Helsinki University of Technology, Lighting Laboratory
Espoo, Finland 2007 Report 42

LIGHTING, PRODUCTIVITY AND PREFERRED ILLUMINANCES - FIELD STUDIES IN THE INDUSTRIAL ENVIRONMENT

Henri Juslén

Dissertation for the degree of Doctor of Science in Technology to be presented with due permission of the Department of Electrical and Communications Engineering for public examination and depate in Auditorium S4 at Helsinki University of Technology (Espoo, Finland) on the 19th of October at 12 noon.

Helsinki University of Technology
Department of Electrical and Communications Engineering
Lighting Laboratory

Helsinki University of Technology
Lighting Laboratory
P.O. Box 3000
FI-02015
TKK FINLAND
Tel +358 9 451 4971
Fax +358 9 451 4982
http://www.lightinglab.fi

ISBN 978-951-22-8961-5
ISBN 978-951-22-8962-2 (pdf)
ISSN 1455-7541
ISSN 1795-9039 (pdf)
URL:http://lib.tkk.fi/Diss/2007/isbn9789512289622

Multiprint Oy
Espoo 2007

ABSTRACT OF DOCTORAL DISSERTATION	HELSINKI UNIVERSITY OF TECHNOLOGY P.O. BOX 1000, FI-02015 TKK http://www.tkk.fi

Author Henri Juslén

Name of the dissertation
Lighting, productivity and preferred illuminances – field studies in the industrial environment

Manuscript submitted 27.11.2006	Manuscript revised 14.5.2007
Date of the defence 19.10.2007	
☐ Monograph	☒ Article dissertation (summary + original articles)

Department	Electrical and Communications Engineering
Laboratory	Lighting Laboratory
Field of research	Illumination Engeneering
Opponent(s)	Prof. Marc Fontoynont
Supervisor	Prof. Liisa Halonen
Instructor	Dr. Ariadne Tenner

Abstract

The main objectives of this work were to study which task illuminances industrial workers prefer and to find out if increasing the task illuminance from the levels given in the relevant Norms (CIE S 008/E-2001, EN 12464-1) can increase their productivity, and if so, what the possible reasons for the productivity increase when the lighting is changed are.

Six field studies were conducted in real industrial environments. The preferred illuminances of the industrial workers covered a wide range of values. However, most people tend to select levels higher than the minimums found in the norms and they prefer to be able to influence their task lighting.

The results from the productivity-related field studies show that increasing task illuminance above the minimum level given in norms can increase productivity even though the effect is influenced by the starting conditions, tasks and subjects. Productivity increases in the field tests were found between zero and 7.7 per cent. Additionally, two field studies where absenteeism was measured showed a decrease in absenteeism when the illuminance was increased. One study also showed that increasing the task illuminance can be achieved without increasing the energy consumption – the energy consumption can even be reduced. The results of this work encourage the building of industrial lighting installations where at least part of the task lighting has been provided by localised lighting. A change of the lighting can be achieved in several ways and an increase in productivity can take place via several mechanisms, such as visual performance, visual comfort, visual ambience, interpersonal relationships, biological clock, stimulation, job satisfaction, solving problems, the halo effect and/or change process. These mechanisms can be used to plan successful lighting renovations and changes.

Keywords Lighting, productivity, preferred illuminances, case studies

ISBN (printed) 978-951-22-8961-5	ISSN (printed) 1455-7541
ISBN (pdf) 978-951-22-8962-2	ISSN (pdf) 1795-9039
Language English	Number of pages 74 + 124

Publisher Lighting Laboratory, Helsinki university of Technology

Print distribution Lighting Laboratory, Helsinki university of Technology

☒ The dissertation can be read at http:/2007/lib.tkk.fi/Diss//isbn9789512289622

VÄITÖSKIRJAN TIIVISTELMÄ	TEKNILLINEN KORKEAKOULU PL 1000, 02015 TKK http://www.tkk.fi
Tekijä Henri Juslén	
Väitöskirjan nimi Valaistus, tuottavuus ja valaistusvoimakkuusmieltymykset - kenttäkokeita teollisuusympäristössä	
Käsikirjoituksen päivämäärä 27.11.2006	Korjatun käsikirjoituksen päivämäärä 14.5.2007
Väitöstilaisuuden ajankohta 19.10.2007	
☐ Monografia	☒ Yhdistelmäväitöskirja (yhteenveto + erillisartikkelit)
Osasto Sähkö- ja tietoliikennetekniikan osasto Laboratorio Valaistuslaboratorio Tutkimusala Valaistustekniikka Vastaväittäjä(t) Prof. Marc Fontoynont Työn valvoja Prof Liisa Halonen Työn ohjaaja Dr. Ariadne Tenner	

Tiivistelmä

Tämän työn tavoitteena oli tutkia teollisuustyöntekijöiden valaistusvoimakkuusmieltymyksiä sekä selvittää vaikuttaako työalueen valaistustason nostaminen nykyisten normien (CIE S 008/E-2001, EN 12464-1) määrittämiä ylläpidettäviä minimitasoja korkeammalle työntekijöiden tuottavuuteen. Jos näin tapahtui, kartoitettiin syitä miksi valaistusmuutos lisää tuottavuutta.

Todellisessa teollisessa ympäristössä suoritettiin kuusi kenttäkoetta. Teollisuuden työntekijöiden valaistusvoimakkuusmieltymykset vaihtelivat suuresti. Suurin osa ihmisistä valitsi kuitenkin valotasoja, jotka ovat selkeästi korkeampia kuin normeissa määrityllyt minimitasot ja halusi mahdollisuuden vaikuttaa työalueensa valaistustasoon.

Kokeet, joissa mitattiin tuottavuutta, näyttivät että nostamalla työalueen valaistusvoimakkuutta normien määrittelemien minimitasojen yläpuolelle voi parantaa tuottavuutta. Tuottavuusmuutokseen vaikuttavat lisäksi muun muassa lähtöolosuhteet, työtehtävät ja työntekijät. Valaistusparannuksen yhteydessä havaittu tuottavuusparannus oli nollasta seitsemään prosenttia. Kahdessa kokeessa mitattiin poissaoloprosentti ja havaittiin sen laskeneen valaistusmuutoksen kanssa samaan aikaan. Yksi kenttäkoe osoitti työalueen valaistusvoimakkuutta voitavan parantaa lisäämättä energiankulutusta - energiankulutusta voidaan jopa laskea. Tämän työn tulokset rohkaisevat käyttämään paikallista valaistusta vähintäänkin osittaisena valaistusratkaisuna teollisessa ympäristössä. Valaistusmuutos voidaan tehdä monilla tavoin ja tuottavuusparannus voidaan saavuttaa erilaisten mekanismismien avulla. Näitä mekanismeja ovat: Näkötehokkuus, näkömukavuus, visuaalinen ympäristö, henkilöiden väliset suhteet, biologinen kello, vireystila, työtyytyväisyys, ongelman ratkaisu, Halo efekti ja/tai muutosprosessi. Lueteltuja mekanismeja voidaan käyttää onnistuneen valaistussaneerauksen ja muutoksen suunnittelussa.

Asiasanat Valaistus, tuottavuus, valaistusvoimakkuusmieltymykset, kenttäkokeet	
ISBN (painettu) 978-951-22-8961-5	ISSN (painettu) 1455-7541
ISBN (pdf) 978-951-22-8962-2	ISSN (pdf) 1795-9039
Kieli Englanti	Sivumäärä 74 + 124
Julkaisija Valaistuslaboratorio, Teknillinen korkeakoulu	
Painetun väitöskirjan jakelu Valaistuslaboratorio, Teknillinen korkeakoulu	
☒ Luettavissa verkossa osoitteessa http://lib.tkk.fi/Diss/2007/isbn9789512289622	

Acknowledgements

First of all, I would like to thank Ariadne Tenner, Marius Wouters, and Liisa Halonen for all the help they gave me during my research. Ariadne was my scientific support during the whole project. She discussed the design of every study and patiently managed to read and improve my texts, in which every third sentence was missing. – I have a habit of thinking that the reader can see my thoughts between the lines. Ariadne has natural coaching talents. Typically, after a discussion concerning some issue or other, she would just say, “Think about it.” And when I did so, the penny dropped, and I was able to see the point. Marius and his wife Carla helped me and my family over various practical issues when we were living and working on this project in Eindhoven. We were working next to each other for almost three years. Marius mirrored my ideas, protected me from other work, and offered me daily support and advice in his very personal and logical way. This support made it possible for me to really do something new. Liisa managed to arrange very stimulating licentiate courses, which made postgraduate studying a pleasure. Her role has been essential in really pushing me to summarise the work in this thesis. Thank you, Ariadne, Marius and Liisa.

I have so many colleagues to thank. First, to name just a few who had an important role in the process in which I was nominated to do research work and which I was able to finalise. Here my thanks go to Hans Geerts, Dorien van der Wheele, Emile van Dijk, Jan de Wringer, Harri Hämäläinen and Esko Salmi. I especially want to thank Dorien, my former boss, who always believed in me. She gave me freedom to work and was able and willing to give support when I needed it. And then, from the scientific point of view, there were the discussions with real professionals like Wout van Bommel and Gerrit van den Beld that were so essential at the beginning of this work. I salute you, dear colleagues.

And, for making my working days in Eindhoven such a pleasure, my thanks go to Marike, Lin, Yolanda, Ulrike, Markus, Sjef, Brigitte and Ton. For turning lunch breaks into stimulating walking and talking events, I want to express my appreciation to you, Markus, Sjef, Brigitte and Ton. I also want to thank the late Chris Martens, Noël Bonné and, especially, Henk Verstegen, whose help with data-logging software was vital for many studies. The six field studies described in this work needed a lot of effort from several persons from those sites. Thanks go to my contact persons Martti Koskikallio, Rob Lamers, Minje Afheld, Klaus Deike, Jos Verbossen, and Erik Kremer. I also want thank my colleagues Jorma, Rauli, Ritva-Liisa, Marjut, Risto, Arto and Tero, with whom I have recently been working in a challenging and interesting environment. Marjukka Eloholma I want to thank for her valuable comments concerning the manuscript. My deepest thanks go to Jennifer Veitch and Stephan Völker for their reviewing of the thesis. I also wish to thank Derek Parker, who has worked through the text of the articles to make my “English” readable.

Last but not least, my deepest thanks go to my relatives and friends. Actually, one incentive to finalise this work was that I did not want my wife to be the only doctor in the family! Seriously, my dear Aino, thank you for all your loving support during this process and especially for the extra efforts you made during the past two years to give me time to finalise this thesis during the weekends. Iisak and Aaro, you are great sons. Do not lose the child in you. Asking questions and looking for new things is what life is all about. Your existence, attitude, remarks and philosophy are carrying me every day. I was encouraged to be intellectually independent from quite a young age. I especially want thank my father Heikki for those numerous hours he spent reading to me and my brothers books such as Välskärin kertomukset, Seitsemän veljestä, Tarzan, and so on. And my most heartfelt thanks to my mother Helena for those discussions and arguments concerning all the issues in the world. I think they have all provided an important background, even in writing this thesis. Thanks also go to my parents-in-law Erkki and Kaija for taking care of Iisak and Aaro and for keeping in close contact, even when distances were great. Thanks go to my younger (and significantly smaller) brothers Harri and Ilari, too, and to my baby sister Heidi, to my sister-in-law Liisa, and to their families. It is just nice that you exist. I must also thank several other friends and relatives for their patience during the past years when I have been too busy for many social contacts. But instead of naming all of you, I give you a promise: “I will take time for you and for my family”.

Kerava, September 2007

Henri Juslén

Contents

List of publications

I Juslén HT, Tenner AD. (2005), Mechanisms involved in enhancing human performance by changing the lighting in the industrial workplace. International Journal of Industrial Ergonomics. 35, 843-855.

II (A) Juslén HT, Wouters MCHM, Tenner AD. (2005) Preferred task-lighting levels in an industrial work area without daylight. *Lighting Research & Technology*. 37,3, 219-233.

III(A) Juslén HT, Wouters MCHM, Tenner AD. (2007) The influence of controllable task lighting on productivity: a field study. Applied Ergonomics. 38, 39-44.

IV(A) Juslén HT. (2005) The influence of the preset level on the preferred illuminances in the industrial environment. Proceedings, Lux Europa 2005, Berlin, 463.

V(B) Juslén H. (2006) Influence of the colour temperature of the preferred lighting level in an industrial work area devoid of daylight. Ingineria Iluminatului, 8,18, 25-36.

VI(C) Juslén HT, Tenner AD. (2007) The use of task lighting in an industrial work area provided with daylight. Journal of Light & Visual environment, 31,1, 25-31.

VII(D) Juslén HT, Wouters MCHM, Tenner AD. (2007) Lighting level and productivity: a field study in the electronics industry. Ergonomics, 50,4, 615–624.

VIII(D) Juslén H, Fassian M. (2005) Lighting and productivity – Night-shift field study in the industrial environment. Light & Engineering, 13, 2, 59-62.

IX(E) Juslén H, Verbossen J, Wouters M. (2007) Appreciation of localised task lighting in shift work – a case study in the food industry. International Journal of Industrial Ergonomics. 37, 433–443.

X(F) Juslén H, Kremer E. (2005) Localised lighting for efficient use of energy and better performance – Field Study in the factory. Proceedings of CIE mid-term meeting and international lighting Congress, León 2005.

