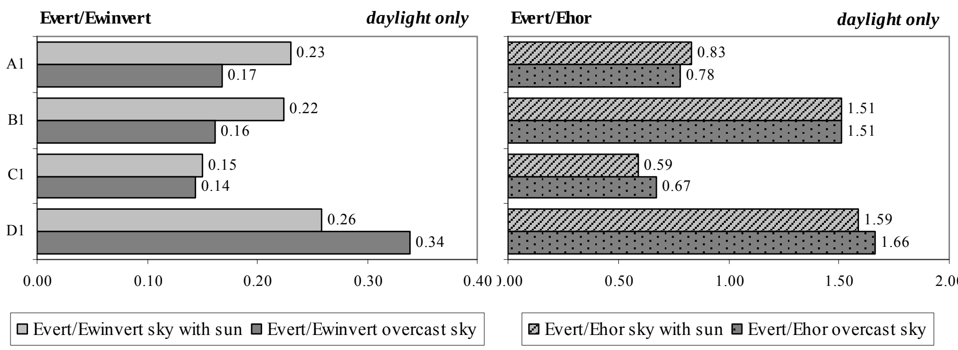


Figure 2.11 The difference between the $\underline{E}_{vert}/\underline{E}_{winvert}$ and $\underline{E}_{vert}/\underline{E}_{hor}$ ratio for four positions in the Swift room at two different weather conditions.

Building orientation, number and arrangement of windows can optimize the availability of natural daylight in the interior of the building. Per orientation daylight openings must be designed to allow light to enter in the interior, without causing visual discomfort. In the Etap test room, the influence of the **orientation** on the vertical illuminance and Troland value was investigated for two working positions (A and B). The situation in the room remained constant. The room and daylight opening turned towards the four main orientations.

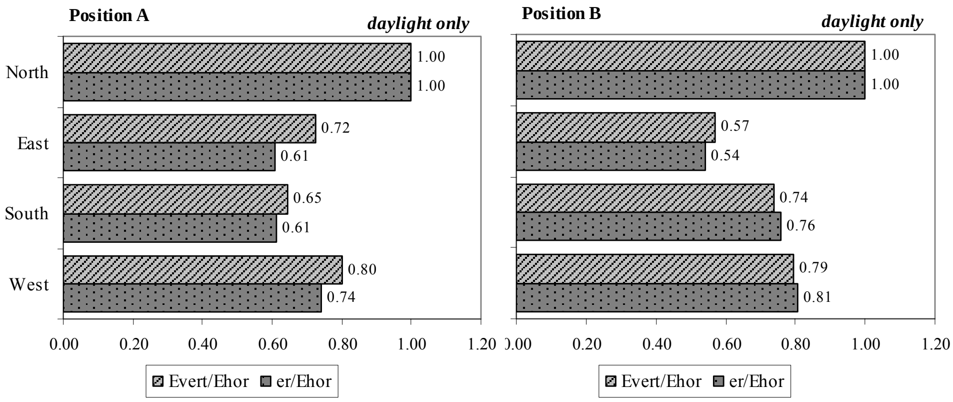


Figure 2.12 Comparison between four main orientations for the vertical illuminance and Troland value (both corrected by $\underline{E}_{winvert}$ for changing daylight conditions) for positions A and B.

The measurements were performed on a semi-overcast day (with sun) in July. The north orientation was taken as the basic position (set as 1.00). According to Figure 2.12, the north orientation is most favorite to obtain high $\underline{E}_{vert}/\underline{E}_{hor}$ (or $\underline{e}_{r}/\underline{E}_{hor}$) ratios. The absolute illuminance levels - caused by daylight - may be much higher for an east, south or west façade but this light does not reach the vertical plane at eye level. A vertical plane at the east orientation received only a factor 0.72 times the light of a north orientation for similar $\underline{E}_{hor}$ levels. The $\underline{E}_{vert}/\underline{E}_{hor}$ ratio of position B, at an east orientation, decreased to 0.57.

Diffuse daylight entering through a vertical window causes a higher vertical illuminance than direct sunlight. Especially in summer, the direction of direct sunlight is more vertical (downward) and less effective to cause high vertical illuminances. Although $\underline{E}_{winvert}$ may be high enough on sunny days, this usually causes visual discomfort and sunscreens are used to reduce the amount of daylight entering the room. Designing a daylight opening in an office to meet non-visual light criteria means that enough light should reach the eye. Assuming that $\underline{E}_{vert}$=1000lux or $\underline{e}_{r}$=1000td is required for non-visual effects the minimum required values for $\underline{E}_{winvert}$ for the tested orientations (compared to the north orientation) are shown in Figure 2.13 for both position A and B.

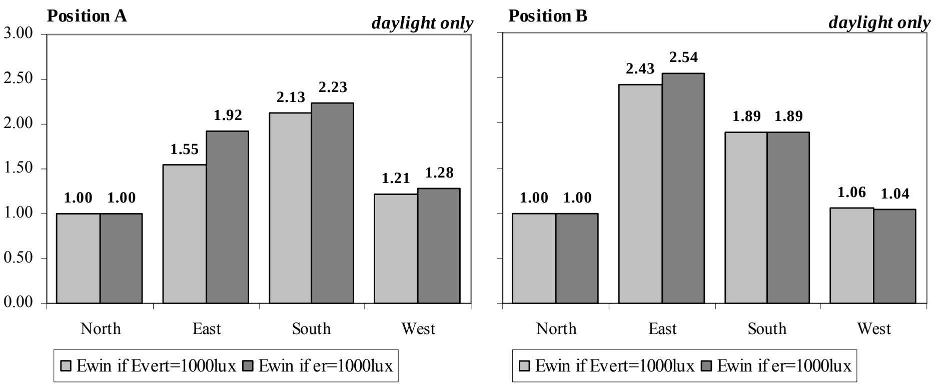


Figure 2.13 The minimum required values of $\underline{E}_{winvert}$ (compared to the north orientation) for $\underline{E}_{vert}$ or $\underline{e}_{r}$ =1000lux for positions A and B.

Results for the north orientation show that reflections from clouds and high reflective areas were more effective in increasing the amount of light at eye level than direct sunlight at the façade, e.g. position A at a south orientation requires 2.13 times more light at the façade to receive an $\underline{E}_{vert}$=1000lux when compared to a north orientation. The Troland values demand even higher quantities of $\underline{E}_{winvert}$.

A **daylight opening** design is possible in many ways (see for example the Daylight Design Variations Book, 2000). The choice of dimensions and the exact location of the opening often depend on both the architectural design and the function. In an office environment, 'daylight entrance' and 'view' are two of the fundamental functions of a window. An opening in the upper part of the façade is favorable for deep daylight entrance (see Figure 2.14) although an opening in the line of sight is necessary for a view. In Dutch office buildings, all daylight openings satisfy the demand of view.

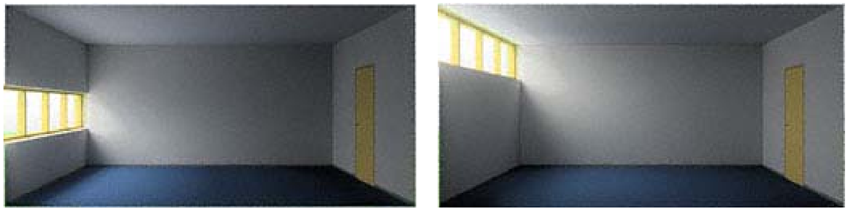


Figure 2.14 Variations in daylight openings: design with either a sight or a light part (from Daylight Variations Book, 2000)

On an overcast day, the influence of window height was investigated in the Etap room. The graphs in Figure 2.15 show the difference between the situation with a maximum daylight opening and a reduced opening. The 'normal' dimensions of the daylight opening were 1.9 x 1.35m (glass area 35% of the entire facade) and after lowering the height of the window top from $\underline{h}$=2.7 to $\underline{h}$=2.4m, the reduced dimensions were 1.6 x 1.35m (glass area of 30% of the entire facade). The height was reduced by means of a light tight screen.

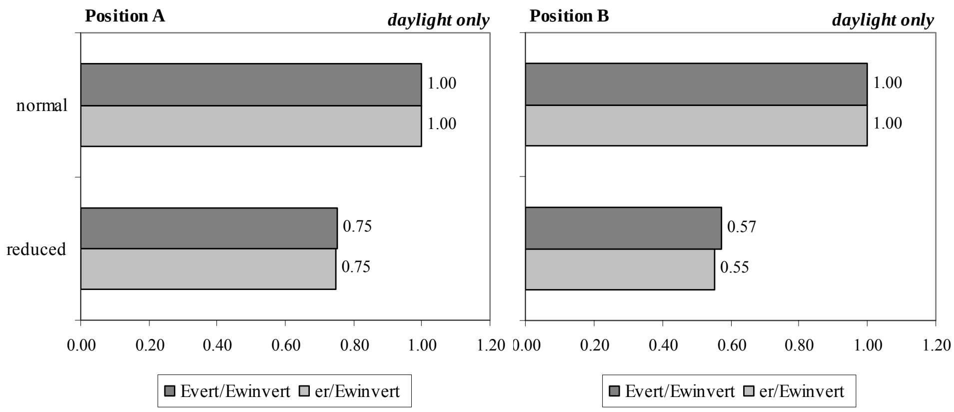


Figure 2.15 The maximum and reduced daylight opening situation for the vertical illuminance and Troland value (both corrected by $\underline{E}_{winvert}$ for changing daylight conditions) for positions A and B.

Although the opening was reduced with only 15%, the ratios $\underline{E}_{vert}/\underline{E}_{hor}$ and $\underline{e}_r/\underline{E}_{hor}$ decreased with a factor 0.25 for position A and 0.44 for position B. In the window zone, the upper part of the façade delivers an important contribution to the illuminances in a vertical plane.

The window configuration can block daylight entrance if, for example, the upper part of the façade is not used as opening. Also different types of **daylight control devices** are used to block or reduce the daylight. However, in some situations they block almost all the light. Although there are different types of daylight control devices, the impact of the devices was investigated by means of white Venetian blinds in the Swift room. On an overcast day in March, the blinds were successively set in three settings: 'open' (which meant that they were horizontally turned), 'half-open' (which meant that they were slightly turned at ~45°) and 'closed' (which meant they were completely turned at ~90°). Figure 2.16 shows that half-open blinds screened the vertical illuminance at position A with a factor 0.64 and at position B with a factor 0.77. The influence on the Troland value was a little smaller. For half-open blinds on position B, the vertical illuminance and the Troland value show a difference (factor 0.10). Horizontal blinds apparently screen the light in a region of the visual field that corresponds with the field of the facial shield.

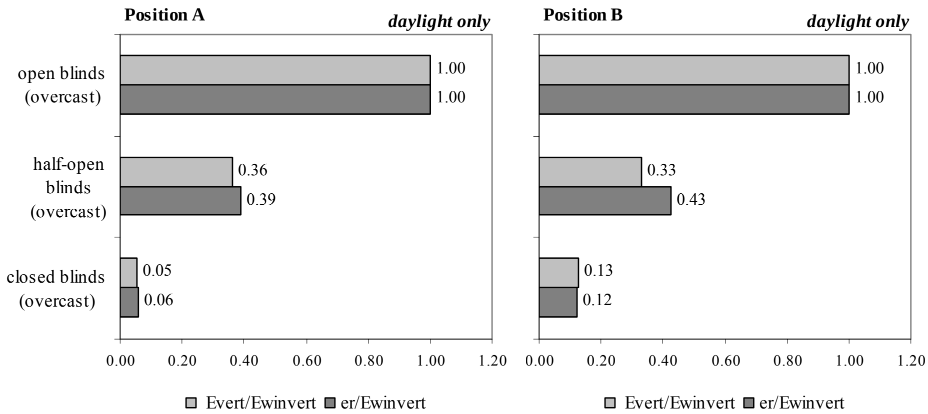


Figure 2.16 Comparison between a situation with open (horizontal, basic position), half-open and closed blinds for the vertical illuminance and Troland value (both corrected by $\underline{E}_{winvert}$ for changing daylight conditions) for position A and B.

The previous studies already showed differences between positions A and B. The influence of the **user position** and the accompanying viewing directions were investigated in the Swift room on an overcast day in February. Position A in this room was taken as the basic position (see Figure 2.17). The figure clearly shows the differences in vertical illuminance at the positions and the influence of the facial shield is also clear. The efficiency almost doubled for position B (increase 0.90). The results for position D showed that a window-facing position is effective, even in the back of the room. The vertical plane at this rear position still received 0.76 times the light of position A in the window zone. Not surprisingly, a position viewing the rear wall is not effective for receiving daylight (position C). Only a factor 0.14 to 0.24 of the daylight (compared to position A) reached the vertical plane.

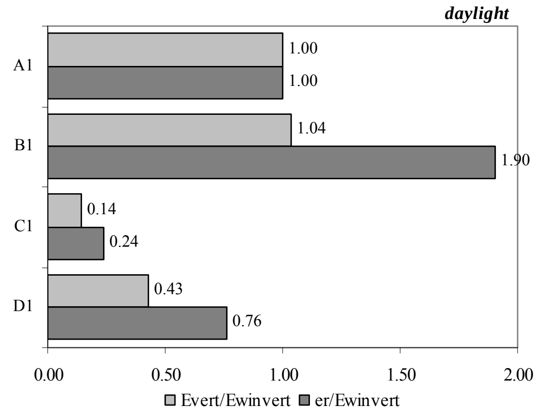


Figure 2.17 Comparison between four standard positions in an office room for the vertical illuminance and Troland value (both corrected by $\underline{E}_{winvert}$ for changing daylight conditions)

An employee changes his/her attitude during work. Therefore, three different **body positions** were taken into account in several measuring positions: a basic position ‘upright, looking straight ahead’, an inclined reading or writing position ‘25° down’ and a turned position ‘45° turned’. The computer is often placed on the right or left corner of the desk. The office employee has to turn approximately 45° and this position was only measured if reasonable.

For position A, a 25° forward inclination meant a factor 0.19 reduction of vertical illuminance and 0.17 reduction of the Troland value (Figure 2.18). A 45° horizontal turn towards the window projects the window in the entire field of view and therefore the light at the vertical plane increased with a factor 2.10. In this situation, the influence of the facial shield of the RED is clearly noticeable. Both the increased projected window area and the decreased ‘functioning’ of the shield contributed to a tripling of the Troland value (factor 3.28). For position B, a 25° forward inclination showed no reduction of the ‘vertical’ illuminance and the Troland value. The turned position was not measured.

Both positions did not show the expected strong reduction at forward inclination. Apparently daylight, which reflected via the table surface, contributed considerably to the vertical illuminance level and Troland value.

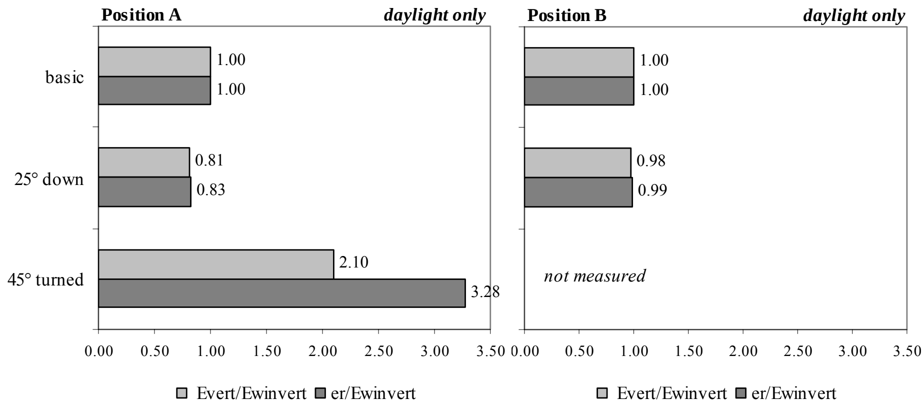


Figure 2.18 Comparison between three body positions for the vertical illuminance and Troland value (both corrected by $\underline{E}_{winvert}$ for changing daylight conditions) for position A and B.

In present-day offices, the electric lighting is nearly always turned on during daytime. Moreover, each workstation must be provided with daylight in the Netherlands. Current electric lighting was designed for the illumination of horizontal areas. In the Swift room, both **daylight** (DL) and **electric lighting** (EL) were investigated. The daylight contribution at four working positions in the room was studied. For three locations, the positioning with regard to the electric lighting was investigated. The electric lighting was set to deliver approximately 500lux at the horizontal desk. The condition with electric lighting only was measured in an evening situation without daylight. The determination of the daylight amount was concurred in both an overcast sky and a sunny sky condition (March). Table 2.3 shows that for an overcast sky, the daylight contribution at position A was two-third of the entire light amount, both for the vertical illuminance and the Troland value (contribution factor = 0.65). Position B is favorable for a large daylight amount. Expressed as a percentage, 80% of the light at (in) the eye was delivered by daylight. Although both positions were located in the back of the room, the illuminance on the retina differed considerably between positions C and D. The position facing the rear wall (C) received only a factor 0.42 of the entire light amount from the daylight compared to position D, which received a factor 0.66 / 0.71 of the light amount.
In a sunny sky situation, daylight contributions were very high and electric lighting was hardly noticeable in the measurements. For both the vertical illuminance and the Troland value, the daylight contribution is a factor 0.90 to 0.95 of the entire light amount at the eye.

Table 2.3 Comparison between a situation with both daylight and electric lighting (DL+EL=basic position) and a condition with daylight only (DL) for the vertical illuminance and the Troland value for four positions.

		Overcast sky		Sky with sun	
Pos.		$\underline{E}_{vert}$	$\underline{e}_r$	$\underline{E}_{vert}$	$\underline{e}_r$
A	Daylight and electric lighting	1.00	1.00	1.00	1.00
	Daylight	0.65	0.65	0.95	0.81
B	Daylight and electric lighting	1.00	1.00	1.00	1.00
	Daylight	0.80	0.82	0.94	0.93
C	Daylight and electric lighting	1.00	1.00	1.00	1.00
	Daylight	0.42	0.42	0.91	0.92
D	Daylight and electric lighting	1.00	1.00	1.00	1.00
	Daylight	0.66	0.71	0.90	0.91

The contribution of electric lighting with regard to position was studied separately. Position A had a viewing direction parallel to the luminaire and positions B and C had a viewing direction perpendicular to the luminaire. Position B was located directly underneath the luminaire and position C was located ±0.5m further on (see also Figure 2.8).

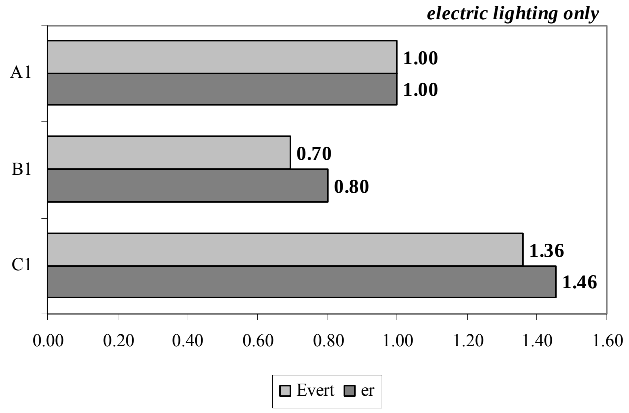


Figure 2.19 Comparison between three positions with different locations with regard to the electric lighting: position A (parallel), B (perpendicular close) and C (perpendicular far)

In current lighting designs, a position parallel to the luminaire is favorable because most luminaires have special louvers to screen the direct light from the tube. This position (A) was taken as the basic position and comparison with position B showed a reduction of 0.30 of the vertical illuminance and 0.20 of Troland value. The 'remote' location of position C caused higher light levels in the vertical plane because the location was favorable according to the photometric distribution of the luminaire. The vertical illuminance increased to a factor 1.36; the Troland value to a factor 1.46.

2.3.3 Concluding remarks

Although a 'sunny sky' caused higher absolute illuminance levels, its contribution to $\underline{E}_{vert}$ and $\underline{e}_{r}$, inside the room, was not always efficient. To receive daylight at a vertical plane, a sunny sky was approximately 1.4 times more effective for window zone positions. In the back zone, the influence of direct sunlight is less noticeable. More daylight at the facade does not always mean higher vertical illuminances. On a sunny day, the facade receives a large amount of light but this quantity does not always contribute effectively to the vertical illuminance in the space.

The ratios $\underline{E}_{vert}/\underline{E}_{hor}$ and/or $\underline{e}_{r}/\underline{E}_{hor}$ are suitable for making comparisons between situations with direct sunlight on the condition that there is direct sunlight present (or absent) at both the vertical and the horizontal detector. Results for the north orientation showed that reflections from clouds and high reflective areas were more effective in increasing the amount of light at eye level than direct sunlight at the façade.

A window-facing position is effective, even in the back of the room. However, even for a position that 'normally' faces the side wall; a slight horizontal turn towards the window increased the effective daylighting contribution with a factor 2.10. During reading or writing, a person has a slightly inclined position. The positions investigated in the window zone did not show the expected strong reduction during forward inclination. Apparently, daylight that reflected via the table surface contributed considerably to the vertical illuminance level and Troland value.

Especially in summer, the direction of direct sunlight is more vertical (downward) and less effective to cause directly high vertical illuminances. Although the vertical

illuminance at the window may be high enough on sunny days, this usually causes visual discomfort and sunscreens are used to reduce the amount of daylight entering the room. Half-open (Venetian) blinds screened the vertical illuminance window zone positions with a factor 0.70. Closed blinds allow only a factor 0.05 – 0.10 of the light at the façade to enter the room. In situations with closed blinds or less daylight, the light at the eye must be delivered by the electric lighting.
Current electric lighting is designed to illuminate of horizontal areas. A position with a view parallel to the luminaire received one-third more light than a position right below a luminaire with a perpendicular view. A location with a perpendicular view and with a little distance (±0.5m) with regard to the luminaire received the highest light levels in the vertical plane (1.4 times the illuminance of a parallel view). The location in relation to the photometric distribution of the luminaire was favorable.
Daylight contributed two-third of the entire light amount at a position that faces the side wall for an overcast sky. In sunny sky conditions, the facial shield of the RED screened a large part of the direct sunlight. The daylight contribution for the Troland value is sensitive for different weather conditions, dependent of position. The vertical illuminance is more stable.
A position facing the window is favorable for a large daylight amount. With a sunny sky, the daylight contributions were very high and the electric lighting was hardly noticeable in the measurements. The design of a daylight opening in an office plays an important role by delivering enough light at the eye to meet non-visual light criteria. Even a small reduction (~15%) in the upper part of the daylight opening causes an important decrease (up to a factor 0.45) in vertical illuminance levels (window zone).

2.4 Determination of contribution of light sources

2.4.1 Introduction

The light, which is measured in an office building, is nearly always an accumulation of daylight and electric lighting. However, it is not (always) possible to turn off the electric lighting to explore both contributions, during working shifts in current offices. In many offices, electric lighting remains constant for each working position (for offices with no daylight controlled systems) and the daylight contribution changes. A subdivision between the contributions of both light sources determined the quantity and quality of illuminance levels more specifically.
A determination methodology was developed to split the measured vertical illuminance in a daylight and an electric lighting component. Long-term measurements in a laboratory office were used to control the methodology. The parameter study showed that daylight contribution for the Troland value is sensitive for different weather conditions, dependently of position. The vertical illuminance is more stable. Therefore the $\underline{E}_{\text{vert}}$ was taken as parameter for the determination of light source contributions.

2.4.2 Method

The daylight contribution changes all day and comparison between different working situations is not possible with different sky conditions. The daylight contribution must be corrected for the different window illuminances. The vertical daylight illuminance ($\underline{E}_{vert\ DL}$) was therefore divided by the vertical window illuminance. To calculate the $\underline{E}_{vert\ DL}/\underline{E}_{winvert}$ only the contribution of the daylight must be known and this is calculated by means of other detectors at stands in the room.

Vertical illuminance (at eye level) and horizontal desk illuminance are easy to obtain in the offices. For each working location, the ratio between these two parameters was calculated (see also paragraph 2.3.2 about the weather condition). This ratio $\underline{R}_{VH}$ was defined as follows:

$$R_{VH} = \frac{E_{vert}}{E_{hor}}$$

To use the $\underline{R}_{VH}$ properly, direct sunlight must be present <u>or</u> absent for both detectors simultaneously.

The horizontal desk illuminance is compared to the horizontal illuminance of a stand in the back of the room to determine the electric lighting contribution (see Figure 2.20). This stand was located far from the window and the daylight contribution is low. The position with regard to the luminaire of the horizontal detector at the stand was comparable to the desk detector (see Figure 2.20).

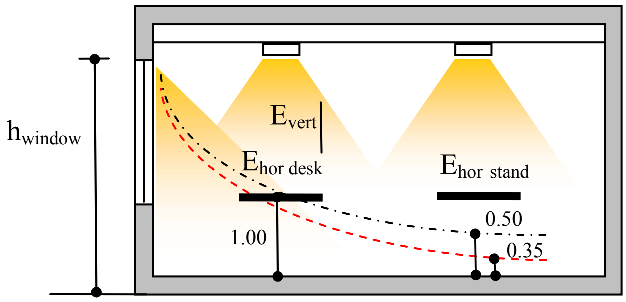


Figure 2.20 Determination of daylight and electric lighting contribution with the help of a stand in the back.

The horizontal illuminance of the stand detector is described as follows:

$$E_{hor\,sd} = E_{hor\,sd\,EL} + E_{hor\,sd\,DL}$$

The daylight amount (dashed lines in the figure) rapidly decreases when the distance to the window increases. At a distance of 4 · $\underline{h}_{window}$ the amount of horizontal illuminance is strongly reduced. In comparison to a desk at ~1m from the window, a desk at ~4m receives less daylight. In a situation without direct sunlight, the light level at the back reduced with 60-70% to approximately 0.35 · $\underline{E}_{hor.}$ In situations with sun, internal reflections a direct sunlight at the desk can increase the level in the back of the room. In comparison to the level at a window position, the light level in the back reduced 50%, to approximately 0.50 · $\underline{E}_{hor}$. The reduction factors of 0.35 and 0.50 were used for stands at a distance of ~4m from the window. In case the stand distance was larger (≥6m), a factor

0.15 was used (10-20% daylight contribution). The reduction factor is indicated as $\underline{F}_R$ and for calculation of the electric lighting contribution the equation used was:

$$E_{hor\,sd\ EL} = E_{hor\,sd} - (F_R \cdot E_{hor\,sd})$$

Because the luminaires applied in the room were equal, by means of the stand detector, the electric lighting contribution to the horizontal illuminance at the desk is known ($\underline{E}_{hor\ sd\ EL} = \underline{E}_{hor\ EL}$). The contribution of daylight is calculated by subtracting the electric amount from $\underline{E}_{hor}$:

$$E_{hor\,DL} = E_{hor} - E_{hor\,EL}$$

In the last step, the ratio R_{VH} was used to calculate the contribution of the daylight on the vertical illuminance ($E_{vert\ DL}$).

$$E_{vert\,DL} = E_{hor\,DL} \cdot R_{VH}$$

The contribution of electric lighting ($\underline{E}_{vert\ EL}$) on the vertical illuminance was calculated by simply subtracting $\underline{E}_{vert\ DL}$ from $\underline{E}_{vert}$.

2.4.3 Validation method

Long-term measurements under laboratory conditions were performed in the Swift-room in March and April. The data, which were collected each minute between 9h00 and 12h00, were used for a validation of the developed method to split daylight and electric lighting contributions. On sunny days, there will be sun in the shift because the Swift room is east orientated. First, the situation with both daylight and electric lighting was measured at four positions. Each position was measured half a day in a situation with and without direct sunlight. The electric lighting was set to deliver approximately 500lux at the desk. Next, the daylight ($\underline{E}_{vert\ DL}$) and electric lighting ($\underline{E}_{vert\ EL}$) contributions were calculated according to the method as described in the previous section. The results are presented in the columns 'Calculation' in Table 2.4. In the evening, with no daylight available, the electric lighting contribution was measured. The daylight contribution was received by subtracting the electric lighting contribution for the overall measurements.

Table 2.4 The results of the calculation and measurements of daylight (DL) and electric lighting (EL) contributions (with and without direct sunlight)

		Sky without sun		Sky with sun	
Pos.	$\underline{E}_{vert}$	Calculation	Measurement	Calculation	Measurement
A	$\underline{E}_{vert\ DL}$	368	338	3228	3305
	$\underline{E}_{vert\ EL}$	154	184	260	184
B	$\underline{E}_{vert\ DL}$	402	499	2338	2446
	$\underline{E}_{vert\ EL}$	225	128	236	128
C	$\underline{E}_{vert\ DL}$	281	182	2462	2471
	$\underline{E}_{vert\ EL}$	152	251	260	251
D	$\underline{E}_{vert\ DL}$	178	247	668	1099
	$\underline{E}_{vert\ EL}$	198	128	559	128

Correlations were calculated between the measurement and the calculation results for the situation without and with direct sunlight. The situation without direct sunlight showed a strong correlation (r=0.735; N=8; p=0.04). The correlation for the situation with direct sunlight showed a very strong correlation (r=0.984; N=8; p<0.01). The results for both groups were plotted in a scatter plot (Figure 2.21) and the measurements are shown as function of the calculation (logarithmic scale).

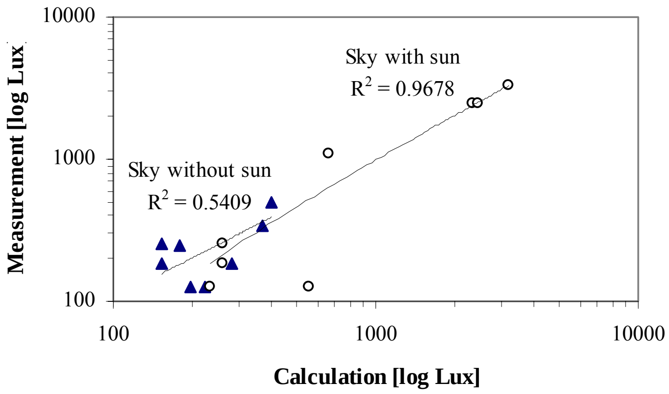


Figure 2.21 Measurement results as function of the calculation results

Although the method for the specific light source contribution is a global approach, the significant correlations showed that it is possible to roughly split up vertical illuminances to their original light sources.

2.4.4 Concluding remarks

The light, which is measured in an office building, is nearly always an accumulation of daylight and electric lighting. However, it is not (always) possible to turn off the electric lighting to explore both contributions, during working shifts in current offices. A determination methodology was developed to split the measured vertical illuminance in a daylight and an electric lighting component. Long-term measurements in a laboratory office were used to control the methodology. The measured vertical illuminance (E_{vert}) was taken as the parameter at the determination of light source contributions.
Correlations between the measurement and the calculation results were calculated for the situation without and with direct sunlight. Both conditions showed strong, significant, positive correlations. The method for determination of the specific light source contributions is a global approach. However, with this method it is possible to roughly split up vertical illuminances to their original light sources.

3 Actual lighting in the office environment (field study)

3.1 Introduction

Since the introduction of electric lighting, the time people spend inside buildings during daytime has increased enormously. The consequences of the move from a dynamic illuminated exterior to a static interior environment are incalculable. Based on an evaluation of office buildings in the Netherlands, the actual lighting situation is characterized. As already mentioned in chapter 2, the differences in (lighting) conditions between offices are the result of inter-architectural parameters; differences inside buildings are the result of intra-architectural parameters. Horizontal and vertical illuminances are the light parameters that were used to describe the lighting situation physically. The field study took aim at four research questions:

1. How do office employees assess different architectural parameters?
2. Do the measured illuminances (vertical and horizontal) meet visual and non-visual criteria?
3. Do different architectural parameters influence (vertical) illuminance?
4. Does vertical illuminance in the room influence individual parameters?

The aim of the field-test is to get a representative inventory for the current office environment by measuring old and new, visual and non-visual parameters and to find correlations between physical parameters and the questionnaires response.

3.2 Method

In April 2003, field tests started in offices by measuring lighting at workstations. The first office building was visited on the 8th of April 2003, the last on the 6th of May 2003. A schematic floor plan of the building and its surroundings, together with a short description can be found in Appendix B. During approximately five minutes per working place, the mean illuminance levels were investigated. Per working place, the median of the absolute illuminance levels was calculated to exclude incidental outliers. The mobile measuring equipment, as described in chapter 2, was developed especially for the measurements. In addition to the physical measurements $\underline{N}$=351 questionnaires were distributed among the employees to obtain data of the assessment of the office environments. The questions were about visual and non-visual items.