XI Juslén H. (2006) Lighting and Productivity in the Industrial Working Place. Proceedings of Fifteenth international symposium, Lighting Engineering Society of Slovenia. Lighting of work places. Slovenia, Bled. 53-62.

The author has played a major role in all aspects of the work presented in this thesis. He planned the study designs and analysed the data and results in all the field studies with the exception of X(F), where the main responsibility for lighting design and data collection was in the hands of Erik Kremer. In the above publications, Ariadne Tenner and Marius Wouters provided support by discussing and commenting on the study design as well as improving the manuscripts. The author was the responsible author in all the publications.

List of abbreviations

ANOVA	Analysis of variance
CEN	Comité Européen de Normalisation, European Committee for Standardisation
CIE	Commission Internationale de l'Eclairage, International Commission on Illumination
Eh	Horizontal illuminance
Ev	Vertical illuminance
F	F-test value
HSD	Honestly Significant Difference
n	Sample size
KSS	Karolinska Sleepiness Scale
p	probability value
r	correlation coefficient
SD	Standard Deviation
t	t-test value
V(λ)	Photopic spectral luminous efficiency function, 2° field

Definitions

General lighting – Lighting that illuminates a large area and that is typically installed very high up in the industrial hall.
Localised lighting – Lighting that illuminates a small area and that is installed at a height of 2 m - 4 m in the industrial hall.
Task lighting – Sub-group of localised lighting; intended for one or two persons. This kind of lighting is installed at a height of 2 m-3 m and might be controlled by users.
Productivity – Rate and efficiency of work (for example, in industrial production); amount of output per unit input.
Individual performance – The performance of a single employee.
Workforce productivity – Combined productivity of all employees.
Visual performance – Performance of the visual system as measured by, for instance, the speed and accuracy with which a visual task is performed.
Profitability – Capacity of being profitable (making profit).
Selected illuminance – Illuminance selected by subjects – measured illuminances.
Preferred illuminance – Illuminance preferred by subjects – preferred illuminances are discussed and studied by using the measurement data of selected illuminances.
Non-image-forming (Photo-biological) pathway – The "pathway" that starts from the photosensitive retinal ganglion cell and goes via the suprachiasmatic nucleus to the pineal gland, which regulates human circadian rhythms.
Visual pathway - The "pathway" that starts from cones and rods and goes to the visual cortex.
Lighting change – A lighting change is any kind of intentional change in the lighting environment (but not, for example, daylight dynamics). It can be generated by changing the artificial lighting or the daylight contribution.
Lighting change mechanism – Used to describe a chain of effects that influence human performance when lighting change occurs.

1 Introduction

1.1 Objectives of the work

Real-life case studies are important sources of information when endeavouring to find out the effects of lighting on industrial work. The first objective of the present work was to define the state of the art of field-study data on the relation between task illuminance and productivity in industrial environments and to estimate the reasons behind the possible productivity increases.

To be able to establish future lighting design criteria, industrial workers' lighting preferences in the real working environment are also important. This area has so far been partly neglected by research. The second objective was therefore to find out the lighting preferences of industrial assembly workers, concentrating especially on localised lighting. These preferences would provide a basis for lighting design in industry.

The third objective was to determine whether or not increasing task illuminance affects the productivity of present industrial workers in those situations where the starting maintained minimum illuminance is already in accordance with present norms (CIE S 008/E-2001, EN 12464-1).

1.2 State of the art

1.2.1 General

The link between productivity and lighting in real industrial environments was studied actively during the first half of the 20th century (Ruffer, 1925 and 1927; Schneider, 1938; Goldstern and Putnoky, 1931). These studies were typically before-and-after studies and their results indicated clear productivity increases. After this period, the interest waned. New technologies such as fluorescent lamps replaced incandescent-based solutions, allowing higher illuminances with lower energy consumption. The research shifted towards office lighting, reflecting the dramatic rise in the prevalence of office work, whereas the amount of industrial work had been stable or even decreased.

Another important reason for the low level of research activity related to lighting and productivity in the industrial area might be the misunderstanding of the Hawthorne effect. This is the effect that a study or an evaluation itself has on people, i.e. the feeling of being observed and cared for, which can lead to improved performance (Mayo, 1933; Roethlisberger and Dickson, 1939). This effect was first revealed in studies in the relay-assembly test room of the Hawthorne plants between 1927 and 1932 (Parsons, 1974). The duration of the work and the rest pauses were manipulated in these studies. A group of five women was separated and observed intensively. These studies had nothing to do with lighting. However, before these studies, researchers had conducted three lighting studies at the same place (Parsons, 1974). These lighting studies were not very well reported. They did not show a correlation between lighting level and productivity (Snow, 1927). From the Hawthorne studies, we can draw the conclusion that lighting is not the only variable that affects human performance. However, the conclusion is not that the Hawthorne effect is more connected to industrial field studies than other types of studies. In industry, actual performance can be measured without disturbing the subject's work. In an office environment, new measurements that can give subjects the feeling of being studied have to be introduced. In laboratory environments with simulated settings, this feeling will be particularly apparent. For these reasons, it can be assumed that field tests in the industrial field are less susceptible to the Hawthorne effect than field studies in offices or laboratory studies.

1.2.2 Literature study

Several references to the lighting and productivity field studies in the industrial environment were found [I]. Typically, they were very old and simple before-and-after studies and more like examples than studies with detailed data. The problem with before-and-after studies is that controlling all possible changing variables is very difficult. This means that the reason behind the possible productivity increase might have also been something else than the lighting change. It is not clear in which way the lighting has increased productivity in these older studies. Is the increase achieved for visual, biological or psychological reasons? The illuminance before the change was also often very low compared to present standards. This, together with possible other changes in the industrial environment, training of the industrial workers etc. raises the question of whether the old data is valid in the present industrial environment. Practically all field studies found showed an increase in performance when illuminance was increased [I]. Figure 1 shows the combined results of old field studies [I]. The dotted lines connect the “before” and “after” the change situation for each study or example found in the literature. For example, the dotted line starting from 0 (productivity increase) and 500 lux (illuminance) and ending at 28 (productivity increase) and 1500 lux (illuminance) refers to a before-and-after study, in which the illuminance has been increased from 500 lux to 1500 lux and the productivity increased 28 per cent. The solid curve is drawn by calculating the average slope from reported results (slopes of the lines between before-and-after values) as a function of the illuminance. As can be seen from the figure, most of the old examples describe the change from a very low illuminance (< 100 lux) to a higher level, which is most probably an important reason for the huge increase in productivity. People might have been able to see better than before. Examples where the starting illuminance was more than 100 lux show more modest results. The solid curve, which should not be used to predict a certain increase in productivity, shows the same flattening of the increase when the starting level is already “high”.

Recent discoveries of non-image-forming psychobiological effects via a photo-biological pathway in the brain show that our biological processes, such as melatonin suppression, have sensitivity curves different from V(λ) (Brainard et al., 2001; Hattar et al., 2002). These discoveries have increased the understanding of the influence of light. The novel photoreceptor, intrinsically photosensitive retinal ganglion cell (Berson et al., 2002) is one of the ca. 20 known ganglion cells in the human retina. It is found that the novel photoreceptor is responsible for regulating light-dependent human biological rhythms (circadian rhythms) by synchronising the body to the environmental light/dark cycle (Gooley et al., 2003). The photoreceptor has also been supposed (Duffey and Wright, 2005) to mediate light-induced increases in alertness and pupillary response. During the past few years, performance and circadian-lighting-related studies have been carried out, especially concerning shift work and light. Bright light exposure at nighttime can be used to improve alertness and performance (Campbell and Dawson, 1990; Daurat et al., 2000). Adaptation to shift work is strongest if total light exposure is under control and if, after bright light at night, light exposure is limited in the morning. (Eastman et al., 1994; Yoon et al., 2002; Boivin and James, 2002). There is also some evidence that bright light during the daytime can reduce the impact of sleep loss on sleepiness levels and performance after a short (5h) night’s sleep (Phipps-Nelson et al., 2003).

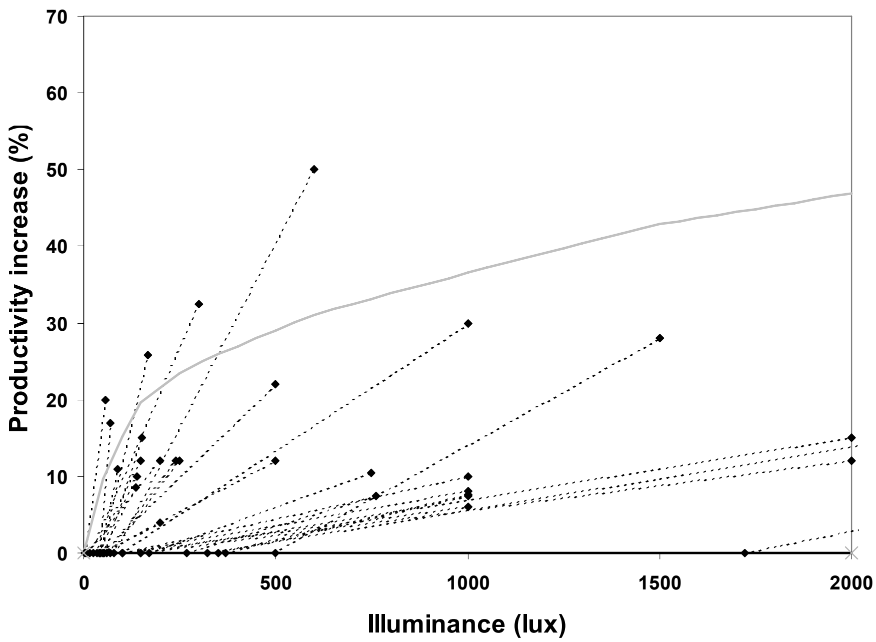

Figure 1. Illuminance change effect for productivity. The dotted lines show the results of the individual tests (Ruffer, 1925 and 1927; Schneider, 1938; Goldstern and Putnoky, 1931; Bitterli, 1955; Stenzel, 1962a and 1962b; Crouch, 1967; Lindner, 1975; Carlton, 1980) and the solid curve shows the calculated average slopes (29 cases) [I].

The lighting preferences of office workers have been studied actively during recent decades (for example, Begemann et al., 1997; Maniccia et al., 1999; Escuyer and Fontoynont, 2001; Moore et al., 2003; Love, 1998; Boyce, 1980; Jennigs et al., 2000; Veitch and Newsham, 2000). However, so far the research has neglected to study the lighting preferences of the industrial workers using long-term field studies. Industrial work and the industrial environment are quite different from office work and its environment. The degree of freedom in industrial work is often less than in office work, and the working environment in industry might be more noisy. From the lighting point of view, the main difference is perhaps daylight contribution. In offices, light coming from windows can from time to time provide vertical illuminances of more than 1000 lux (Aries, 2005), while, in industry, daylight is often totally missing or is delivered via skylights.

2 Lighting change and productivity

2.1 Model of the mechanisms of lighting change

Several examples of productivity increase occurring together with lighting change were found in the literature study (see Chapter 1.2.2.). However, the exact reason for the productivity increase was not clear. This chapter discusses the possible effects of a lighting change on productivity. Based on the lighting and the biological and psychological literature, it was possible to create a model of the influence of light and lighting change on profitability [I]. The model is shown in Figure 2. Light influences people via a visual and a non-image-forming pathway in the brain. Via the visual pathway we see things, while the non-image-forming pathway influences our biological rhythms. However, the influencing pathway for some effects like alertness is not clear, but the effect might be influenced by both pathways. The change process, describes here "the third pathway", which is more psychological. Physiologically this third "pathway" actually takes information coming from all our senses and our whole history influences our reactions. Even lighting change not have any effect via the visual or non-image-forming pathways if something might happened for change-related psychological reasons. Via these three "pathways", lighting change can start several mechanisms, which are described later, and these might have an effect on human performance. Just how much effect the mechanisms have on human performance of an individual person may be different for different people. So even in the same working area, human performance-related effects of the lighting change for different individuals are not necessarily the same. In industrial work environments, human performance is normally linked directly to profitability, meaning that, if persons are performing better, the productivity is also higher, thus improving profitability also. The lower the investment and maintenance costs needed for the change, the higher the profitability. In some cases, customers' presumptions of the working area might have an effect on the sales or profit level of the goods produced. So, for example, if the factory area is used as a showroom or is continuously on view to customers, this might affect sales and thus the profitability of the lighting change. And if employees relate in someway to customers, their performance, alertness and feelings influence customers, thus influencing profitability also.

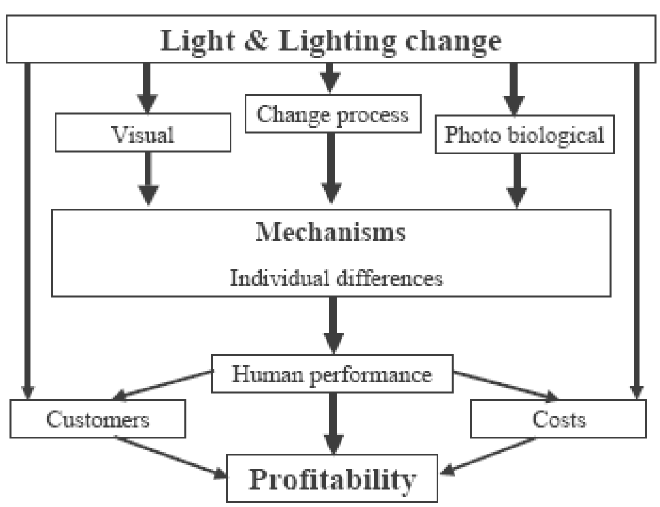

Figure 2. Model of the effects of light and lighting change on profitability in the industrial environment [I].

A lighting change is any kind of lighting change in the environment. It can be brought about by changing the artificial lighting or the daylight contribution. Wyon (1996) introduced a kind of step-by-step method to describe the relationships between an environmental change and human performance in terms of specific mechanisms that explain the effects of the change. When these mechanisms are defined as chains of hypotheses, each of which must be true for the mechanism to be valid, each hypotheses can be tested separately. Different mechanisms (chains of effects) can affect the increase in human performance when lighting is changed. For example, the chain for visual performance is:

A. Lighting influences visual performance
B. Visual performance influences task performance
C. Task performance influences total individual performance
D. Individual performance influences workforce productivity
E. Workforce productivity influences business profitability.

The first effect A, "Lighting influences visual performance", is true (see, for example, Rea and Ouellette, 1991). If visual performance is not needed in the task, this mechanism is not valid for that type of work (B). Even if it were needed, the next effects (C, D and E) would have to be true in that work before this mechanism has a real effect on profitability. A total of ten mechanisms have been described [I] in the same way.

1. Visual performance
   When people can see the task better, they can perform better.
2. Visual comfort
   Decreasing discomfort glare influences performance because of increased concentration.
3. Visual ambience
   Lighting influences visual ambience, which, being part of the working environment, influences performance.
4. Interpersonal relationships
   How people see each other influences how they feel about each other, which influences co-operation and productivity.
5. Biological clock
   Light adjusts the biological clock, which controls the circadian rhythms and thus influences performance at certain times.
6. Stimulation
   Light stimulates psychological and physiological processes, which enhances performance.
7. Job satisfaction
   Improving lighting conditions might increase job satisfaction by way of improved task significance and autonomy, which influences performance.
8. Solving problems
   Solving existing complained-about lighting problems increases well-being and motivation, which enhances performance.
9. The halo effect
   The effect of the belief in the superiority of a new technology or product might itself result in enhanced performance.
10. Change process
    Good change management increases the positive effects of the lighting change whilst diminishing the negative effects.

This mechanism model can be used not only to plan new field studies and explain their results, but also in practical lighting design projects. Figure 4 shows an example of the form [XI] that could be used to evaluate the needs of the user in the situation where lighting change is under consideration. It is intended as a check list for the lighting designer or as a discussion tool between the designer and the customer. For example, if the planned work is individual industrial assembly work, the most important issues could be visual performance, visual comfort, biological clock (in the case of shift work), stimulation and job satisfaction. Things like visual ambience, interpersonal relationships, flexibility and how customers see the area might be less important issues. For the office worker, the relative importance of these issues would be quite different. The points total at the end of the form gives a rough indication of how demanding (and costly) the project is.

Check list for the base of the lighting design **(workplace lighting)**

Mark the importance of the following items to the list

0 Not important at all
3 Very important

Visual performance	0	*(Use lower maintained lighting level than defined in norm)*
(How well we are able to see)	1	
	2	
	3	*(Use higher maintained lighting level than defined in norm.)*
Visual comfort	0	*(Use solution, which is just according minimums in norm.)*
(How comfortable it is to look)	1	
	2	
	3	*(Concentrate on optics and glare limitation & indirect lighting)*
Visual ambience	0	*(Do nothing special for this purpose)*
(How the environment looks like)	1	
	2	
	3	*(Add some ambience and accent lighting)*
Interpersonal relationships	0	*(Do nothing special for this purpose)*
(How people work together)	1	
	2	
	3	*(Concentrate on vertical illuminance and colour rendering)*
Biological clock	0	*(Do nothing special for this purpose)*
(When we are awake)	1	
	2	
	3	*(High lighting levels and/or special spectra as on option.)*
Stimulation	0	*(Do nothing special for this purpose)*
(How alert we are)	1	
	2	
	3	*(High lighting levels and/or special spectra as on option.)*
Job satisfaction	0	*(Do nothing special for this purpose)*
(How happy we are for our work)	1	
	2	
	3	*(Clear lighting improvements and consider using personal control)*
Solving problems	0	*(Do nothing special for this purpose)*
(Is there something so wrong)	1	
	2	
	3	*(Correct the problem and make note of it)*
Change process	0	
(How to do the change)	1	
	2	
	3	*(Always important to inform and involve people)*
Flexibility	0	*(Do nothing special for this purpose)*
(Is the purpose of the space always same)	1	
	2	
	3	*(Take flexibility under the consideration)*
Customers	0	*(Do nothing special for this purpose)*
(Does it matter how visitors see the space)	1	
	2	
	3	*(Use higher lighting levels and consider shop type solutions)*
Total		

0 Standard 11 — 22 Demanding 33

Figure 4. Lighting-change estimation form [XI]. (The customer and designer can together weigh up whether the issues presented are important in the workplace. The form also gives some very simple recommendations for when the importance of the issue is clear. The points total gives an indication of the complexity of the lighting design.)

2.2 Lighting change as a management intervention

When the lighting is changed in a working environment, this can be seen as a management intervention. Someone has decided to change the lighting for a reason, so something is hoped to be achieved. The reason for lighting changes in practical situations might be a desire to save energy or reduce maintenance costs, a need to update the working environment to abide as closely as possible with law-related codes, a willingness to update the working environment or to reward the workers, etc. In the following, lighting change as a management intervention is discussed from the point of view of a desire to improve the performance of the worker(s) by improving lighting conditions.

In the previous chapter (2.1), the possible ways in which a lighting change can influence human performance are described by ten different mechanisms. The first six are related to visual and biological effects of the lighting change. These effects can be estimated to be achieved when the lighting is changed independently of the way the change process has been handled. The other four effects – job satisfaction, solving problems, the halo effect and change process – are very much related to how the management intervention has been carried out. The way the change has been communicated to the participants influences the effect it has on task significance or autonomy increase and, through this, on "job satisfaction". Getting effects via the "solving problems" mechanism requires some co-operation with the workers to find out what the lighting-related problems are. The way the lighting change is performed and communicated might influence the size and direction of "the halo effect". The "change process" mechanism includes, for example, the training of the workers for the new lighting system, which might decrease the possible problems.

One way to proceed with the management intervention is via so-called participative management, where the workers are involved in the decision-making. The effect of participation in the decision making on human performance is not clear. Based on a review of participation studies, Wagner (1994) concluded that the link between participation and performance is not very strong (correlation 0.08 to 0.25, with very small effect size) but the link between participation and satisfaction is stronger (correlation 0.44). Some researchers (such as Cotton et al., 1988) are more positive about the relation between participation and performance. Researchers also seem to have a different view on the term *participative management* (Cardy and Selvarajan, 2001). Is it a process in which influence is shared among individuals who are otherwise hierarchically unequal (Locke, Alavi and Wagner, 1997)? Or is it a more multidimensional construct (Cotton et al., 1988 and Black and Gregersen, 1997)? From a lighting change point of view, it is, however, crucial that participation in the lighting improvement cannot be expected to create many negative influences; even the size of positive influence is not clear. It is also important to note that lighting improvement is not a very difficult management intervention unless the users start to think that the reason for it is doubtful or if it is connected to some other unwanted changes. Generally speaking, it can be estimated that most of the users do not object to an improvement of their working environment.

The right level of involvement in lighting change depends most probably on the individual case. The extreme ways to handle a lighting change are leaving the decision making fully to the users or just do it without even informing the users. If the users are not informed about the lighting change, then the possibilities of getting positive effects via job satisfaction and problem solving are reduced and there is the risk that the halo effect (for example, the belief that the new lighting is unhealthy) or change process (users cannot use a new lighting control system) create also negative effects. On the other hand, giving users full freedom to control the lighting change and choose what they want might make them use their time on work they can not handle, and it may lead to installations that are not optimal from a cost or energy point of view and that do not improve human performance via mechanisms 1-6 (see Chapter 2.1). The right level of involvement is, in most cases, somewhere between these two extremes. To be able to implement lighting design, knowledge of lighting, technological possibilities, and norms etc. is needed. For this reason, it is always good to consult a professional lighting designer. The right level of user participation in the lighting change depends on the individual case. It can be said that users should be at least informed about the lighting change and the reasons behind it. This blocks the possible negative effects via the halo effect and might strengthen the positive ones. In case the using of the new lighting installation requires some knowledge (for example, of a control system) users should be trained. However, an even larger involvement of end users can be recommended in those cases where the aim of the change is to improve performance. Without involvement of the users, it is very difficult to really know about users tasks (what they are doing and when) and their special characteristics (like defects in vision). This information needs to be the basis of the lighting design if the positive effects of the mechanisms are to be maximised 1-8 [I].

3 Field studies on lighting preferences and the relation between lighting and productivity

3.1 General introduction

The objectives of this work were to find out what the lighting preferences of the assembly workers are and whether increased task illuminance has an effect on productivity in real working conditions. The method selected was long-term field studies. The literature study showed that long-term field data on lighting preferences of industrial assembly workers is not available and the lighting- and productivity-related field study data is generally old, making it unsuitable to be adapted for the present industrial environment. The old studies were also mainly examples of before–and-after settings, where the possible reason for productivity increase could have been any of the mechanisms described in Chapter 2.1, or even some other intervening variable. Long-term field studies are probably the best way to achieve the objectives of this work. Laboratory studies or short-term field studies can give only partial answers. They cannot really give an answer to the question of whether or not an increase in human performance or productivity can really be detected in a real working environment, or to that of whether this possible effect stays for a longer period. However, field studies are very demanding, especially because the number of possible interfering variables is huge. This means that study design has to be undertaken very carefully.

In this work, six different lighting studies were started in 2003 and 2004 in various industrial premises in Europe [II(A), III(A, IV(A), V(B), VI(C), VII(D), VIII(D), IX(E), X(F)]. Table 1 gives an overview of the studies. The data-logging period was in all cases several months, and in those places where selected illuminances were monitored, selected values were recorded over one year. Studies of this kind have not been performed in industry before.

Table 1 Overview of the field studies.

Study	**A**	**B**	**C**	**D**	**E**	**F**
Country	Finland	Germany	France	Netherlands	Netherlands	Netherlands
Type of work	Assembly	Assembly	Assembly	Electronics assembly	Machine maintenance	Assembly
Type of study	Users control lighting	Users control lighting	Users control lighting	Forced illuminance changes	Forced illuminance changes	Before / After
Number of subjects	49	40	72	119	45	42
Task illuminance (lux)	200….3500	200….1000	300….1200	800 / 1200	500 / 1500	500 / 1000
Questionnaire	After	-	After	After	Before / After	Before / After
Productivity aspect	Productivity	Productivity	-	Speed & Errors	Machine breaks, Absenteeism & Alertness	Productivity & Absenteeism
Preferred lighting levels study	Yes	Yes	Yes	No	No	No
Total study period (1)	2 years	1.4 years	1 year	2 x 2 months	1.8 years	Before/After

(1) The datalogging periods of some sub studies differ for total study periods in studies A, B and E

Employee opinions have been collected in five studies (A, C, D, E, F) by means of questionnaires. Lighting-related questions were included in all questionnaires. Some questionnaires also included questions relating to the factory environment in general and to employee perceptions of their own working environment. Some of the questions were the same in all questionnaires. In three studies (A, C and D), the users only received the questionnaires after the main study period. In two studies (E and F), questionnaires were filled in before and after the test period. A summary of the questionnaire results is given in Chapter 3.8, after the descriptions of the studies (3.2-3.7).

The basic principle in studies A, B and C, where lighting preferences were studied, was the installation of controllable task lighting and monitoring how the employees used it. The work was normal luminaire assembly, the same as in the same workstation before the test periods. The used illuminances were measured by data logging the dimming voltages of the lamps in the luminaires, without adding sensors to the work area.

The productivity-related aim of this work was to find out whether increased task illuminance has an effect on productivity, although the starting illuminance was already in accordance with present Euro Norms (EN 12464-1). In studies A, B, D and E, where productivity was measured, the lighting-change mechanisms, described in Chapter 2.1, were taken into account when planning the studies. The idea was to limit the influence of certain mechanisms so as to better see the effect of others; namely to limit the effects of the more psychological mechanisms (the halo effect, problem solving and job satisfaction). Productivity related studies were aiming to study influence of the task illuminance on productivity and no special emphasis was placed on studying the effect of light spectra outside the lamp spectra typically used. Questionnaires before the change were not used in studies A, B and D. In studies A, B, D and E, factors such as illuminance level or functioning of the control system were varied several times to exclude the psychological mechanisms. This approach also helps to eliminate the effect of the change process. In cases A, B and E, the general lighting was not changed at all, so as to limit the effect of visual ambience and visual comfort. In all locations, the work was normal industrial work and no extra work settings were made for the purposes of research. Productivity measurements varied depending on the location.

One of the underlying principles of all the studies was that the industrial workers should be disturbed as little as possible to ensure that they did not feel like study subjects. However, in each study, the subjects were informed that a lighting study was being undertaken. In the studies where users had to make lighting choices, it was pointed out that no specific results were preferred and that they were able to use the lighting as they personally needed or desired. The participants were not informed of the exact details of the experiments. In almost all cases, the lighting installation was improved in terms of higher task illuminance levels. The only exception was study D in the Dutch electronic factory. But even in study D, the lower task illuminance level was higher than required in the European norms. Only common lighting fixtures, lamps and installations were used in all places. Filling in the questionnaires was not obligatory.