The questionnaire was divided into four categories: questions about the office room, questions about the visual perception of the office room, questions about personal feelings (health, mood, alertness, sleep, etc.), and general questions about e.g. age, gender and eye correction. The questionnaire (in Dutch) can be found in Appendix C. The questions as well as the scoring were based on methods that were developed in the past mainly for visual lighting application or medical research (Rosenthal *et al*., 1987; Opmeer *et al.*, 1996; SBI, 1997; TNO, 2002; Tenner, 2002).

The relation between the office employee (individual) and the building (architecture) as well as the relation to the light parameters is shown in Figure 3.1. An overview of the parameters investigated is represented schematically. Dotted paths and variables in grey text are not investigated. The group of parameters, which probably influences the received vertical illuminances most effectively, are the climatic parameters. These are caused by the solstice and the twenty-four-hour rhythm (e.g. weather, time). This group influences both the architectural and the individual parameters.

The office employees were not informed about the exact purpose of the questionnaire. Both questions concerning the office environment in general and questions concerning light/lighting were put among various office-related questions (e.g. about heating, decoration and ventilation systems). The final analysis is restricted to light-relevant questions.
The statistical analyses were performed with SPSS 11.0 and the significance was only accepted with $p<0.05$. The statistical techniques and tests used are mentioned with each analysis.

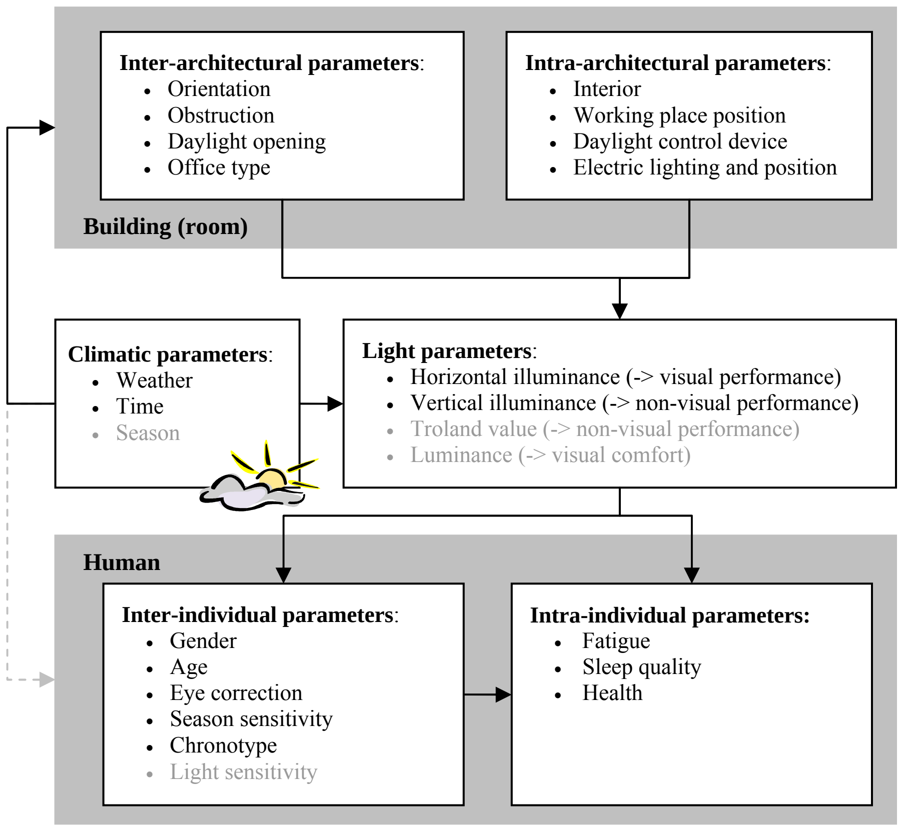


Figure 3.1 Schematic structure of the procedure that was used for analyzing the data from field study (dotted paths and variables in grey text were not investigated)

3.3 Results and discussion

3.3.1 General

In total, N=87 workstations were investigated and N=333 completed questionnaires were returned. The division of measured positions and questionnaires over the ten office buildings is shown in Table 3.1. For each building, at least 20 questionnaires and 4 measurements were available.

Table 3.1 Division of questionnaires and measurements over the office buildings

Building			Measured positions		Questionnaires	
	Surrounding	Floors	Number	Percentage	Number	Percentage
1	Urban	7	12	14%	46	14%
2	Urban	2	5	6%	21	6%
3	Urban	12	4	5%	29	9%
4	Urban	0	8	9%	29	9%
5	Urban	8	9	10%	51	15%
6	Industrial	8	8	9%	20	6%
7	Industrial	2	13	15%	25	8%
8	Industrial	8	9	10%	39	12%
9	Urban	9	12	14%	44	13%
10	Industrial	12	7	8%	29	9%

It was expected that the measurement of three or four workstations per building would be enough to give an indication of the lighting conditions in that building. One measurement had to be representative for several workstations and the results of the questionnaires could be related to this measurement. However, the conditions in buildings were very different. In building 6, for example, all measurements were performed in cell offices with a south orientation. Although the weather condition was almost equal (clear, sunny sky) during all measurements, the vertical illuminances varied between 226 and 2067lux. The differences were mainly the result of user behavior. Like Figure 3.2 shows, in office room 4, the position of the desks was changed and the placement of closets is different in all rooms.

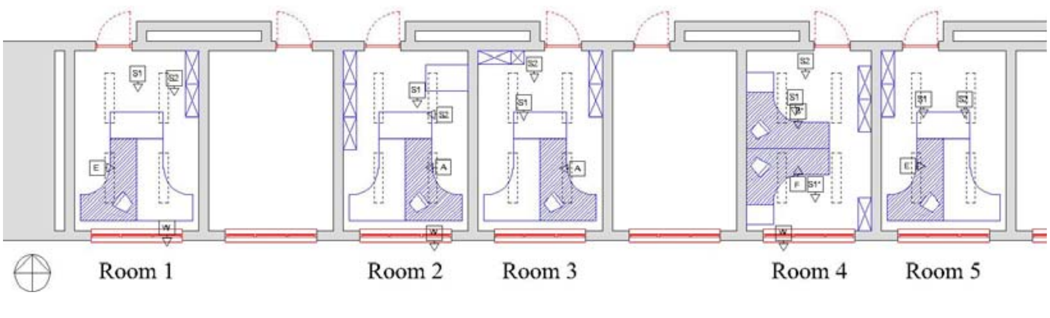


Figure 3.2 Floor plans of five office rooms in building 6. The measured vertical illuminance levels in the cell offices were: Room 1: E_{vert}=2067lux, Room 2: E_{vert}=519lux, Room 3: E_{vert}=462lux, Room 4: E_{vert}=226lux (pos F), E_{vert}=993lux (pos B) and Room 5: E_{vert}=346lux

The use of daylight control devices was also different. Room 1 and 3 had Venetian blinds with horizontal (open) slats. In room 2 and 4, the blinds were nearly closed and in room 5 the Venetian blinds were replaced by a blue, transparent screen. This example is representative for all offices and shows that almost each workstation is different. Therefore, it was necessary to conduct many more measurements than expected in advance.

The analyses concerning the influence of architectural parameters and illuminances on the working position were conducted for $\underline{N}$=87 workstations. The individual parameters were studied based on $\underline{N}$=333 persons. The response of the humans was related to their workstations. Because the workstations differed fairly, a selection was made for this analysis. Only the questionnaires relating directly to one of the measurements were used. In other words, when somebody's workstation was measured, his/her questionnaire was used. For $\underline{N}$=42, this comparison was possible. The remaining 45 positions were either empty or the employee was not present but these positions were still worthwhile to measure. The results of the complete field study will be presented and discussed in the following order:

1. Architectural parameters and the assessment of these parameters
2. Measurements of the light parameters horizontal and vertical illuminances
3. Individual parameters
4. Influence of light parameters on specific individual parameters

3.3.2 Architectural parameters

Office buildings differ greatly. These differences can be **inter-architectural** (between buildings) or **intra-architectural** (inside buildings). The eight architectural parameters that were demonstrated in Chapter 2 and Figure 3.1 are described and discussed.

3.3.2.1 Inter-architectural parameters

Building **orientation** influences the availability of daylight in the building. In the field study, the orientation of the 87 measured workstations is divided into four main directions (North, East, South and West). The division of workstations and questionnaires over these orientations is shown in Table 3.2.

Table 3.2 Division of measurements and questionnaires over the four orientations

	Measurements	Questionnaire
North	14 positions (16%)	89 persons (27%)
East	28 positions (32%)	85 persons (25%)
South	21 positions (24%)	60 persons (18%)
West	24 positions (28%)	99 persons (30%).

In answer to the question about the availability of direct daylight, 92 (28%) persons said not to have direct daylight in their offices at any moment of the day. An explanation for this could be that these employees were located at a north orientation (53 persons, 58%) or that the light from window to person was obstructed. **Obstructions** make it nearly

impossible for direct daylight to enter the room. Adjoining high buildings in the close vicinity of a building obstruct the entrance of light into the room. Fixed building extensions (e.g. an overhang) can limit the (direct) daylight entrance. Even closets and plants can block the light. For 31% of the measured workstations (_N_=27), the light is hindered in a way as described above.
The employees were asked about the blockage of their view from their working positions. 95 persons (29%) answered that it was blocked, 237 persons had an unobstructed view and one person left the question unanswered. According to the respondents, the obstructions were mainly furniture (14 times), dimensions of the window (5 times), building elements (40 times), permanent screens/awnings (39 times) or other obstructions (13 times). The respondents were allowed to mention more than one type of obstruction in their answers.

It does not require a large **daylight opening** to have a view but the entrance of light into the room requires more specific demands. The parameter study (chapter 2) showed that even a small reduction in window height may cause an important decrease in light entrance. The daylight openings in the office buildings were very different (see Figure 3.3 for an impression). Despite these mutual differences, a subdivision of the daylight openings was made based on the glass percentages. Three groups of percentages were used: 30-50%; 50-70% and 70-100%. A glass percentage of 30% means that 70% of the entire façade contains light tight materials and 30% contains glass. At 87 working places, 18 positions have daylight openings with a glass percentage of between 30 and 50%, 64 positions have a glass percentage between 50 and 70% and five positions have 70 to 100%.

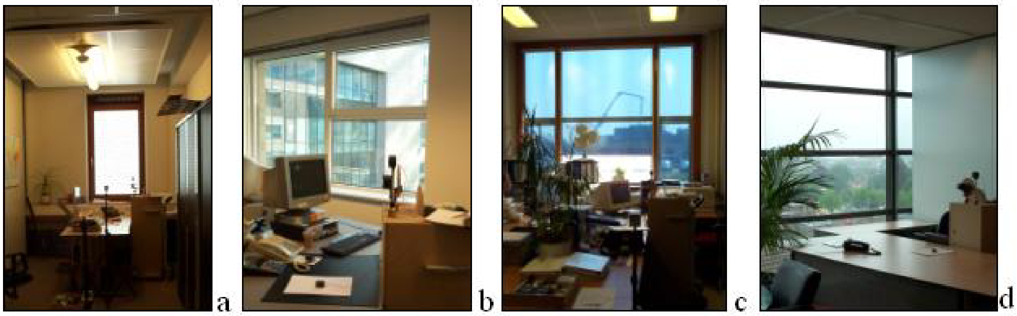


Figure 3.3 Daylight openings with different dimensions (a=30-50% glass; b, c=50-70% glass and d=70-100%)

The test persons were inquired after the daylight openings in their office. The individuals indicated the importance of a daylight opening on a five-point scale for six items (view, daylight availability, time indication, weather indication, diversion and status). The majority (81%) of respondents answered that it is very important to have a daylight opening in their office, 13% said it is important, 4% was neutral, one person said it is not very important and three persons did not consider the window to be important. Daylight availability is clearly the most important reason for a window and status is the least important (see Figure 3.4).

The main layouts for offices are the cellular office (1-2 persons), the group office (3-5 persons) and the landscape office (>5 persons). The measured **office types** in this research were: 28 cell offices (32%), 28 group offices (32%) and 31 landscape offices (36%). The questionnaires were divided in an almost similar way: 73 persons in a cell office (22%), 106 persons in a group office (32%) and the majority in an open-plan office (154 persons, 46%).

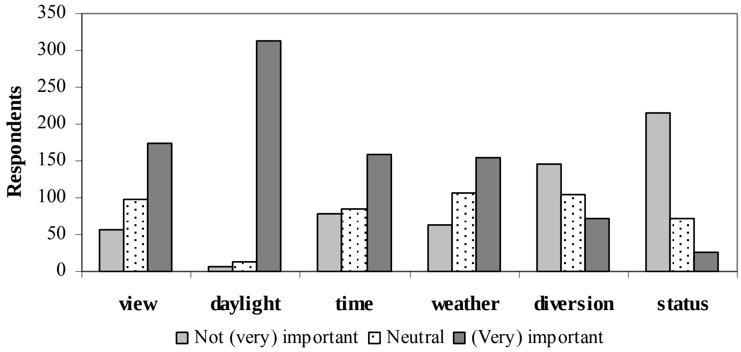


Figure 3.4 The importance of different functions of a daylight opening (window) in an office

3.3.2.2 Intra-architectural parameters

It is not possible to measure an entire office **interior** with one single parameter. For each office, the organization, colors and arrangement of furniture is different. Used materials and their properties play an important role with regard to light distribution in a room. In order to give an indication about the office interior, the reflection coefficients of the inner wall, floor and desk were compared per office building. These coefficients were measured with a spectrophotometer (Minolta CM-2600d). The results of the measurements are plotted in Figure 3.5. Only for building 7 no measurements are available. The reflection coefficient of the walls was almost equal for all buildings (*M*=0.89, *SD*=0.04). Both the floor and the desk finish differed.

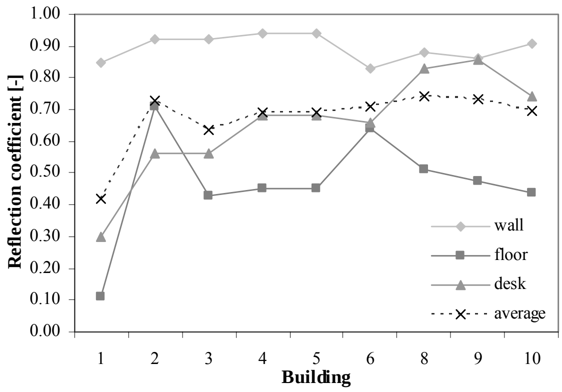


Figure 3.5 Reflection coefficients of wall, floor and desk for nine buildings. No reflections coefficients are available for building 7

The mean reflection coefficient for the floor was ρ=0.45, *SD*=0.17 with a minimum in building 1 (ρ=0.11) and a maximum in building 2 (ρ=0.71). The mean reflection coefficient of the desk was ρ=0.65, *SD*=0.17 (minimum ρ=0.30 in building 1, maximum

ρ=0.85 in building 9). The average coefficient shows that building 1 had a relatively dark interior while building 2, 8 and 9 had the lightest interiors.
The employees were asked to give their general impression of the office room. 13 items were presented and could be scored from ‘very negative’ to ‘very positive’ on a five-point scale. For example, an employee who thinks his/her office room is very quiet marked this item as ‘very positive’. The results are presented in Figure 3.6. The negative (positive) and very negative (positive) answers were summarized. The items ‘light’, ‘enjoyable’ and ‘clean’ scored most positively and ‘attractive’, ‘warm’ and ‘quiet’ were the three most negative items. Not surprisingly, the majority of persons (48%) who assessed quietness in their office as negative had a position in an open-plan office.

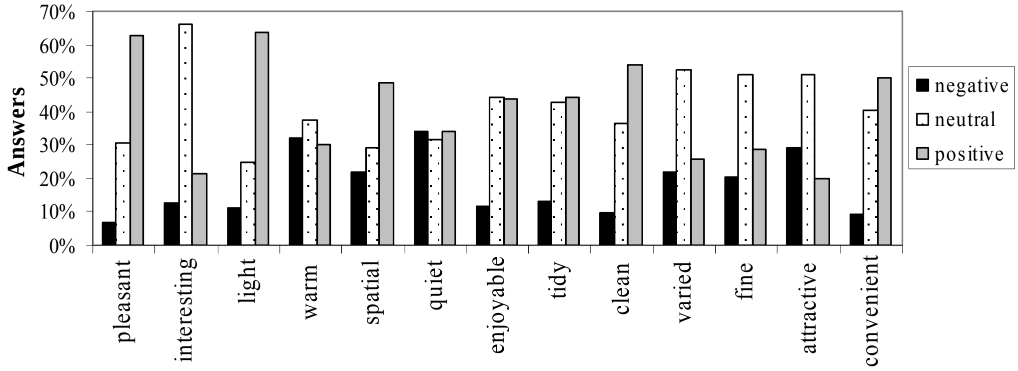


Figure 3.6 The scoring of impression items in the office interior

The employees were then asked to rate the lighting in the office, both electric lighting and daylight. They were to distinguish between the light level at their desks, computers and in the room as a whole. Possibilities of indication were ‘(slightly) too little light’, ‘good’ or ‘(slightly) too much light’. 80% of the persons responded that the light levels at the desk are good. 12% assessed the quantity as too much, 6% marks the levels as too little. With regard to the entire office room, the majority of office employees (85%) was satisfied with the lighting.

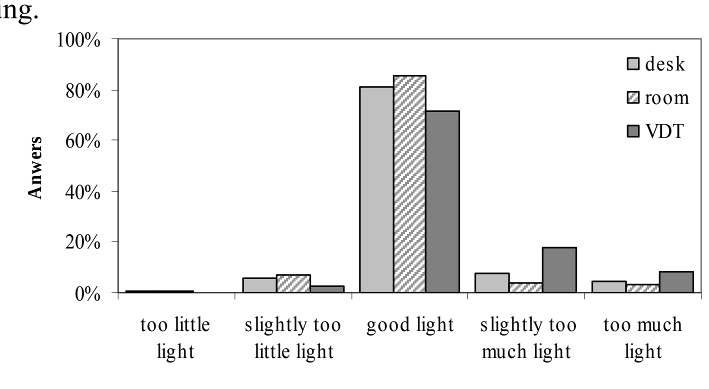


Figure 3.7 Score of the question about the light levels at the working place

The rating of light levels in the entire office room was studied per building as well. In building 1, 8 and 9, the score ‘good light’ in the room is below 80%. Building 1 had the lowest reflection coefficients (see Figure 3.4) and this might influence the light distribution and impression in the office room. Building 8 and 9 had a high average reflection coefficient. However, the opinions in the buildings were divided. The results for the light in the room show that in building 1, 15% of the employees assessed the light as (slightly) too little and 20% as (slightly) too much. In building 8, 21% assessed the light as (slightly) too little and 3% as (slightly) too much. In building 9, 5% assessed the light as (slightly) too little and 32% as (slightly) too much.

The quantity of light falling on the computer display is (slightly) too much for 26% of the employees. Only building 8 had a ‘good light’ score of 90%. Light and computer screens are always a critical combination. The current recommendations (ISO 9241-7, 1997) for maximum luminances in offices are mainly based on office work with VDT’s (visual display terminals). Nine offices used CRT (Cathode-Ray Tube) screens. CRT-screens have a low luminance (~100cd/m²) and are therefore more demanding with regard to luminances and illuminances in offices. Office building 8 uses LCD (Liquid Crystal Displays) with TFT (Thin Film Transistor) technology. LCD-TFT monitors have a higher luminance (250-300cd/m²).
An independent-samples t-test was conducted to compare the evaluation of the light at the VDT for CRT and LCD-users. The Levene's Test for Equality of Variances was significant. Therefore, equal variances were not assumed. There was a significant satisfaction difference between CRT-users (M=3.35, SD=0.68) and LCD-users [M=3.00, SD=0.32, $t(92)$=5.39, p<0.01]. The magnitude of the differences was moderate (η^2=0.08).

Table 3.3 Score of the question about the light levels at the visual display terminal (VDT)

Type	Too little light	Slightly too little light	Good	Slightly too much light	Too much light
CRT	0 (0%)	7 (2%)	199 (69%)	57 (20%)	26 (9%)
LCD	0 (0%)	2 (5%)	35 (90%)	2 (5%)	0 (0%)

As already defined in chapter 2, four working positions (A, B, E, F) in the window zone were assumed in this study and four in the back of the room (C, D, G, H). A working place is called position A when the daylight opening is located on the left of the user. Position E is the opposite of position A. The user at position B faces the daylight opening and at position F the user’s back is to the window. Working places further in the room (back zone) are indicated with the letters C, D, G and H. An overview of the number of measurements and questionnaires per working place is shown in Table 3.4.

In office environments, the majority of daylight openings are equipped with different types of **daylight control devices** - awnings, sun screens, blinds, brightness screens - to regulate the daylight entrance without causing glare or visual discomfort. Especially on sunny days, the high daylight levels cause visual discomfort and the devices are used to reduce the amount of daylight entering the room. In the buildings in this experiment, three types of inside daylight control devices were found: Venetian blinds (33 places; 38%), vertical blinds (39 places; 45%) and screens (one place; 1%). 11 places had an awning on the outside (screens: 4 places; 5% and metal shutters: 7 places; 8%).

Table 3.4 Amount and percentages of measurements and questionnaires per working position

	Measurements		Questionnaires	
	Number	Percentage	Number	Percentage
A	26	30%	121	36%
B	11	13%	41	12%
C	2	2%	14	4%
D	3	3%	15	5%
E	27	31%	102	31%
F	8	9%	31	9%
G	4	5%	6	2%
H	6	7%	3	1%
Total	87	100%	333	100%

The awning situation was subdivided into 'open', e.g. pulled up blinds or pushed aside lamellas; 'half-open' e.g. horizontal and slightly turned blinds or lamellas, and 'closed'. The classification 'half-open' was made for situations with at least 40% of the glass percentage visible. Three locations (3%) were equipped with both an inside and an outside device. The measurements were performed with open (30 places; 35%), half-open (48 places; 55%) en closed devices (9 places; 10%).
The questionnaire inquired after the presence of awnings (sun screening) and whether it was operated manually or controlled automatically. 66 persons (20%) answered that the awnings were absent in their office room. 241 persons (90%) had manually controlled awnings and 25 (9%) persons had automatically controlled awning. One person did not answer the question. The majority of employees with a daylight control device ($\underline{N}$=267) responded that their awnings were always open (42%) or half-open (43%) and 39 persons had a position with permanently closed awning (15%). This means that a large part of the daylight entrance is blocked. The awnings or blinds were frequently closed because of discomfort and closed screens generally remained closed, although the problem had already been solved. The questionnaire also inquired after the satisfaction with the sun screening. The results of this question are presented in Figure 3.8 and this graph shows that 66% of the office employees were (very) satisfied. There is a significant, positive correlation between the situation of the control device and the satisfaction ($\underline{r}$=0.254, $\underline{N}$=265, $\underline{p}$<0.01). Closed awnings or blinds are dissatisfactory to many individuals.

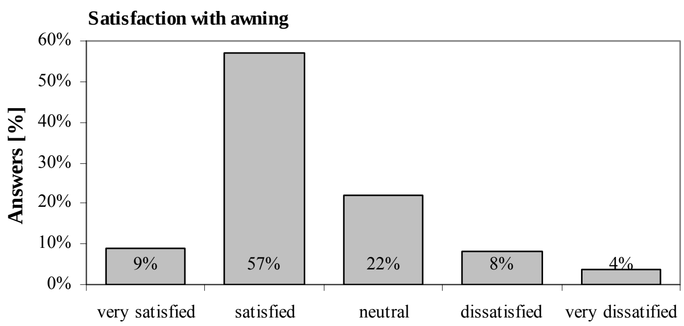


Figure 3.8 Satisfaction with the awning possibilities

In present-day offices, the **electric lighting** is nearly always on during daytime. Current electric lighting that is applied in office buildings has been designed to illuminate mainly horizontal areas. Figure 3.9 shows an impression of the luminaires as found in the office buildings. All offices were equipped with (long) fluorescent tubes.

Figure 3.9 Different types of electric lighting

The color temperature of a lamp indicates how the light appears to the human eye when looking directly at the illuminated part. When the desired effect should be warm, light sources in the 3000K - 3500K range are used. For a slightly cooler effect, lamps with 4000K are used. At 18 measuring places, 4000K lamps were found; 69 workstations were equipped with 3000K lamps. The power of the lamps were between 35 and 60W and depending on the design, the luminaire contained one, two or four lamps. However, in the luminaires with four lamps, one of the lamps was disconnected by the users to save energy.

Optics are the light-controlling part of the luminaire, including the reflector, diffuser and louvers. In the field studies, four different optic types were found: mirror optics with straight (43 workstations) and parabolic louvers (26 workstations), indirect parabolic reflectors (10 workstations) and prismatic covers (8 workstations). The optics play an important role in the distribution of light. Most luminaires are down-lighters and the light at the vertical plane depends on the position. Figure 3.10 (left) shows that a vertical plane underneath or very close to the luminaire (distance $\underline{a}_{xy}$=0-0.5m) receives less light than a more remote vertical area ($\underline{a}_{xy}$>0.5m). This corresponds with the measurements as a function of the luminaire position in the parameter study (chapter 2). The picture on the left (Figure 3.10) shows a position perpendicular to the luminaire. More often, a position with a viewing direction parallel to the luminaire is chosen and most luminaires are designed for this position. The picture on the right shows an example of the photometric light distribution of a luminaire with mirror optics. The louvers of a luminaire reduce the amount of light in a parallel viewing direction to avoid glare. In the viewing direction perpendicular to the luminaire, the light level at the vertical plane is higher. 57% of the measurements were performed at a position parallel to the luminaire ($\underline{N}$=32 with $\underline{a}_{xy}$<0.5m; $\underline{N}$=18 with $\underline{a}_{xy}$>0.5m) and 43% were performed at a position perpendicular to the luminaire ($\underline{N}$=23 with $\underline{a}_{xy}$<0.5m; $\underline{N}$=14 with $\underline{a}_{xy}$>0.5m).

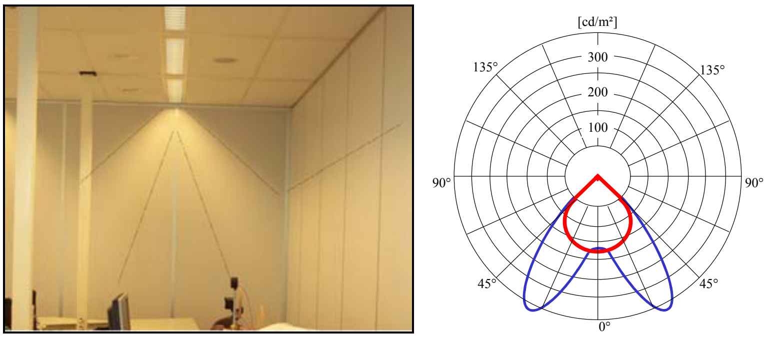


Figure 3.10 The influence of position with regard to the electric lighting source and an example of a diagram for photometric light distribution of a luminaire

The results of measuring the interior (average reflection coefficients and light levels) of office buildings demonstrated that the employees were very satisfied with the combination of daylight and electric lighting. Three questions were specifically asked about electric lighting. The first question inquired after the possibility of manual activation of the electric lighting. 136 persons (41%) were able to switch on the electric lighting themselves, for 196 employees (59%) the lighting is controlled automatically and one person did not answer the question.

In general, 139 persons (41%) of the respondents indicated to agree with automatic lighting control and 191 persons (57%) prefer to activate the lighting themselves, in response to the second question. Three persons did not answer this question. The combination of the two questions shows that 40% of the respondents could not switch on the lighting manually and was not bothered by this. The third question inquired after the importance of the possibility to manually switch the electric lighting on and off. As Figure 3.11 shows, the opinions about regulation diverge considerably.

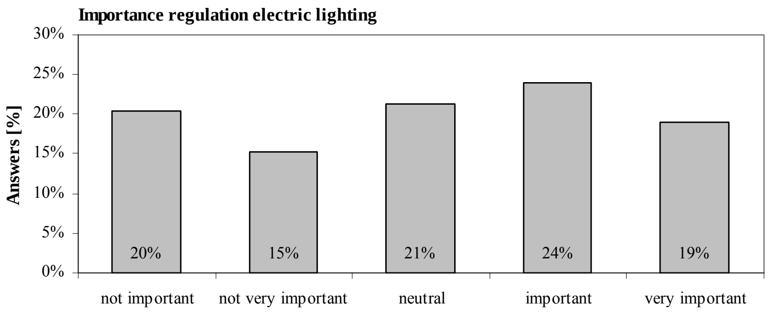


Figure 3.11 Answers about importance of the electric lighting regulation

3.3.2.3 Climatic parameters

The measuring period April/May was a period with frequent changes of weather conditions. From the N=87 measurements, N=15 were executed with an overcast sky and at N=20 measurements there was a semi-overcast sky. However, the majority of locations (N=52; 60%) were measured on sunny days with a blue sky. The measuring time in the office buildings was very short (3-5 minutes) to avoid too much disturbance for the employees. Only one measurement per position was made, either morning or afternoon, and not repeated. Therefore, only one value is available per position. That is why conclusions with regard to absolute measurements must be drawn very carefully. The results depend on influences of climatic parameters (time, weather condition and season) in relation with the orientation of the building. Table 3.5 shows that 47 measurements were performed before 12h00 and 40 measurements after 12h00. Measurements were achieved at every orientation.

Table 3.5 Amount of measurements per shift and orientation

	Orientation				
	North	East	South	West	Total
Morning (< 12h00)	7	15	12	13	47
Afternoon (>12h00)	7	13	9	11	40

3.3.3 Architecture and light parameters

3.3.3.1 Horizontal illuminances

Foveal vision and the required task illuminance (luminance) to see 'adequately' in the traditional administrative office have been the main determining factors for the lighting standards. The fact that desks and tables are used to work at and to put papers on has resulted in 'horizontal illuminance on the working plane' as the dominant lighting installation design parameter. In an office, occupants need enough light to do their tasks. A poor lighting environment may reduce accuracy, increase the time to do a task and cause fatigue or eyestrain. In the current standards (e.g. ISO/CIE standard, 2002), there are recommendations for illuminance and luminance levels and luminance ratios. There is no exact satisfactory light level because an effective light level depends on a particular task and individual preference. With regard to the horizontal illuminance on the working plane, the standard is set at a minimum of 200lux. The installed electric lighting is largely responsible for the horizontal illuminances at the desk (often 500lux) and was turned on during most measurements. Most offices meet the standards ($\underline{N}$=77 with $\underline{E}_{hor\ desk}$>500lux). Figure 3.12 shows that the horizontal illuminance differed from 300 to 1600lux [$\underline{M}$=884lux, $\underline{SD}$=342 $\underline{N}$=87].

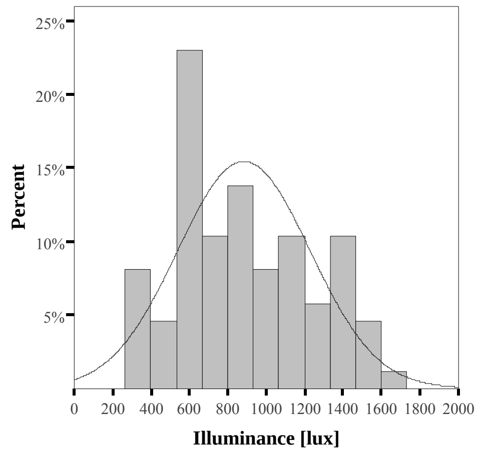


Figure 3.12 Horizontal illuminance levels at the working plane for all measured positions ($\underline{N}$=87)

The horizontal illuminance was between 300 and 500lux for N=9 positions and below 300lux for one position. A subdivision of a room into two regions showed no differences between the window zone (less than 4 meters from the window) and the back zone of the office. The horizontal illuminance for measurements in the window area (N=72) were above the standard values of 200-750lux. In the back zone, where 17% of measurements were performed (N=15), the horizontal illuminance at the desk was almost equal or even higher.

Table 3.6 Mean, absolute horizontal illuminance levels (±SD) at different weather conditions (April-May) per position

		A	B	E	F
Window zone	Overcast	909±788	762±226	867±410	1025*
	Sky with sun	1023±173	580±140	1408±65	760±315
	Sunny	926±313	828±349	907±320	520±110
		C	D	G	H
Back zone	Overcast	-	-	362*	314±15
	Sky with sun		911±20	-	828±390
	Sunny	1322±211	1069±223	1022±417	1160*

* One measurement only

The amount of luminaires did not increase in the back of the room. An independent-samples t-test was conducted to compare the horizontal illuminance of the front and the back positions. There was no significant difference in scores between the front (M=882lux, SD=335) and back positions [M=892lux, SD=402, $t(85)$=0.108, p=0.914]. Table 3.6 shows the mean, absolute horizontal illuminance levels (±SD) in different weather conditions (April-May) per position.