Lighting of the work places was measured by recording horizontal illuminance at the task area. In most cases, work tasks included a series of smaller tasks, and individuals were working in different ways (for example, some were seated and some were not). Because of this, luminance measurements would have been relatively variable, so luminance values were not reported. However, luminance maps are shown as an example in the summaries of studies C and D, where the work and the viewing angle was the most stable. Figure 3 shows typical working areas employed in the various studies.

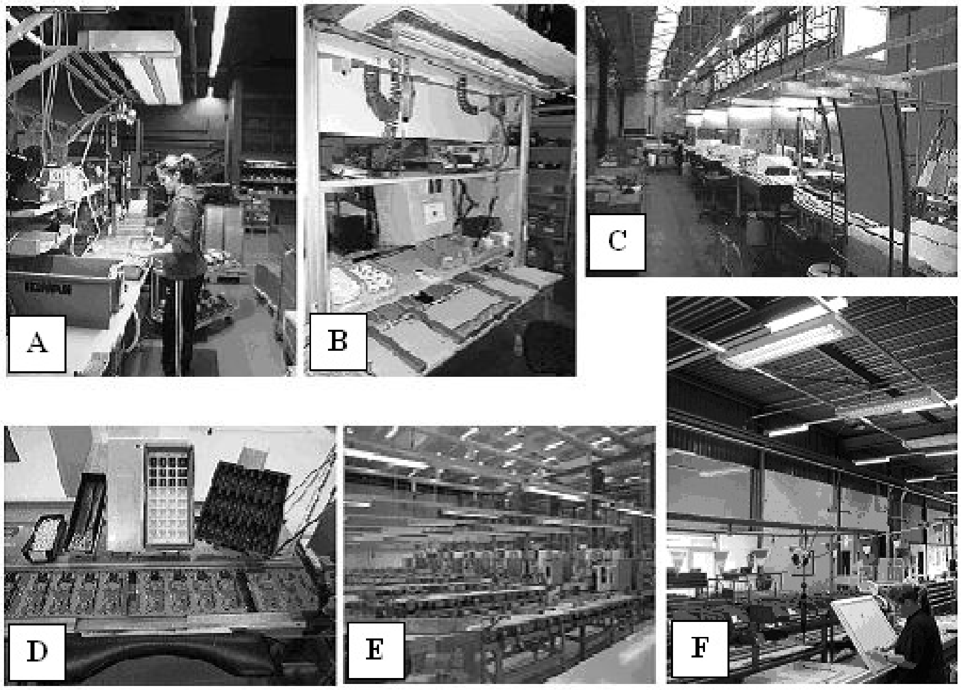

Figure 3. Typical work areas employed in the study.

- Study A: Luminaire assembly station with dimmable task lighting. The illuminance can be controlled by employees using a remote control [II(A), III(A), IV(A)] (Finland).
- Study B: Luminaire assembly station with a choice of colour temperatures for the task lighting. The illuminance can be controlled by employees using a remote control [V(B)] (Germany).
- Study C: Luminaire assembly station with dimmable task lighting. The illuminance can be controlled by employees using a remote control [VI(C)] (France).
- Study D: Assembly station of the electronics factory. Employees are inserting components in printed-circuit boards. Two horizontal illuminance levels at the assembly table, 800 lux and 1200 lux, are employed during the test and controlled by researchers. The individual worker does not have control over the lighting installation [VIII(D), VII(D)] (The Netherlands).
- Study E: Packaging area of the food factory where operators were monitoring production and solving problems when they occurred. Additional dimmable localised lighting controlled by researchers. The individual worker does not have control over the lighting installation [IX(E)] (The Netherlands).
- Study F: Luminaire assembly station with improved lighting conditions after the change, which was made once. The individual worker does not have control over the lighting installation [X(F)] (The Netherlands).

3.2 Study A

3.2.1 Introduction

The literature study showed that the data of task illuminance preferences for industrial workers is not available. The first aim of this study was to discover the preferences for lighting, especially the task illuminance preferences of the industrial assembly workers, by giving them freedom to control their task lighting and monitoring its use. The literature study also showed that the available field-study data concerning lighting and productivity is relatively old and might have limited relevance for industrial work and conditions today. The old studies were also mainly before–and-after studies. In order to study the effect of the visual and biological mechanisms (1-6, see Chapter 2.1), the study design should be performed in such a way that lighting changes are made more than once or that participants would use different task lighting levels unconsciously. The second objective of the study was to find out if task illuminance or the possibility of controlling it influences the productivity of assembly workers. This was studied in several ways: firstly, by changing the parameters of the lighting system (dimming speed and switch-on illuminance) to make participants unconsciously select different levels and then monitor productivity with different task illuminance; secondly, by comparing the productivity of the test group and a reference group; thirdly, by analyzing whether there is any correlation between the selected illuminance and productivity on that day.

3.2.2 Methods

Study area

The study area was an assembly area of a luminaire factory located in southern Finland. Figure 4 shows one of the assembly tables.

Figure 4. One of the assembly tables in the test area of study A.

Participants and work description

Altogether 23 assembly workers (3 men, 20 women; average age 35) had been working in the area longer than 20 days during the study period. The products assembled were different for the different workstations, but the tasks that had to be performed were quite similar for all assembly workstations. The subjects assembled luminaire components such as the frame, the gear and optical parts. Connecting the wires is visually the most demanding part of the work. The smallest diameter of white wire was 2mm and the diameter of unisoleted copper end

0.8mm. White wires were connected to a white connector block by screws or by just pushing the wire into the hole. Viewing distances of most of the tasks were less than a meter. The participants were free to make the tasks in the way and order they felt to be most suitable for them. Thus the same luminaire type might have been assembled in different ways and in a different order by different participants. The tasks were mainly on the horizontal plane. In the European standard EN 12464-1 (2.6 electrical industry, 2.6.2 assembly work, medium) the minimum maintained illuminance for this kind of work is 500 lux. Depending their way of working, disturbing reflections might have been produced. Light coming from task-lighting luminaires or from general-lighting luminaires might have reflected from glossy aluminium (veiling reflections) or from white painted metal (diffuse reflection) that were handled every now and then.

Since the study period was very long (two years), in total more than 50 subjects were working in the test area. Depending on the studied issue, the test group comprised persons who were working in the area during that part of the study. The reference group used in the productivity comparison was a group of persons having similar training and experience background as the test group and who were working in the reference area during the measurement period. More information about the participants can be found from articles II(A) (page 220), III(A) (page 41) and IV(A) (page 1).

Lighting conditions

In field study A, constant task lighting (1*1*58W T8, 4000K), which, together with the general lighting, provided a horizontal illuminance at the table of about 700 lux, was replaced by dimmable task lighting (2*2*49W T5, 4000K) at ten luminaire assembly tables. The employees used infrared transmitters to select the illuminance they wanted. The maximum available task lighting was about 3000 lux, while the general lighting provided only 100 to 380 lux, depending on the workstation. The general lighting was not controllable and it was always on when work was in progress. The reference group kept the old task lighting system. Lighting conditions are described in more detail in articles II(A) (page 221-222), III(A) (page 40) and IV(A) (page 1).

Procedure

The presence of the employees, as well as the dimming levels of the luminaires, was recorded over a period of two years. Two preset values of the switch-on level of task lighting were used during the study period. During the first eighteen-month period, when employees switched on the task lighting, it was switched to the minimum, and if they wanted to have more light they had to set it themselves. Task illuminance levels were measured by data logging the values selected. The productivity of the test group (which was mainly working in the test area) was compared with that of the reference group. Standard data from the factory was used to study the effect of lighting on productivity. That is to say, no extra productivity monitoring was performed during the test period. In order to quantify productivity independently from the product produced for each production workplace, the "standard working hour" was used. In a "standard working hour", the standard output (number of products) is produced. The productivity of individual employees has been expressed in terms of this standard output. The productivity for a group of employees is the average of the individual productivity values.

Preferred illuminance-rhythm-related things (day, week, season) were studied during first seven-month period. There were participants who were in the area for long periods (all weekdays and seasons), which offered the possibility of studying the day and week rhythms of the group and its individual members.

After eight months, a half-year period was started, during which the dimming speed was alternated randomly between slow (nine seconds to maximum) and fast (five seconds to maximum). The aim was to see if this influenced the lighting levels selected. Further on it was to be studied whether lighting levels influenced productivity.

During the last five months of the total two-year measuring period, the study protocol was different. In order to see if the switch-on level influenced the illuminance selected, the switch-on level of the system was changed between minimum and maximum almost every week. Further on, it was to be studied whether lighting levels influenced productivity.

At the beginning of the two-year measuring period in study A, the participants were informed that new lighting would be installed and that their selections would be monitored. It was made clear that it was fully up to them how they did or did not use the system. Participants were not informed of different changes in the dimming speed or preset value. They did not know either that productivity figures were used in this study. However, they knew that their productivity was measured all the time as always.

Dependent variables

The statistical method used to study the day, week and seasonal rhythms was Factorial ANOVA together with Tukey´s HSD post hoc tests.

- Dependent variable: selected illuminance; factors: person and day or time slot or season)

ANOVA was also used to study the effects of different dimming speeds and switch-on levels of task lighting on selected illuminances

- Dependent variable: selected illuminance; factors: dimming speed or switch-on illuminance and person

Productivity differences were analysed between the test group and the reference group (t- test of independent samples). The correlation between productivity and lighting level employed per user was calculated, and one-way ANOVA was used to evaluate the influence of dimming speed on productivity (factor dimming speed).

3.2.3 Results

Figure 5 shows the average selected illuminances of the employees who worked in the area during the first eighteen months of the study. Only one person selected a level lower than 500 lux. The task lighting was always used. There was a weak, but statistically significant, negative correlation between the age of the worker and the task illuminance selected. Seven employees who were present during the summer and winter period during all weekdays selected an average of 300 lux lower illuminance in the summer than in the winter.

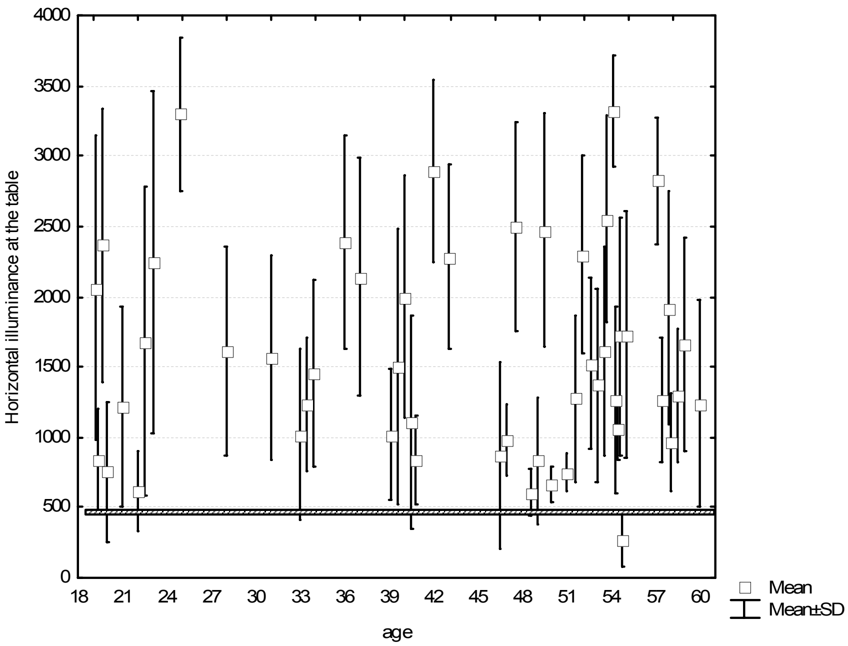

Figure 5. Selected horizontal illuminance at the worktable as a function of the age of the employee over eighteen-month measuring period. Means and standard deviation are shown. The minimum maintained illuminance according to EN 12464-1 for this type of work (500 lux) is indicated by a line.

Figure 6 shows the week rhythms of the illuminances selected by the seven employees who were working in the test area for long periods and full weeks. As can be seen from Figure 6, two of the employees have clear week rhythms (top curve and curve with Wednesday drop). As a group, participants of study A also tend to select higher task illuminance in the early, rather than later, morning (less than 150 lux difference) and to use higher task illuminances during winter than summer time (app. 300 lux difference depending on the day). However, these "rhythms" were not followed by all participants (see II(A) page 227).

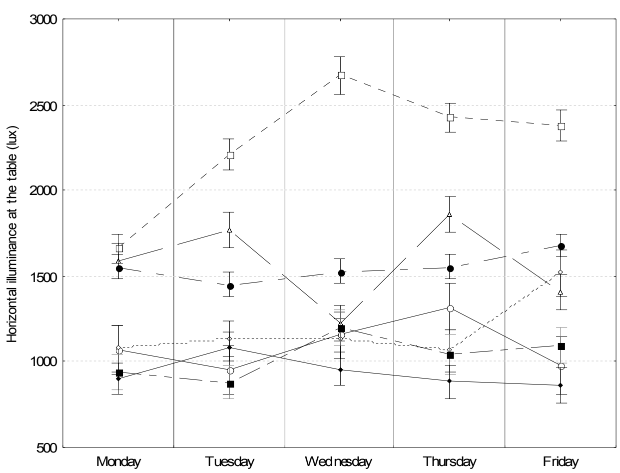

Figure 6. Average selected illuminances of seven workers per weekday per person, when only full weeks have been taken into account. (Vertical bars denote 0.95 confidence intervals.) [II(A)]

The changes in dimming speed influenced the illuminances selected, but not very much. There was a more clear change in dimming times used by users to push the control button.