3.3.3.2 *Vertical illuminances*

Daylight entering through a vertical window has a strong vertical illumination component. It was assumed that daylight in spring (April-May) contributes substantially to the light in office buildings, especially in the window zone. Figure 3.13 shows that the vertical illuminance varied from 200 to 1200lux [M=601lux, SD=325, N=87].

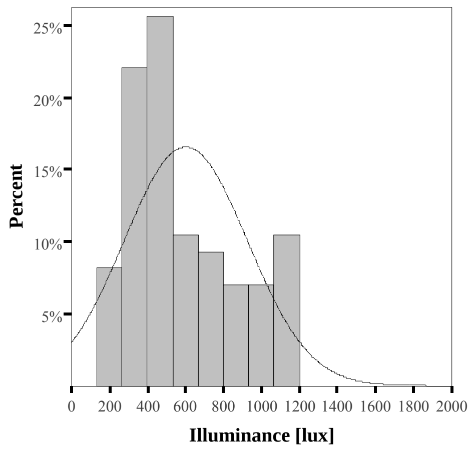


Figure 3.13: Vertical illuminance levels at the eye height for all measured positions (N=87)

The figure also shows that nearly 50% of the workstations had an illuminance below 500lux. The ceiling-based electric down-lighting systems are largely responsible for horizontal illuminances. As a rule of thumb, the ratio between the vertical and horizontal illuminance by electric lighting is approximately 1: 2. For 800lux at the desk, this means 400lux at the eye.

Table 3.7 Mean, absolute vertical illuminance levels (±SD) at different weather conditions (April-May)

		A	B	E	F
Window zone	Overcast	631±342	928±280	595±406	295*
	Sky with sun	817±137	466±140	958±150	361±120
	Sunny	585±276	803±166	679±436	325±104
		C	D	G	H
Back zone	Overcast	-	-	144*	195±64
	Sky with sun	-	836*	-	457±169
	Sunny	354±129	785±488	565±284	646*

* One measurement only

An independent-samples t-test was conducted to compare the vertical illuminance to the front and back positions. There was no significant difference in scores between the front (M=623lux, SD=330) and back positions [M=490lux, SD=286, $t(85)=-1.453$, $p=0.150$]. Table 3.7 shows the mean, absolute vertical illuminance levels (±SD) in different weather conditions (April-May) per position.

3.3.3.3 *Influence of architectural parameters on the vertical illuminance*

Analyses of variance were performed to find a relationship between one or more architectural differences and the measured vertical illuminance. The measurements were performed during working hours with the employees doing their work and therefore it was not possible to turn off the electric lighting. The daylight contribution on the E_{vert} was not determined but there was a sensor at the window that measured the vertical illuminance. The value of this measurement was used as covariate in the conducted factorial analyses of variance. A covariate is a (continuous) variable that is supposed to influence the score of the dependent variable. Vertical illuminance at eye level was the dependent variable because it was suspected that more illuminance at the window meant the more illuminance inside. In this manner the differences in weather condition were compensated.

First, a factorial ANOVA was performed with E_{vert} as dependent, continuous variable, four independent inter-architectural variables (categorical: orientation, obstruction, daylight opening and office type) and $E_{winvert}$ as continuous independent covariate. Only the main effects were tested and interaction effects were not taken into account. The Levene's test of equality of error variances was not significant (p=0.753), which means that the variance between the groups was equal. For the five tested independent variables, only the $E_{winvert}$ showed a significant main effect on the vertical illuminance in the room ($F(2,74)=6.151$, $p=0.015$) and this effect was moderate ($\eta_p^2=0.08$).

Second, a factorial ANOVA was performed with $\underline{E}_{vert}$ as dependent, continuous variable, four independent intra-architectural variables (categorical: average reflection coefficient, working place position, situation of the awnings and position with regard to the electric lighting) and $\underline{E}_{winvert}$ as continuous independent covariate. The Levene's test was significant and this means that the variance of the dependent variable across the groups was not equal. In these situations, it is recommended to set a more stringent significance level ($\underline{\alpha}$=0.01 instead of $\underline{\alpha}$=0.05). There were no significant main effects for the tested variables.

There was no main reason which explained the differences between the illuminances measured. Interaction effects were not taken into account, although the possible reason of illuminance differences may lay in a combination of effects. The differences between the offices were very large (see also the example in section 3.3.1) and an interaction study with this amount of variables is impossible. Furthermore, the measuring time was very short (3-5 minutes). Only an indication of the vertical illuminance in office rooms can be given and this may be another reason for the large amount of low illuminances.
Instead of a statistical analysis for interaction effects, an alternative subdivision was made. The different reasons for the low vertical illuminances were inventoried (by the researcher) for all $\underline{N}$=87 working positions and their properties.
The main reasons for having low vertical illuminance in the office rooms measured were:

- Obstruction: e.g. adjoining high buildings that obstruct light entrance, overhang, furniture or plants
- Daylight opening: e.g. no window in the direct view, very small window
- Position: e.g. position with the back to the window (C or F) or position in the back of the room (C, D, H or G), far from the window
- Daylight control devices: e.g. closed almost all day
- Electric lighting: e.g. only downward light distribution, position of luminaires

With regard to the reasons for low vertical illuminances, three groups were distinguished:

1. No-chance: the number of reasons is high and the nature of the reasons is such that high vertical illuminances are not expected. Fixed building circumstances (like window size or adjoining buildings) cannot be changed.
2. Maybe-chance: the number of reasons is low and the nature of reason can be easily altered. Changing 'wrong' positions into 'better' positions combined with removing small obstructions like plants and opening blinds may provide improvements.
3. Chance: no special reasons for having low vertical illuminance.

All 87 measured working places were categorized into one of the groups. The categorization was based upon subjective observations. The measured vertical illuminances distributed over the three 'chance' groups were plotted in a graph (see Figure 3.14).

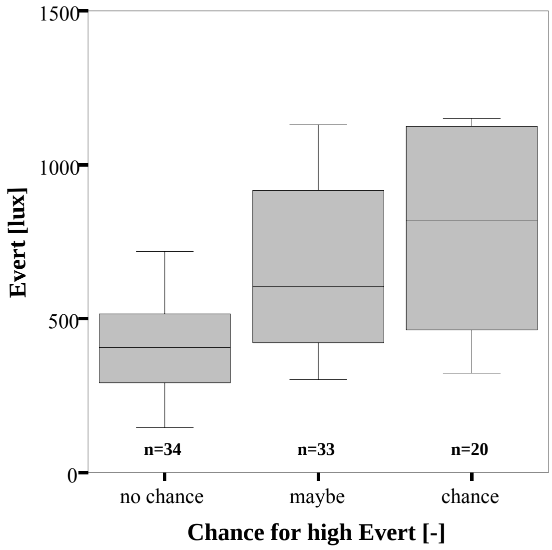


Figure 3.14 Measured vertical illuminances distributed over the three 'chance' groups

Between-groups analysis of variance was conducted to explore a demonstrable difference in measured vertical illuminances between the three 'chance' groups. There was a statistically significant difference between the groups (p<0.01). Post-hoc comparisons using the Tukey HSD test indicated that the mean rating for the 'no-chance' group was significantly different from the 'maybe-chance' and the 'chance group' for E_{vert}. In the offices that are marked as no-chance group, lower vertical illuminances were measured than in the other offices (means ratings M=404lux, SD=155 versus M=684lux, SD=361 / M=802, SD=325). 34 working places were classified in the 'No-chance' category.

Figure 3.15 shows an impression of working places with low vertical illuminances and the potential reasons for low illuminances: restricting building elements, adjoining high buildings, small windows, obstruction by plants combined with position at the back of the room, position with back to the window, obstruction by furniture combined with position at the back of the room and closed Venetian blinds. Generally, it is a combination of reasons why a working place had no chance for more than 1000lux. The average vertical illuminance for the 'no-chance' category was 404lux (SD=155) but the range was large in this category (minimum: 144lux; maximum: 718lux).
23 workstations were categorized in the 'Maybe-chance' category. The 'Chance' category (N=20) already had a high illuminance during the measurements or a good chance with other daylight conditions. The daylight contribution mainly depends on the weather and the related (vertical) illuminance level on the window. Assuming that E_{vert}=1000lux is needed for non-visual effects in the brain; the minimum required values for $E_{winvert}$ for the measured locations were calculated. The determination method, as described in Chapter 2, was used to calculate $E_{vert\ DL}$ and $E_{vert\ EL}$.

Figure 3.15: Impression of working places with low vertical illuminances and explanatory reasons (restricting building elements, adjoining high buildings, small windows, obstruction by plants combined with position at the back of the room, position with back to the window, obstruction by furniture combined with position at the back of the room and closed Venetian blinds).

In Figure 3.16, the percentages of working places that have a chance to get $\underline{E}_{vert}$>1000lux are shown for five vertical window illuminance levels (5000 to 25000lux). A subdivision is made for the three categories of 'chance'. According to this figure, 50% of the offices in the 'no-chance'-category may have a chance for a high $\underline{E}_{winvert}$ with 25000lux at the façade. However, different environmental, building or room properties restrict the light entrance. For these working places, the solution for increasing the illuminance level is found in electric lighting. For the category 'Maybe-chance', vertical window illuminances from 5000-25000lux are not sufficient for the majority of positions in this category. Before taking measures to increase the light on the façade, it is more appropriate to eliminate interior restrictions (closed awnings, back position, etc.). The offices in the 'Chance'-category indeed have a good chance for high vertical illuminances. With 5000lux at the façade, only 20% of the working places get an $\underline{E}_{vert}$ over 1000lux; with 10000lux at the façade, the percentage of offices increased to 70%.

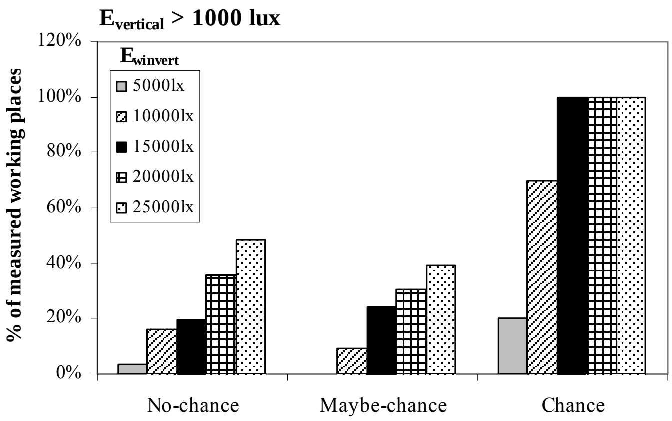


Figure 3.16 Different levels of $\underline{E}_{winvert}$ and the percentage of measured working places with $\underline{E}_{vert}$>1000lux for the three categories of 'chance'

As already stated in the parameter study in Chapter 2, an entire day with a dark overcast sky condition is the worst-case situation but fortunately during an average 80% of the year the Dutch climate has days with sunshine (clear sunny days or days with clouds and sun). For a north orientation (wall-to-wall window from sill $\underline{h}$=0.9m to ceiling), the percentage of the time between 8 and 18 hours that the daylight level at the window exceeded 10000lux has been plotted in Figure 3.17.
High illuminances at the window, necessary to get 1000lux at eye level (with daylight only) are available at least 50% of the time from May to July. Especially in the dark period (October-March), when non-visual light stimulation is particularly relevant, daylight levels are much too low to achieve $\underline{E}_{vert}$ values >1000lux and additional electric lighting is required.

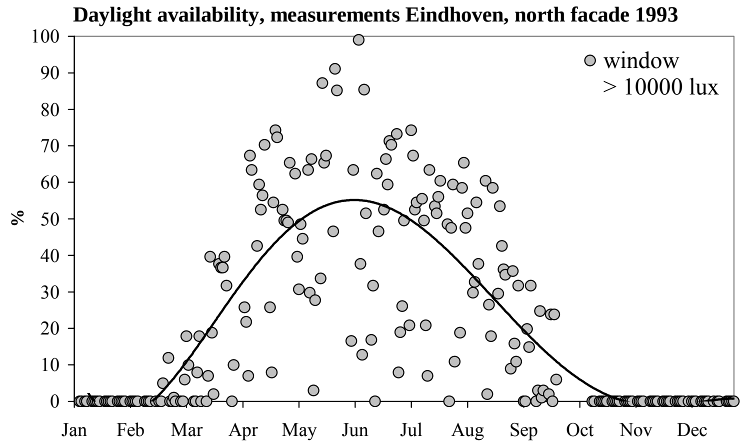


Figure 3.17 Exceeding levels for $\underline{E}_{winvert}$ if more than 10000lux is demanded (graph according to Tenner, 1993)

3.3.3.4 Concluding remarks

The horizontal illuminance in present-day offices satisfied the standards (>500lux) in the majority of the cases measured. There was no significant difference between the horizontal illuminance scores of the front and back positions. The vertical illuminance in present-day offices, as measured in the field test, showed values between 200 and 1200lux. There was no significant difference between the vertical illuminance scores between the front and back positions.
For the five tested inter-architectural variables - orientation, obstruction, daylight opening and office type - only the covariate $\underline{E}_{winvert}$ shows a significant main effect on the vertical illuminance in the room. The effect is moderate; 8% of the variance in vertical illuminances in the room is explained by the vertical illuminance on the window. This effect is not found for the ANOVA with the intra-architectural variables (reflection coefficient, position, awnings situation and position to the electric lighting). The five intra-architectural variables showed no significant main effects on the vertical illuminance at eye level.
Interaction effects were not taken into account although the possible reason of the illuminance differences may lay in a combination of effects. The differences between the

offices were very large and an interaction study with this amount of variables is impossible. Furthermore, the measuring time was very short.
Instead of an (impossible) statistical analysis for interaction effects, an alternative subdivision was made. The different reasons for low vertical illuminances were inventoried. As a result of this inventory, the working places were categorized into three groups. The 'No-chance'-category might still have a chance for $\underline{E}_{winvert}$=25000lux at the façade, according to the ratio $\underline{E}_{vert}/\underline{E}_{winvert}$. However, different surrounding, building or room properties restrict the light entrance and for these working places the solution for increasing the illuminance level at eye level has to be found in electric lighting. The restrictions of the 'Maybe-chance' category must be studied and probably eliminated before measures are taken to increase the window illuminance. The offices classified as 'Chance' indeed have a good chance for high vertical illuminances. With 5000lux at the façade, only 20% of the working places get an $\underline{E}_{vert}$ higher than 1000lux; with 10000lux vertical at the façade, the percentage of offices increased to 70%.
At least 50% of the time from May to July, the illuminance at the window is sufficient to get 1000lux at the eye (with daylight only). In the 'dark' period (October-March), when non-visual light stimulation is particularly relevant, daylight levels are much too low to achieve $\underline{E}_{vert}$ values >1000lux and additional electric lighting is required.

3.3.4 Individual parameters

The effects of light may vary for different people. Analog to architectural parameter differences in chapter 2 and in consensus with the literature (Parsons, 2000; Veitch, 2001), distinctions were made for differences 'between' and 'within' individuals. Differences between persons could affect their answers to questions about the light environment. Differences in parameters between persons are called **inter-individual** differences. Examples of this type of parameters are e.g. gender, age, season-sensitivity, and chronotype. **Intra-individual** differences 'occur' within the same person over time. Examples for these parameters are fatigue, emotional state, circadian rhythm and menstrual cycle changes in females.

3.3.4.1 Inter-individual parameters

In the office buildings measured, 193 (59%) employees were men and 140 (41%) were women. Age was ranked into 5 categories: under 30, 30-39 years, 40-49 years, 50-59 years and older than 60. Like Figure 3.18 shows, approximately 80% of the male office employees are between 30 and 59 years old. Female employees were a little younger; 80% were under 49. 115 persons (35%) of the respondents did not wear glasses or contact lenses at work, 42% wore glasses and 23% had contact lenses.

Some people arrange their days differently according to their chronotype: 'morning' or 'evening' type. A morning-type is defined as a person whose circadian rhythm shifted approximately two to three hours earlier compared to the mean for the entire population. 92 individuals (28%) reported to be morning types. Circadian rhythms of an evening-type shifted approximately two to three hours later than the mean. 118 persons (35%) categorized themselves as evening types. 85 respondents (26%) declared not to be a specific chronotype and they were categorized as 'all day' persons. 38 persons (11%) did not know their specific chronotype.

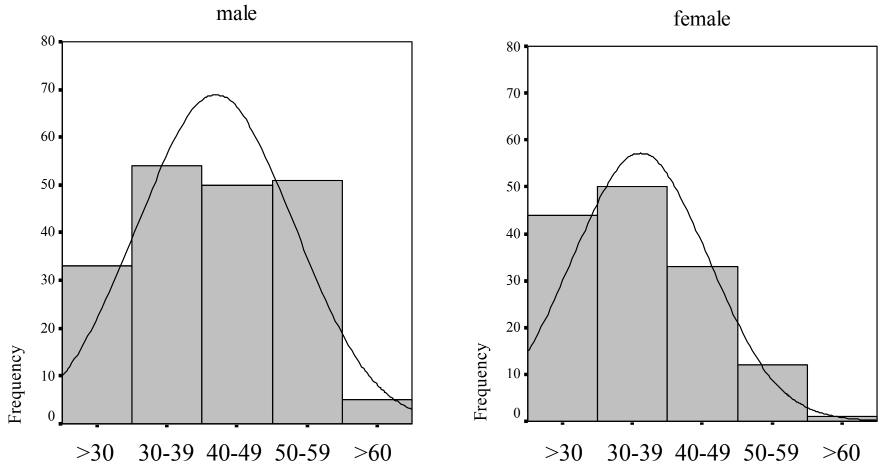


Figure 3.18 Age distribution of the respondents, distinguished by gender

Many people are affected considerably by the change of seasons, but most of these changes do not cause serious problems. To determine the differences in behavior and social interaction in summer and winter, questions about different items (sleep demands, social activities, mood, weight and energy level) were used (part I). Each question had five possible answers (from 'no difference'= 1 point to 'very clear difference'= 5 points) and the scores were added. The new scale had a good internal consistency, with a Chronbach's apha coefficient of 0.82. According to Pallant (2001) a scale has good consistency, with a Cronbach's alpha coefficient above 0.7. The employees were also asked to what extent seasonal changes influenced their activities (part II). This question had five possible answers, from 'no hindrance'=A to 'very clear hindrance'=E. The score of part I was combined with the answer to part II (see Table 3.8). The total score resulted in three categories of persons according to seasonal influence. Persons in category 1 declared to feel no influences by seasonal changes. Category 2 contains persons with a moderate influence and persons who experienced great differences between the dark (winter) and light season (rest of the year) form category 3.
153 out of 316 employees (48%) responded to have experienced no disturbing differences in behavior and social interaction between summer and winter (category 1). 123 persons (39%) were moderately influenced and 40 persons (13%) indicated very clear influences. 17 persons missed one or more items of the questions and were not included.

Table 3.8 Categories of seasonal influence

		Part I			
		5-9 points	10-12 points	13-16 points	> 16 points
Part II	A	Category 1	Category 1	Category 1	Category 1
	B	Category 1	Category 1	Category 2	Category 2
	C	Category 1	Category 2	Category 2	Category 3
	D	Category 1	Category 2	Category 2	Category 3
	E	Category 1	Category 2	Category 3	Category 3

3.3.4.2 *Intra-individual parameters*

Three intra-individual parameters were investigated: fatigue, sleep quality and health. The word 'fatigue' is chosen as the general term for a collection of disorders: concentration, tiredness, dazedness, irritability and headache. All 'fatigue' items are related to a state of being observant and paying attention. The office employees were asked to indicate on a scale from 'none' (1 point) to 'extremely' (5 points) whether they were subject to all aspects of 'fatigue'. The subjective assessment by the office employees about the items 'concentration' and 'tiredness' during a (general) day are shown in Figure 3.19. Both graphs show that at least one-third of the entire population experienced disorders during the day (slightly, considerably or extremely).

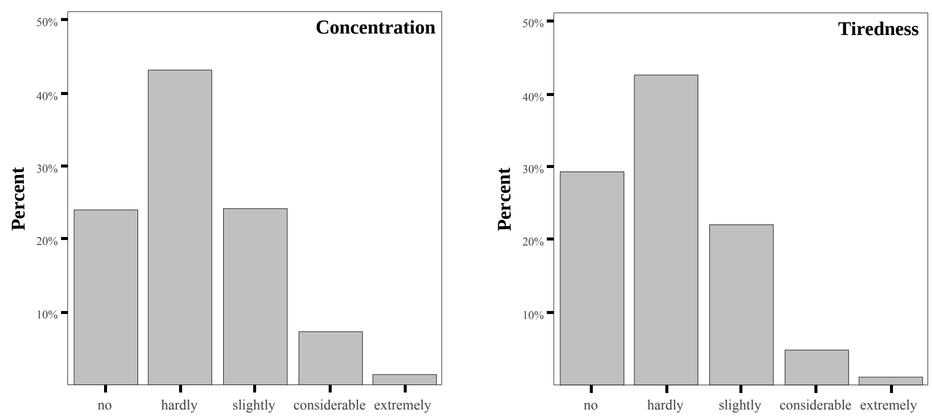


Figure 3.19 Examples of subjective assessment by office employees: concentration and tiredness disorders during a (general) day (N=330)

Answers to the five disorders were summarized in the parameter 'fatigue'. The Chronbach's alpha for fatigue is 0.76, so the scale can be considered reliable with the sample. The results were subdivided into three groups. A score from 5 to 10 points indicated no considerable fatigue disorders, 11 to 15 points showed moderate fatigue disorders and over 16 points indicated clear fatigue disorders. 188 persons (57%) of the respondents had no considerable fatigue disorders, 118 persons (35%) indicated moderate fatigue disorders and 20 persons (6%) felt clear fatigue disorders.
The questions about the presence or absence of decreased alertness and the subdivision into categories of fatigue disorder were correlated to each other. Table 3.9 shows that the individuals who experienced fatigue problems also felt a moment of decreased alertness during the day (r=0.354, N=326, p<0.01). The five main conditions that people required to keep their minds on their work are 'silence' (51% of the respondents), 'coolness' (31%), 'much light' (23%), 'separation' (22%) or 'nothing' (20%).

Table 3.9 Fatigue disorders related to the presence of absence of an alertness decrease moment

	No disorders	Moderate disorders	Clear disorders
No moment	45%	14%	0%
Moment	55%	86%	100%

During the day several humans have a little ‘dip’: moments when they feel less alert and more tired. The question about alertness/tiredness had six answering possibilities and the results are shown in Figure 3.20. 101 respondents (30%) answered not to have experienced any moment of decreased alertness during the day. The remaining individuals ($\underline{N}$=232) responded to felt moments of tiredness; 15 persons (5%) in the morning, 24 persons (7%) around lunchtime, 192 persons (58%) in the afternoon (the ‘after lunch dip’) and one person did not answer the question.

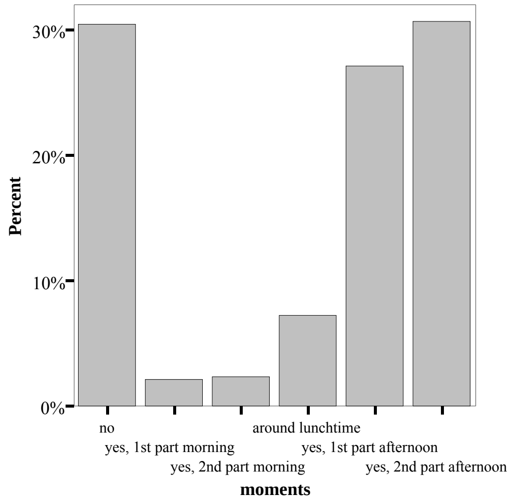


Figure 3.20 The results of the question about the alertness / tiredness

The next question inquired after the actions that were undertaken to prevent or reduce the alertness decrease. The majority of actions were non-productive. Many persons got food or drinks, walked around or talked with colleagues.

Too little sleep leaves an individual somnolent and unable to concentrate fully on (mental) tasks the following day. Sleep appears indispensable for the human nervous system to work properly. Subjective ‘sleep quality’ was defined by answers to a question with seven statements about sleep rhythm, sleep duration, etc. from the Groninger Sleep Quality Scale. Five out of seven statements were phrased negatively; two were phrased positively. Only ‘agree’ or ‘disagree’ were possible answers. If a negative statement was answered with ‘Yes’, no point was scored, ‘No’ scored one point. Scoring by positive statement was opposite. The answers to this question resulted into three categories of sleep quality: good (6-7 points), moderate (3-5 points) and bad (0-2 points). 225 persons (69%) of the respondents had a good sleep, 101 persons (31%) indicated a moderate sleep and one person (1%) had a bad sleep. Six persons did not (completely) answer the questions.

Disorders that are related to the human body are called ‘physical health’. This term is the generic term for five disorders: dry throat, bad vision, dry eyes, irritated skin and sniffles. The physical condition can influence behavior. The office employees were asked to indicate on a scale from ‘none’ (1 point) to ‘extremely’ (5 points) whether they were subject of all aspects of ‘physical health’. Answers are summarized for the five disorders and the results were subdivided into three categories. A score from 5 to 10 points indicated no considerable physical health disorders, 11 to 15 points showed moderate disorders and over 16 points indicated clear disorders. 224 persons (69%) of the respondents had no health disorders, 89 persons (27%) indicated moderate health disorders and 13 persons (4%) had clear health disorders.

3.3.5 Individuals and light parameters

3.3.5.1 Intra-individual parameters

It was expected that some individual differences were related to the non-visual performance of a workstation. The difference between individuals was represented by response to questions about fatigue, sleep and physical health. For this analysis, a selection was made and only those questionnaires were used that were directly related to one of the measurements. The workstations of $\underline{N}$=42 employees, who filled in a questionnaire were measured. They were divided over the ten buildings.

The non-visual performance is represented by the light at eye level (vertical). Both the light at the desk and on the eye is an accumulation of daylight and electric lighting. A short measurement shows vertical illuminances (daylight and electric lighting) for one, specific moment. However, for the measured office buildings the electric lighting was constant for each working position. Daylight contributions were different. Therefore, the $\underline{E}_{vert}$ was split into an $\underline{E}_{vert\ EL}$ (electric lighting) and the $\underline{E}_{vert\ DL}$ (daylight) and the daylight contribution was converted to the amount as $\underline{E}_{winvert}$=7500lux. This level was chosen as a moderate level for a Dutch façade during a year. The (converted) vertical illuminance, with both daylight and electric lighting contributions, was used in the comparison between individual differences and conditions. The comparison between several responses and measured workstations was used to find out if there is a relationship between the amount of light at eye level and light-relevant parameters that are related to the direct brain effects and the circadian rhythm.

The relationship between the vertical illuminance at eye level and the intra-individual parameters 'fatigue', 'sleep quality' and 'physical health' was investigated using Pearson product-moment correlations coefficients. The variables showed all Chronbach's alpha's above 0.7 for $\underline{N}$=42 questionnaires. Preliminary analyses (inspection of scatter plots) were performed to ensure no violation of the assumptions of normality, linearity and homoscedasticity. The correlation results are presented in Table 3.10. There was a significant, negative correlation between $\underline{E}_{vert}$ and fatigue, with high levels of vertical illuminance associated with lower levels of fatigue. The correlation between $\underline{E}_{vert}$ and the sleep quality was also significant. The negative correlation meant that higher levels of vertical illuminance increased the level of sleep quality. The correlation between the illuminance and the physical health was not significant. Correlations from 0.30 to 0.49 or -0.30 to -0.49 were interpreted as relationships with medium strength.

Table 3.10 Correlations between the vertical illuminance and three intra-individual parameters

		Fatigue	Sleep quality	Physical health
$\underline{E}_{vert}$	Pearson Correlation	-0.330*	0.343*	-0.205
($\underline{E}_{winvert}$ = 7500lx)	Sig. (2-tailed)	0.033	0.026	0.193
	<u>N</u>	42	42	42

* Correlation is significant at the 0.05 level (2-tailed).

3.3.5.2 *Inter-individual parameters*

Partial correlation was used to explore the relationship between the vertical illuminance and the intra-individual parameter 'fatigue', while controlling for the inter-individual parameters gender, age, eye correction, seasonal sensitivity and chronotype. The zero order correlation was significant ($\underline{r}$=-0.330, $\underline{p}$=0.033) and most inter-individual parameters had only a very little effect on the strength of the relationship. Only the parameter 'eye correction' seemed to influence the relationship. The correlation slightly decreased and was not significant anymore ($\underline{r}$=-0.298, $\underline{p}$=0.058). Inspection of the data showed that for the higher vertical illuminances there were no individuals with contact lenses. None of the inter-individual parameters had effects on the strength of the relationship.
Partial correlation was used also to explore the relationship between the vertical illuminance and the intra-individual parameter 'sleep quality', while controlling for the inter-individual parameters gender, age, eye correction, seasonal sensitivity and chronotype. The zero order correlation was significant ($\underline{r}$=-0.344, $\underline{p}$=0.026) and the inter-individual parameters only had very little effect on the strength of the relationship.

3.3.5.3 *Concluding remarks*

The comparison between several questionnaire responses and measured working locations was used to find out whether there is a relationship between the amount of light at eye level and light-relevant parameters that are related to the direct brain effects and the circadian rhythm. The correlation between the vertical illuminance and the parameters 'fatigue' and 'sleep quality' were significant. The relationships had medium strength. High levels of vertical illuminance were associated with lower levels of fatigue and higher levels of sleep quality.
The inter-individual parameters gender, age, eye correction, seasonal sensitivity and chronotype had only a very little effect on the strength of the relationship between the vertical illuminance and the intra-individual parameters 'fatigue' and 'sleep quality'. This suggested that the relationship is not influenced by inter-individual parameters.

4 Evaluation of several healthy lighting conditions

4.1 Introduction

This chapter starts with the definition and composition of lighting conditions. Non-visual human lighting demands require high vertical illuminance levels. This has to be realized in harmony with the visual criteria. A preliminary investigation based on computer simulations proposed conditions and examined the feasibility of chosen 'healthy lighting' conditions. Acceptance studies were not possible with simulations and these investigations need to be performed in full-scale environments with individuals. This chapter presents the results of a study for feasibility and acceptance (satisfaction) of healthy lighting environments by individuals. Psychobiological performance was not investigated.

Lighting standards and practice in offices today are solely based on visual criteria. However, lighting based on visual demands only is not very relevant for non-visual stimulation, where the amount of light falling on and entering the eye appears to be important. There are two basic types of lighting:

- General lighting that provides fairly uniform lighting. Examples are ceiling luminaires that light up large areas;
- Local or task lighting that increases the light levels over the work and immediate surroundings. Local lighting often allows the user to adjust and control lighting and provides flexibility for each user.

The complete lighting installation controls and distributes light. Various types of luminaires are designed to distribute light in different ways: direct, direct-indirect or indirect (see Figure 4.1).

Figure 4.1: Examples of generic forms of office lighting

The luminaires can be ceiling-mounted, furniture-based, free-standing or wall-mounted. Current office lighting conditions in Western Europe are combinations of daylight and electric lighting. Daylight mainly originates from vertical windows.
For lighting conditions where both visual and non-visual demands are taken into account, a subdivision can be made:

- One-component lighting design: General lighting (visual comfort and performance) and non-visual performance integrated in one lighting solution (see Figure 4.2a);

- Two-component lighting design: General lighting (visual comfort and performance) integrated in one lighting solution. Non-visual performance in another lighting solution (see Figure 4.2b).

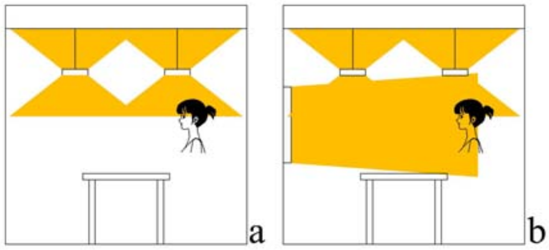


Figure 4.2: One (a) and two (b) component lighting design (both visual and non-visual)

4.2 Simulation of possible solutions

Healthy lighting conditions were conceived and evaluated with the validated light simulation software 'Radiance' (Larson and Shakespeare, 1998). Radiance is a rendering system that uses techniques based on physical principles of light behavior for local and global illumination. The simulation uses a light-backwards ray-tracing method. The program includes specular, diffuse and directional-diffuse reflection and transmission in any combination to any level in any environment, including complicated, curved geometries (Ward, 1994). The designed conditions were reviewed with regard to human visual and non-visual demands. During the design process, a number of alternatives were examined with differences in daylight situation and artificial lighting systems. A pre-study (Baak, 2002) with Radiance showed that the required levels for non-visual stimulation can be fully achieved for the standard seating positions.

4.2.1 Method

The simulated office room (façade and room arrangement) was designed as described in the International Energy Agency task 27 Reference Room documents (van Dijk, 2001). Five possibilities were chosen for the user positions: A to E (see Figure 4.3), consistent with the positions as defined in chapter 2. In the simulations a special retinal exposure detector was not used. The vertical illuminance at eye level was taken as the representative parameter for the light at the eye (see Chapter 2). The vertical illuminance was calculated at a height of 1.25m and at a distance of 100mm from the desk edge.

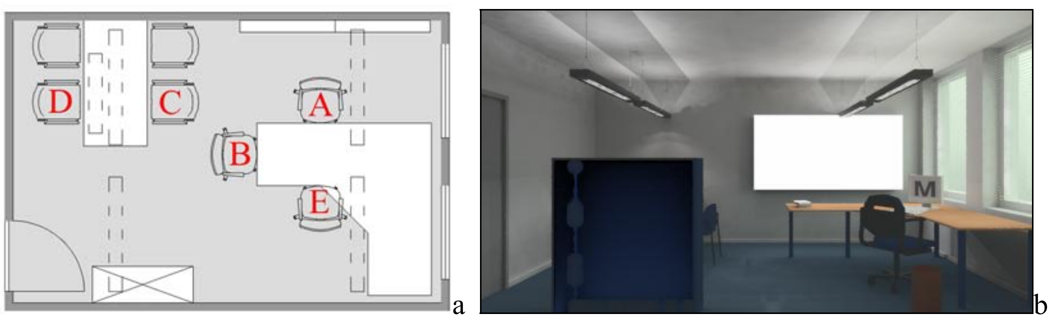
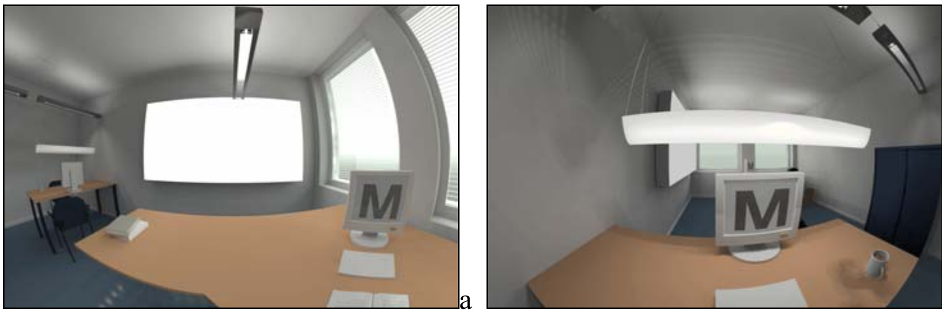


Figure 4.3 Floor plan with simulation positions A, B, C, D and E (a) and side view (b)

Out of a wide variety of possible solutions for single cell offices, two generic lighting conditions were chosen that can 'easily' be put in practice. The conditions were applied to two main working positions: E and D. The general office lighting (visual performance and comfort) was identical for both variants and realized by suspended luminaires with mirror optics, with an up-and-down lighting component at 0.65m below the ceiling. Additional office lighting (for non-visual performance) was split up for two working positions:

- A large luminous area at the wall, opposite of the office worker, for position E. Although a close luminous area may be more efficient, this area moved to the opposite wall to eliminate the obstruction of the incoming daylight (see Figure 4.4a)
- A small luminous area above the desk, close to the office worker, for position D. A (extra) single-suspended luminaire was chosen as the light source for position D. As a result of the low position ($\underline{h}$=1.5m) of the luminaire, the faces of the employees are lit directly (see Figure 4.4b).



a b

Figure 4.4 Radiance images of the wall-mounted luminous area for position E (a) and the single-suspended luminaire at position D as ceiling-mounted luminous area (b). For each position, the contribution of daylight, general lighting and additional lighting was summarized to calculate the vertical illuminance. NOTE: Additional lighting systems were not switched on simultaneously.

For each position, four conditions were calculated separately (see also Appendix D):

1. A condition with daylight only under a CIE overcast sky and an outside $\underline{E}_{hor}$ in the free field = 10000lux);
2. A condition with general lighting only at full power (100%);
3. A condition with the large luminous area only at the wall at full power (100%);
4. A condition with the small luminous area only above the desk at full power (100%)

The addition of values delivered the vertical illuminance for position D or E. All separate contributions of the conditions can be scaled to the level that is demanded to create the total, required vertical illuminance. For a summer period, the horizontal illuminance in the outside field was scaled to $\underline{E}_{hor\ field}$=15000lux. For a winter period, this $\underline{E}_{hor\ field}$ was scaled to 8000lux. The general lighting was turned on at 25% of its power. The contribution of the daylight and the general lighting to the $\underline{E}_{vert}$ at position D and E were summarized. This amount was supplied by a contribution of the luminous area to get a vertical illuminance of approximately 1000lux (both for the summer and winter period). In winter, the general lighting was increased to 50% of its power to compensate for the lack of daylight. This increase resulted in comparable luminances in the office rooms in summer and winter. Only levels were compensated; daylight was not replaced by electric lighting. Both in summer and in winter, the dynamic changes of daylight were available. A view to the outside was possible in any case.

Two levels of vertical illuminance at eye level were investigated. Besides the 1000lux level, a situation with $\underline{E}_{vert}$=2000lux was created to find out if higher levels than the assumed 1000lux will be realizable within human (visual) comfort limits.

In Radiance, the luminance images were corrected for sensitivity of the human eye and the pictures were helpful to consider the comfort level of a variant in reality. A distinction was made for the opening angles with regard to visual performance and visual comfort (Boff and Lincoln, 1988). The angles for the visual performance pictures were 80° horizontally by 60° vertically and the opening angles for the visual comfort pictures were 180° horizontally by 120° vertically. The luminance pictures were assessed for ratios above 1:20. To avoid glare, the maximum luminance ratios between a bright (light) source in a room and a wall should not exceed the 1:20 ratio (Velds, 1999).

4.2.2 Results

The results of the simulations are discussed for a two-component lighting design and subsequently for a one-component lighting design.

4.2.2.1 Two-component lighting design

In order to create a two-component lighting design, the outcome of the simulations for the general lighting system (visual comfort and performance) and the two luminous areas (non-visual performance) were used. The large area was used for window position E and the small area for room position D. With the outcome, several presets were formed that provide 1000 and 2000lux respectively on the eye. The results are presented in Table 4.1. Deviations of approximately 200lux were accepted. In a real situation, illuminances of exact 1000lux are not possible because of the continuous daylight changes.

Table 4.1 Presets for the vertical illuminance levels in summer and winter for position D and E. The contribution of electric lighting is mainly delivered by the luminous area (condition with daylight and electric lighting)

Period	Level	pos	$\underline{E}_{vert}$	$\underline{E}_{task}$	General	Area
Summer	1000lux	D	1187	1110	25%	50%
($\underline{E}_{hor\ field.}$ ~15000lx)		E	1185	1436	25%	30%
	2000lux	D	1749	1710	25%	90%
		E	1945	1906	25%	70%
Winter	1000lux	D	1173	1275	50%	50%
($\underline{E}_{hor\ field.}$ ~8000lx)		E	1213	1542	50%	40%
	2000lux	D	1735	1735	50%	90%
		E	1973	1973	50%	80%

Besides the numerical results, luminance distribution images were used to asses the visual comfort in the room. The images were used to asses the visual comfort in the room. Figure 4.5 shows an assessment image for position D and E with the variant that delivered 1000lux at eye level (winter period). According to the images, the maximum luminance ratios do not exceed the 1:20 ratio for the 1000lux variants in both seasonal periods. The false color images in Figure 4.5 show that the ratio between the luminous area and the surrounding wall is approximately 1:13 for the large luminous area and 1:18 for the small luminous area. The luminance of the daylight opening was reduced with white Venetian blinds (horizontally turned).
The maximum luminance ratios do not exceed the 1:20 ratio for the 1000lux variants in both summer and winter and for the 2000lux variant in summer. The 2000lux variant in winter exceeds the maximum ratio (1:27) and because this causes (too much) visual discomfort, this variant will not be tested in a real winter situation.

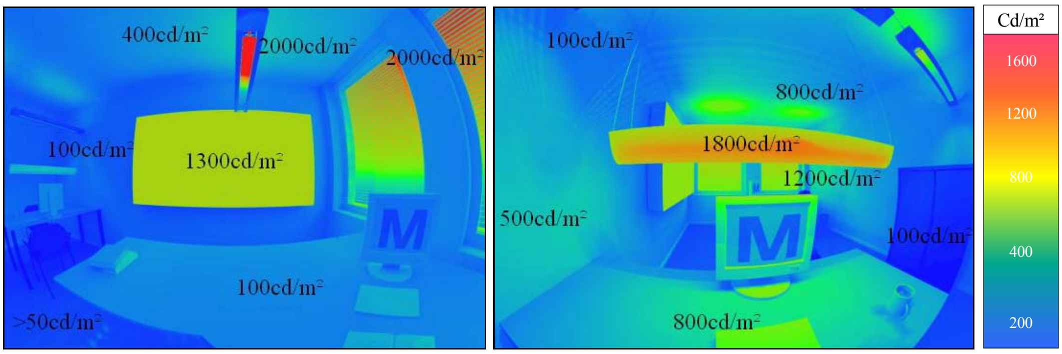


Figure 4.5 Luminance images of the visual comfort assessment (for the 1000lux winter variant) at position E (picture on the left) and position D (picture on the right)

4.2.2.2 One-component lighting design

In order to create a one-component lighting design, the outcomes of the simulations for the general lighting system were used. The system was set at full power (100%). Results of chapter 2 and 3 showed that the position of the user according to a luminaire with mirror optics is important for the amount of light at the eye. The position of the luminaires is carefully chosen in such a way that they efficiently generate light at the employee's face. The visual and non-visual performances were integrated in one lighting solution (1000lux). The one-component concept (in this configuration) was not able to create a 2000lux level. The numerical results of the simulation are shown in Table 4.2.

Table 4.2 Presets for the vertical illuminance levels in summer and winter for position D and E. The contribution of electric lighting is mainly delivered by the suspended luminaires (condition with daylight and electric lighting)

Period	Level	pos	E_{vert}	E_{task}	General	Area
Summer	1000lux	D	1173	1164	100%	-
($E_{hor\ field.}$ ~15000lx)		E	1352	1884	100%	-
Winter	1000lux	D	1007	1087	100%	-
($E_{hor\ field.}$ ~8000lx)		E	1103	1472	100%	-

Both in summer and in winter periods, this condition delivers at least 1000lux at the vertical plane. The maximum luminance ratios did not exceed the 1:20 ratio for the 1000lux variant with the suspended luminaires at full power in both summer and winter.

4.2.3 Concluding remarks

The Radiance simulation study showed (for a standard cell-office) that lighting conditions that meet both human visual and non-visual demands without causing visual discomfort are possible. Depending on the daylight availability and the chosen illuminance level at the eye (1000 or 2000lux), it is possible to establish the desired condition with the different light sources.
The maximum luminance ratios of the concepts investigated did not exceed the 1:20 ratio for the 1000lux variants in both summer and winter and for the 2000lux variant in summer. The 2000lux variant in winter did exceed the maximum ratio. The 2000lux variant will not be tested in a real winter situation because of the high visual discomfort.
A lighting condition that integrates the visual and non-visual performance in one lighting solution delivered both in summer and in winter periods at least 1000lux at the vertical plane. The position of the user in relation to a luminaire (with mirror optics) was important for the amount of light at the eye. The position of the luminaires was carefully chosen in such a way that they efficiently generate light at the employee’s face.
The simulations generated practical information (presets) for realization.

4.3 Validation of visual acceptance in full scale test offices

The simulations showed that conditions with high vertical illuminances, necessary for non-visual stimuli, are realizable. The conditions met the visual performance and comfort criteria. Acceptance studies were not possible with simulations and the acceptance by individuals needs to be investigated in full-scale environments with ‘healthy lighting’. For example, in real situations, an office employee moves and luminance ratios in the field of view therefore change.

4.3.1 Experimental set-up

In the laboratory of the building physics group of the Technical University Eindhoven (department of Architecture, Building and Planning) in the Netherlands, two identical offices were realized that satisfied most specifications for the IEA Reference Office (van Dijk, 2001). The two test rooms were used for user acceptance studies. One room was occupied by the test person. The other room, the measuring room, was used to obtain illuminance and luminance data. This room contained measuring equipment only. In these settings, the subject was not disturbed by any measuring equipment and vice versa. In the measuring room, illuminance was measured every minute and luminance was measured every fifteen minutes. The sensors for illuminance measurements were mounted on the locations that were recommended in Monitoring Procedures (Velds and Christoffersen, 2000). To be certain that both offices indeed had identical light conditions, comparison measurements were performed. Both offices were nearly identical (deviation <5%). Figure 4.6 shows an impression of the front part of test person room (on the left) and the measuring room (on the right).

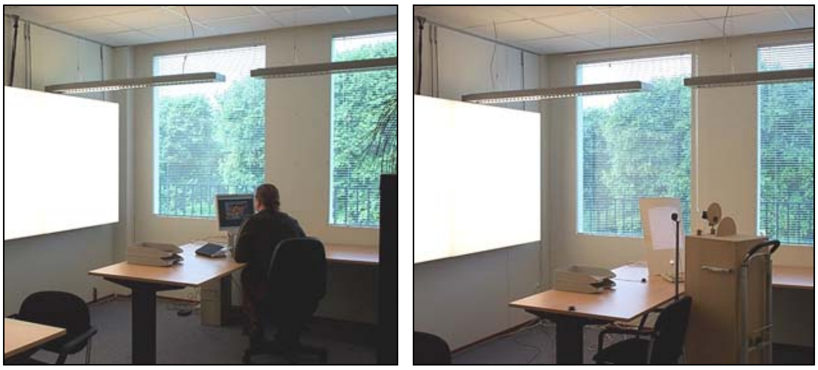


Figure 4.6 Impressions of the test person room (on the left) and the measuring room (on the right) for the window position E.

Both test offices had the dimensions 5.4 x 3.6 x 2.7m and were located on the top floor of a two story-high building, facing west. The distance between the two office rooms was approximately 5m and their view was identical. The façade arrangement was built as defined in IEA task 27, with two vertical glazed daylight openings (1,7 x 1,2m). The façade is provided with white Venetian blinds. The windowsill was at a height of 0.9m above the floor. The color of the walls and ceiling was white (ρ=0.85) and the carpet on the floor was mixed blue (ρ=0.20). The large desk in front of the window (position E) and the table on the back (position D) had a light wooden desktop (ρ=0.40). Other furniture in the room was a black closet and chairs with black seats. At both working places, a Pentium-IV computer with a 17inch TFT screen (Eizo FlexScan L550 with maximum brightness 300cd/m²) was available. The measuring room had no computer screens but luminous areas with a maximum brightness of 300cd/m² were created with the help of Bright Light systems.

The test rooms were equipped with four suspended luminaires (Etap R4801/180 P1, see Figure 4.7 - left picture) with 80W lamps, high frequency ballasts and mirror optics, located parallel to the façade. The luminaires provided the necessary light levels and reduced the luminance difference between luminaire and surroundings. During the tests, these luminaires were constantly turned on. The luminaires were located 1.2m from the facade, had a mutual distance of 2.7m and were suspended 0.6m below the ceiling. A high vertical illuminance at the eye was initially realized with additional lighting. Therefore, two conditions of lighting solutions were realized: a large luminous area at the wall and a small luminous area slanting above the employee (see Figure 4.7 – picture in the middle and on the right). Two luminaires with a uniform diffuse cover (Philips Strato Sky TPH710 4*2*TL5 28W/827/865) were used to create a large, luminous area (1.2 x 2.4m). The small luminous area (1,2 x 0,15m) was realized with a standard TL5 54W/830 tube with a diffuse, self-made parabolic cover (see Figure 4.7). The cover had a light transmission of 0.83.

The room was mechanically ventilated and both temperature and humidity in the test room were registered with an Escort logger during the sessions.

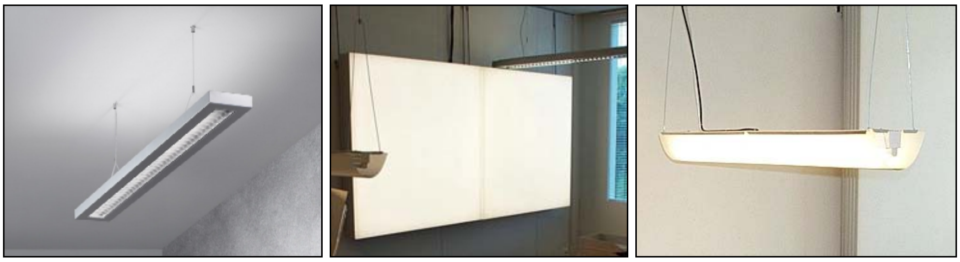


Figure 4.7 General lighting (suspended luminaire-left), large luminous area (middle) and small luminous area (right)

4.3.2 Method

The daylight situation is totally different in summer than in winter. With shorter daylight availability and lower daylight levels during working hours in the winter period, electric lighting is the main source for non-visual performance. To obtain the high vertical illuminance levels in the summer period, 50-60% of the light was delivered by daylight. In winter, the daylight contribution was much lower: 10-20%. To investigate different satisfaction experiences under similar electric lighting presets, two different seasons were taken into account (summer: May 26th to June 25th 2004 and winter: November 22nd to December 16th 2004). In the summer period, the entire population contained 32 persons (18 male and 14 female). In the winter period, 29 persons (18 male and 11 female) participated in the tests. Short-term measurements with shifts of four hours (8h30-12h30 or 13h30-17h30) were enough for satisfaction assessment of new lighting conditions. The subjects who participated in the experiment were all used to working in an office environment and they were asked to bring their own work (computer and/or desk tasks). Their age ranged between 20 and 65 years. In the winter period, 15 persons were new to the experiment, the rest ($\underline{N}$=14) had also participated in the summer period. The groups of test persons were composed randomly (see Table 4.3 for the distribution of age and eye correction).

Table 4.3 Distribution of age and eye correction

	Age				Eye correction		
	<30 years	31-40 years	41-50 years	>50 years	No correction	Glasses	Contact lenses
summer	16	4	7	5	16	11	5
winter	6	7	8	8	9	16	4

The majority of test persons had a normal to good mood, good condition and night's rest (sleep) as Figure 4.8 shows. The influence of negative values was not taken along in this investigation because the amount per group was too small.

All test persons worked at two lighting levels: $\underline{E}_{vert}$=1000 and 2000lux. As already explained for the simulations, the level of 2000lux was tested to find out if higher levels than the assumed 1000lux were accepted as well. With several presets, the required vertical illuminance levels were realized with maximum use of available daylight. On a dark cloudy day, more artificial lighting was added than on a bright sunny day. In combination with changing daylight, it was nearly impossible to realize exactly 1000lux and therefore standard deviations of ±200lux were accepted.

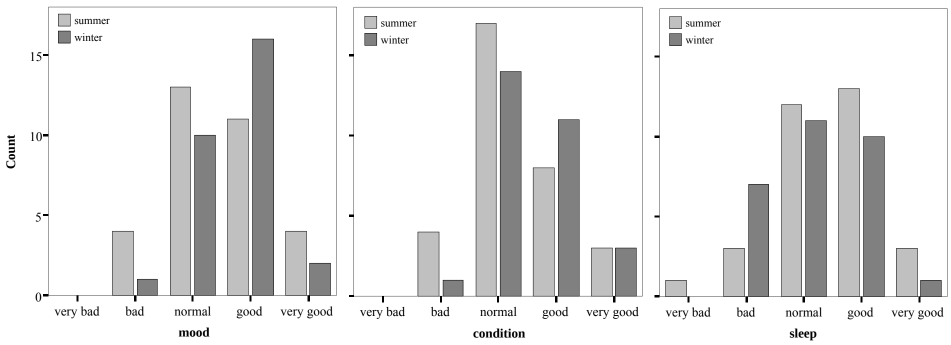


Figure 4.8 The mood, condition and night's rest (sleep) of the test persons for both seasonal periods

4.3.2.1 Lighting conditions

The field research (chapter 4) showed that 83% of office employees have a working place near the window and that the remaining persons sit in the back of the room (>4m from window). In the laboratory experiments, lighting variants for two room zones were therefore taken into account. A room position is usually not directly related to a specific lighting solution. In one-person office rooms, the walls could be used for additional (non-visual performing) lighting. In landscape office rooms, a solution (furniture or ceiling-mounted) is more reasonable. In the laboratory study, three different electric lighting systems were used. In combination with daylight, they were called 'conditions':

- **Condition 1: large luminous area**
  For the working location in the window zone, a large luminous area at the wall was chosen as an additional light source because of its similarities with a daylight opening (large bright area). The test person at the window position received light at the eye from the large luminous area, the daylight opening and slightly from the general lighting system. This condition was tested both in summer and in winter and at two levels.
- **Condition 2: small luminous area**
  In the back of the room, a small luminous area was suspended. The position of the luminaire was chosen in such a way that the luminaire mainly lightened the face of the employee during computer tasks and still enabled a free view from one person to another during conversation. The test person at the room position (facing the window) received light from the small luminous area, slightly from the daylight opening and the general lighting system. This condition was tested both in summer and in winter and at two levels.
- **Condition 3: suspended luminaires**
  For condition 3, both visual, the non-visual performance and visual comfort were integrated in one lighting solution. This (general lighting) system was created by the

suspended luminaires. These luminaires are ceiling-mounted and therefore created full flexibility for different office types. The suspended luminaires were available at both positions D and E. The test person at the window position (E) received light at the eye in a combination from the suspended luminaires and the daylight opening. The test person at the room position received light from the suspended luminaires and slightly from the daylight opening. The electric lighting systems for condition 1 and 2 were not removed during the test of condition 3. They were very slightly turned on but their contribution to the entire vertical illuminance is nil. This condition was tested only in the winter period and on one level.

Figure 4.9: The test room with all different light sources used to create the variants: large luminous area (picture on the left), daylight (picture on the left), suspended luminaires (both pictures) and small luminous area (picture on the right)

4.3.2.2 Sessions

The test persons were not informed about the settings of the lighting condition they were exposed to. The test persons were asked six times to fill in a questionnaire that was presented on the computer. The questionnaire (in Dutch) can be found in Appendix C. The assessment of the different lighting conditions, particularly focused on visual comfort, was derived from the user responses. The questionnaires dealt with personal information and preferences, the illumination of the room, computer screen and task, the additional lighting systems, the impression of the room and possible disturbance factors. The questions and the scoring were based on methods that were developed in the past for mainly visual lighting application and medical research (Opmeer *et al.*, 1996; SBI, 1997; TNO 2002; Tenner, 2002; Osterhaus, 2004).
At the beginning of the experiment, all employees replied to a list of general questions about their offices, mental and physical condition, age, gender, eye correction and light preferences. During a period of 40 minutes, the test person was not disturbed when doing his/her own work. Each test person worked alone in the room. At the end of these 40 minutes, he/she was asked to fill in a questionnaire about the light situation and the office environment. Once finished, the test person came out of the room, the light was changed to another level and for another 40 minutes, the test person got back to his/her work. An identical questionnaire about the light situation and office environment closed the second work session. After a short (coffee/tea) break of 15 minutes (outside the test room), the test person changed working place. All persons changed from position E to position D

and vice versa halfway the session. To avoid effects that were the result of order in start position, half of the group started at the front position and half started in the back zone. This procedure was also followed with regard to start lighting level and shift.
After the break, the cycle of two work sessions (2 times 40 minutes) with two different lighting conditions and questionnaires started again. After the working sessions at the second position, the test person was asked to fill in a last, short questionnaire. In this final list, they were inquired after an overall assessment and the preference for the different variants.

Finally, the test persons participated in a light sensitivity test (summer period $\underline{N}$=30, 2 missing, winter period $\underline{N}$= 28, 1 missing). The aim of this test was to find the upper and lower limits with regard to visual comfort. Several recent studies (Boyce *et al*., 2000; Roche *et al.,* 2000, Veitch, 2001; Geerts, 2003) found that individual lighting preferences differ from person to person. It was assumed that the different sensitivity to light influenced the assessment of lighting conditions. Simple light sensitivity tests or questionnaires were not yet available, although first initiatives were already observed for a Mediterranean population [Bossini *et al.,* 2005].
In the test, the test person was seated behind the desk in the window zone (position E) with his/her body turned to the luminous areas on the wall. Next to the person, a stand with a Hagner SD2 light detector was placed to register the vertical illuminance at eye level ($\underline{h}$=1.25m). During the test, the researcher was present in the test room to read the lux-meter. The luminous area was programmed to increase the light level from low (‘off’) to high (‘maximum’) within two minutes (with help of a Philips Scenio100 system). This corresponded to approximately 250 to 1700lux vertically. The test person was asked to indicate when the area was going to be too bright. At the moment the comfort limit was reached, the researcher registered the corresponding illuminance. The procedure from low to high illuminance was repeated four times. In the second measurement set, the procedure was inverse, from high to low. The employee had to indicate the moment that the light in the room was too low and ‘gloomy’. Between all measurements, there was enough time for the eyes of the test persons to adapt to the changed lighting levels (see also Appendix F).

4.3.2.3 Data analysis

The entire summer dataset was pre-studied and in this study, the data was mainly analyzed as separate questions (Kole, 2004). The test protocol did not change after this pre-study, so time span of the winter session was equal. Four small questions were added to the general questionnaire. During the winter session, the subjects were asked for their chronotype and how they travel from home to work. A question about the influence of the change of time due to daylight saving was also added. In the closing questionnaire, the test persons were asked to rank the lighting conditions.

The method of analyses was comparable with the method that was used in chapter 3. The used procedure for the laboratory studies is shown in Figure 4.10.

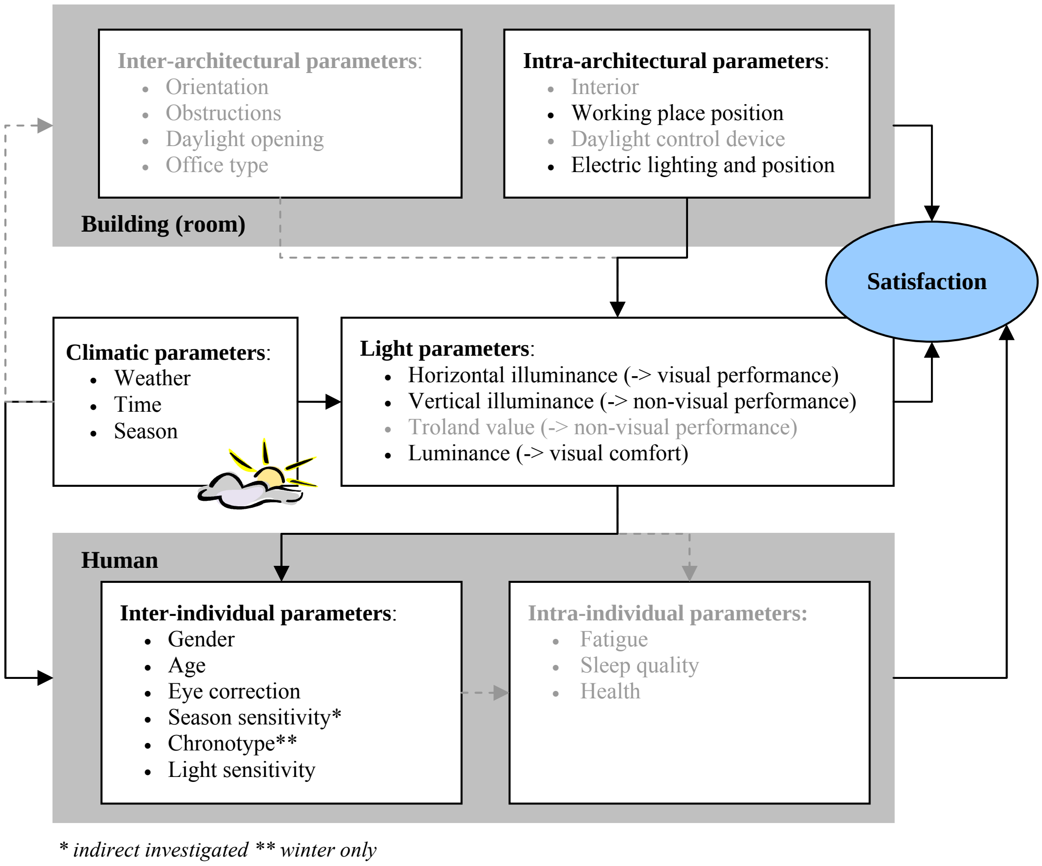


Figure 4.10 Schematic structure of the procedure that was used for analyzing the data from the laboratory office environment (dotted paths and variables in grey text were not investigated)

Because a test room was used, all inter-architectural parameters were constant. The intra-architectural parameters 'interior' and 'daylight control devices' are also equal for all situations. There were two different work positions (D and E) in the room and these are discussed separately. The general lighting system in the room did not change during the tests; specific lighting solutions - workplace-related - were also separately discussed.
The results of the laboratory study are presented and discussed in the following order:

1. Measurements of the light parameters, horizontal and vertical illuminances and luminance (characterization of the rooms during the test session)
2. Assessment of the lighting situation by individuals. The acceptance and satisfaction with the lighting condition were the main issues in the laboratory tests. One single question might give an indistinct or even wrong assessment of the situation and therefore several questions were grouped. Clustering makes that possible outliers exert less influence on the entire assessment. The following questions have been grouped to the parameter **'satisfaction'**: a question concerning the general satisfaction with the light level in the room, questions concerning the level on the desk, at the VDT and in the entire office room, questions about nuisances, questions about reflections and questions about ambiance. The satisfaction parameter was drawn up

with illuminance- and luminance-related variables. The exact composition of the parameter and all Chronbach's alpha's can be found in appendix E.

3. Influence of individual parameters on the satisfactions ratings. The classification of test persons to their light sensitivity was determined according to the results of both the light sensitivity test and different questions in the questionnaire. The determination of the parameter **'light sensitivity'** can be found in Appendix E.

An overview of the investigated parameters is schematically represented in Figure 4.10. Dotted paths and variables in grey text were not investigated in the laboratory study.

4.4 Results

4.4.1 Light parameters

An overview of the lighting conditions and descriptive statistics of the presented illuminance and luminance values are shown in Table 4.4 (four different variants in two seasonal periods). For all sessions, the mean (± *SD*) values of measured vertical illuminance are presented. As already mentioned, deviations of approximately 200lux were accepted. In real situations, illuminances of exact 1000 of 2000lux were not possible because of the continuous daylight changes. The table shows that instead of the demanded vertical illuminance level of 1000lux, the levels were 200lux higher in the summer period. During the summer tests, the weather was very nice and the daylight contribution was high. This happened at almost all sessions and therefore this had no consequences for comparison. For sessions with extraordinary high levels, special attention was paid to the answers of individuals in these sessions, or these sessions were excluded.

Table 4.4 Descriptive statistics of the presented illuminance and luminance values (area and sky) for the four different variants in the summer and winter period.

	Condition (position)	Level	*N*	Mean E_{vert} [lux]	*N*	Mean L_{area} [cd/m²]
Summer	1 (E)	1000-lux	32	1362 ± 261	16*	978 ± 130
	1 (E)	2000-lux	32	2104 ± 338	16*	1884 ± 344
	2 (D)	1000-lux	32	1206 ± 138	16*	1837 ± 365
	2 (D)	2000-lux	32	2023 ± 247	16*	3861 ± 399
Winter	1 (E)	1000-lux	29	1098 ± 268	27**	977 ± 279
	3 (E)	1000-lux	29	1093 ± 302	27**	371 ± 73
	2 (D)	1000-lux	29	1157 ± 151	27**	2563 ± 51
	3 (D)	1000-lux	29	1201 ± 181	27**	321 ± 39

* 16 measurements missing; ** 2 measurements missing

In both the summer and the winter period, the illuminance values for condition 1 (window position) and 2 (room position) were kept at ±1000lux. The levels were created with as much daylight as possible. However, the luminous areas were not turned off. In winter, daylight contribution was much lower so more electric lighting was added. Daylight entrance influences the entire room and in the winter period, the general lighting systems were set higher to make the light situation in the entire room comparable to a

summer situation (from 25 to 50%). In the summer period, the average daylight contribution to create condition 1 was 35%, in the winter period, this was 25%. For condition 2, the average daylight contribution was 40% in summer and 10% in winter.
A comparison between the simulation results (see paragraph 4.2) and the measurements showed higher values measured for the vertical illuminance at the window position than simulation results. For the simulations, a horizontal illuminance in the free field of 15000lux was assumed, but the measured outside levels were higher than 15000lux. In the back of the room (position D), the impact of the daylight was less and only small differences between simulations and measuring values were shown.