Table 2 shows the effect of the dimming speed on illuminance and dimming time. When the dimming speed was slow, the selected illuminance was 13 per cent lower than when the dimming speed was fast. But the subjects pressed the button of the remote control significantly longer (55 per cent) when the slow dimming speed was in use. Nobody commented or complained to the management on the changing of the dimming speed.

Table 2. The means and the standard deviations (SD) of the selected illuminance and dimming time for the test group for the different dimming speeds. (Dimming time is the time users pushed the dim-up button of the remote controller.)

	Illuminance (lux)		**Dimming time (s)**	
Dimming speed	Mean	SD	Mean	SD
Fast	1359	691	3.3	0.65
Slow	1181	642	5.1	1.17

The switch-on level did not have a major effect on the user's illuminance selection. Figure 7 shows the average illuminance chosen by the workers during both switch-on settings (low and maximum). The black circles refer to average selection with the low switch-on level and white rectangles to selections when the switch-on level was maximum. Eleven persons were working in the test area for long periods when the switch-on level was alternated. On average, employees selected 1370 lux (general lighting + task lighting) when the switch-on level was low (0.1 x maximum) and 1340 lux when it was maximum. The difference is statistically significant ($p<0.05$), but still very small. As can be seen from Figure 7, differences in selected values are also very small per person.

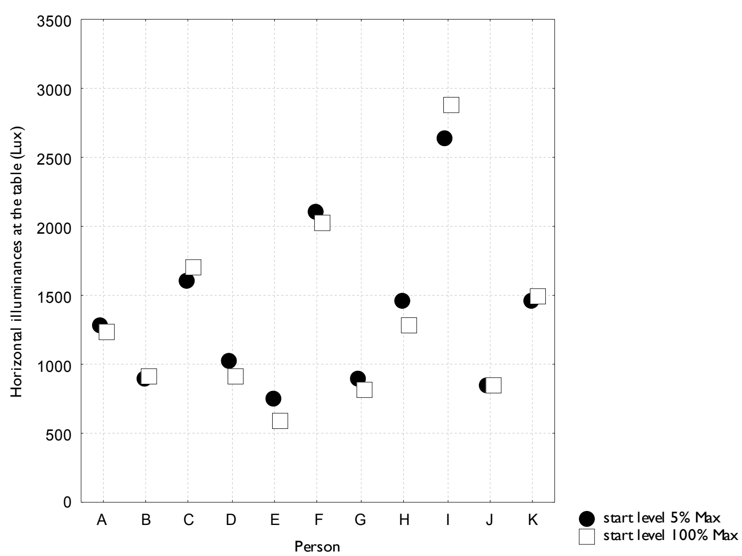

Figure 7. Mean selected horizontal illuminance at the worktable per person during both switch-on settings [III(A)].

Table 3 shows the productivity changes and standard deviations per year. There is a statistically significant difference between the productivity of 2002 and that of 2003 for the test group ($t (605)=-2.49$, $p<0.05$, $n=625$). The difference for the reference group is not significant ($t (278)=-0.97$, $p=0.33$, $n=282$). Maximum task illuminance for the reference group was about 700 lux, while for the test group the average was about 1300 lux.

Table 3. Productivity figures and standard deviations (SD) for the "test group" that used dimmable task lighting in 2003 and for the "reference group" that had on/off task lighting all the time [V].

	2002		2003	
	Productivity	SD	Productivity	SD
Test group	100	27	108.42	30
Reference group	100	29	103.82	21

There is a very weak but significant positive correlation between illuminance and productivity for the test group ($r=0.14$, $p<0.05$, $n=2151$) during the six-month period when dimming speed was altered. Different dimming speeds of the system lead to small differences in selected illuminance, but the difference in productivity for different dimming speeds is not statistically significant.

The main results of study A are:

- All users used controllable task lighting.
- Variation in the selected lighting levels was high (300 to 3300 lux).
- Two users had clear week rhythms in selected lighting levels.
- Switch-on level of the task lighting or dimming speed of the system had only a small influence on the selected lighting level.
- Giving employees controllable task lighting (max around 3000 lux) increased study group productivity significantly, and more so compared to that of the reference group, which had stable task lighting (max around 700 lux).
- There is a weak, but significant correlation between selected lighting level and productivity.
- A 180 lux illuminance difference resulting from the use of different dimming speeds did not result in significant productivity changes.

3.2.4 Discussion

This study confirmed the results of studies made in office environments (for example, Begemann et al., 1997), where individual differences in the used task illuminance values for different persons were high. The reported individual week rhythms for two persons were interesting, since they seem to show that something in week rhythms outside the working hours might influence the lighting preferences. However, the exact reason for this will be the issue for future research. Changing the dimming speed or switch-on illuminance had only a very modest effect on selected illuminance. Since dimming speed and switch-on illuminance did not create differences in selected illuminance, the possibilities of studying productivity differences based on illuminance differences were limited also. If changes in dimming speed or switch-on illuminance would have created real differences in selected illuminances, procedure of changing dimming speed and switch-on illuminance would have been very strong when trying to get rid of possible variables, other than lighting-related, related to possible productivity changes. Higher productivity of the test group compared to the reference group could have been caused by higher task illuminance, job satisfaction (new controlling system and positive effect of perceived control (Veitch, 2001)) or some other variable. Correlation between selected task illuminance and productivity for the test group indicates that the reason could have been task illuminance, as even the correlation was weak.

3.3 Study B

3.3.1 Introduction

The literature study showed that data on task illuminance preferences of industrial workers is not available. The first aim of this study was to find out the lighting and, especially, the task illuminance preferences of industrial assembly workers by giving them freedom to control their task illuminance and to monitor its use by using two different task lighting colour temperatures. This also provided the possibility of seeing whether colour temperature influences the selected task illuminance.

The literature study showed also that studies concerning lighting and productivity are relatively old and that their relevance for work and conditions today is not clear. Available field studies were also mainly before-and-after studies were changes were done once. To be able to see the effect of more visual and biological mechanisms (1-6, see Chapter 2.1) study design should be carried out in the way that lighting changes are done several times or that users are guided to use different task lighting levels unconsciously. The second aim of the study was to find out if task illuminance or the colour temperature of task lighting influences the productivity of assembly workers. To eliminate the effect of the more psychological mechanisms 7-10 (see Chapter 2.1), the switch-on values of the task lighting system were changed between four settings.

3.3.2 Methods

Study area

The study area was an assembly area of a luminaire factory located in Germany. Figure 8 shows the two types of assembly table used in study B.

a)

b)

Figure 8. a): Luminaire assembly workstation. b): Optics assembly workstation.

Participants and work description

The participants assembled luminaire components, such as the frame, gear, and optical parts, at the luminaire assembly tables (Figure 8a). Connecting the white wires is visually the most demanding part of the work. The smallest diameter of white wire was 2mm and the diameter of unisoleted copper end was 0.8mm. White wires were connected to a white connector block (or lamp holders) by screws or by just pushing the wire into the hole. Participants were free to carry out the tasks in the way and order they felt most suitable for them. When participants were sitting, the main tasks were around 50cm from the eyes. During the productivity measurement period (8 months), 26 female workers (average age 45 years) were working in the luminaire assembly area. There were no sources of direct glare from luminaires in the direction of the task at the workstation under normal conditions. However, when reflective materials (glossy aluminium) were handled, disturbing reflections might have been produced, depending on the participants' way of working.

Six female workers (average age 41 years) were working during the study period on the optics assembly area (Figure 8.b) where luminaire optics were assembled manually. The material was relatively glossy aluminium. Workers put
together lamellae on side reflectors. When optics were handled, depending on the participants' way of working, disturbing reflections might have been produced. General lighting luminaries had open reflectors but, as can be seen from figure 8b, the installed ceiling blocked them from sight when working. Task lighting luminaries had a wide illuminated surface limiting the risk of veiling reflections appearing.

Lighting conditions

A dimmable task-lighting system was installed above four luminaire assembly workstations and four individual optics assembly tables. The luminaires were fitted with two different lamps (2700 K and 6500 K); by changing their balance the colour temperature could be changed. The general lighting provided a constant illuminance of 200-300 lux at the middle of the tables; in addition to this, the task lighting provided a maximum of 700 lux in the luminaire assembly workstations. For the optic assembly tables, the general lighting provided a constant illuminance of 200-300 lux to the middle of the tables, while the new task lighting provided a maximum of 900 lux in addition to this. More information about the lighting installation can be found from article V(B) (pages 3-4).

Procedure

The colour temperature and the switch-on illuminance of the task-lighting luminaries were preset. The settings were changed between four preset values *(4400K/350 lux, 4400 K/820 lux, 3500 K/350 lux, 3500 K/820 lux)* every 1.5 weeks on average. Participants themselves were able to change the illuminance using only IR-transmitters.

The selected illuminances in the luminaire and optics assembly tables were recorded to see the task illuminance preferences and whether the preset value affects these. The exact position of individual participants was not recorded.

The influence of the preset colour temperature and illuminance on productivity was studied by collecting the productivity figures of four luminaire assembly workstations between August 2004 and April 2005. The daily productivity values were compared to preset colour temperature and to switch-on illuminance values. The productivity of the assembly work is calculated by comparing the planned and real working time. The nominal value was 60 minutes. If a person does 150 minutes of work in 100 minutes, the productivity value is 90 minutes (150/100=1.5; 1.5x60=90). If the same job takes 200 minutes, the value would be 45 minutes (150/200=0.75; 0.75x60=45). So the higher the value, the higher the productivity.

Participants were informed that new lighting would be installed and that their selections would be monitored. It was made clear that it is fully up to them how they do or do not use the system. Participants were not informed of the changes in the preset values. The union representative was informed that productivity figures were used in this study. The participants knew that their productivity was measured all the time as always.

Dependent variables

The task lighting levels selected, as well as productivity figures, have been studied by two-way ANOVA. Selected values were monitored per different colour temperature or switch-on illuminance.

- Dependent variable: selected illuminance; factors: switch-on illuminance (high or low) and colour temperature (3500K or 4400K)
- Dependent variable: Day value of productivity; factors: switch-on illuminance (high or low) and colour temperature (3500K or 4400K)

3.3.3 Results

Figure 9 shows how the switch-on level and colour temperature of the task-lighting influenced the selected illuminances. Black circles and rectangles show the switch-on levels of the task lighting. The white symbols indicate selected illuminance values. (3500K/low - mean 547 lux, SD 273 lux; 3500K/high – mean 848 lux, SD 117 lux; 4400K/low – mean 499 lux, SD 234 lux; 4400K/high – mean 829 lux, SD 110 lux). When the colour temperature of the task lighting luminaire was 3500 K, users selected 5 per cent higher illuminances compared to the situation when the colour temperature was 4400 K (ANOVA: $F(1, 48213)= 295.8$, $p<0.01$, $n=48217$). When the switch-on illuminance of the task lighting luminaire was higher, users selected 60 per cent higher task lighting illuminances than when the switch-on illuminance was low (ANOVA: $F(1,48213)=26294$ $p<0.01$, $n=48217$). The differences in selected illuminances were statistically significant. The task lighting was used over 75 per cent of working time. General lighting was on during working times. During the morning shift, the average illuminance values per hour varied between 621 lux and 643 lux. During the evening shift, the variation was from 603 lux, (18:00-19:00 hours, this time the evening shift included a meal break) to 670 lux (21:00-22:00 hours - last working hour).

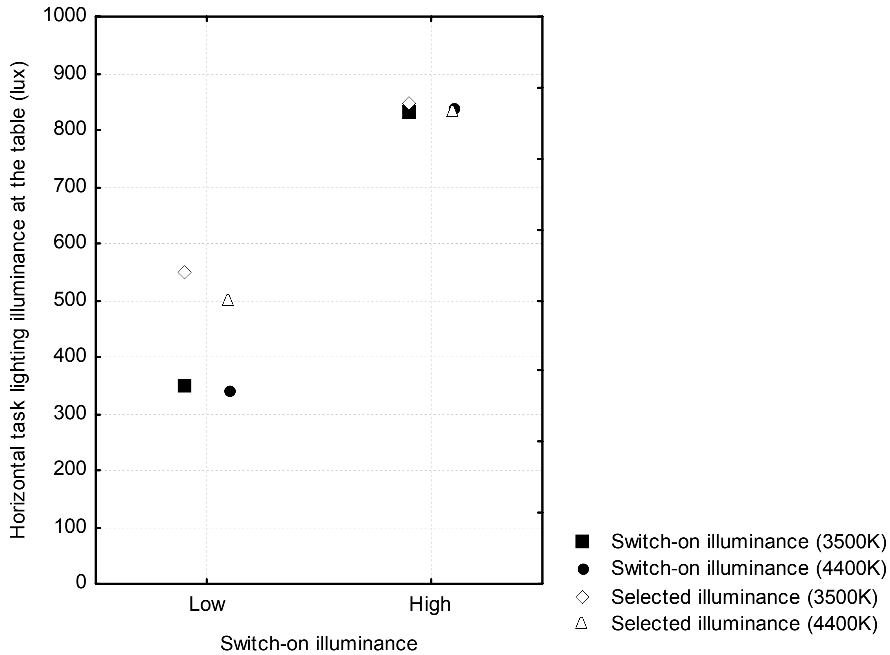

Figure 9. The influence of the colour temperature and the switch-on illuminance on the selected illuminances (task lighting + general lighting) [V(B)].