The last column in Table 4.4 shows the mean (± *SD*) values for the luminance of the luminous areas. In the summer period, 16 luminance measurements were missing and in the winter period, two measurements were missing due to technical problems. Literature (e.g. Velds, 1999; Veitch, 2003) recommends luminance ratios between direct surroundings and light sources that remain within 1:40 to avoid situations with disability glare. To also prevent discomfort glare, lower ratios (1:20) are strongly recommended. For the large area, the highest luminance ratio was found between the luminous area and the wall in the winter period (1:7). For the small luminous area, the highest luminance ratio was also found in the winter period: the ratio between the light source and the wall was 1:19. The ratio did not exceed the 1:20 ratio, but was still high. In both seasons, the luminances remained within the recommended ratios (1:20) for all light sources. Figure 4.11 and Figure 4.12 show an example of the luminances values in both seasons for both positions.

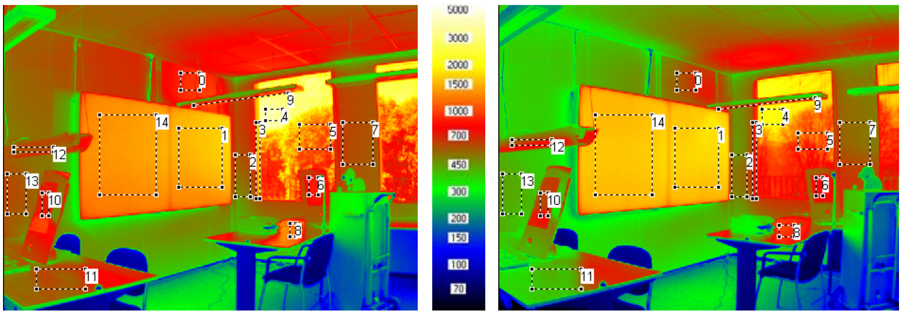


Figure 4.11 An example of the luminances values in the summer (left) and the winter (right) period for condition 1 (position E). The dotted areas with numbers are the areas analyzed

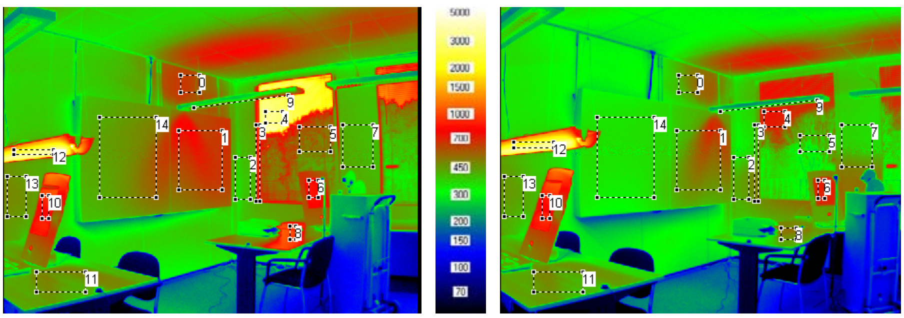


Figure 4.12 An example of the luminances in the summer (left) and the winter (right) period for condition 2 (position D). The dotted areas with numbers are the areas analyzed

4.4.2 Visual satisfaction at the window position

This paragraph discusses the results of the influence of inter-architectural and light parameters on subjective satisfaction ratings. It also discusses the influence of inter-individual parameters on the satisfaction ratings.

Table 4.5 shows an overview of variants for the window position and the tested variants are indicated (✓). The satisfaction ratings between groups of individuals in difference situations were compared. The absolute satisfaction ratings were also shown for the investigated conditions. Three comparisons were made:

1. Illuminance level: For condition 1, in summer, it was possible to compare the situation with $\underline{E}_{vert}$=1000lux and $\underline{E}_{vert}$=2000lux. A paired-samples t-test was conducted to compare the satisfaction ratings for both levels. Factorial ANOVA's investigated the influence of inter-individual parameters.
2. Condition: In winter, it was possible to compare the situations between condition 1 and 3. A paired-samples t-test was conducted to compare the satisfaction ratings for both conditions. Factorial ANOVA's investigated the influence of inter-individual parameters.
3. Season: For condition 1, it was possible to compare the summer with the winter period. An independent-samples t-test was conducted to compare the satisfaction ratings for both seasons. Different t-tests were used to investigate the inter-individual parameter 'seasonal sensitivity'.

Table 4.5 Tested variants window position

		Summer	Winter
Condition 1	1000lux	✓	✓
	2000lux	✓	-
Condition 3	1000lux	-	✓
	2000lux	-	-

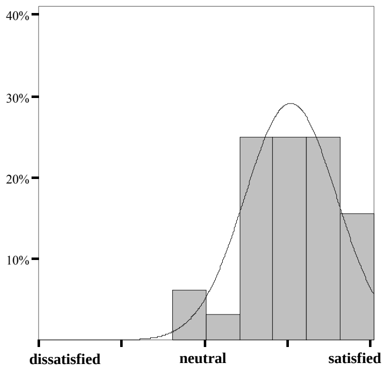
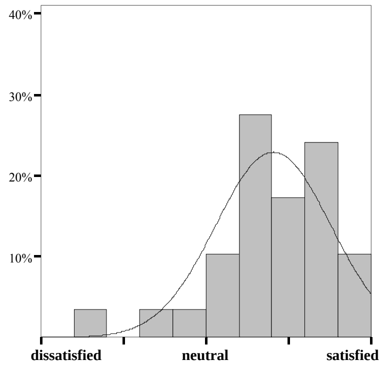
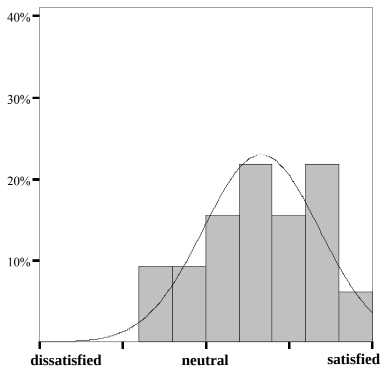
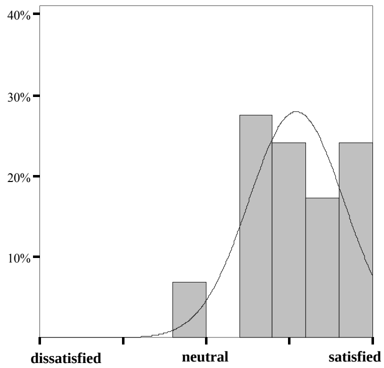
- Illuminance level

In the summer period, the vertical illuminance at eye height of the test person was varied (~1000lux and ~2000lux). The satisfaction ratings for both variants are shown in the first column of Table 4.6. The majority of the population for the 1000lux level had a satisfaction rating from 'neutral' to 'totally satisfied'. In the summer period, 84% of the test persons was satisfied with the 1000lux level. Only three persons were (slightly) dissatisfied. For the 2000lux level, the percentage of satisfied individuals decreased to 56%. Seven persons (22%) were dissatisfied with this variant.

A paired-samples t-test was conducted to compare the satisfaction ratings between the two vertical illuminance levels to find out if there is a change in participants' satisfaction score from the 1000lux to the 2000lux level. A significant difference was found in ratings between the 1000lux [$\underline{M}$=121.09, $\underline{SD}$=16.57] and the 2000lux level [$\underline{M}$=110.06, $\underline{SD}$=20.82; $\underline{t}(31)=4.86$, $\underline{p}<0.01$]. The magnitude of the differences in the means was large

(η^2=0.43). Expressed as a percentage, 43% of the variance in satisfaction rating is explained by difference in presented illuminance levels.
Half of the test persons (N=16) started at the position with the large luminous area. The other half (N=16) started in the back of the office, with the small luminous area. The start position, the start level and the shift did not influence the satisfaction ratings. A factorial ANOVA showed that there was no statistically significant difference in satisfaction ratings for start position, start level and shift (main and interaction effects) for both illuminance levels.

Table 4.6 Satisfaction rating for the four variants at the window position for the summer and winter period

<table>
<tr><th></th><th>Summer (N=32)</th><th>Winter (N=29)</th></tr>
<tr><td>Condition 1
~1000lux</td><td>
</td><td>
</td></tr>
<tr><td>Condition 1
~2000lux</td><td>
</td><td>not tested</td></tr>
<tr><td>Condition 3
~1000lux</td><td>not tested</td><td>
</td></tr>
</table>

In the summer period, the illuminance levels were related to the luminance levels in these variants. Assessment of measured vertical illuminances (E_{vert}) as a function of the absolute area luminances (L_{area}) showed a very strong, significant, positive correlation (r=0.871; N=16; p<0.01) at the 2000lux level. The correlation at the 1000lux level did not reach statistical significance (r=0.436; N=16; p=0.092). Especially for the 2000lux level, the variance in satisfaction could be explained by either the illuminance level or the luminance level or the combination of illuminance and luminance.

The satisfaction parameter was divided into illuminance- and luminance-related variables. Paired-samples t-tests were repeated for the subdivided parameters. According to the conducted t-test for the illuminance-related variables, there was a significant difference in ratings between the 1000lux [M=33.69, SD=4.10] and the 2000lux level [M=32.03, SD=4.00; t(31)=2.11, p=0.04]. The magnitude of the differences in the means was moderate (η^2=0.13). 13% of the variance in satisfaction rating is explained by illuminance-related variables. The presented levels were not too high for most individuals. The reduced mean value for the 2000lux level suggested a preference for the 1000lux level.
For the luminance-related variables, there was a significant difference in ratings between the 1000-lux [M=87.41, SD=14.38] and the 2000-lux level [M=78.03, SD=17.36; t(31)=5.10, p<0.01]. The magnitude of the differences in the means was large (η^2=0.46). The results showed that the variance in satisfaction rating from the 1000 to the 2000lux level was explained by luminance related variables. 46% of the variance in satisfaction rating was explained by the luminance related variables as nuisance, reflection and ambiance. The luminances for the 2000lux level were apparently too high.

The results of the light sensitivity test were used to understand the acceptance of the variants (see also Appendix F). According to this test, the test persons experienced the first signs of visual discomfort at luminances levels between 1200 and 2000cd/m² [M=1650cd/m²; SD=682]. The box plot in Figure 4.13 shows an average visual comfort limit of around 1600 cd/m². The chance of complete satisfaction increases if the luminance level of bright, additional light sources is kept below L_{area}=~1500cd/m².

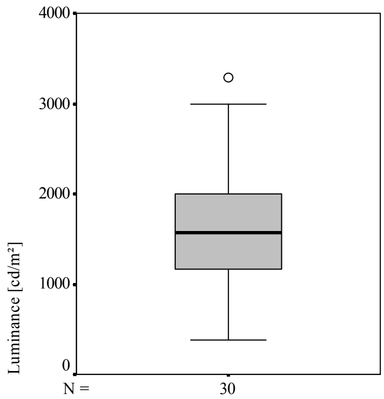


Figure 4.13 Box plot of the luminance levels where the first visual discomfort were indicated by test persons (N=30). The majority of limits is shown between 1200 and 2000cd/m²

In both seasons, the test persons were asked and tested for their light sensitivity. Subjects were divided into three levels of light sensitivity (photophobic, neutral and photophilic). Test persons who love to have much light are called ‘photophilic’ and test persons who prefer darker rooms are called ‘photophobic’. Test persons who have no specific preference are grouped as ‘neutral’.
Factorial ANOVA’s were conducted to explore the impact of the independent variables gender, age, eye correction and light sensitivity on satisfaction levels.
For the 1000lux level, there was a statistically significant difference in satisfaction ratings for light sensitivity [$F(2, 21)=3.40$, $p=0.05$]. The effect was large ($\eta_p^2=0.25$). Post-hoc comparisons using the Tukey HSD test indicated that the mean rating for the photophobic groups was significantly different from the neutral and the photophilic group. Photophobic persons were less satisfied than neutral or photophilic persons (means ratings $M=105.86$, $SD=\pm214.82$ versus $M=123.41$, $SD=16.58$ / $M=126.83$, $SD=7.78$). For the 2000lux level, there were no statistically significant differences in satisfaction ratings.

- Condition

In the winter period, the vertical illuminance was kept invariable (~1000lux). Condition 1 was equal to the summer variant. For condition 3, the demanded vertical illuminance was mainly delivered by the suspended luminaires. The luminance level for both electric lighting systems was kept below ~1500cd/m² (see Table 4.4). The satisfaction ratings for both variants are shown in the second column of Table 4.6. The majority of both populations had a satisfaction rating from ‘neutral’ to ‘totally satisfied’. Only two persons were slightly dissatisfied. In the winter period, 89% (condition 1) and 84% (condition 3) respectively of the test persons were satisfied. Equal to the summer period start position, the start level and shift did not influence the satisfaction ratings.
A paired-samples t-test was conducted to compare the satisfaction ratings for the two conditions in the winter period. There was no significant difference in ratings between condition 1 [$M=114.52$, $SD=20.89$] and condition 3 [$M=122.59$, $SD=17.12$; $t(28)=1.98$, $p=0.058$].

The satisfaction parameter was divided into illuminance- and luminance-related variables. Paired-samples t-tests were repeated for the subdivided parameters. According to the conducted t-test for the illuminance-related variables there was no significant difference in ratings between condition 1 and 3 ($p=0.657$). For the luminance-related variables, there was a significant difference in ratings between the 1000-lux [$M=90.21$, $SD=14.53$] and the 2000-lux level [$M=82.55$, $SD=17.58$; $t(28)=2.13$, $p=0.04$]. The magnitude of the differences in the means was large ($\eta^2=0.14$). The results showed that the variance in satisfaction rating at the two conditions was explained by luminance related variables (14%).
Factorial ANOVA’s were conducted again to explore the impact of the independent variables gender, age, eye correction and light sensitivity on satisfaction levels. For both conditions, there was no statistically significant difference in satisfaction ratings for the investigated inter-individual parameters.

- Season

The tests were performed in summer and winter. Condition 1 was tested once again during the winter tests. Although the illuminances were not exactly identical as a result of the changing daylight, the two seasons were compared. The luminances of the luminous area were almost similar and remained within the formulated limits (≤1500cd/m²) and recommended ratios (1:20). The group of test persons was not equal in both seasons. An independent-samples t-test procedure was conducted to compare the means for two seasons for the entire population of test persons. The significance value for the Levene's test was high (p=0.559). Equal variances for both groups were therefore assumed. There was no significant difference in satisfaction ratings between summer [M=121.09, SD=16.57], and winter [M=114.52, SD=20.89; $t(57)$=1.34, p=0.176] for the entire population.

The ANOVA's, which were conducted concerning the light level and the different conditions, showed a difference between summer and winter. In summer, the satisfaction was mainly influenced by the light sensitivity of individuals. In winter, there was no difference. As already mentioned, the group of test persons was not equal in both seasons. Some people are affected considerably by the change of seasons, others feel small differences and the majority declares not to experience differences. An independent-samples t-test procedure was conducted to compare the means for two seasons for the group of test persons who participated only once in the experiment (summer N=18, winter N=15). There was no significant difference in satisfaction ratings between the summer and winter period for this population (p=0.836).

A paired-samples t-test were conducted for the population of persons who participated twice in the experiment for two seasons (N=14). The start position, start level and shift were similar for summer and winter period for all persons. There was a significant difference in ratings between the summer [M=123.43, SD=20.21], and the winter period [M=108.21, SD=22.99; $t(13)$=2.63, p=0.02]. The magnitude of the differences in the means was very large (η^2=0.37). 37% of the variance in satisfaction is explained by the season for the individuals who participated in the experiment twice. 11 out of 14 test persons were more satisfied in summer than in winter, with almost comparable light presets (see also Figure 4.14). It seems that, next to light sensitivity, season sensitivity is a very important inter-individual parameter.

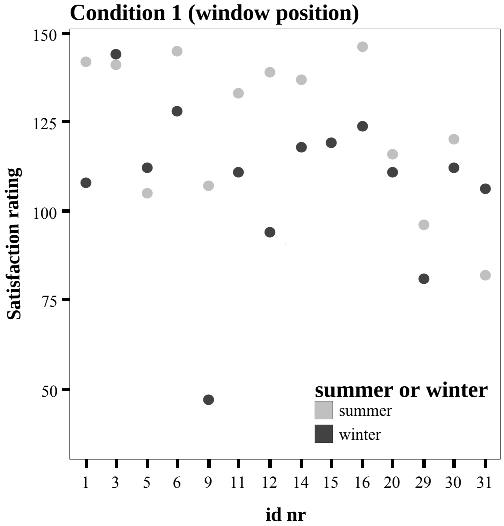


Figure 4.14 Satisfaction ratings for the persons who participated in both seasons (condition 1)

4.4.3 Visual satisfaction at the room position

Similar to the window position, the experiments for the room position were varied for three different conditions: illuminance level, lighting condition and season. This paragraph discusses the results of the influence of inter-architectural and light parameters on subjective satisfaction ratings. It also discusses the influence of inter-individual parameters on the satisfaction ratings. Table 4.7 shows an overview of variants for the room position and the tested variants were indicated (✓).

Table 4.7 Tested variants room position

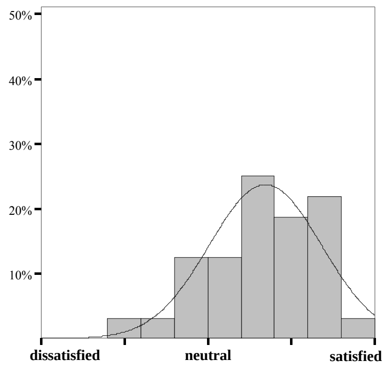
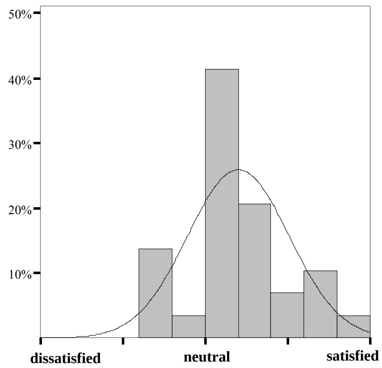
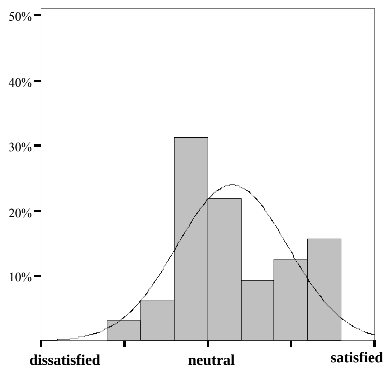
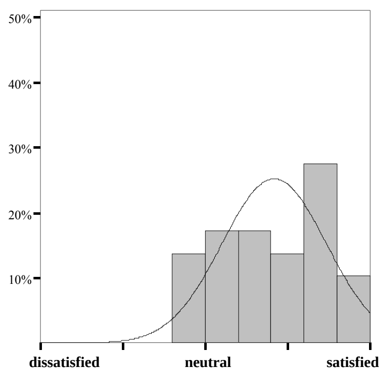
		Summer	Winter
Condition 2	1000lux	✓	✓
	2000lux	✓	-
Condition 3	1000lux	-	✓
	2000lux	-	-

- Illuminance level

In the summer period, the vertical illuminance at eye height of the test person was varied (~1000lux and ~2000lux). The satisfaction ratings for both variants are shown in the first column of Table 4.8. In the summer period, 93% of the test persons was satisfied (from ‘neutral’ to ‘totally satisfied’) with the 1000lux level. Only two persons were (slightly) dissatisfied. For the 2000lux level, the percentage of satisfied individuals decreased to 74% and eight persons were dissatisfied with this variant. The start position, the start level and the shift did not influence the satisfaction ratings. A paired-samples t-test was conducted to compare the satisfaction ratings between the two vertical illuminance levels to find out if there is a change in participants’ satisfaction score from the 1000lux to the 2000lux level. A significant difference was found in ratings between the 1000lux [$\underline{M}$=92.28, $\underline{SD}$=16.84] and the 2000lux level [$\underline{M}$=82.41, $\underline{SD}$=16.68; $\underline{t}(31)=5.341$, $\underline{p}<0.01$].

The magnitude of the differences in the means was large (η^2=0.48). Expressed as a percentage, 48% of the variance in satisfaction is explained by illuminance level.
Also for the small luminous area, the illuminance levels were proportionally related to the luminance levels in these variants. Assessment of measured vertical illuminances (E_{vert}) as function of the absolute area luminances (L_{area}) showed a very strong, significant, positive correlation (r=0.761; N=16; p<0.01) for the 2000lux level. The correlation for the 1000lux level did not reach statistical significance (r=0.484; N=16; p=0.057).

Table 4.8 Satisfaction rating for the four variants at the room position for the summer and winter period.

	Summer (N=32)	Winter (N=29)
Condition 2 ~1000lux		
Condition 2 ~2000lux		*not tested*
Condition 3 ~1000lux	*not tested*	

The comprehensive satisfaction parameter was subdivided into illuminance- and luminance-related variables. The variance in satisfaction rating from the 1000 to the 2000lux level is explained by luminance-related variables. Paired-samples t-tests were repeated for the subdivided parameters. According to the conducted t-test for the illuminance related variables, there was a significant difference in ratings between the 1000lux [M=34.34, SD=3.89] and the 2000lux level [M=31.97, SD=4.43; $t(31)=4.15$, $p<0.01$]. The magnitude of the differences in the means was large ($\eta^2=0.36$). Also, for the luminance related variables, there was a significant difference in ratings between the 1000lux [M=57.93, SD=14.17] and the 2000lux level [M=50.43, SD=13.00; $t(31)=4.86$, $p<0.01$]. The magnitude of the differences in the means was large ($\eta^2=0.43$).

Expressed as a percentage, 36% of the variance in satisfaction is explained by illuminance related variables and 43% by luminance related variables. Apparently, both the illuminances and the luminances for the 2000-lux variant were too high for a small luminous area. In the discussion about the window position it was assumed that L_{area} was below 1500cd/m², avoiding visual discomfort. Table 4.4 shows that the luminances of the small area were above for both levels: 1837±365 cd/m² and 3861±399cd/m².

Also for the room position, one-way between groups ANOVA's were conducted to explore the impact of the independent variables gender, age, eye correction and light sensitivity on satisfaction levels. For both levels there was no statistically significant difference in satisfaction ratings for the investigated inter-individual parameters.

- Condition

The satisfaction ratings for conditions in the winter are shown in Table 4.8. 94% of the population had a satisfaction rating from 'neutral' to 'totally satisfied' for condition 3. Only one person was dissatisfied. The start position, the start level and the shift did not influence the satisfaction ratings. For condition 2, the 'neutral' to 'totally satisfied' percentage decreased to 85% and four persons were dissatisfied with this variant.

For condition 2, a factorial ANOVA showed a significant influence of the start position on the satisfaction ratings [$F(1,21)=6.57$, N=29, $p=0.02$]. The effect was large ($\eta^2=0.24$). The majority of dissatisfied subjects started at the window position with condition 1 (large area).

A paired-samples t-test was conducted to compare the satisfaction ratings for the two conditions in the winter period. In the winter period there was a significant difference in ratings between the condition 2 [M=85.10, SD=15.14] and condition 3 [M=95.97, SD=15.82; $t(28)=3.11$, $p<0.01$]. The magnitude of the differences in means was large ($\eta^2=0.26$). 26% of the variance in satisfaction is explained by the conditions.

Also the comprehensive satisfaction parameter with regard to the small luminous area was subdivided into illuminance- and luminance-linked variables. Not surprisingly, there was no significant difference for the two variants with regard to illuminance related variables. For the luminance related variables there was a significant positive difference in ratings between condition 2 [M=52.66, SD=13.06] and condition 3 [M=62.86, SD=12.36; $t(24)=3.66$, $p<0.01$]. The magnitude of the differences in the means was large ($\eta^2=0.32$). 32% of the variance in satisfaction rating between the conditions is explained by luminance-related variables. In the winter period it was not possible to keep all luminance levels below ~1500cd/m² because condition 2 (with 1000lux) was equal to the summer variant (average $\underline{L}_{area\ small}$=2563cd/m²). Condition 3 delivered the vertical illuminance (1000lux) mainly from the suspended luminaires and the luminance did not exceed the 1500cd/m² (average $\underline{L}_{area\ small}$ =321cd/m²].

Factorial ANOVA's were conducted to explore the impact of the independent variables gender, age, eye correction and light sensitivity on satisfaction levels. There were no statistically significant differences in satisfaction ratings for both conditions.

- Season

Condition 2 was identical for both seasons. The daylight influence at this position is less and therefore the illuminance levels in summer and winter were similar (see Table 4.4). The luminance of the area was a little higher in winter. An independent-samples t-test was conducted to compare the means for two seasons for the entire population. There was no significant difference in satisfaction ratings between the summer and winter periods for the entire population ($\underline{p}$=0.09).

Analog to the window position, an independent-samples t-test procedure was conducted to compare the means for two seasons for the group of test persons who participated only once in the experiment. There was no significant difference in satisfaction ratings between the summer and winter period for the population that participated <u>once</u> in the experiment. Next, a paired-samples t-test was conducted for the population of persons who participated <u>twice</u> in the experiment for two seasons ($\underline{N}$=14). The start position, start level and shift were similar for summer and winter period for all persons. There was a significant difference in ratings between the summer [$\underline{M}$=94.57, $\underline{SD}$=13.48], and the winter period [$\underline{M}$=84.14, $\underline{SD}$=15.84; $\underline{t}$(13)=3.38, $\underline{p}$=0.05]. The magnitude of the differences in the means was very large ($\underline{\eta}^2$=0.49). 49% of the variance in satisfaction is explained by the season for the individuals who participated in the experiment twice. 11 out of 14 test persons were more satisfied in summer than in winter, with almost comparable light presets (see also Figure 4.15). It seems that season sensitivity is an important inter-individual parameter.

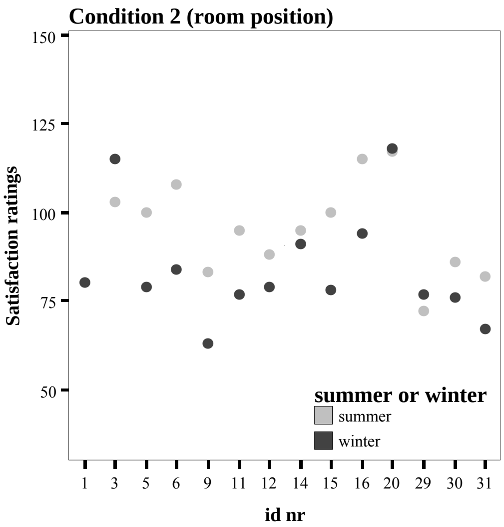


Figure 4.15 Satisfaction ratings for the persons who participated in both seasons (condition 2)

4.4.4 Preferences

At the end of the entire session, the test persons were asked for their overall preferences according to workstation and lighting. Explaining answers were not expressed in numbers or percentages.
Many test persons indicated in personal remarks that they want to sit near the window. In the questionnaires, there were no questions about a preferred position. Some persons preferred the small luminous area as a light system but only if suspended at a window position. Also, many subjects responded that the areas were too bright. This complies with the conclusions of the previous analysis. In several cases, the luminances of the areas were too high (>1500cd/m²).

In the winter period, the subjects were asked to rank the four variants they had been in. Many subjects responded in personal communication to the researcher that they did not notice the increase in lighting level of the suspended luminaire in condition 3. 17 test persons indicated this condition, combined with a window position, as their first preference. Condition 3 in the back of the room was often chosen as second preference. Condition 2, the small area with the highest luminances, was least popular. The ranking of the conditions in the winter period is shown in Figure 4.16.

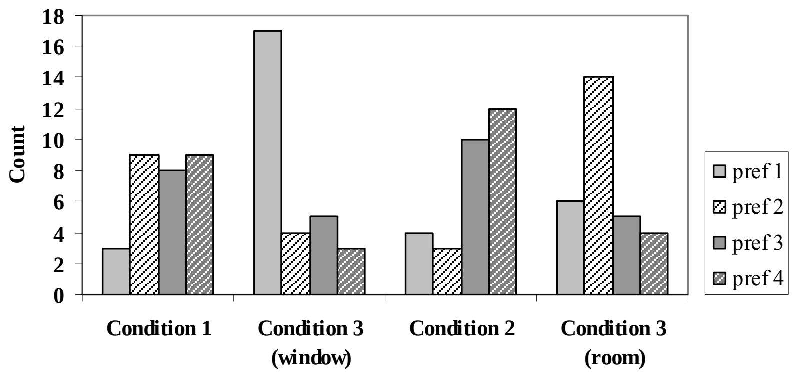


Figure 4.16 Ranking of the conditions in the winter period

4.4.5 Concluding remarks

The targeted vertical illuminance levels of 1000lux in the summer period were actually 200lux higher than the demanded levels. The daylight contribution was high for all sessions and therefore this had no consequences for comparison. Other levels approached the demanded values well. In both seasons, the luminances remained within the recommended ratios (1:20) for all light sources.

For the window position, the start position, the start level and the shift did not influence the satisfaction ratings. The satisfaction rating for the 1000lux level was very high (summer 84%). The 2000lux level was too high for many individuals; the percentage of satisfied people decreased to 56%. The variance in satisfaction ratings between the tested illuminance levels is mainly explained by luminance related variables (nuisance, reflection and ambiance). The effect is large: the luminances (~1900cd/m²) were apparently too high. The illuminance related variables show no significant differences in the winter period and in the summer period the effect is moderate. Most individuals had no problems with the high illuminance levels.

The results of the light sensitivity test were used to understand the acceptance of the variants. According to this test, the average visual comfort limit of the tested persons was around 1600 cd/m². The chance for complete satisfaction increases as the luminance level of bright, additional light sources is kept below L_{area}=1500cd/m².

The impact of the independent variables gender, age, eye correction and light sensitivity on satisfaction levels was investigated. For the 1000lux level (in summer), there was a statistically significant difference in satisfaction ratings for light sensitivity. Photophobic persons were less satisfied than neutral or photophilic persons.

In the winter period, the luminances were kept below 1500cd/m² and the satisfaction increased to 84-89% for both conditions. In the winter period, the vertical illuminance was kept invariable (~1000lux) and the condition (the electric lighting system) changed. There was no significant difference in satisfaction ratings between condition 1 and condition 3. For both conditions there was no statistically significant difference in satisfaction ratings for the investigated inter-individual parameters.

Condition 1 has been tested once again during the winter tests. Although the illuminances were not exactly identical as a result of the changing daylight, the two seasons were compared. There was no significant difference in satisfaction ratings between the summer and winter conditions for the entire population. The ANOVA's, which were executed concerning the light level and the different conditions, showed a difference between summer and winter. In summer, satisfaction was mainly influenced by the light sensitivity of individuals. The group of test persons was not equal in both seasons. The comparison between the seasons was made for the group that participated once and twice in the experiment. There was no significant difference in satisfaction ratings between the summer and winter period for the population that participated once in the experiment. There was a significant difference in satisfaction ratings between the summer and winter period for the population that participated twice in the experiment. 37% of the variance in satisfaction is explained by the season for these individuals. 11 out of 14 test persons were more satisfied in summer than in winter, with almost comparable light presets. It seems that, next to light sensitivity, season sensitivity is a very important inter-individual parameter. Both must be taken into account in assessments of a lighting design.

For the room position, the start level and the shift did not influence the satisfaction ratings in general. Only for condition 2 in the winter period there was a significant, positive correlation between the satisfaction and the start position. The majority of dissatisfied subjects started at the window position with condition 1 (large area).

The satisfaction rating for the 1000lux level was very high (summer 93%). The 2000lux level was too high for some individuals; the percentage of satisfied people decreased to 74%. The variance in satisfaction ratings between the tested illuminance levels is explained by luminance-related variables (nuisance, reflection and ambiance). The luminances (~3800cd/m²) were too high. The illuminance-related variables show no significant differences. Individuals had no problems with the high illuminance levels.