The influence of colour temperature on productivity was analyzed by using daily productivity data. The results of two-way ANOVA are shown in Figure 10 (3500K – 70.6 minutes, SD 16.7 minutes; 4400K – 74.6 minutes, SD 15.5 minutes). When the colour temperature of the task lighting luminaire was 4400 K, productivity was 5.7 per cent higher compared to the situation when the colour temperature was 3500 K (ANOVA: $F(1, 323)= 4.9$, $p<0.05$, $n=326$). When the switch-on illuminance was low, participants selected an approximately 300 lux lower illuminance than when the switch-on illuminance was high. However, this illuminance difference did not significantly affect productivity.

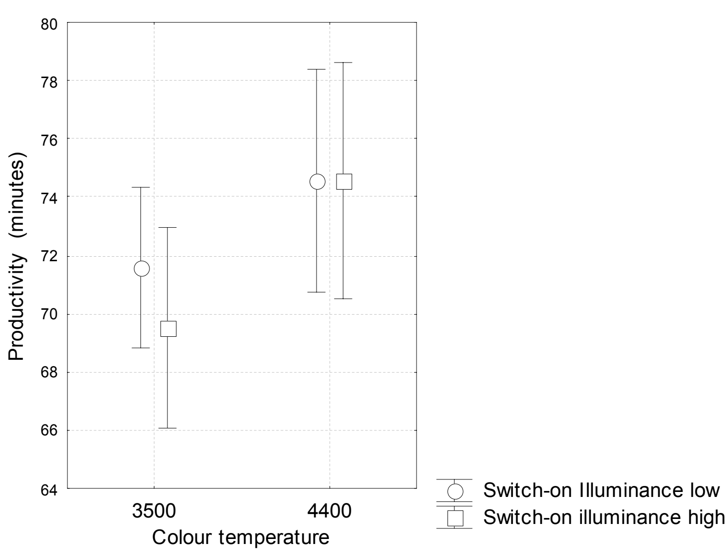

Figure 10. The influence of the colour temperature and the switch-on illuminance on productivity. Higher value means higher productivity. Vertical bars denote 95 per cent confidence intervals.

The main results of study B are:

- Most users used controllable task lighting.
- The selected lighting levels varied within the available illuminance range.
- When the colour temperature of the task lighting luminaries was 3500 K, users selected a 5 per cent higher lighting level than when the colour temperature was 4400K.
- The switch-on level of the task lighting strongly influenced the selected lighting levels.
- The colder colour temperature increased productivity by 5.7 per cent compared to the warmer one (3500 K/4400 K).
- 300 lux illuminance difference did not significantly affect productivity.

3.3.4 Discussion

In this study, the switch-on values of the task-lighting system affected the selected illuminance values significantly more than in study A. This means that the study design successfully managed to decrease the possible effects of mechanisms 7-10 (see Chapter 2.1) to the productivity results. The higher colour temperature seemed to result in a lower selected illuminance. However, the 5 per cent difference in illuminance is not large enough to be discernible (perceived by the eye). The differences in selected illuminances under different colour temperatures are interesting, especially since the higher colour temperature resulted in higher productivity. So, for productivity as well as for energy reasons, the results seem to indicate that a higher colour temperature (4400 K) is a better solution for task lighting than a lower colour temperature (3500 K). (See also the discussion in V(B), pages 9-11.)

3.4 Study C

3.4.1 Introduction

The literature study showed that the lighting preferences of the industrial workers have not been studied in longer-term studies in real industrial environments. The aim of this study was to find out the lighting and, especially, the task illuminance preferences of the industrial assembly workers by giving them freedom to control their task lighting and monitoring its use. The main difference between this and the other studies is the amount of daylight coming from skylights. In the other study sites, there was no direct sunlight.

3.4.2 Methods

Study area

The study area was an assembly area of luminaire factory located in France. Figure 11 shows assembly tables and Figure 12 the position of skylights.

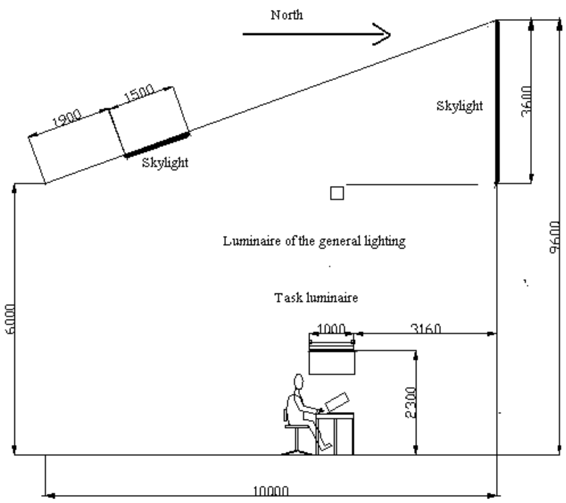

Figure 11. (left) Assembly tables in the test area of study C.

Figure 12. (right) Assembly area and the position of skylights (dimensions in mm).

Participants and work description

The participants were 23 assembly workers (average age 35: 3 men, 20 women) who were working in the area longer than 20 days during the study period. The components assembled were different for the different workstations, but the tasks that had to be performed were quite similar for all assembly workstations. There were six workstations in the line. The first four were assembly stations, the fifth was a testing station, and the sixth was a packaging station. In the assembly stations, different components, such as wires and lamp caps, were mounted in the luminaire frames. The frame was then moved to the next assembly station, where more components were installed. The speed of the line was defined by machinery before the line. At the fifth station, the luminaire was tested. Here the worker had to connect the supply voltage to the luminaire and check if a test lamp on a vertical plane above his/her head lit up. At the packaging station, a worker put the luminaire into a cardboard box. Connecting the wires is visually the most demanding part of the work. The smallest diameter of white wire was 2mm and the diameter of unisoleted copper end 0.8mm. White wires were connected to white connector blocks or lamp holders by pushing the wires into the holes. The tasks were mainly in the horizontal plane and viewing distances to the main tasks were around 50 cm. There were no sources of glare in the direction of the task during the dark time, except at the testing workstation, where the worker has to look at the test lamp (to check whether it goes on or not). During daytime, direct sunlight might have created disturbing reflections from white and shiny materials from time to time.

Lighting conditions

A task-lighting system was installed at six workstations. Two controllable luminaires (2*54 W 4000K T5, low-luminance optics) were installed crosswise above each test workstation. The general lighting (4000 K) was controlled by a daylight sensor (three control levels: 0per cent, 50per cent, and 100per cent light output). The general lighting could provide approximately 320 lux (100per cent) on the tables. This was also guaranteed as a minimum level, since the 50per cent dimming only occurred when the daylight provided more than 300 lux in the area. In addition to that, the task lighting provided between 800 and 1500 lux on the different work tables. To limit the influence of the task light on the adjacent workstations, gray plates were installed between the assembly stations to block the light. Daylight entered from large horizontal and vertical skylights in the area. The vertical skylights were facing north. Two illuminance meters were installed in the test area, one on top of the task-lighting luminaires and one below the vertical skylight. Both were registering values up to around 10000 lux during the measuring period. Figure 13 shows an example of the luminance distribution at one of the workstations (Workstation 4).

Figure 13. Luminance distribution of one assembly table in study C. (cd/m^2)

Procedure

The participants had the opportunity to control the task lighting by infrared remote controllers when and how they wanted. The switch-on level of the task lighting was around 70 per cent of the maximum. At the beginning of every break, the task lighting was automatically switched off. Daylight and the amount of task lighting employed were recorded between the winter of 2004 and the spring of 2005. During this period, a record was kept of who was in which workstation and when. Via this data usage of the task lighting at different times, at different workstations and by different participants was monitored.

Participants were informed that new lighting was to be installed and that their selections would be monitored. It was made clear that it was fully up to them how they did or did not use the system.

Dependent variables

In study C, one and two-way ANOVAs were used to analyse differences between selected illuminance levels (and between usages of task lighting) depending on different variables.

The usage of the task lighting at different workstations

- Dependent variable: use of lighting, factor: workstation

The selected illuminance per workstation

- Dependent variable: illuminance, factor: workstation

The usage of task lighting depending on amount of daylight

- Dependent variable: illuminance (daylight + general light), factors: task lighting (on or off) and time (one-hour time slots)

The usage of lighting at different times

- Dependent variable: use of lighting, factor: time (one-hour time slots)

3.4.3 Results

The most obvious result of this study was that the additional task lighting was not used very frequently in the conditions prevailing, i.e. where an abundance of daylight was available during the main part of the working period. The workers who were in the area during the study for more than 20 days used the task lighting on average only 6.5 per cent of their working time.

The task lighting of all the workstations was never on at the same time for the whole working period between two breaks. During 54.5 per cent of the time that task lighting was used, only one person at a time was using it (23 per cent, two persons; 15 per cent, three persons; 6 per cent, four persons; and 1.5 per cent, five persons). The activity to use lighting as well the selected illuminance varied between workstations. The age of the workers did not correlate significantly with frequency of lighting use or with selected values.

The lowest curve in the Figure 14 presents the variation of the selected values during the day and the two upper curves show the influence of daylight on the frequency of task lighting use. As can be seen from the lower solid (marked o) curve in this figure, the selected illuminances were slightly higher during the midday than during the evening and morning. The differences are, however, relatively small. The upper curve (marked +) shows the general lighting plus the daylighting for all working hours. The middle curve (marked □) shows the general lighting plus the daylighting for those periods when someone was using the task lighting. The differences between the values of the upper and middle curves are statistically significant ($p<0.05$) for all working periods, indicating that the amount of daylight did influence the use of task lighting. Task lighting was used more frequently when the amount of daylight was limited. Task lighting was used more frequently in the early morning and evening. During the more than one-year-long measuring period, the task lighting was on during 16 per cent of the total working time in the early mornings compared to less than 6 per cent for the rest of the day (excluding evenings). During the summer period, the frequency of task-lighting use was lower than during the winter.

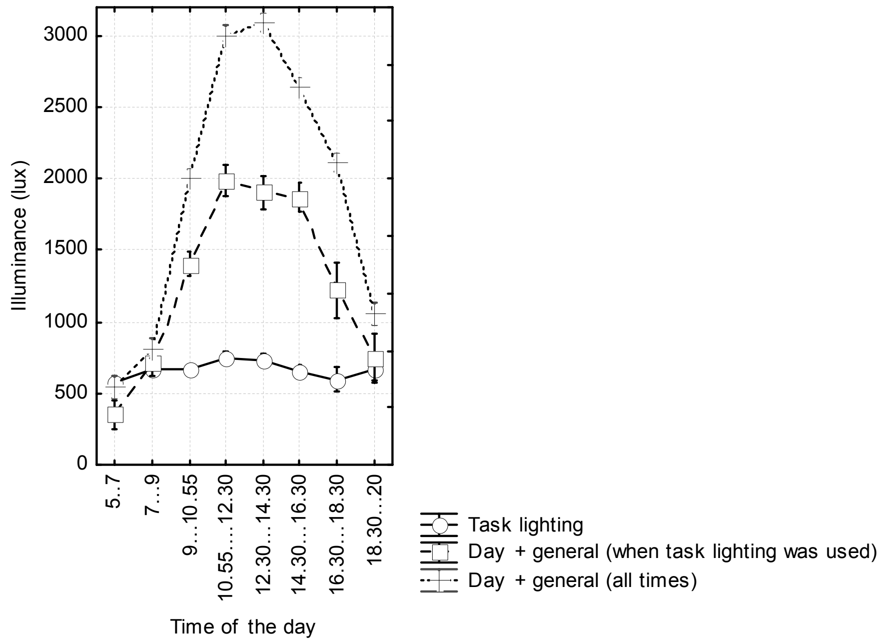

Figure 14. Average illuminances per work period. Upper curve (marked +) shows the average daylight + general lighting illuminance on the top of the task-lighting luminaires for all times when employees were working in the area. The middle curve (marked □) shows the average daylight + general lighting illuminance on the top of the task-lighting luminaires when task lighting was used. The lower curve (marked o) shows the average task-lighting illuminances on the table (no daylight or general lighting) selected by employees [VI(C)].

The main results of study C are

- Most participants used controllable task lighting, but only for very limited periods
- The selected lighting levels varied on the available scale
- The amount of daylight from skylights influenced the frequency of use of additional task lighting. The higher the amount of daylight, the lower the frequency of task-lighting use
- The activity to use lighting as well the selected illuminance was used varied between workstations.
- The age of the workers did not affect the frequency of lighting use or the selected illuminance values.

3.4.4 Discussion

Study C gave additional information compared to studies A and B. It confirmed that the results of study A, that there are marked individual differences between selected lighting levels. The amount of daylight influenced the frequency of additional task-lighting use. The participants who were in the area for more than 20 working days used the task lighting on average only 6.5 per cent of their working time. The fact that for 54.4 per cent of the time during which task lighting was used only one person at a time was using it indicates that using the task lighting was a clear individual choice, not an action influenced by other users switching the lighting on. The results of this study encourage the use of skylights, where possible, as a source of daylight. They can provide light, and save lighting energy. (See also the discussion in VI(C), page 30.)

3.5 Study D

3.5.1 Introduction

The literature study showed that studies concerning lighting and productivity are relatively old and their relevance for work and conditions today is not clear. Available field studies were also mainly before-and-after studies in which changes were made only once. One way to see the effect of the visual and biological mechanisms of the mechanism model 1-6 (see Chapter 2.1) is to design the study in such a way that lighting changes are made more than once. The objective of study C was to find out if task illuminance influences the productivity of assembly workers. To eliminate the more psychological mechanisms (7-10, see Chapter 2.1), illuminance levels were alternated between two values during winter and summer measurements.