The impact of the independent variables gender, age, eye correction and light sensitivity on satisfaction levels was investigated at the two illuminance levels. For both levels there were no statistically significant differences in satisfaction ratings for the investigated inter-individual parameters.
It was not possible to keep the luminance level under ~1500cd/m² because condition 1 was equal to the summer variant. This variant shows a satisfaction percentage of 85%. The variant with the suspended luminaires (condition 3) satisfied 94% of the individuals. There was no significant difference in satisfaction ratings between condition 1 and condition 3.
The impact of the independent variables gender, age, eye correction and light sensitivity on satisfaction levels was also investigated for the two conditions. For both conditions there were no statistically significant differences in satisfaction ratings.
Condition 1 has been tested during summer and winter. The daylight influence at this position is less, the illuminance levels in summer and winter are therefore similar and the two seasons were compared. There was no significant difference in satisfaction ratings between the summer and winter conditions for the entire population. Analog to the window position, a comparison between the seasons was made for the group that participated once and twice in the experiment. There was no significant difference in satisfaction ratings between the summer and winter period for the population that participated once in the experiment. There was a significant difference in satisfaction ratings between the summer and winter period for the population that participated twice in the experiment. 49% of the variance in satisfaction is explained by the season for these individuals. 11 out of 14 test persons were more satisfied in summer than in winter with almost comparable light presets. It seems (again) that season sensitivity is a very important inter-individual parameter.

5 Design elements for lighting concepts with 'healthy lighting'

5.1 Introduction

This chapter presents recommendations for design elements for 'healthy' lighting systems that meet the visual and non-visual demands of humans in the office environment (see definition in chapter 1). The recommendations are based on:

1. literature and current standards;
2. the conclusions of the parameter study in chapter 2, combined with confirmations from the field study in chapter 3 and extra insights;
3. the visual satisfaction of humans as experienced in the laboratory study of chapter 4

In a room where an office employee works for more that two hours per day, transparent daylight openings must be available. The overall opening areas should have a surface of at least 5% of the floor area of this room (NEN-EN 12464-1). Most Dutch office buildings have vertical daylight openings. Working locations are mainly in the vicinity of the window (0-4 meters) or with a view to the window (5-6 meters). Large open-plan offices with considerable distances to the daylight opening like e.g. the North American cubicles do not exist in the Netherlands. The majority of the Dutch office buildings have several floors but there are no high-rise buildings.

Office rooms with vertical daylight openings in (Dutch) multi-storey buildings were taken as starting point for design recommendations. Working positions are in the vicinity of the window.

5.2 Light parameters

5.2.1 Visual demands

Most of the current lighting recommendations are formulated from the visual point of view. The recommendations prescribe horizontal illuminance levels from 200 to 700lux (task illuminance). An $\underline{E}_{hor}$ of 500lux is commonly applied, although a level of $\underline{E}_{hor}$>800lux is by humans. The current recommendations for maximum luminances are (mainly) based on office work with visual display terminals (VDT's). The standard recommends limiting the average luminance of lighting fixtures, window or surfaces that can be reflected in the computer screen to 1000-1500cd/m² (according to the software used and the screen type, see also NEN 3087, 1997). Luminance ratios between task and remote surroundings should not exceed 1:10. The ratios between luminaires, windows etc. and adjacent surfaces should not exceed 40:1 (preferably 20:1). Over the entire office, a balance between uniform and variable lighting is necessary. Luminance variation will increase visual interest and reveal the space accurately. Complete uniformity creates a flat, dull scene. The visual demands are summarized in Table 5.1.

5.2.2 Non-visual demands

With regard to non-visual performance, light intensities on the vertical plane of 1000-1500lux are required according to literature and standards. These high light levels are not demanded all day and a dynamic light dosage is therefore recommended. The current recommendations for maximum luminances are based on work with VDT's. With increasing lighting levels in the room, not only the visibility at the computer monitor might be critical, also the visual comfort limits of human beings could be reached. Until now, nothing is mentioned about luminances in relation with non-visual performance. Satisfaction experiments and assessments (chapter 4) showed that high illuminances can be realized and illuminance levels of 1000lux (and often even 2000lux) at the vertical plane were not problematic. The levels are fine; however the light source is often 'too bright'. The performed light sensitivity tests showed that there are human comfort limits. To satisfy the majority of individuals the maximum luminances in relatively dark rooms must be kept between 1000 and 1500cd/m². In well lit rooms, 1500cd/m² is the maximum. The non-visual demands also are summarized in Table 5.1.

Table 5.1 Visual and non-visual demands

Parameter	Demands	Remarks
Horizontal illuminance	500-800lux	E_{hor} of 500lux is commonly applied, a level of E_{hor}>800lux is preferred.
Vertical illuminance	1000-2000lux	The levels are fine; the light source might not be too bright. Levels are not demanded all day.
Luminance	1000-1500cd/m²	Based on both office work with visual display terminals (VDT's) and human preferences. In well lit rooms, 1500cd/m² is the maximum. The ratios between bright sources and adjacent surfaces should not exceed 40:1 (preferable 20:1).

Realization of lighting that meets both visual and non-visual demands of people without causing visual discomfort ('healthy lighting') is <u>not</u> simply accomplishing 800lux horizontally at the desk, 1000lux vertically at the eye with luminances that stay below 1500cd/m².

5.3 Solutions of 'healthy lighting'

The two light sources in a daytime office environment are daylight through daylight openings (windows, skylights) and electric lighting (luminaires). Daylight is a very energy-efficient, flicker-free light source containing the full wavelength spectrum. Naturally, it has high intensities and a dynamic character. However, no building can be lit by daylight alone because daylight is not reliable (weather, time of day, time of year, etc), and it generally does not reach all areas in a building. Each building is therefore equipped with electric lighting systems and this is compulsory. Even with an excellent daylighting system, electric light must be provided to maintain the desired illuminance levels under all circumstances. To what extent daylight is available and the actual daylight design should be considered before the electric lighting is designed (Veitch *et al.,* 2003). The electric lighting can supply the illuminance when needed.

Figure 5.1 shows the daylight course on a vertical plane at eye level, for an overcast day in February 2004. The measurements were performed in the Swift room that has an east orientation. On this day, little daylight was available and almost all day the level had to be supplemented with electric lighting to reach high illuminance levels at the eye. As a guideline for the light demand, the 'dynamic light dosage protocol' as proposed by Van der Beld (2001) was used.

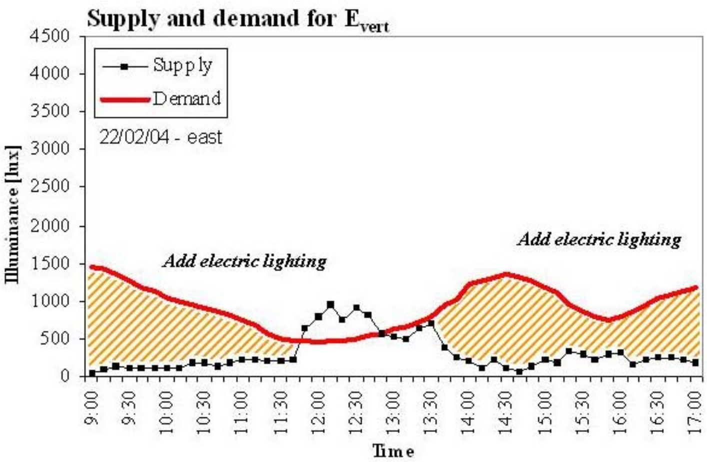


Figure 5.1 Dose of daylight and electric lighting during application of a dynamic light protocol in February in an east orientated room

Figure 5.2 shows the daylight course of the vertical illuminance at eye level in the Measuring room, for a day with sun in early September 2004. This room is west oriented and therefore in the afternoon there is chance for much daylight. To get high vertical illuminances, electric lighting must be added in the early morning.

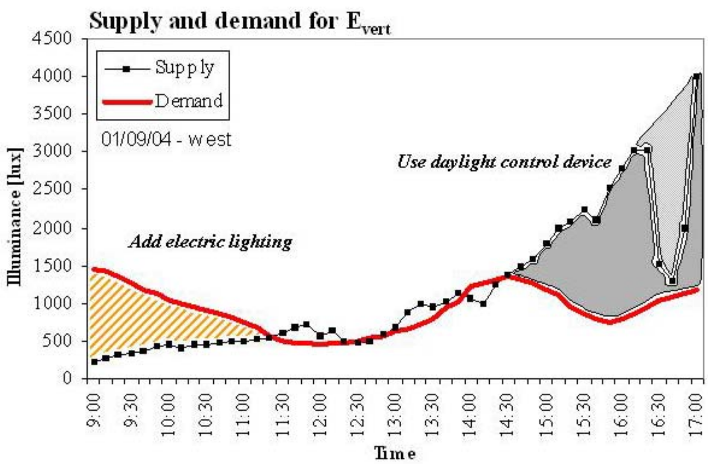


Figure 5.2 Daylight dose and electric lighting during application of a dynamic light protocol in September in a west orientated room

In the afternoon the daylight had to be reduced. Glare protection is necessary to decrease the luminance of the window. Direct daylight should not be blocked or screened but dosed or reduced (Zonneveldt and Aries, 2002). If daylight is reduced to the required level instead of completely blocked, no (additional) electric lighting is necessary.

As already mentioned in chapter 1, no building can be lit by daylight alone because daylight is not reliable according to the weather, the time of day or the time of year. Generally, it does not even reach all areas in a building and sometimes the intensity is too low. Three different (electric) lighting concepts, each representing a generic concept, were tested in the laboratory study. These concepts (see also Figure 5.3) were:

1. a two-component lighting system with a combination of general lighting and a local lighting system that was wall mounted (condition 1),
2. a two-component lighting system with a combination of general lighting and a local lighting system that was pending from the ceiling (condition 2)
3. an one-component lighting system with general lighting only (condition 3).

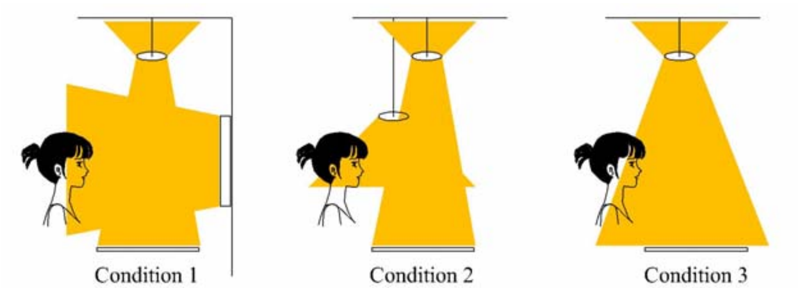


Figure 5.3 Schematic representation of the three (electric) lighting concepts

The results show that all three lighting concepts satisfy the visual and non-visual demands. With common but adapted techniques it is possible to provide sufficient vertical illuminance and maintain visual comfort.

5.3.1 Inter-architectural parameters

5.3.1.1 Orientation

The field study showed that the orientation of the façade has no significant main effect on the vertical illuminance in the office room. According to the parameter study, the north orientation is most favorite to obtain high vertical illuminances. For an east, south or west façade the absolute illuminance levels - caused by daylight - can high in the Dutch climate. In practice, this light does not always reach the vertical plane at eye level. Because of the angle of incidence, the contribution of direct daylight on the vertical illuminance is low. Diffuse daylight entering trough a vertical window causes a higher vertical illuminance than direct daylight. More daylight at the façade does not always mean higher vertical illuminances. The east, south and west orientations particularly demand adjustable daylight control devices (see section 5.3.2.3) to avoid too large luminances and glare.

5.3.1.2 *Obstructions*

The adjoining buildings and vegetation can influence the daylight entrance into buildings. High buildings are permanent obstructions and they reduce the daylight contribution considerably. Trees, for example, can provide a screening in the summer season with (too) high daylight amounts while the screening leaves are absent in the 'dark' winter season. This solution may be effective for low floors; high floor still need daylight control devices.

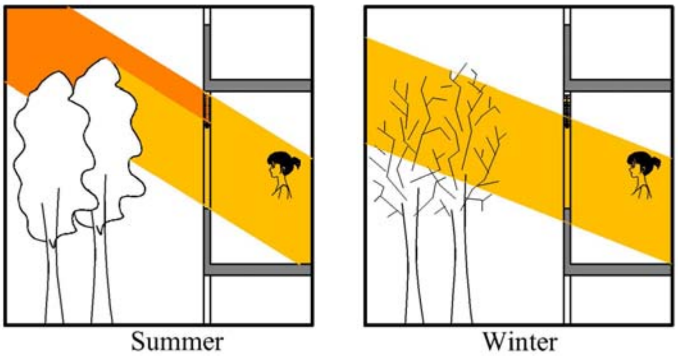


Figure 5.4 Trees as' useful' obstruction with screening leaves in summer and leafless in winter

5.3.1.3 *Daylight openings*

To make best use of daylight design, (diffuse) daylight from windows is the main light source. The larger the window height, the deeper daylight can be used in the room. However, the size of the daylight opening is not unlimited. Approximately 30-50% of the façade area must be constructed to serve as a daylight opening. Larger openings cause thermal problems and visual discomfort as a result of high amounts of daylight. The field study shows that the size of the daylight opening does not influence the vertical illuminance inside. An opening in the upper part of the façade is favorable for deep daylight penetration although an opening in the line of sight is necessary for a view. The parameter study shows that a window in the upper part of the façade delivers an important contribution to the vertical illuminances in the room. High positioned facade openings also allow the daylight to enter deeply into the room. When designing daylight openings, attention must be paid to the detailing of the light openings (sides, materialization, color etc.; see Figure 5.5). This favors the spread of daylight and reduces unpleasant contrasts.

Figure 5.5 Gradually changeover at daylight openings in a church

Daylight openings are strongly favored in work places for the daylight they deliver and the view out they provide, as long as the do not cause visual or thermal discomfort or a loss of privacy. Whether windows will provide an improvement of health and mood seems to depend on what the individual's preferences and expectations are. The light sensitivity of an individual plays an important role.

5.3.1.4 Office type

The office type has no significant effect on the vertical illuminance in the room according to the field test. With more people in a room, the chance increases that the daylight entrance is obstructed by closets, plants or closed daylight control devices. The parameter 'office type' relates more to the acoustic environment. The majority of persons who assessed quietness in their office as negative had a position in an open-plan office.
The smaller the office room is the more chance for an employee to have a favorite position with regard to the window. People have preferences for a window position (see chapter 4). With less people in a room, electric lighting controls and daylight control devices can be adjusted according to individual demands.

5.3.2 Intra-architectural parameters

5.3.2.1 Interior

Light levels must be verified in a completely furnished room, with and without daylight contributions (if possible). Traditional lighting calculation methods assume an empty room without allowance for light absorbed by room contents. An empty room has a different light distribution than a room that is filled with furniture (Carter and Hadwan, 2003). Surface characteristics (reflectance) are especially important for indirect or direct/indirect lighting installations and for offices in which daylight plays a major role (Zonneveldt and Mallory-Hill, 1998). Materials with high reflection coefficients 'distribute' the light through the room. Specular reflections can cause annoying glare (see also Figure 5.6). Using light colors do not mean that all colors need to be the same. Color variation is important to create visual interest and to suit the user's preference.

Figure 5.6 Windowsill with a (too) strong reflection coefficient is covered with material by the users

5.3.2.2 *Position of the work station*

The position of occupants and tasks are important parameters for a lighting design. People indicate to feel well with a workplace near the window. In the field study, the employees responded that they wanted a window because of the daylight and the (unobstructed) view outside. 'Status' is the least important reason for the demand of a window. In the laboratory study, no questions were asked about the preference for a window or room position. However, many test persons indicated in their comments that they want to sit near the window. The parameter study showed that a window-facing position (B or D) is effective for a high daylight illuminance at the eye, even in the back of the room (Figure 5.7).

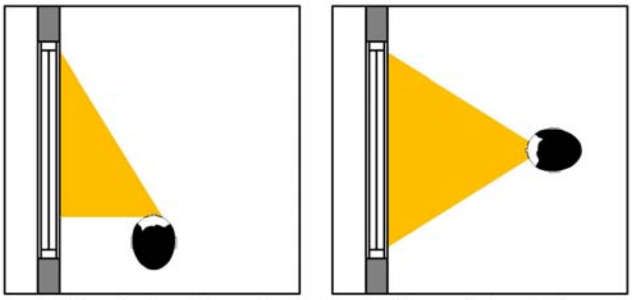


Figure 5.7 A window-facing position (B or D) is more effective for a high daylight illuminance at the eye than a position that faces the side-wall

All employees use a computer in the office. The field study showed a significant difference in satisfaction between CRT-users and LCD-users. The LCD-users were more satisfied with the light level at their computer screen while the majority of CRT-users said to have too much light on their screen. Current technologies for computer monitors (TFT-LCD) reduce the visibility problems because of the high screen luminances (±300cd/m²) and flat screens. In the laboratory study, TFT-LCD computer screens were used in combination with high illuminances levels and the individuals were satisfied.

5.3.2.3 *Daylight control devices*

Office employees have no influence on the façade design. They have to use additional devices to regulate the available daylight. In current offices, the majority of daylight openings are equipped with daylight control devices - awning, sun screens, blinds, brightness screens - to regulate the daylight entrance without causing glare or visual discomfort. The choice for a daylight control device or a specific daylighting system is preferably based on the lighting quality criteria that need to be achieved in accordance with the climate. Simple blinds can often realize an equal or even higher lighting quality than innovative daylighting systems (Velds, 2001).

Effective, adjustable, user-friendly daylight control devices have to be added to an office to allow users to benefit from daylight, while excluding direct daylight and the resulting glare problems (see for example Figure 5.8). There is a large difference between blocking and reducing direct sunlight or diffuse daylight. The parameter study showed that half-open blinds screened approximately 60-70% of the vertical illuminance in comparison with open blinds. Individuals are dissatisfied with permanently closed awning or blinds. Awnings or blinds are often closed because of discomfort and once closed screens generally remained closed, although the problem had already been solved. It is recommended to use re-setting protocols (e.g. opening blinds each evening) for the daylight control devices that can be controlled and overruled by users. In present-day offices, 40% of the respondents indicated to agree with automatic lighting control and 60% prefers to activate the lighting themselves.

Figure 5.8 Examples of daylight control devices with adjustable zones (on the left: inside system, on the right: outside system, photo by the NRC-IRC)

Field studies all over the world in a large number of offices have identified two factors for high levels of satisfaction: individual control and the depth of the building (Boyce *et al.*, 2003; Veitch *et al.,* 2003). Windows should always be fitted with some means of control (see Figure 5.8). Shallow buildings which allow daylighting and natural ventilation are preferred over deep buildings with electric lighting and mechanical ventilation. However, a study of occupant's reactions to having individual control of lighting in a number of multi-occupied offices has revealed a potential for conflict between occupants (see section 5.3.1.4), so much so that some occupants avoid using the controls (Moore *et al*., 2002).

5.3.2.4 Electric lighting (type, position, controls)

In current offices, the electric lighting is nearly always switched on during daytime. Current electric lighting installations used in office buildings have been designed mainly to lighten horizontal areas. All performed studies showed that a position with a view, parallel to the (present-day) luminaire receives more light at the eye than a position right below a luminaire with a perpendicular view. A location with a perpendicular view and with a little distance (0.5m) with regard to the luminaire received the highest light levels in the vertical plane (see for example Figure 5.9).

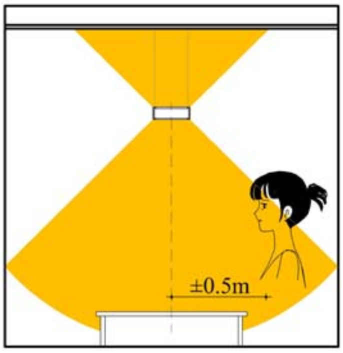


Figure 5.9 A slight distance (0.5m) with regard to the luminaire received the highest light levels in the vertical plane.

A combination of direct and indirect lighting is recommended for office rooms because it provides the necessary light levels and it also reduces the luminance difference between luminaire and surroundings (see also Figure 5.9).

Controls ensure light is on when, where, and at the level that is needed. Controls can reduce the amount of electric light used, provide energy savings, and allow occupants to set their preferred light levels. Settings are particularly relevant in relation to the light sensitivity of individuals. The laboratory study showed that photophobic persons were less satisfied with higher light levels than neutral or photophilic persons.

Settings are also relevant in relation to the season (sensitivity) influence. The study showed that the season (sensitivity) had a significant influence on acceptance. The season (sensitivity) must be taken into account in (assessments of) lighting design and controls make different presets possible for e.g. summer and winter. Controls are also necessary to create a dynamic electric lighting protocol (for a day, a week or a year).

6 Conclusions and recommendations

6.1 Conclusions

Present-day offices are it by a combination of daylight and electric lighting. Daylight entering through a vertical window has a very strong vertical illumination component, as opposed to a ceiling-based electric down-lighting system, with mainly a horizontal illumination component. Designs for a daylight opening, façade and/or office room based on visual criteria for sufficient light on the horizontal working plane do not (automatically) meet criteria for healthy office lighting. The amount of light entering the human eye is not directly and related proportionally to the horizontal illuminance on the working plane. Therefore, when designing healthy office lighting, both the horizontal illuminance and the vertical (or retinal) illuminance should be used as design parameters.

Horizontal illuminances of >500lux were measured in 90% of the cases. The present-day office lighting does satisfy the visual lighting criteria. The minimum visual lighting criterion of 200lux is satisfied in all investigated cases. In general, the majority of office employees (85%) was (very) satisfied with the lighting in the office room.

Current office lighting does not satisfy the non-visual lighting criteria (assumed as 1000lux at the eye). Vertical illuminances of >1000lux were measured in only 20% of the cases. In spring (April-May), the daylight contribution was considerably higher than in the dark period of the year (October-March). Especially in this dark period, when non-visual light stimulation is particularly relevant, daylight levels are much too low to achieve vertical illuminance levels of >1000lux and additional electric lighting is required.

Various inter-architectural parameters (e.g. orientation, obstruction, daylight opening and office type) are not separately related to the vertical illuminance at eye level. These parameters showed no significant influence on the vertical illuminance. Neither did the various intra-architectural parameters (e.g. interior, working place position, daylight control device and electric lighting).
Interaction effects were not taken into account, although the possible reason of the illuminance differences may lay in a combination of effects. The differences between the offices were very large and an interaction study with this amount of variables is impossible.

The illuminance on the window is determined by climatic parameters (e.g. weather, time and season). The vertical illuminance on the window showed a significant main effect on the vertical illuminance in the room. This shows that climatic parameters (each separately or in combination) have a significant influence on the vertical illuminance at eye level.

People with a work station with lower vertical illuminance levels indicated significant more fatigue and the intra-individual parameter fatigue therefore seems related to the vertical illuminance level at eye level. People with a work station with lower levels indicated worse sleep quality and the intra-individual parameter sleep quality therefore seems related to the vertical illuminance level at eye level. High levels of vertical illuminance were associated with lower levels of fatigue and higher levels of sleep quality. The intra-individual parameter (physical) health state was not significantly related to the vertical illuminance at eye level. The intra-individual parameters fatigue and sleep quality are not influenced by inter-individual parameters gender, age, eye correction, seasonal sensitivity and chronotype.

Simulation studies with the Radiance light simulation software showed that lighting concepts that meet both the visual and psychobiological demands of humans without causing visual discomfort are possible (for a standard cell-office). Depending on the daylight availability and the chosen illuminance level at the eye (1000 or 2000lux), it is possible to establish the desired condition with the different light sources. The maximum luminance ratios of the concepts investigated did not exceed the 1:20 ratio for the 1000lux variants in both summer and winter and for the 2000lux variant in summer. The 2000lux variant in winter did exceed the maximum ratio. The 2000lux variant will not be tested in a real winter situation because of the high visual discomfort. The simulations generated practical information (presets) for realization.

The test persons' responses on the new lighting concepts were investigated at different illuminance levels (1000 and 2000lux) with different systems (condition 1, 2 and 3), different working positions (D and E) and in different seasons (summer and winter).
For window position E, increasing the vertical illuminance to 1000lux did not influence acceptance of individuals. Approximately 85% of the test persons had satisfaction ratings from 'neutral' to 'satisfied' for the two concepts in the different seasons. The high vertical illuminance levels were realized within the human visual comfort limits. Increasing the vertical illuminance to 2000lux influenced acceptance. For the 2000lux level, the percentage of satisfied individuals decreased to 56%. The 2000lux level was too high for many individuals.
For room position D, increasing the vertical illuminance to 1000lux did not influence acceptance of individuals. Approximately 93% of the test persons had satisfaction ratings from 'neutral' to 'satisfied' for the two concepts in the different seasons. The high vertical illuminance levels were realized within the human visual comfort limits. Increasing the vertical illuminance to 2000lux influenced acceptance. For the 2000lux level, the percentage of satisfied individuals decreased to 74%.

The variance in satisfaction ratings between the tested illuminance levels is mainly explained by luminance-related variables (nuisance, reflection and ambiance). The results of the light sensitivity test were used to understand the acceptance of the variants. According to this test, the average visual comfort limit of the tested persons was around 1600 cd/m². The chance for complete satisfaction increases as the luminance level of bright, additional light sources is kept below 1500cd/m². Many test persons responded that the areas were too bright. In several cases, the luminances of the areas were too high (>1500cd/m²). Most individuals had no problems with high illuminance levels but did have problems with luminance levels that were too high.

In the winter period, the vertical illuminance was kept invariable (~1000lux) and the condition (the electric lighting system) changed. There was no significant difference in satisfaction ratings between condition 1 and condition 3. Neither was there a difference between condition 2 and condition 3. Condition 1 and 2 were not compared because the working place position was different. The specific lighting conditions tested with a vertical illuminance of 1000lux had no significant influence on acceptance. Acceptance of 1000lux seems not related to lighting conditions.

Conditions 1 and 2 have been tested in a summer (May/June) and a winter (November/December) period. There were no significant differences in satisfaction ratings between the summer and winter periods for the entire population. The season had no significant influence on the acceptance. However, the group of test persons was not equal in both seasons.

The impact of the independent variables gender, age, eye correction and light sensitivity on satisfaction levels was investigated. For the 1000lux level (in the summer) there was a statistically significant difference in satisfaction ratings for light sensitivity. Photophobic persons were less satisfied than neutral or photophilic persons. This effect was found for the 1000lux level at the window position only (E). For the room position, the impact of the independent variables gender, age, eye correction and light sensitivity on satisfaction levels was investigated at the two illuminance levels. For both levels there were no statistically significant differences in satisfaction ratings for the investigated inter-individual parameters. Light sensitivity seems to have a significant influence on acceptance.

Season sensitivity was not tested separately during the laboratory experiments. However, the group of test persons was not equal in both seasons. The comparison between the seasons was made for the group that participated once and twice in the experiment. For both positions investigated, there was no significant difference in satisfaction ratings between the summer and winter period for the population that participated once in the experiment. For the individuals who participated twice in the experiment, 11 out of 14 test persons were more satisfied in summer than in winter with almost comparable light presets. The season sensitivity must be taken into account in (assessments of) lighting design. The season (sensitivity) has a significant influence on acceptance.

The start position, the start level and the shift did not influence the satisfaction ratings. This applies to both the window and the room position. Only for condition 2 (small area – room position), a factorial ANOVA showed a significant influence of the start position on

the satisfaction ratings. The majority of dissatisfied subjects started at the window position with condition 1 (large area – window position).
Many test persons indicated in personal remarks that they want to sit near the window. In the questionnaires, there were no questions about a preferred position. Some persons preferred the small luminous area as a light system but only if suspended at a window position.

Lighting has both a visual and non-visual influence on humans according to subjective assessments. The results confirmed that it is possible to realize lighting concepts for office rooms that meet both the human visual and non-visual demands within human comfort limits. With common but adapted techniques, it is possible to provide sufficient vertical illuminance and to maintain visual comfort.

6.2 Recommendations

The architecture of a building, inside and outside, plays an important role for both daylight availability and design of electric lighting installations. The variety in the current office environments is enormous. Extensive studies about inter- and intra-architectural parameters (e.g. interior, office planning and colors) are necessary to investigate main and interaction effects of the different variables on light parameters.

Repeated, long term physical measurements and user assessments are necessary to confirm the main conclusions of the field test for an entire year. Extensive tests for intra-individual influences like ‘fatigue’ and ‘sleep’ may enforce the conclusion of the relationship between the amount of light at eye level and light-relevant parameters that are related to the direct brain effects and the circadian rhythm.

Next to extended field studies in current buildings, field studies in real office buildings with high vertical illuminance must also be performed. This improves the knowledge of satisfaction and long-term effects. All seasons must be taken into account and therefore long term experiments of at least one year are preferred.

The investigated electric lighting in the laboratory study was static. The entrance of daylight provided is dynamic. In a winter period, the influence of daylight is less and illuminance is mainly delivered by electric lighting. Effects of dynamic (electric) lighting protocols must be studied in both summer and winter. This improves the knowledge (of satisfaction) of ‘healthy lighting’.

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List of symbols and abbreviations

a_{xy}	Distance in the xy-plane [m]
A_p	Area of the pupil of the eye [mm²]
E	Illuminance [lux]
E_{hor}	Horizontal illuminance [lux]
$E_{hor\ desk}$	Horizontal illuminance at the desk [lux]
$E_{hor\ field}$	Horizontal illuminance in the free field (outside) [lux]
$E_{hor\ room}$	Horizontal illuminance in the room at desk level [lux]
$E_{retinal}$	Retinal illuminance [lux]
E_{vert}	Vertical illuminance [lux]
$E_{winvert}$	Vertical illuminance at the window [lux]
d_p	Eye's pupil diameter [mm]
d_{eye}	Eye's diameter [mm]
e_r	Troland value [td]
F	Ratio between to variances [-]
F_R	Reduction factor [-]
h	Height [m]
h_{window}	window height [m]
L	Luminance [cd/m²]
$L_{direct\ surr.}$	Luminance of the direct surroundings [cd/m²]
$L_{light\ source}$	Luminance of a light source [cd/m²]
L_{scene}	Scene luminance [cd/m²]
L_{task}	Task luminance [cd/m²]
L_{area}	Luminance of a luminous area [cd/m²]
L_{sky}	Luminance of the sky [cd/m²]
M	Mean [-]
N	Quantity [-]
p	Statistic significance level [-]
R	Effectivity ratio [-]
R_a	Color index [-]
r	(Pearson) correlation [-]
r_p	Radius of pupil [mm²]
α	Probability level [-]
β	Unique contribution value [-]
γ	Inclination (down) angle of the head [°]
ρ	Reflection coefficient [-]
η^2	Eta Squared [-]
η_p^2	Partial Eta Squared [-]
χ^2	Chi-Squared [-]

CIBSE	Chartered Institution of Building Services Engineers
CIE	Commission International d'Eclairage
ISO	International Organization for Standardization
IEA	International Energy Agency
IES	Illuminating Engineering Society
KCBS	Knowledge Center for Building and Systems
UC Louvain	Université Catholique Louvain la Neuve
NSVV	Nederlandse Stichting voor Verlichtingskunde
RUG	Rijksunivisiteit Groningen
SBI	Statens byggeforskningsinstitut
SOLG	Stichting Onderzoek Licht en Gezondheid
TNO	Toegepast Natuurwetenschappelijk Onderzoek
Tema	Techniek en Maatschappij
TU/e	Technische Universiteit Eindhoven

ANOVA	Analyses of variance
CBT	Core body temperature
CRT	Cathode-ray tube
EEG	Electro-encenphalogram
EL	Electric lighting
ECG	Electro-cardiogram
EOG	Electro-oculogram
DL	Daylight
FSFL	Full-spectrum fluorescent lamp
LCD	Liquid crystal display
PVT	Psychomotor vigilance task
RED	Retinal exposure detector
RGC	Retinal ganglion cells
SAD	Seasonal Affective Disorder
SEM	Slow eye movements
SCN	Suprachiasmatic nucleus
SD	Standard deviation
VLPO	Ventro preoptic area
VDT	Visual display terminal
TL	Tube light
TFT	Thin film transistor
WWFL	Warm-white fluorescent lamp

Appendices

Appendix A Specifications used measurement equipment

A.1 Design of the experimental set-up

New measurement equipment was developed to measure purposefully and rapidly in the office environment. Retinal and vertical detectors were mounted at eye-height at a mobile, experimental set-up. The 'head' of the set-up was able to make an inclined angle. Equipment was stored inside the set-up. Collected data were directly saved on a laptop that was positioned in a drawer of the mobile set-up. Figure A.1 shows a drawing of the designed mobile measuring equipment.