3.5.2 Methods

Study area

The study area was an assembly area of an electronics factory located in the Netherlands. Figure 15 shows the task and the area.

Figure 15. Assembly area of study D

Participants and work description

There were approximately 17 workers simultaneously present at one production line. Depending on the product type, four to five of them were working in manual assembly. Three production lines were operational during the morning and the evening shifts. The total number of people working on the production lines during the test period was 119 (mean age 35 years). The participants (the manual assembly workers) were mainly females. The working schedules (see Table 4) stayed the same during the study period, and the changing of the shift took place every week on Thursday.

Table 4. The working schedules of study C

	Schedule 1	Schedule 2
Thursday	06:00-15:00	15:00-24:00
Friday	06:00-15:00	15:00-24:00
Monday	06:00-15:00	15:00-24:00
Tuesday	06:00-15:00	15:00-24:00
Wednesday	06:00-12:00	12:00-18:00

Groups are changing the schedule on Thursday morning.

In the factory concerned, electronic control gear (namely ballasts) for gas-discharge lamps were produced. Some of the component parts were installed non-manually before the semi-finished products were transported to the manual assembly area. The number of manually installed components depended on the product type. The tasks were performed mainly in the horizontal plane. Connecting small electronic components (diameter of "legs": 0,4mm) with different colours to the circuit boards was visually the most demanding part of the work. Participants were sitting while working and the viewing distance for task area was, for most participants, less than 50cm. There were no sources of glare in the direction of the task.

Lighting conditions

An automated sunblind system at the glass facade prevented direct sunlight from reaching the production line closest to the window. The lighting installation consisted of continuous lines of luminaires at a height of 4.2m (each with two 49 watt T5 4000K lamps and a white reflector). The installation provided a horizontal illuminance of approximately 1200 lux at the work tables. Maximum differences in the horizontal task area illuminances between the assembly lines were 70 lux (1150 lux / 1220 lux). At the one line, differences were within 20 lux when all luminaires were on and when every third one was switched off (see procedure). Task-lighting luminaires were available in the inspection areas, but not in the assembly area. Floor and walls were white throughout the area. Figure 16 shows an example of the luminance distribution at one of the workstations.

Figure 16. Example of the luminance distribution of workstation of study D (cd/m^2)

Procedure

The horizontal illuminance at the assembly table was alternated between two presets: 800 lux and 1200 lux. The changes were made between the shifts and one level existed per shift. Productivity was measured by using the system that was already running in the factory. The data of the scanners that detected the products when entering the manual assembly area were used to determine the production time. The data of the errors in the manual assembly had to be extracted from error reports.

Participants were informed that the lighting study would be started. (Questionnaire results showed afterwards, however, that many (37 per cent) did not remember that any kind of study was going on.) They were not informed that productivity measurements were used in the study. However, all participants knew that their productivity was measured all the time as always.

Dependent variables

Three-way ANOVA was used and planned comparisons (for light and shift) were performed separately for both study periods (summer and winter).
Influence of the task illuminance on productivity and errors during morning and evening shift were monitored.

- Dependent variable: production time; factors: illuminance (low or high), shift (morning or evening) and product type
- Dependent variable: number of errors; factors: illuminance (low or high), shift (morning or evening) and product type

Two-way ANOVA was used to study if task illuminance influenced productivity during the night shift

- Dependent variable: production time; factors: illuminance (low or high), and product type

3.5.3 Results

The average production time per product type ranged from 36 to 63 seconds for the summer period and from 44 to 60 seconds for the winter period. The difference is due to the fact that the types and quantities of products were not equal in these two periods. To make it possible to compare the results for the different products, the relative increase or decrease in production time with respect to the 800 lux situation has been calculated ($\Delta = (t_{1200} - t_{800})/t_{800}$, where t = production time). The relative difference has been calculated per product; this dataset has been used for statistical testing. The average relative production speed change, where speed is the inverse of production time per product type, and the average of these average values, are shown in Table 5 for different time spans.

At task illuminance1200 lux, the speed of manual assembly was significantly higher than at 800 lux. The effect was a 2.9 per cent increase of production speed in the summer ($F(1,18526)=6,9$ $p<0.01$, $n=18586$) and a 3.1 per cent increase in the winter ($F(1,39004)=63,9$, $p<0.01$, $n=39045$). During the winter, the effect was significant for both shifts and, during the summer, for the evening shift only. For the evening shift in the summer, the increase was 6.3 per cent. In the winter study, the increase (with increase in illuminance) of the production speed was 4.6 per cent during the morning and 1.6 per cent during the evening.

Table 5. a) Production time (mean and standard deviation) in seconds during the summer study. b) Production time (mean and standard deviation) in seconds during the winter study.

a)

	Summer	
	mean (s)	SD (s)
1200 lux, whole days	48.9	21.3
800 lux, whole days	51.5	20.9
Mornings only	50.7	21.9
Evenings only	50.0	20.4
1200 lux Mornings	48.3	22.6
800 lux Mornings	52.5	21.1
1200 lux Evenings	49.4	20.1
800 lux Evenings	50.5	20.6

b)

	Winter	
	mean (s)	SD (s)
1200 lux, whole days	49.7	14.3
800 lux, whole days	51.4	15.2
Mornings only	50.9	15.1
Evenings only	50.0	14.4
1200 lux Mornings	49.8	14.4
800 lux Mornings	52.1	15.7
1200 lux Evenings	49.4	14.2
800 lux Evenings	50.5	14.6

During the winter period, some of the employees also worked on the night shift. Only products that were produced under both lighting conditions during the night shift have been analysed. Seven product types were produced under both conditions. Five of these were produced faster and two slower under the higher illuminance level. The average production times for these products ranged from 36 seconds to 78 seconds per product. The data have therefore been normalised in the same way as the morning and evening shift data, and the relative difference in production time between the higher and lower lighting level has been calculated for each product. At 1200 lux, the speed of manual assembly was significantly (7.7 per cent) higher than at 800 lux and the increase was statistically significant ($F(1, 3174)=26$, $p<0.01$, $n=3187$;1200 lux – mean 50.5, SD 17s; 800 lux - mean 54.9s, SD 16s).

The main results of study D are:

- The changes in task illuminance did not result in statistically significant changes in error rates.
- Winter and summer tests both showed approximately a 3 per cent statistically significant increase in speed of manual assembly with higher horizontal illuminance. However, the results per shift varied.
- During the night shift (winter period), the productivity increase with the higher task illuminance was 7.7 per cent greater than with the lower task illuminance.

3.5.4 Discussion

The choice to alternate the illuminance for short periods was made to minimize potential intervening effects. The possible intervening effects were, for example, experience, motivation, and health of the manual assembly workers. It is not very likely that these effects alternate synchronously with the lighting change scheme. Due to this approach in which illuminance was changed several times during the study period, no conclusions can be drawn about the durability of the effects. Lighting might also affect quality of sleep, which then would affect the next day's performance. These longer-term effects cannot be studied when illuminance is altered often. The results show clearly that task illuminance under these conditions affects productivity. Improving task illuminance from the required minimum level

(European standard EN 12464-1 (2.6 electrical industry, 2.6.2 assembly work, medium 800) can lead to improved productivity. (See also the discussion in VII(D), page 622.)

3.6 Study E

3.6.1 Introduction

The literature study showed that studies concerning lighting and productivity are relatively old and their relevance for work and conditions today is not clear. Available studies were also mainly before-and-after studies in which changes were made only once. In order to see the effect of more visual and biological mechanisms (1-6, see Chapter 2.1) the study should be designed in such a way that lighting changes are made more than once. The objective of the study was to find out if task illuminance influences the productivity of machine operators or their subjective alertness. To eliminate more psychological mechanisms (7-10, see Chapter 2.1) the illuminance level was alternated weekly between two values.

3.6.2 Methods

Study area

The study area was a packaging area of the food factory located in the Netherlands. Figure 17 shows the area.

Figure 17. Working area in study E.

Participants and work description

Participants were working in the packaging hall, where eight packaging machines were in use. The participants were operators (section operators, machine minders and shift co-ordinators) who monitored the packaging machines. Their work did not change during the test period. If something goes wrong, it is their job to fix it as quickly as possible so as not to disturb the production process. Tasks used in the measurements were:

Wrapping paper input is blocked. The machine stops and the operator has to take action. The operator opens the door of the cabinet on the machine and visually inspects the situation. A small tool is used to remove the blockage. The operator adjusts the paper, cuts it once, then prepares the machine. After closing the door of the cabinet, the machine is again started.

Photocell does not see a spot. This failure, in which the machine has missed some registration spots, occurs frequently when the previous paper roll is changed over to the next. The operator reads the error at the control panel, presses some buttons, and the machine starts again. In general, it is not required to open the cabinet.

Streamer blocks. This error occurs in the chocolate delivery line near to the packaging area. As this is the most frequently occurring error, the operator first examines the streamer before looking at the control panel. A bar of chocolate blocks the streamer (two on top of each other or a mis-shaped chocolate). After opening the cabinet, the offending chocolate is removed manually, the cabinet is closed, and the machine can be re-started.

Wrapping roll open. This error is the continuation of some other errors (cabinet door open, indicating that someone would like to adjust the machine). Solving the problem can take less than a minute or up to 20 minutes.

All these repairing operations required different visual tasks. Depending on the severity of the problem, the amount and visual size of those tasks varied. The viewing distance to the task was below one meter. Depending on their way of working, disturbing reflections might have been produced during some operations, but there were no sources of direct glare in the direction of view when machines were repaired.

The operators were mainly men, (average age 40 years). Six to eight participants were working in the area during each shift. The shift system was the so-called fast-rotating five-shift system. A shift group works during the morning shift (07:00 – 15:00) on days 1 and 2, during the afternoon shift (15:00 – 23:00) on days 3 and 4, during the night shift (23:00 – 07:00) on days 5 and 6, and have four days off - days 7, 8, 9 and 10. On day 11, the morning shift starts once again.

Reference groups were used only in absenteeism comparison. Reference groups consisted of other personnel of the factory. The test group was the sub-group of all personnel working in the packaging rooms, which was the sub-group of total production personnel. The number of production personnel was not the same for the period 2003-2005, since the number of employees was decreasing. The groups were homogeneous, and no management interventions were focused on the test groups other than the lighting change.

Lighting conditions

The original lighting installation was mounted at ceiling level at a height of 7m and consists of traditional water-protected luminaires (fluorescent lamps, 2*58 W T8, 4000 K, $R_a > 85$). This old installation, which provided a horizontal illuminance approximately 400 lux in the open space at one meter height, was left as it was. When needed during the test period, maintenance to the lighting installation was carried out to secure unchanged lighting conditions. Daylight was not available in the packaging room. A dimmable task-lighting system was installed above the chocolate-packaging lines. This was installed in eight rows parallel to the packing lines, consisting of 72 closed luminaires (fluorescent lamps, 2*58 W T8, 4000 K, $R_a > 85$) installed at a mounting height of 2.8 m.

Procedure

The task illuminance level was alternated weekly. Illuminance at the reference point above the machines was 2000 lux during the even weeks and 350 lux during the odd weeks. Measurements were carried out on the productivity of the process and employees, alertness of the employees, and opinions of employees by means of questionnaires. The performance of operators was measured by recording the reaction/repair times of four error types. These four error types were considered to be influenced by human aspects. Participants were also asked to fill in the KSS (Karolinska Sleepiness Scale) questionnaires four times per shift to monitor subjective alertness.

Participants were informed that new lighting would be installed and they were aware of changes in the preset values. Participants knew that repair times of the machines were recorded.

Dependent variables

ANOVA was used to study machine repair times and subjective alertness. Four-factor analysis of variance was performed to test the differences in machine repair times.

- Dependent variable repair time; factors: illuminance (high, low), error type (1,2,3,4), shift (Morning, Evening, Night) and machine (1-8)

Three-factor analysis of variance was performed to test the difference in KSS.

- Dependent variable KSS averages per break; factors: Illuminance (high, low); break (1, 2, 3, end of the shift); and shift (Morning, Evening, Night)

Absolute values of absenteeism of test group and reference groups were monitored to get an indication of the effect of lighting change on absenteeism. Absenteeism results, however, have not been tested statistically for two reasons. Firstly, since with absenteeism we are only looking at before-and-after results, many other variables might have had their effect, and significance testing would not make results any stronger. Secondly, individual absenteeism data were not available for researchers for confidentiality-related reasons.

3.6.3 Results

Only reaction/repair times longer than 10 seconds and shorter than 150 seconds were taken into consideration. The illuminance level in the task area above the machines was varied between 350 lux and 2000 lux every week. There was a significant main effect for the illuminance factor, showing that repair time was on average 3 per cent shorter when the lighting level was higher ($F(1, 37182)=4.9961$, $p<0.05$, $n=37373$; higher illuminance - mean 60.4s, SD 27s; lower illuminance – mean 62.7s, SD 26s)). However, the results per individual error type during different shifts were not so clear. Only for one error type during the morning shift was the difference in productivity between different illuminances clear.

The results of the subjective alertness test, measured by KSS questionnaires, did not show any significant effect between lower and higher task-illuminance level.