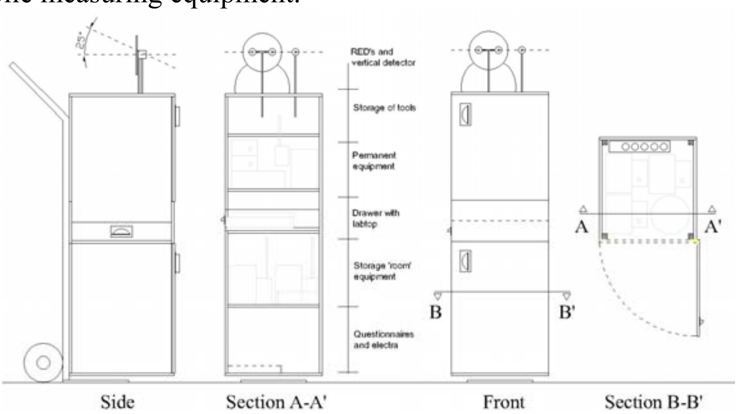


Figure A.1 Drawing of the mobile measuring equipment (sides and sections)

A.2 Illuminance

The illuminances were measured with ten standard, cosine corrected Hagner SD2 detectors. Table A.1 shows an overview of the detectors, their height of placing and their sensitivity (field study).

Table A.1 Sensitivity of light detectors that are used in the field study

No.	Illuminance in lux	Height [m]	Sensitivity [pA/lux]
1	Vertical eye height	1.35	108.6
2	Horizontal desk	0.80	92.4
3	Vertical window	± 1.25*	133.6
4	Horizontal window	± 1.30*	132.6
5	Vertical room middle	1.25	126.5
6	Horizontal room middle	0.80	118.5
7	Vertical room back	1.25	113.6
8	Horizontal room back	0.80	121.7

* Dependent of field situation

Table A.2 shows the values for the laboratory study and their location in the measuring room. The detectors were connected to a Multilab, manufactured at the TU Eindhoven (serial number 3804 301). In the field study, the Multilab was connected to a receiver. This receiver (Hanwell radiologger CR-1), located in the mobile set-up, received information radio-graphically, via transmitters, of all detectors in the room.

Table A.2 Sensitivity of light detectors that are used in the laboratory study

No.	Illuminance in lux	Position			Sensitivity
		x	y	z	[pA/lux]
1	Horizontal desk front	1.6	1.2	0.75	131.0
2	Horizontal desk middle	1.6	2.2	0.75	106.0
3	Horizontal desk back	1.8	3.9	0.75	110.8
4	Vertical rear wall	1.8	5.4	1.25	120.0
5	Vertical South wall	3.6	0.25*	1.25	129.8
6	Vertical North wall	0	1.2	1.25	90.0
7	Vertical back position	1.6	4.2	1.25	86.5
8	Vertical front position	1.5	1.5	1.25	106.7
9	Vertical window (West)	-	-	1.50**	133.6
10	Horizontal window (West)	-	-	1.55**	132.6

* Next to lighting system ** In a neighbor room and at h=1.50 to overlook a balustrade

The vertical illuminance detector at the mobile measuring equipment was directly connected to the Multilab for both the field test and the laboratory test. Both Retinal Exposure Detectors were also attached to the Multilab. Table A.3 shows the sensitivity values for the retinal detectors and their location in the measuring room.

Table A.3 Sensitivity of the retinal exposure detectors

No.	Description	Position			Sensitivity
		x	y	z	
left	Retinal illuminance / Troland value	1.3	1.3	1.25	99.8 pA/lux
right	Retinal illuminance / Troland value	1.5	1.5	1.25	98.2 pA/lux

A separate Hagner E4-X digital lux meter (no. 4149) was used for light sensitivity tests. A stand with the light detector was placed next to the test person to register the vertical illuminance at eye level (*h*=1.25m).

A.3 Calibration of detectors

Each light detector was calibrated separately. Calibration was executed twice because in the studies (field and laboratory study) different receiver cards were used. Several gain and offset values were determined for each light detector. The values were determined for different illuminance ranges with help of an Ulbricht sphere (no. EAO186) and three different lamps (Philips Halogena 60W, Osram Halolux 150W and Osram Halolux 250W). The gain and offset values are shown in Table A.4 and Table A.5. The detectors were calibrated for three or four illuminance ranges (Channel 1 low = 0-1000lux, high = 0-800lux, Channel 2: low = 0-12500lux, high = 0-10000lux).

Table A.4 Calibration light detectors: gain and offset values field study

Span		RED Right		RED Left	
		Channel 1	Channel 2	Channel 1	Channel 2
Low	Gain [mV^{-1}]	0.3418	4.1454	0.3610	4.4098
	Offset [mV]	0	-2	-4	-2
High	Gain [mV^{-1}]	2.6498	-	2.8054	-
	Offset [mV]	0	-	0	-
		E_{vert}		E_{hor}	
Span		Channel 1	Channel 2	Channel 1	Channel 2
Low	Gain [mV^{-1}]	0.3015	3.6869	0.3627	4.5233
	Offset [mV]	-2	-1	0	-1
High	Gain [mV^{-1}]	2.3568	-	2.8915	-
	Offset [mV]	0	-	0	-
		$E_{winvert}$		E_{winhor}	
Span		Channel 1	Channel 2	Channel 1	Channel 2
Low	Gain [mV^{-1}]	0.1867	1.6940	0.1858	1.6809
	Offset [mV]	-2	-1	-5	-2
High	Gain [mV^{-1}]	1.7544	12.9769	1.7478	12.8700
	Offset [mV]	0	-1	-3	-1
		E_{SD1}		E_{SD2}	
Span		E_{vert}	E_{hor}	E_{vert}	E_{hor}
Low	Gain [mV^{-1}]	1.5695	1.6317	1.5945	1.5801
	Offset [mV]	0	0	0	0
High	Gain [mV^{-1}]	15.1869	15.7767	15.3302	15.2225
	Offset [mV]	0	0	0	0

A.4 Luminance

Luminances were measured with a Hagner S2 Universal Photometer (no.4). More sophisticated luminances were measured with a LMK 96-2 CCD camera, fabricated by TechnoTeam (serial number DXP 1330). The LMK is a universal digital imaging photometer for luminance measurements. The provided measuring and evaluation software (LMK-2000) was used for data analyzing.

A.5 Temperature and humidity

Temperature and humidity measurements were performed both in summer and winter period with an Escort logger, fabricated by ESCORT Data Logging Systems Ltd (serial number 0346-084).

A.6 Reflection coefficients

The reflection coefficients of materials were measured with a spectrophotometer (Konica-Minolta CM-2600d). This device is a portable integrating sphere spectrophotometers designed for versatility in various color measurement applications.

A.7 Distance

Distances were measured with a laser distance meter (Leica DISTO™ pro4a). This is a hand-held laser meter for fast and easy distance measurements of length, squares and volumes with the press of a button.

Table A.5 Calibration light detectors: gain and offset values laboratory study

		RED Right		RED Left	
Span		Channel 1	Channel 2	Channel 1	Channel 2
Low	Gain [mV^{-1}]	0.2550	3.1160	0.2650	3.2050
	Offset [mV]	-2	-1	-7	-2
High	Gain [mV^{-1}]	2.0250	-	2.0795	-
	Offset [mV]	0	-	-4	-
		E_{hor1}		E_{hor2}	
Span		Channel 1	Channel 2	Channel 1	Channel 2
Low	Gain [mV^{-1}]	0.2037	2.4191	0.2677	3.2514
	Offset [mV]	0	-1	-3	-1
High	Gain [mV^{-1}]	1.5805	-	2.1131	-
	Offset [mV]	0	-	-3	-
		E_{hor3}		$E_{vert\ back\ wall}$	
Span		Channel 1	Channel 2	Channel 1	Channel 2
Low	Gain [mV^{-1}]	0.2416	2.946	0.2237	2.7048
	Offset [mV]	0	0	0	0
High	Gain [mV^{-1}]	1.9239	-	1.7686	-
	Offset [mV]	0	-	0	-
		$E_{vert\ left\ wall}$		$E_{vert\ right\ wall}$	
Span		E_{vert}	E_{hor}	E_{vert}	E_{hor}
Low	Gain [mV^{-1}]	0.2041	2.4180	0.4311	5.2724
	Offset [mV]	0	-1	-6	-2
High	Gain [mV^{-1}]	1.581	-	3.4295	-
	Offset [mV]	0	-	-4	-
		E_{vert}		$E_{vert\ back}$	
Span		Channel 1	Channel 2	Channel 1	Channel 2
Low	Gain [mV^{-1}]	0.2914	3.6690	0.2360	2.8850
	Offset [mV]	-2	-1	-4	-2
High	Gain [mV^{-1}]	2.356	-	1.8723	-
	Offset [mV]	0	-	-4	-
		$E_{winvert}$		E_{winhor}	
Span		Channel 1	Channel 2	Channel 1	Channel 2
Low	Gain [mV^{-1}]	0.1944	2.3170	0.2075	2.455
	Offset [mV]	-2	-1	-6	-2
High	Gain [mV^{-1}]	1.5055	18.507	1.6095	19.659
	Offset [mV]	0	-1	-4	-2

Appendix B Buildings of the field study

B.1 Introduction

In April 2003, field-tests started in offices with lighting measurements at workstations. On the basis of the evaluation of ten office buildings in the Netherlands the lighting situation in practice was shown. For each building, a schematic floor plan of the building and its surroundings, together with a short description is shown in the paragraphs below. The grey areas were adjoining buildings. The height of these buildings is specified in the text if necessary. These heights were relevant if the measured location was positioned at a lower floor. The marks in the buildings are the measuring locations of the field study. These locations were distributed over different floors and in some cases different measurements were done at one of these locations (close working stations).
For privacy reasons, no names or images/photos of the buildings were mentioned.

B.2 Building 1

Office building 1 (see Figure B.1a) is located in urban surroundings (Eindhoven, the Netherlands). The office building has seven floors and the measurements were taken on the second and fourth floor. The floors contain cell offices and open-plan offices. On the west side of the building a high office building (20 floors) is located with a totally glass façade. A building with equal height is located on the east orientation. The other orientations have a free view.

Figure B.1 Schematic floor plan and surroundings of building 1 (left) and building 2 (right)

B.3 Building 2

Office building 2 (see Figure B.1b) is part of a big complex of buildings and located in urban surroundings (Eindhoven, the Netherlands). The office building had two floors and the measurements were taken on the ground floor. The floor contains group offices for four persons. The back of the group office is open. On the north, east and west side of the building higher parts of the building complex screen the daylight and the view. The south orientation has a free view.

B.4 Building 3

Office building 3 (see Figure B.2a) is part of a big complex of buildings and the complex is located in urban surroundings (Eindhoven, the Netherlands). The measured office building has fourteen floors and the measurements were taken on the sixth floor. The floor contains cell office rooms for one or two persons on the east and west orientations and group offices for four persons on the building corners (south orientation). All office rooms have a free view.

Figure B.2 Schematic floor plan and surroundings of building 3 (left) and building 4 (right)

B.5 Building 4

Office building 4 (see Figure B.2b) is located in urban surroundings (Eindhoven, the Netherlands). The measured office building has only a ground floor. The floor contains cell office rooms for one or two persons on the north and west orientations and open-plan offices on mainly east and south orientations. On the north, east and west side of the building adjoining buildings screen the daylight and the view.

B.6 Building 5

Office building 5 (see Figure B.3a) is located in urban surroundings (Eindhoven, the Netherlands). The measured office building has eight floors and the measurements were taken on the fifth floor. The floor contains cell office rooms for one or two persons on the south orientation and open-plan offices on the north orientations. All office rooms have a free view. A building on the west has equal height.

Figure B.3 Schematic floor plan and surroundings of building 5 (left) and building 6 (right)

B.7 Building 6

Office building 6 (see Figure B.3b) is located in industrial surroundings (Eindhoven, the Netherlands). The measured office building has eight floors and the measurements were taken on the ground floor. The floor contains cell office rooms for one or two persons and one group office for four persons. All office rooms were south orientated and have a free view.

B.8 Building 7

Office building 7 (see Figure B.4a) is located in industrial surroundings (Son and Breugel, the Netherlands). The measured office building has three floors and the measurements were taken on the first floor at all orientations. The floor contains cell office rooms for one or two persons, a group office for four persons and open-plan offices. All office rooms have a free view.

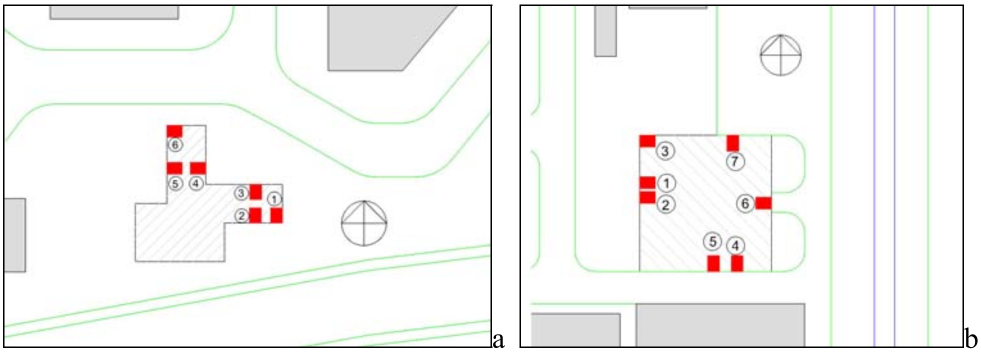


Figure B.4 Schematic floor plan and surroundings of building 7 (left) and building 8 (right)

B.9 Building 8

Office building 8 (see Figure B.4b) is located in industrial surroundings (Delft, the Netherlands). The measured office building has eight floors and the measurements were taken on the fifth floor at all orientations. The floor contains cell office rooms for one person and group offices for two to three persons. The building on the south is low and therefore all office rooms have a free view.

B.10 Building 9

Office building 9 (see Figure B.5a) is located in urban surroundings (Eindhoven, the Netherlands). The office building has nine floors and the measurements were taken on the fifth floor with the east and west orientations. The office contains cell-offices, group offices for four persons and open-plan offices. On the east side a building with equal height is located with a totally glass façade. The other orientations have a free view.

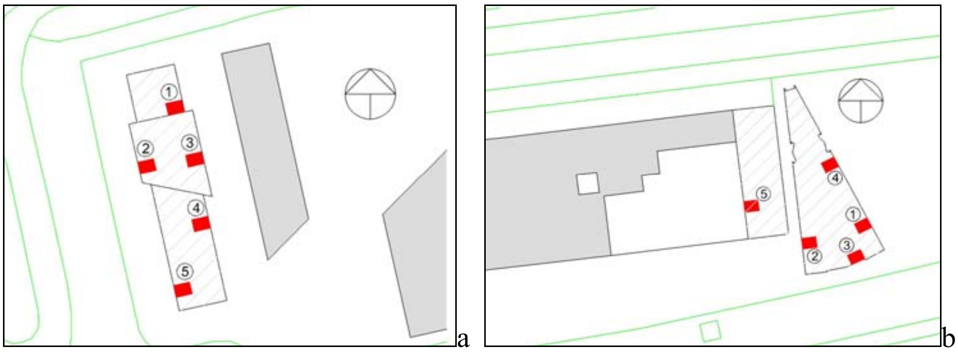


Figure B.5 Schematic floor plan and surroundings of building 9 (left) and building 10 (right)

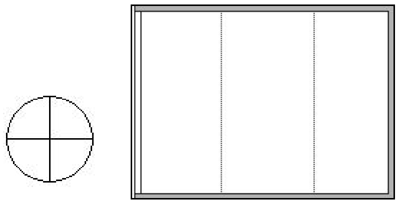
B.11 Building 10

Office building 10 (see Figure B.5b) is located in industrial surroundings (Eindhoven, the Netherlands). The office building has twelve floors and the measurements were taken on the ground, the seventh and the eight floor. The orientations were east, south and west. The building contains cell-offices and group offices for two to three persons. A building with five floors is located on the east orientation but all measured locations have a free view.

Appendix C Questionnaires

C.1 Questionnaire Field study

Volgnummer … … … … … …
Gebouwcode … … … … … …



Vragenlijst

Werkomgeving kantoren

In het kader van mijn promotieonderzoek aan de Technische Universiteit Eindhoven, faculteit Bouwkunde wil ik u vragen deze vragenlijst in te vullen. De bedoeling van deze vragenlijst is inzicht te krijgen in hoe kantoorgebruikers vandaag de dag hun omgeving beleven en wat ze belangrijk vinden. Invullen geeft de mening van degene die de vragen invult. Er zijn geen ‘goede’ of ‘slechte’ antwoorden. Probeert u a.u.b. alle vragen in te vullen. Er is steeds één antwoord mogelijk, tenzij dit anders is vermeld.

Deze vragenlijst heeft 43 vragen en het invullen kost ongeveer 15 minuten. De pagina’s zijn dubbelzijdig bedrukt.

Voor alle vragen geldt dat ze uitsluitend gebruikt worden ten behoeve van dit onderzoek. Ze zullen niet gebruikt worden om gegevens over u bekend te maken. Ze worden anoniem verwerkt en ze zullen niet aan derden worden verstrekt.

Ik kom de vragenlijst weer bij u ophalen en als dank ontvangt u bij het inleveren een kleine attentie. Bij voorbaat dank voor het invullen!

Myriam Ariës
TU Eindhoven
April 2003

Vragen over de kantoorruimte

1 Met hoeveel mensen deelt u uw kantoorruimte?

- ❑ Geen
- ❑ 1 persoon
- ❑ - 4 personen
- ❑ 5 of meer personen

2 Hoe lang zit u gemiddeld per dag achter uw bureau?

- ❑ minder dan 2 uur
- ❑ 2-4 uur
- ❑ meer dan 4 uur

3 Wat voor werk doet u <u>voornamelijk</u>?

- ❑ Schrijfwerk
- ❑ Leeswerk
- ❑ Computerwerk
- ❑ Overleg
- ❑ Telefoneren

4 Als u recht vooruit kijkt (van achter uw bureau), wat ziet u dan? *(meerdere antwoorden mogelijk)*

- ❑ Een raam
- ❑ Een collega
- ❑ Een van de zijwanden van de kantoorruimte
- ❑ De achterwand van de kantoorruimte
- ❑ Meubilair (bijv. een kast of scheidingswand hoger dan ooghoogte)
- ❑ Iets anders, namelijk ……

5 Hoe ver is het dichtstbijzijnde raam verwijderd van uw werkplek?

- ❑ minder dan 2 meter
- ❑ 2-4 meter
- ❑ meer dan 4 meter

6 Vindt u het belangrijk om een raam te hebben in uw kantoor?

niet belangrijk zeer belangrijk

❑ ❑ ❑ ❑ ❑

7 Hoe belangrijk zijn voor u de volgende eigenschappen bij het hebben van een raam in uw kantoor?

	Niet belangrijk				Zeer belangrijk
Uitzicht	❑	❑	❑	❑	❑
Daglicht	❑	❑	❑	❑	❑
Indicatie tijd van de dag	❑	❑	❑	❑	❑
Indicatie van het weer	❑	❑	❑	❑	❑
Afleiding	❑	❑	❑	❑	❑
Status	❑	❑	❑	❑	❑

8 Kunt u het raam zelf openzetten?

❑ Nee
❑ Ja

Indien ja, wanneer zet u het raam open?

Nooit				Altijd
❑	❑	❑	❑	❑

9 Als u, vanaf uw werkplek, uit het raam wilt kijken, is het uitzicht dan geblokkeerd?

❑ Nee
❑ Ja

Indien ja, waardoor wordt dat uitzicht geblokkeerd? *(Meerdere antwoorden mogelijk)*

❑ Meubilair
❑ Raamafmetingen
❑ Gebouwdelen
❑ Permanente zonwering/helderheidswering/gordijn
❑ Iets anders, namelijk ……..

10 Hoe beoordeelt u in het algemeen het lichtniveau, kunst- en daglicht samen?

	te weinig licht	beetje weinig licht	ongeveer goed	beetje veel licht	te veel licht
Op de werkplek	❑	❑	❑	❑	❑
In de gehele ruimte	❑	❑	❑	❑	❑
Op het beeldscherm	❑	❑	❑	❑	❑

11 Heeft u een voorkeur om te werken in een ruimte verlicht met daglicht, kunstlicht of een combinatie van dag- en kunstlicht?

❑ Geen voorkeur
❑ Voorkeur voor daglicht
❑ Voorkeur voor kunstlicht
❑ Voorkeur voor dag- en kunstlicht

12 Kunt u zelf de kunstverlichting aan en uitschakelen?
- ❑ Ja
- ❑ Nee

13 Vindt u het belangrijk de kunstverlichting aan en uit te kunnen schakelen?

niet belangrijk ❑ ❑ ❑ ❑ ❑ zeer belangrijk

14 Vindt u het vervelend als de <u>verlichting</u> automatisch aan en uit geschakeld wordt?
- ❑ Ja
- ❑ Nee

15 Vindt u het vervelend als de <u>verwarming</u> automatisch aan en uit geschakeld wordt?
- ❑ Ja
- ❑ Nee

16 Is uw kantoorruimte voorzien van zonwering en zo ja, kunt u deze handmatig bedienen?
- ❑ Nee (ga door naar vraag 19)
- ❑ Ja, handmatig bedienbaar
- ❑ Ja, niet handmatig bedienbaar

17 Welke situatie is op uw kantoorruimte m.b.t. de zonwering van toepassing?
- ❑ De zonwering is altijd/meestal open
- ❑ De zonwering is altijd/meestal geheel gesloten
- ❑ De zonwering is altijd/meestal halfopen

18 In welke mate bent u tevreden over de mogelijkheden tot zonwering?
- ❑ Zeer tevreden
- ❑ Tevreden
- ❑ Niet tevreden of ontevreden
- ❑ Ontevreden
- ❑ Zeer ontevreden

19 Zijn er tijdstippen op de dag dat u direct zonlicht in uw kantoorruimte krijgt?
- ❑ Ja
- ❑ Nee

20 Zijn er momenten gedurende het jaar dat u graag direct zonlicht in uw kantoorruimte wilt? *(meerdere antwoorden mogelijk)*

- ❑ Nee
- ❑ Ja, in de winter
- ❑ Ja, in de lente
- ❑ Ja, in de zomer
- ❑ Ja, in de herfst

21 Geef aan in welke mate u tijdens uw werk gehinderd wordt als gevolg van direct zonlicht in uw kantoorruimte?

	Geen hinder	Weinig hinder	Matige hinder	Veel hinder	Erg veel hinder
Door de warmte van de zon	❑	❑	❑	❑	❑
Door direct zonlicht op het bureau	❑	❑	❑	❑	❑
Door reflecties op het beeldscherm	❑	❑	❑	❑	❑

Vragen over hoe u zich voelt in uw kantoorruimte

22 Zijn er, in het algemeen, momenten gedurende dag dat u zich meestal moe of minder alert voelt?

- ❑ Nee
- ❑ Ja, met name in het eerste deel van de ochtend
- ❑ Ja, met name in het tweede deel van de ochtend
- ❑ Ja, met name rond de lunch
- ❑ Ja, met name in het eerste deel van de middag
- ❑ Ja, met name in het tweede deel van de middag

23 Wat doet u als u zich moe of minder alert voelt tijdens uw werk?

- ❑ Niets
- ❑ Iets eten of drinken
- ❑ Ruimte lichter maken
- ❑ Veranderen van activiteit (bijvoorbeeld schrijven i.p.v. lezen)
- ❑ Naar buiten kijken
- ❑ Stukje lopen
- ❑ Praatje maken
- ❑ Iets anders, namelijk ………..

24 Wat is uw algemene indruk van uw kantoorruimte?

	Zeer negatief	Negatief	Neutraal	Positief	Zeer positief
Plezierig	❑	❑	❑	❑	❑
Interessant	❑	❑	❑	❑	❑
Licht	❑	❑	❑	❑	❑
Warm (temperatuur)	❑	❑	❑	❑	❑
Ruim	❑	❑	❑	❑	❑
Rustig	❑	❑	❑	❑	❑
Gezellig	❑	❑	❑	❑	❑
Ordelijk	❑	❑	❑	❑	❑
Schoon	❑	❑	❑	❑	❑
Gevarieerd	❑	❑	❑	❑	❑
Mooi	❑	❑	❑	❑	❑
Sfeervol	❑	❑	❑	❑	❑
Overzichtelijk	❑	❑	❑	❑	❑

25 Zijn er activiteiten waarbij u in het algemeen moe/minder alert wordt? *(meerdere antwoorden mogelijk)*

- ❑ Geen
- ❑ Lezen
- ❑ Schrijftaken
- ❑ Computertaken
- ❑ Overleg
- ❑ Iets anders, namelijk …………

26 Kunt u zichzelf gemakkelijk van de buitenwereld afsluiten als u aan het werk bent (d.w.z. gemakkelijk in staat afleidingen en geluiden te negeren)?

erg gemakkelijk erg moeilijk

❑ ❑ ❑ ❑ ❑

27 Welke van de onderstaande voorwaarden zijn voor u noodzakelijk om geconcentreerd te kunnen werken? *(meerdere antwoorden mogelijk)*

- ❑ Geen voorwaarden
- ❑ Stilte
- ❑ Veel licht
- ❑ Uitzicht
- ❑ Warmte
- ❑ Geluid (bijv. muziek)
- ❑ Weinig licht
- ❑ Afzondering
- ❑ Koelte
- ❑ Iets anders, namelijk …………

28 Kunt u aangeven hoe belangrijk u de volgende eigenschappen in een kantooromgeving vindt?

	Niet belangrijk				Zeer belangrijk
Comfortabele temperatuur	❑	❑	❑	❑	❑
Veel licht	❑	❑	❑	❑	❑
Gelijkmatig verlicht	❑	❑	❑	❑	❑
Goede ventilatie	❑	❑	❑	❑	❑
Ramen	❑	❑	❑	❑	❑
Aankleding van het kantoor	❑	❑	❑	❑	❑
Weinig geluid	❑	❑	❑	❑	❑
Privacy	❑	❑	❑	❑	❑
Veel ruimte	❑	❑	❑	❑	❑
Uitzicht	❑	❑	❑	❑	❑
Mogelijkheid tot het zelf regelen van installaties	❑	❑	❑	❑	❑
Aanwezigheid van collega's	❑	❑	❑	❑	❑

Vragen over gezondheid, stemming, algemene activiteit, slaap en eetpatronen

Deze vragen zijn afkomstig uit een wetenschappelijke test die is gebaseerd op de 'Seasonal Pattern Assessment Questionnaire', een vragenlijst die is samengesteld door experts.

29 Hoe actief bent u als u zichzelf vergelijkt met uw collega's?

❑ Veel minder actief
❑ Minder actief
❑ Even actief
❑ Actiever
❑ Veel actiever

30 Bemerkt u een verschil tussen winter en zomer voor wat betreft...

	Geen verandering	Weinig verandering	Matige verandering	Duidelijke verandering	Zeer duidelijke verandering
Slaapbehoefte	❑	❑	❑	❑	❑
Sociale activiteiten	❑	❑	❑	❑	❑
Stemming	❑	❑	❑	❑	❑
Gewicht	❑	❑	❑	❑	❑
Energieniveau	❑	❑	❑	❑	❑

31 In welke maanden zijn de onderstaande uitspraken voor u het meest van toepassing?
(meerdere hokjes mogelijk)

	dec jan	feb mrt	apr mei	jun jul	aug sep	okt nov	Geen verschil
Ik voel me het beste in	❑	❑	❑	❑	❑	❑	❑
Ik neig tot overgewicht in	❑	❑	❑	❑	❑	❑	❑
Ik heb de meeste sociale contacten in	❑	❑	❑	❑	❑	❑	❑
Ik slaap het minst in	❑	❑	❑	❑	❑	❑	❑
Ik eet het meest in	❑	❑	❑	❑	❑	❑	❑
Ik verlies het meeste gewicht in	❑	❑	❑	❑	❑	❑	❑
Ik heb de minste sociale contacten in	❑	❑	❑	❑	❑	❑	❑
Ik voel mij het slechtste in	❑	❑	❑	❑	❑	❑	❑
Ik slaap het meest in	❑	❑	❑	❑	❑	❑	❑

32 Als u veranderingen ervaart, in welke mate belemmeren ze dan uw functioneren?

❑ Geen belemmering
❑ Weinig belemmering
❑ Matige belemmering
❑ Duidelijke belemmering
❑ Zeer duidelijke belemmering

33 Zijn de onderstaande uitspraken <u>over het algemeen</u> op u van toepassing?

	Ja	Nee
Ik slaap vaak niet langer dan vijf uur	❑	❑
Ik voel mij 's ochtends goed uitgerust	❑	❑
Ik gebruik medicijnen om tekort aan energie aan te vullen	❑	❑
Ik kom naar mijn gevoel meestal slaap tekort	❑	❑
Ik slaap gemakkelijk in	❑	❑
Als ik 's nachts wakker word, slaap ik moeilijk weer in	❑	❑
Ik gebruik slaappillen om in slaap te komen	❑	❑

34 Geef aan in welke mate onderstaande begrippen op u van toepassing zijn.

	Niet	Nauwelijks	Enigszins	Behoorlijk	Zeer
Concentratie problemen	❑	❑	❑	❑	❑
Droge keel	❑	❑	❑	❑	❑
Snel vermoeid	❑	❑	❑	❑	❑
Versuftheid	❑	❑	❑	❑	❑
Prikkelbaarheid	❑	❑	❑	❑	❑
Slechter zien	❑	❑	❑	❑	❑
Hoofdpijn	❑	❑	❑	❑	❑
Droge ogen	❑	❑	❑	❑	❑
Geïrriteerde huid	❑	❑	❑	❑	❑
Loopneus	❑	❑	❑	❑	❑

35 Hoeveel tijd brengt u per week in de winter (oktober tot maart) in uw vrije tijd buiten door?
- ❑ minder dan 2 uur
- ❑ 2 - 8 uur
- ❑ meer dan 8 uur

36 Hoeveel tijd brengt u per week in de rest van het jaar in uw vrije tijd buiten door?
- ❑ minder dan 2 uur
- ❑ 2 - 8 uur
- ❑ meer dan 8 uur

Algemene gegevens

37 Wat is uw geslacht?
- ❑ Man
- ❑ Vrouw

38 Hoe lang werkt u al in dit gebouw?
- ❑ Korter dan 1 jaar
- ❑ 1-5 jaar
- ❑ Langer dan 5 jaar

39 Op welke verdieping werkt u?
- ❑ Begane grond
- ❑ Op verdieping ….. *(nummer invullen)*

40 Wat is uw leeftijd?
- ❑ Onder de 30 jaar
- ❑ 30 - 39 jaar
- ❑ 40- 49 jaar
- ❑ 50 - 59 jaar
- ❑ 60 of ouder

41 Draagt u tijdens uw werk een bril of contactlenzen?
- ❑ Nee
- ❑ Ja, bril
- ❑ Ja, contactlenzen

42 Hoeveel dagen per week werkt u gemiddeld in deze kantoorruimte?
- ❑ 1 dag
- ❑ 2 dagen
- ❑ 3 dagen
- ❑ 4 dagen
- ❑ 5 dagen

43 Bent u een ochtend of avondmens?
- ❑ Ochtendmens
- ❑ Avondmens
- ❑ Geen van beide
- ❑ Weet ik niet

Dit is het einde van de vragenlijst.
Hartelijk dank voor het invullen van deze lijst!

Heeft u nog opmerkingen of vragen naar aanleiding van de vragenlijst?

____

____

____

C.2 Questionnaire Laboratory study

Algemene vragenlijst

1 Met hoeveel mensen deelt u uw kantoorruimte?
- ❑ Geen
- ❑ 1 persoon
- ❑ 2-4 personen
- ❑ 5 of meer personen

2 Hoe lang zit u gemiddeld per dag achter uw bureau?
- ❑ minder dan 2 uur
- ❑ 2-4 uur
- ❑ meer dan 4 uur

3 Wat voor werk doet u voornamelijk?
- ❑ Schrijfwerk/leeswerk
- ❑ Computerwerk
- ❑ Overleg
- ❑ Telefoneren

4 Hoe ver is het dichtstbijzijnde raam verwijderd van uw werkplek?
- ❑ Minder dan 2 meter
- ❑ 2-4 meter
- ❑ meer dan 4 meter
- ❑ Geen raam aanwezig in het kantoor

5 Krijgt u wel eens direct zonlicht binnen op uw kantoor?

- ❑ Ja
- ❑ Nee

6 Is uw werkplek voorzien van handmatig te bedienen zonwering?

- ❑ Nee
- ❑ Ja

7 Indien ja: welke van onderstaande situaties is dan van toepassing?

- ❑ De zonwering is meestal open
- ❑ De zonwering is meestal geheel gesloten
- ❑ De zonwering is meestal half open
- ❑ De zonwering wordt geopend en gesloten naar behoefte

8 Vindt u het belangrijk om een raam te hebben in uw kantoor?

Niet belangrijk				Zeer belangrijk
❑	❑	❑	❑	❑

9 Hoe belangrijk zijn voor u de volgende eigenschappen bij het hebben van een raam in uw kantoor?

	Niet belangrijk				Zeer belangrijk
Uitzicht	❑	❑	❑	❑	❑
Daglicht	❑	❑	❑	❑	❑
Indicatie van tijd van de dag	❑	❑	❑	❑	❑
Indicatie van het weer	❑	❑	❑	❑	❑
Afleiding	❑	❑	❑	❑	❑

10 Kunt u aangeven hoe belangrijk u de volgende eigenschappen in een kantooromgeving vindt?

	Niet belangrijk				Zeer belangrijk
Comfortabele temperatuur	❑	❑	❑	❑	❑
Geen geluidsoverlast	❑	❑	❑	❑	❑
Veel licht	❑	❑	❑	❑	❑
Privacy	❑	❑	❑	❑	❑
Goede ventilatie	❑	❑	❑	❑	❑
Genoeg ruimte	❑	❑	❑	❑	❑
Ramen	❑	❑	❑	❑	❑
Aankleding van het kantoor	❑	❑	❑	❑	❑
Uitzicht	❑	❑	❑	❑	❑
Mogelijkheid tot het zelf regelen van installaties	❑	❑	❑	❑	❑

11 Werkt u wel eens bij alleen daglicht?
- ❑ Ja
- ❑ Nee

12 Vindt u het belangrijk om zelf de kunstverlichting aan en uit te kunnen schakelen?

niet belangrijk ❑ ❑ ❑ ❑ ❑ zeer belangrijk

13 Hoe is uw humeur vandaag?
- ❑ Heel slecht
- ❑ Slecht
- ❑ Normaal
- ❑ Goed
- ❑ Heel goed

14 Hoe goed voelt u zich vandaag? (fysiek)
- ❑ Heel slecht
- ❑ Slecht
- ❑ Normaal
- ❑ Goed
- ❑ Heel goed

15 Hoe heeft u geslapen afgelopen nacht?
- ❑ Heel slecht
- ❑ Slecht
- ❑ Normaal
- ❑ Goed
- ❑ Heel goed

16 Bent u gevoelig voor verblinding?
- ❑ Ja
- ❑ Nee
- ❑ Een beetje

17 Welke uitspraak is op u van toepassing? (meerdere antwoorden mogelijk)
- ❑ U heeft altijd kunstverlichting aan
- ❑ U hebt overdag de kunstverlichting vaak uit
- ❑ U bent gevoelig voor fel licht
- ❑ U kunt fel licht goed verdragen
- ❑ U bevindt zich graag in een ruimte met veel licht
- ❑ U bevindt zich graag in een donkere ruimte

18 Draagt u een bril of contactlenzen terwijl u werkt?
- ❑ Ja
- ❑ Nee

19 Indien ja:
- ❑ Gewone bril
- ❑ Varilux/multifocus
- ❑ Contactlenzen
- ❑ Speciale bril voor beeldschermwerk
- ❑ Leesbril

20 Draagt u geregeld een zonnebril, binnen en/of buiten?
- ❑ Ja, buiten
- ❑ Ja, binnen
- ❑ Ja, binnen en buiten
- ❑ Nee

21 Wat is uw leeftijd?
- ❑ < 30
- ❑ 30-39
- ❑ 40-49
- ❑ 50-60
- ❑ >60

22 Wat is uw geslacht?
- ❑ Man
- ❑ Vrouw

Vragenlijst voor de varianten

23 Wat is uw algemene indruk van dit kantoor op dit moment? (meerdere antwoorden mogelijk)
- ❑ Licht
- ❑ Donker
- ❑ Goede kleuren
- ❑ Gelijkmatig verlicht
- ❑ Ongelijkmatig verlicht
- ❑ Rustig
- ❑ Druk
- ❑ Ruim
- ❑ Sfeervol
- ❑ Anders, te weten...

24 Hoe beoordeelt u op dit moment het totale lichtniveau in het kantoor?

	te weinig licht		ongeveer goed		teveel licht
Op het bureau	❑	❑	❑	❑	❑
In de gehele ruimte	❑	❑	❑	❑	❑
Op het beeldscherm	❑	❑	❑	❑	❑

25 Heeft u last van verblinding door kunstlicht?

	Veel last				Geen last
Als u naar het beeldscherm kijkt	❑	❑	❑	❑	❑
Als u leest met het papier op het bureau	❑	❑	❑	❑	❑
Als u leest met het papier in uw handen (achterover leunend)	❑	❑	❑	❑	❑

26 Heeft u last van verblinding door daglicht?

	Veel last				Geen last
Als u naar het beeldscherm kijkt	❑	❑	❑	❑	❑
Als u leest met het papier op het bureau	❑	❑	❑	❑	❑
Als u leest met het papier in uw handen (achterover leunend)	❑	❑	❑	❑	❑

27 Veroorzaakt de verlichting reflecties in uw werk materiaal?

	niet hinderlijk				erg hinderlijk
De plafondverlichting	❑	❑	❑	❑	❑
Het grote zelf lichtende vlak	❑	❑	❑	❑	❑
Het raam	❑	❑	❑	❑	❑

28 Als er hinderlijke reflecties optreden, waarin dan?

- ❑ Glanzend papier
- ❑ Beeldscherm
- ❑ Anders, te weten..

29 Wat vindt u van het licht van dit kantoor vanaf deze plek? (daglicht+kunstlicht)

Plezierig	❑	❑	❑	❑	❑	Niet plezierig
Storend	❑	❑	❑	❑	❑	Niet storend
Warm	❑	❑	❑	❑	❑	Koud
Fel, scherp	❑	❑	❑	❑	❑	zacht
Verblindend	❑	❑	❑	❑	❑	Niet verblindend

30 Ervaart u moeilijkheden met de zichtbaarheid van de tekst op het computerscherm?

Helemaal niet ❑ ❑ ❑ ❑ ❑ Heel erg veel

31 Kunt u aangeven of u het met de onderstaande stellingen eens of oneens bent?

	Helemaal mee oneens	Mee oneens	Neutraal	Mee eens	Helemaal mee eens
Het daglicht is te fel	❑	❑	❑	❑	❑
Er valt te weinig licht op het bureau	❑	❑	❑	❑	❑
Er is te veel licht in de gehele ruimte	❑	❑	❑	❑	❑
Reflecties van het raam storen mij bij de uitvoering van mijn werk	❑	❑	❑	❑	❑
Er valt te veel licht op het beeldscherm	❑	❑	❑	❑	❑
Het kunstlicht is te fel	❑	❑	❑	❑	❑
Er valt te veel licht op het bureau	❑	❑	❑	❑	❑
Reflecties van het kunstlicht storen mij bij de uitvoering van mijn werk	❑	❑	❑	❑	❑
Er is te weinig licht in de gehele ruimte	❑	❑	❑	❑	❑

32 Hoe tevreden bent u met de hoeveelheid licht op deze werkplek op dit moment?

- ❑ Zeer tevreden
- ❑ Tevreden
- ❑ Neutraal
- ❑ Ontevreden
- ❑ Zeer ontevreden

33 Wat vindt u van het grote zelf lichtende vlak aan de muur?

Plezierig	❑	❑	❑	❑	❑	Niet plezierig
Storend	❑	❑	❑	❑	❑	Niet storend
Fel, scherp	❑	❑	❑	❑	❑	Zacht
Verblindend	❑	❑	❑	❑	❑	Niet verblindend
Nadrukkelijk aanwezig	❑	❑	❑	❑	❑	Niet nadrukkelijk aanwezig

34 Indien u nog op- of aanmerkingen heeft, kunt u deze hieronder noteren.

....
....
....

Afsluitende vragenlijst

35 Hebt u het onbehaaglijk gehad gedurende uw verblijf in dit kantoor, met betrekking tot de volgende klimaatcondities?

	Helemaal niet				Heel erg
Hoge temperatuur	❑	❑	❑	❑	❑
Lage temperatuur	❑	❑	❑	❑	❑
Tocht	❑	❑	❑	❑	❑
Geur	❑	❑	❑	❑	❑
Stof	❑	❑	❑	❑	❑
Geluid	❑	❑	❑	❑	❑

36 Is er iets wat u in het bijzonder aanspreekt in dit kantoor?

❑ Nee
❑ Ja,..

37 Is er iets wat u in het bijzonder verafschuwt in dit kantoor?

❑ Nee
❑ Ja,..

38 Zou u dit kantoor als uw vaste werkplek willen hebben?

❑ Nee, omdat:
....
❑ Ja, omdat:
....

39 Welke variant vond u het prettigste om bij te werken?

❑ Groot vierkant verlicht vlak, omdat:
....
❑ Pendelarmatuur vlak boven het bureau, omdat:
....

40 Indien u nog op- of aanmerkingen heeft, kunt u deze hieronder noteren.

....
....
....

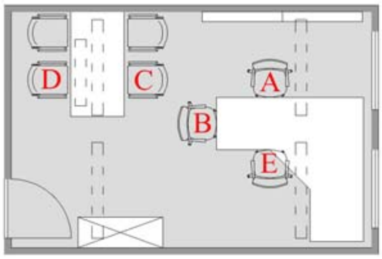
Appendix D Simulation results

Healthy lighting conditions were conceived and evaluated with the validated light simulation software ‘Radiance’. The designed conditions were reviewed with regard to human visual and non-visual demands.

During the design process, a number of alternatives were examined for five different positions (see Table D.1) with differences in daylight situation and electric lighting systems. The final Radiance simulation study showed that lighting conditions that meet both the human visual and non-visual demands without causing visual discomfort are possible. Furthermore, the simulations generated practical information for realization.

Table D.1 Floor plan with simulation positions A, B, C, D and E (coordinates E_{vert})

Position	Room coordinates			Viewing directions		
Name	x	y	z	dx	dy	dz
A	2.7	1.4	1.25	-1	0	0
B	1.8	2.5	1.25	0	-1	0
C	2.8	3.4	1.25	0	1	0
D	2.8	4.4	1.25	0	-1	0
E	1.4	1.4	1.25	1	0	0



D.1 Requirements

The demanded illuminance in an office room depends on size and contrast of the task, age on the observer and required accuracy. For reading and writing, approximately 500lux is sufficient and computer tasks require approximately 300lux. The physiological load is minimal with a horizontal illuminance of 700-800lux ($E_{hor\ desk}$ ≥800 lux (desk level h=0.8m) and $E_{hor\ room}$ ≥400 lux (desk level h=0.8m)).

For adequate non-visual stimulation high illuminances at eye level are necessary. The absolute simulation results were scaled to get an E_{vert} ≥ 1.000 lux (eye level h=1.25m). For assessment of luminances in the room, a distinction was made for a visual field with regard to visual performance and visual comfort. The opening angles of the eyes for the visual performance pictures were 80° horizontally by 60° vertically and the opening angles for the visual comfort pictures were 180° horizontally by 120° vertically.

In the direct visual field (‘visual performance’), the luminance ratios between the task and the light source may not exceed 1:20; neither may the luminance ratio between the light source and direct surroundings of the light source. In the entire visual field (‘visual comfort’) the luminance ratios between the task and the light source may not exceed 1:30 (preferable 1:25). The simulation results were controlled for:

- L_{task}: $L_{light\ source}$ = max. 1:20
- $L_{direct\ surr.}$: $L_{light\ source}$ = max. 1:20
- L_{task} : $L_{light\ source}$ ≤ 1:25-30

D.2 Model

Pictures with a fish-eye view were generated to verify the façade arrangement, the position of the furniture and the lighting elements in the model. The model was correct (see Figure D.1).

Figure D.1 Back and front view of the simulated cell-office with daylight and electric lighting

D.3 Absolute (numeric) results

For each position four conditions (daylight only, general lighting only, large area only small area only) were calculated separately and the results are shown in Table D.2 to Table D.5. The task illuminance ($\underline{E}_{hor}$) and four different viewing directions for $\underline{E}_{vert}$ were calculated for each condition.

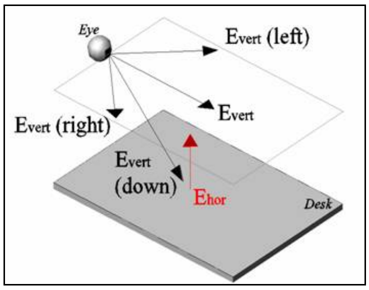


Figure D.2 Task illuminance ($\underline{E}_{hor}$) and different viewing directions for $\underline{E}_{vert}$

Table D.2 A condition with daylight only (CIE overcast sky with $E_{hor\ field}$ = 10000lux)

pos	E_{vert}	E_{vert} (down)	E_{vert} (left)	E_{vert} (right)	E_{hor}
A	352	278	782	123	584
B	566	462	434	424	346
C	78	78	76	75	79
D	225	208	157	205	87
E	345	283	116	776	568

Table D.3 A condition with general lighting only at full power (100%)

pos	E_{vert}	E_{vert} (down)	E_{vert} (left)	E_{vert} (right)	E_{hor}
A	467	266	927	237	1279
B	265	219	237	220	505
C	827	476	656	631	1017
D	581	262	516	588	912
E	356	293	244	630	1234

Table D.4 A condition with the large luminous area at the wall only at full power (100%)

pos	E_{vert}	E_{vert} (down)	E_{vert} (left)	E_{vert} (right)	E_{hor}
A	500	452	541	536	1736
B	1017	807	1927	397	1109
C	200	192	245	160	317
D	477	390	369	385	312
E	1899	1604	1450	1381	1177

Table D.5 A condition with the small luminous area above the desk only at full power (100%)

pos	E_{vert}	E_{vert} (down)	E_{vert} (left)	E_{vert} (right)	E_{hor}
A	16	14	6	60	18
B	8	9	16	8	35
C	1535	1298	1341	1010	1485
D	1405	1230	924	1164	1499
E	37	16	89	12	20

D.4 Assessment of visual performance and visual comfort

In Figure D.3, simulation results are shown of winter period ($E_{hor\ field}$=8000lux) and E_{vert} = 1000lux. The daylight opening was covered with white Venetian blinds turned horizontally. The luminance distribution images (false color) in Figure D. (visual performance) show that the ratio between the luminous area and the direct surroundings is approximately 1:13 for the large luminous area and 1:18 for the small luminous area. The ratio between L_{task} and $L_{light\ source}$ is 1:6 (position E) and 1:9 (position D). All luminance ratios satisfied the requirements.

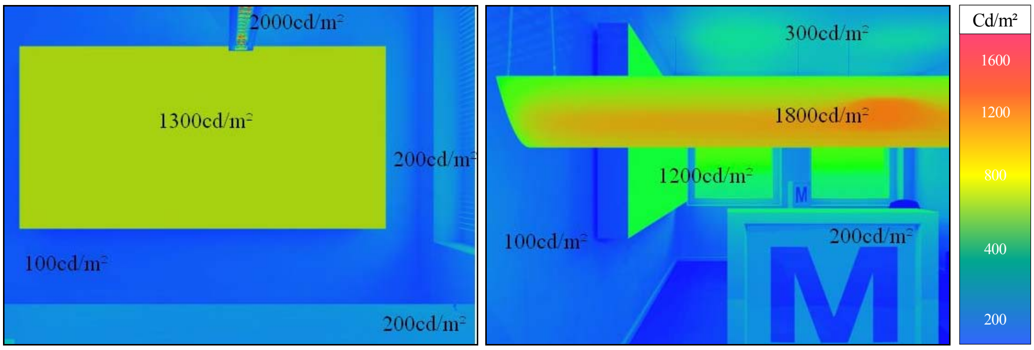


Figure D.3 Assessment of visual performance (on the left: position E and on the right: position D)

The luminance distribution images in Figure D.4 show a wider field (visual comfort). The light sources in the entire field show no exceeding of maximum luminances (1:30). The horizontally turned Venetian blinds kept the luminance of the daylight opening at ~2000cd/m². At position D, the small luminous area was the surface with the highest luminance.

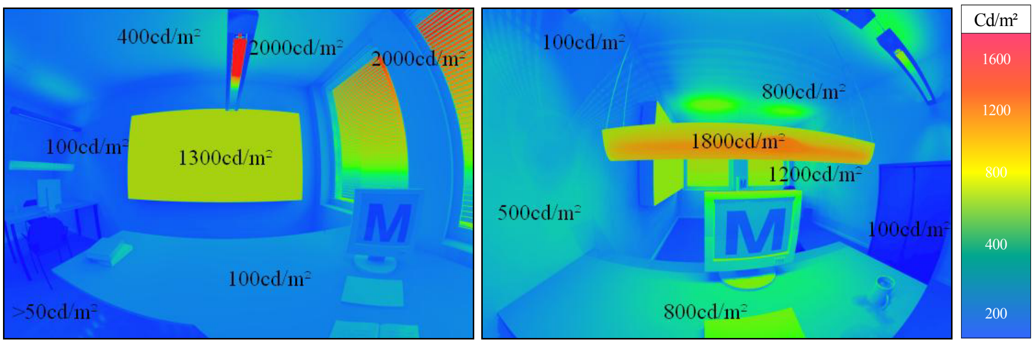


Figure D.4 Assessment of visual comfort (on the left: position E and on the right: position D)

Appendix E Definition of comprehensive parameters

Questions were clustered to new comprehensive variables to reduce the amount of variables and to make the parameters more reliable. The data reduction was applicable to ‘satisfaction’ and ‘light sensitivity’.

E.1 Satisfaction

The comprehensive parameter ‘satisfaction’ is compiled of five parts (general, level, nuisance, reflections and ambiance, see Figure E.1). The illuminance related variables (general and level) were summarized to a new parameter. Likewise the luminance related variables (nuisance, reflection and ambiance) were totalized. Statistical analyses were conducted for the comprehensive parameter firstly and, if necessary, extended to illuminance or luminance related parameters.

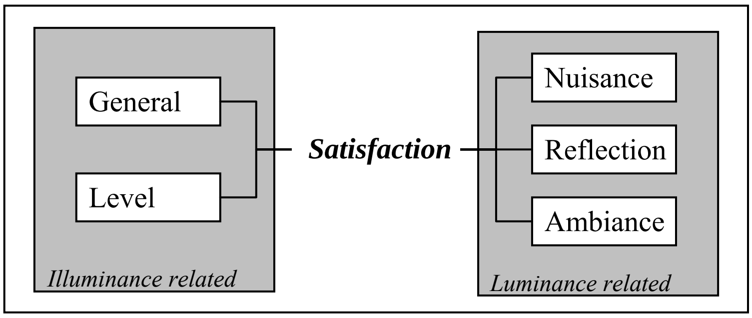


Figure E.1: Schematic composition of the parameter ‘satisfaction’

The five clustered questions were:

1. The rating of the general question about satisfaction. Question 18 was the most general and direct question that inquired after the satisfaction of the light quantity on the working location. The question had a five point scale with a ranking from ‘very dissatisfied’ to ‘very satisfied’. The general satisfaction variable was marked as an ‘illuminance’ related parameter.
2. The rating of clustered questions about the nuisance level. Several questions asked for different types of nuisance. The answers to these questions were all scored on a five-point scale. The questions about the nuisance for both the electric lighting (Q3) and the daylight (Q4[1]) were subdivided in three office tasks (computer work, desk task and consultation). The third question inquired after the visibility of the computer screen (Q8) and the other questions were two different statements with regard to light nuisance (daylight too bright (Q9) and electric lighting too bright (Q14)). The nuisance variable was marked as a ‘luminance’ related parameter.
3. The rating of clustered questions about reflections. Three questions asked for the presence or absence of reflections. The first question (Q5) asked for reflections with regard to three light sources (general lighting, additional lighting and daylight). The

[1] Questions 4, 5c, 9 and 12 were not asked for the room position and therefore not used in the calculation of their parameter ‘Satisfaction’. The difference is settled in the calculation of rating.

rating for these three sub-questions was summarized and recoded into a three point scale. The other questions were statements about the reflections from the window (Q12) or the electric lighting (Q16). The reflection variable was marked as a 'luminance' related parameter.

4. The rating of clustered questions about the light level. The satisfaction with regard to the total amount of light in the office (Q2) was clustered into a three point scale (too much/less light, slightly too much/less light and good lighting). Five different statements with regard to light level (Q10, Q11, Q13, Q15 and Q17) had five point scales. The light level variable was marked as an 'illuminance' related parameter.
5. The rating of clustered questions about the ambiance. The questions 7 and 19 had four comparable items about the ambiance of the specific lighting variant (pleasance, disturbance, luminance and glare). Question 7 asked for the general lighting situation and question 19 for the additional luminous area. All items had a five point scale. The ambiance variable was marked as a 'luminance' related parameter.

Finally, all ratings were summarized. In total 31 items were inquired after for the window position and 25 for the room position. The three questions about level were score on a three-point scale; the other questions were scored on a five-point scale. The score was summarized and the minimum score was 31 points; the maximum was 149 points for the window position. A score of 149 points means that an individual is completely satisfied. A score of 90 points (marked as 'neutral') means that the individual assessed the working environment as good; sometimes asking for slight changes. For the room position 25 points was the minimum, 72 the neutral score and 119 points was the maximum. The satisfaction scales had a good internal consistency, indicated with the Cronbach alpha coefficient, α. The alphas for the summer period are shown in Table E.1 and for the winter period in Table E.2.

Table E.1 Chronbach alphas satisfaction parameter in the summer period

Summer		Variable	N	α	Items	M	SD
Window position concept 1	1000lux	Illuminance related	32	0.68	9	33.69	4.10
		Luminance related	32	0.93	22	87.41	14.38
		Overall satisfaction	32	0.92	31	121.09	16.57
	2000lux	Illuminance related	32	0.63	9	32.03	4.00
		Luminance related	32	0.93	22	78.03	17.4
		Overall satisfaction	32	0.94	31	110.06	20.81
Room position concept 2	1000lux	Illuminance related	30	0.73	9	34.34	15.14
		Luminance related	32	0.94	16	58.63	13.70
		Overall satisfaction	30	0.93	25	93.10	16.08
	2000lux	Illuminance related	31	0.65	9	32.16	4.37
		Luminance related	32	0.93	16	50.44	13.00
		Overall satisfaction	31	0.93	25	82.84	16.77

Ideally, the Cronbach alpha coefficient of a scale should be above 0.7 (Pallant, 2001); incidentally an α=0.6 was also accepted. This coefficient was calculated for the illuminance and luminance related variables and the overall satisfaction variable. An equal amount of items was used for both levels and seasons to make the ratings comparable.

Table E.2 Chronbach alphas satisfaction parameter in the winter period

Winter		Variable	*N*	α	Items	*M*	*SD*
Window position	concept 1	Illuminance related	29	0.68	9	32.38	4.45
		Luminance related	27	0.92	22	90.11	14.97
		Overall satisfaction	27	0.92	31	122.07	17.53
	concept 3	Illuminance related	28	0.55	9	32.39	3.84
		Luminance related	27	0.90	22	85.81	12.75
		Overall satisfaction	27	0.90	31	118.41	15.00
Room position	concept 2	Illuminance related	28	0.75	9	33.32	4.60
		Luminance related	29	0.93	16	62.86	12.36
		Overall satisfaction	28	0.93	25	96.71	15.57
	concept 3	Illuminance related	29	0.61	9	32.45	3.93
		Luminance related	27	0.93	16	53.70	12.80
		Overall satisfaction	27	0.92	25	86.15	15.31

E.2 Light sensitivity

Photophobia, or light sensitivity, is an abnormal sensitivity to artificial or natural light. The opposite of the photophobic person is the photophilic person, literally 'light lover'. Test persons who love to have much light were called 'photophilic' and persons who prefer darker rooms were called 'photophobic'. Test persons who have no specific preference were grouped as 'neutral'. The level of light sensitivity (light type) was determined according to different questions and results of a light sensitivity test. The items clustered were:

1. The ratings of questions about light sensitivity (general list Q15, Q16c, d, e & f). Question 15 asked directly for the sensitivity with regard to glare. There were three answer possibilities and 'yes' meant a rating of -1, 'no' increased the amount with one point and 'a little' lead to no points. The possibility to stand bright light (Q16d) is considered as typical photophilic and is rated with one point. This is equal for an agreement with the statement 'Preferring light space' (Q16e). The total rating is decreased when a test person indicated to be sensitive to glare (Q16c) or agreed the statement about 'Preferring dark spaces' (Q16f; rating = -1).
2. The ratings of question use sun glasses (general list Q18). Wearing sunglasses blocks the light entering the eyes. The score of the persons who answered this question with 'yes' was decreased with one point.
3. Light sensitivity comfort test (high-to-low procedure): There is chosen for the high-to-low protocol because this is comparable with the adaptation situation of the test persons' eyes during the entire 'office' test. The eyes were adapted to much light at the moment of filling the questionnaire. Test persons who reached their comfort limit below 400lux got one point. A rating between 400 and 650lux got two points and above 650lux got three points. These illuminance levels could no be compared with the light levels during the entire test because the light installations was preset

different and the Venetian blinds were closed completely. The rating for the light sensitivity test is doubled in by calculating the final rating. The reason is that this test was repeated and the reliability of this variable is therefore large.

Finally, the ratings were summarized and the entire rating lead to a subdivision into three groups:

- Rating -1 to 2 points = photophobic
- Rating 3 to 6 points = neutral
- Rating 7 to 9 points = photophilic

The distribution of light types is shown in Figure E.2. The figure shows the entire group of test persons in the seasons investigated.

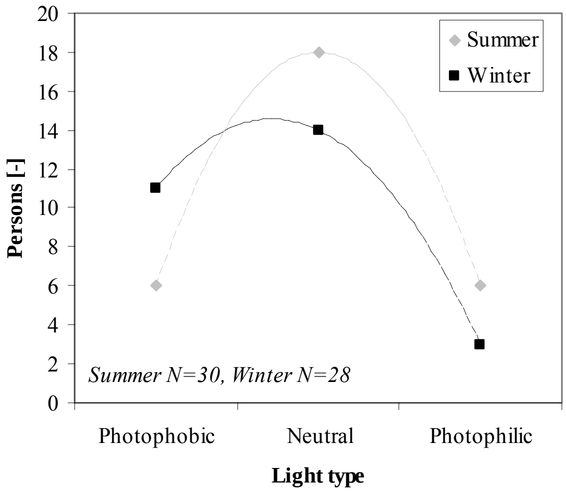


Figure E.2 The distribution of light types for the seasons investigated (all test persons)

Appendix F Light sensitivity test

The human maximum visual comfort criteria were investigated with the help of a 'light sensitivity test'. The aim of this test was to find the upper (and lower) limits with regard to visual comfort.

The test person was placed in front of a large luminous area (position E). Next to the person, a stand with a Hagner SD2 light detector was placed to register the vertical illuminance at eye level ($\underline{h}$=1.25m). The person was asked to report the moment of discomfort while the illuminance level of the area increased (from $\underline{E}_{vert}$=±200 to ±1700lux) or decreased. During increasing, the test person was asked to indicate when the area was going to be too bright. At the moment the comfort limit was reached, the researcher registered the corresponding illuminance.

The procedure from low to high illuminance was repeated four times (with the Venetian blinds open and closed). During deceasing, the test person had to indicate the moment that the light in the room was too low and 'gloomy'. This high-to-low procedure was repeated two or three times (with the Venetian blinds closed). Between all measurements, there was enough time for the eyes of the test persons to adapt to the changed lighting levels.

Afterwards, the corresponding luminance values for the illuminance registered were determined. The luminance results are shown in Table F.1 for all test persons in summer ($\underline{N}$=30) and winter ($\underline{N}$=28). Figure F.1 shows box plots of the luminance levels where the first visual discomfort were indicated by test persons (summer $\underline{N}$=30; winter $\underline{N}$=16) for the situation with the blinds open. Table F.2 shows the results for the test persons who participated twice ($\underline{N}$=14).

Table F.1 Luminance values for the light sensitivity test for all test persons in summer and winter

$\underline{N}$=all			blinds closed		blinds open
			low→high	high→low	low→high
			$\underline{L}$ [cd/m²]	$\underline{L}$ [cd/m²]	$\underline{L}$ [cd/m²]
summer	Mean		831±575	845±482	1650±682
	95% Confidence	Lower Bound	617	665	1395
	Interval for Mean	Upper Bound	1046	1025	1905
winter	Mean		943±787	936±389	1391±878*
	95% Confidence	Lower Bound	641	785	923*
	Interval for Mean	Upper Bound	1244	1087	1859*

*$\underline{N}$=16 because of the absence of daylight

Table F.2 Luminance values for the light sensitivity test for the test persons who participated in both summer and winter

N=14			blinds closed		blinds open
			low→high	high→low	low→high
			L [cd/m²]	*L* [cd/m²]	*L* [cd/m²]
summer	Mean		820±611	937±555	1564±697
	95% Confidence	Lower Bound	451	602	1143
	Interval for Mean	Upper Bound	1189	1272	1985
winter	Mean		695±667	848±438	1123±718*
	95% Confidence	Lower Bound	310	595	667*
	Interval for Mean	Upper Bound	1081	1101	1579*

* *N*=16 because of the absence of daylight

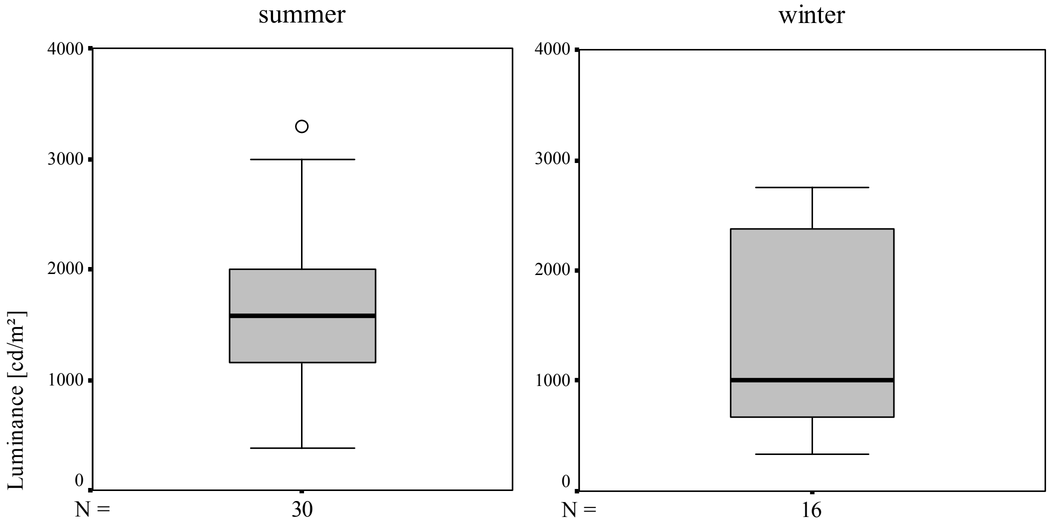


Figure F.1 Box plots of the luminance levels where the first visual discomfort were indicated by test persons (summer N=30; winter N=16) – blinds open.

Dankwoord

Vier jaar geleden heb ik, na mijn studie bouwkunde, Delft weer verlaten om terug te gaan naar Brabant, het gebied 'waarvan ik de taal al sprak'. In Eindhoven ben ik met veel plezier aan een promotieopdracht begonnen. Velen hebben mij, op verschillende manieren, geholpen tijdens het promoveren en bij de totstandkoming van dit proefschrift. Ik ben iedereen daar erg dankbaar voor. Ik zal deze tijd niet snel vergeten want het was gewoon heel leuk!

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Myriam Aries
Eindhoven, juli 2005

De lichtstad

De lichtstad is licht
niet licht als een veertje
dat Eindhoven licht is
dat licht aan het peertje

Freek de Jonge

Curriculum vitae

December 31st 1976	Born in Zevenaar (the Netherlands)
1989-1995	Education at pre-university level (VWO-Gymnasium diploma) at Gymnasium Bernrode in Heeswijk-Dinther
1995-2001	Master of Science in Architecture in the specialization Building Technology at the department of Architecture at Delft University of Technology Graduation project entitled 'The regulation of light on the inside of the façade by means of a vertical anidolic element' under supervision of M. v.d. Voorden, M.Sc., L. Zonneveldt, M.Sc. and J. v.d. Woord, M.Sc.
2001-2005	Ph.D. research at Eindhoven University of Technology, Department of Architecture, Building and Planning, group Building Physics and Systems under supervision of prof. S.H.A. Begemann, Ph.D., A.D. Tenner, Ph.D. and L. Zonneveldt, M.Sc.

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