Table 6 shows absenteeism percentages for the test area compared to the whole factory area and all packaging lines. The figures for years 2003 and 2004 are for a whole year, while for 2005 they are until 5 November. The absenteeism figures for 16 subjects who were working in the test area repairing machines in 2003, 2004 and 2005 are shown in the first column. The columns labelled "less than six weeks absenteeism" show that absenteeism dropped in 2004 for all groups and increased again in 2005. However, absenteeism in the test hall was lower in 2005 than in 2003. In viewing the short-term absenteeism, it can be seen that this decreased in the test area in 2004, when absenteeism was generally higher than in 2003. The trend is that short-term absenteeism is decreasing for the test group and increasing in the packaging rooms generally, as well as on all packaging lines.

Table 6. The percentages of absenteeism in the test area, on all packaging lines and in the whole factory. The relative change compared to 2003 for each area is given brackets.

		Absenteeism					
Area	Number of subjects	< 1 week 2003	< 1 week 2004	< 1 week 2005	< 6 weeks 2003	< 6 weeks 2004	< 6 weeks 2005
Test area	16	1.03% (100%)	1.01% (98%)	0.99% (96%)	4.66% (100%)	2.80% (60%)	3.85% (83%)
All packaging lines	320	0.95% (100%)	0.97% (102%)	1.14% (120%)	3.04% (100%)	2.44% (80%)	3.17% (104%)
Whole factory	540	0.95% (100%)	1.00% (105%)	1.13% (119%)	2.99% (100%)	2.61% (87%)	3.01% (101%)

The main results of study E are:

- When a higher illuminance was used, machine repair times were slightly shorter. However, only for one error type during one shift was the difference clear.
- The absenteeism percentages in the test area had a positive trend (decreasing absenteeism) compared to all packaging lines or whole factory.

3.6.4 Discussion

Although a comparison of repair times showed that the repair was three per cent faster under the higher illuminance level, this was not true for all error types during the different shifts. Actually, the difference was clear only for error "Photocell does not see a spot" in the morning shift. The result of this study shows some – but not very strong – evidence that an increased illuminance level improves performance. (See also the discussion in IX(E), page 441.)

3.7 Study F

3.7.1 Introduction

The reason for the lighting change of study F was to promote the aim of saving energy. The study was made to see if energy saving can be achieved without decreasing productivity. Lighting change was performed only once. This means that mechanisms 7-10 (see Chapter 2.1) were not controlled. A reference group was used to give more indication if the possible result was lighting-change related. However, using a reference group does not mean that all intervening variables that might affect productivity are controlled.

3.7.2 Methods

Study area

The study area was an assembly area of the luminaire factory located in the Netherlands. Figure 18 shows the area.

Figure 18. One of the assembly tables of study F

Participants and work description

A total of 42 persons were working in the test area (average age 42 years). Sixty-nine per cent of the participants were female. The products assembled were different for the different workstations, but the tasks that had to be performed were quite similar for all assembly workstations. The subjects assembled luminaire components, such as the frame, the gear, and optical parts. Connecting the wires was visually the most demanding part of the work. The smallest diameter of white wire was 2mm and the diameter of unisoleted copper end 0.8mm. White wires were connected to white connector blocks and lamp holders by screws or just pushing the wire into the hole. Participants had lot of freedom to perform the tasks in the way and order they felt to be most suitable for them. The viewing distance to the main tasks was below one meter. The reference area was located in the hall next to the test hall. Assembly area, work and workers training and expertise were comparable to similar ones in the test hall. The reference hall could not be seen from the test hall. Disturbing reflections might have been produced in both halls. Light coming from luminaires might have reflected from reflective aluminium material handled every now and then.

Lighting conditions

Originally the factory hall was equipped with lighting installation that provided uniform general lighting to the area (2*58 W, 4000 K). Only limited daylight via windows was available. However, daylight did not contribute to the general illuminance. The lighting was switched off at the end of the working day.

Figure 18 shows the lighting installation after the change. It consists of the old reduced general lighting installation at ceiling level in combination with suspended localised lighting (low-glare luminaries, 2*54 W, 4000 K) above the main task areas. The general lighting was grouped in such a way that time switches switched it on in those areas only where work was actually being carried out. Two or three persons were working at one workplace, and they were able to switch off the localised lighting from the assembly line when they no longer needed it. The task area illuminances in the factory before and after the change are shown in Table 7.

Table 7. Horizontal and vertical illuminances at the assembly tables and in the surrounding area.

	General lighting		Assembly tables	
	E_h (lux)	E_v (lux)	E_h (lux)	E_v (lux)
Old installation	400 – 650	100 - 300	450 - 600	100 - 300
New installation	300 – 380	100 - 170	800 -1300	250 - 500

Procedure

Lighting was changed once and the lighting energy use, productivity and absenteeism were monitored before and after the change.

Participants were informed that new lighting would be installed and they knew that their productivity would be measured all the time as always.

Dependent variables

Energy use, productivity and absenteeism were monitored before and after the lighting change. Results have not been statistically tested because only before-and-after results were observed, many other variables might have had their effect, and significance testing would not make results any stronger.

3.7.3 Results

Although the installed lighting electricity power was reduced by only 7 per cent (from 45 kW to 42 kW), the energy consumption reduced by 39 per cent, from 207 to 127 MWh/year. This reduction in energy consumption is mainly due to the fact that the localised lighting was switched on only when and where it was needed, and the reduced general lighting was grouped per larger working area, and was switched off automatically outside working hours. The grouping of luminaires before the change was not fully in accordance with the working areas – the lighting in the area might have been on because the adjacent working area was occupied.

The productivity measurement system in the factory was changed in 2003. For this reason, the values for 2003 are not comparable with the later values and were thus not used. Table 8 shows changes in both productivity and absenteeism. The productivity in 2004, prior to the lighting change, has been set as a reference value, and changes after the installation of the new lighting are shown as percentages. Values from the reference hall have been shown in the same way, although there was no lighting change there. The productivity change in the test hall together with the lighting change was a 5.5 per cent increase compared to a 1 per cent decrease in the reference hall. Absenteeism was reduced by 2.5 per cent in the test hall and increased by 0.4 per cent in the reference hall.

Table 8. Changes in the productivity and absenteeism rate in both the test hall and the reference hall (NA means Not Available) [X(F)].

	Productivity		Absenteeism	
	Test hall	Reference hall	Test hall	Reference hall
Week 26-52 (2003)	NA	NA	Reference	Reference
Week 01-20 (2004)	Reference	Reference	-5.80 %	-0.60 %
Week 26-52 (2004)	+5.50 %	-1 %	-8.30 %	-0.20 %

The main results of study F are (no statistical tests used):

- Productivity increased in test hall after the lighting change at the same time that the productivity of the reference (no lighting change) groups decreased slightly.
- Absenteeism decreased in test hall after the lighting change and in reference hall (no lighting change) absenteeism slightly increased.

3.7.4 Discussion

Study F further supports the other studies described in this thesis, especially in the area of energy consumption, which was not studied elsewhere. The study showed that general lighting can be reduced by employing task lighting and an improved lighting control system and this can yield an increase in productivity and decrease in lighting energy consumption. Improving the lighting in industry does not automatically mean using more energy. A strong conclusion regarding productivity changes in this type of before-and-after study should have been avoided. This is because keeping all variables controlled is practically impossible.

3.8 Questionnaires

3.8.1 Introduction

The literature study showed that data on the lighting preferences of industrial workers is not available and that the field study data concerning lighting and productivity in the industrial environment are limited. Although, the main targets of this work was to get measured data of productivity and lighting preferences, questionnaires were selected to be an additional method to get information about subjective opinions of the participants. Questionnaires were used in studies A, C, D, E and F to collect data on the users' lighting preferences and for analysing the connections between lighting and productivity.

3.8.2 Methods

Before, the lighting-change questionnaires were use only in studies E and F. Questionnaires were delivered to subjects after the study period in studies A, C, D and F. In study E, a second questionnaire was delivered after the lighting change and the third one was used after the total measuring period. Some of the questions were the same in all questionnaires. Lighting-related questions were included in all questionnaires. Some questionnaires also included questions relating to the factory environment in general and the employees' perceptions of their own working environment. Table 9 gives an overview of the questionnaire types used in the different studies. The English version of the "before" questionnaire (study E) has been shown in Appendix 1 as an example of the questionnaire format used.

Table 9. Overview of the questionnaires used in the different studies. Exact return rates in most cases cannot be given since the "total number of subjects" describes the number of subjects in the areas during the total study period, while questionnaires were submitted to subjects present at a certain time [II(A), VI(C), VII(D), IX(E), X(F)].

Study	A	C	D	E	F
Location	Finland	France	Netherlands	Netherlands	Netherlands
Questionnaires Type(s)	After	After	After	Before/After/Final	Before/After
Questionnaire elements	Lighting	Environment Lighting	Environment Lighting	Environment Preferred shifts Lighting	Environment Lighting
Total number of subjects	49	72	119	46	42
Questionnaires returned	25	34	34	46/39/26	21/26
Type of work	Luminaire assembly	Luminaire assembly	Electronics assembly	Machine maintenance	Luminaire assembly

3.8.3 Results

Figure 19 shows how the subjects in field studies E and F evaluated the importance of different aspects of the factory environment generally before the lighting change. It was only in these two test locations that the "before" questionnaires were used. Good ventilation was rated to be the most important factor, and factory décor the least. Figure 20 shows how the same subjects evaluated their own working environment before and after the lighting change. In both cases, additional localised lighting was installed and illuminance levels in the task area increased. Differences in importance ratings are relatively small. However, space is evaluated as being more important than "brightness" after the change, although, in fact, quite a number of other items were evaluated as being less favourable after the change.

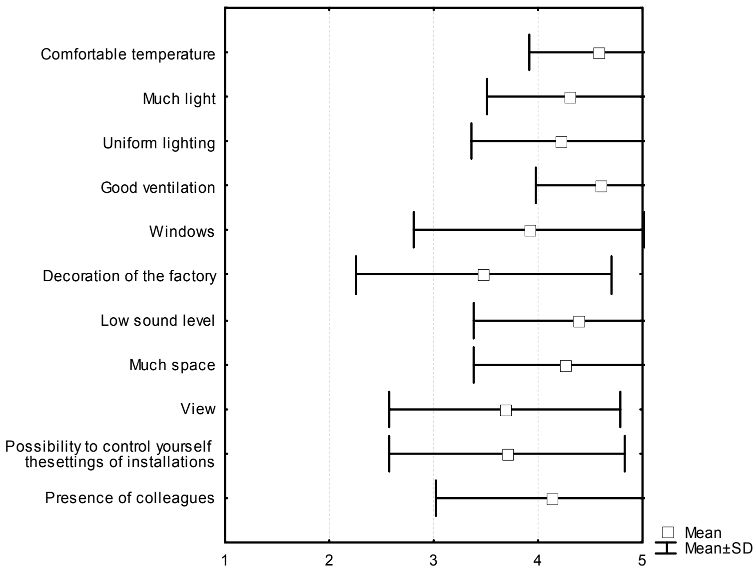

Figure 19. Combined results of studies E and F of the “before” questionnaires. Average answers to the item: Please evaluate how important different things are in the factory environment. (1: Not important, 5: Very important)

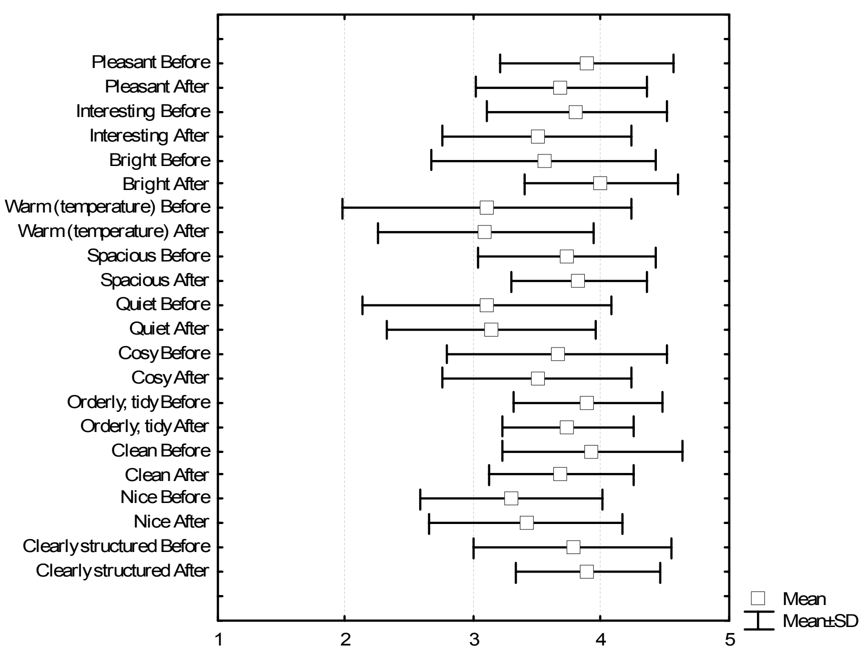

Figure 20. Combined results of studies E and F before-and-after questionnaires. Average answers to the item: Please evaluate your own working environment. The scale was from 1 (very negative) to 5 (very positive).

Figure 21 shows the combined spread of the answers (studies A, C, D, E and F) to the statement “Good lighting has an influence on my work”. Clearly, most of the subjects believed so. Figure 22 shows how much the subjects wanted to control their own lighting in the places where there was no controllable task lighting. The average of the answers is slightly in favour of controllable task lighting, but many subjects did not have an opinion. Figure 23 shows that reflections from the luminaires were not considered to be a big problem, even though in all test places general lighting was accomplished with luminaires without louvres.

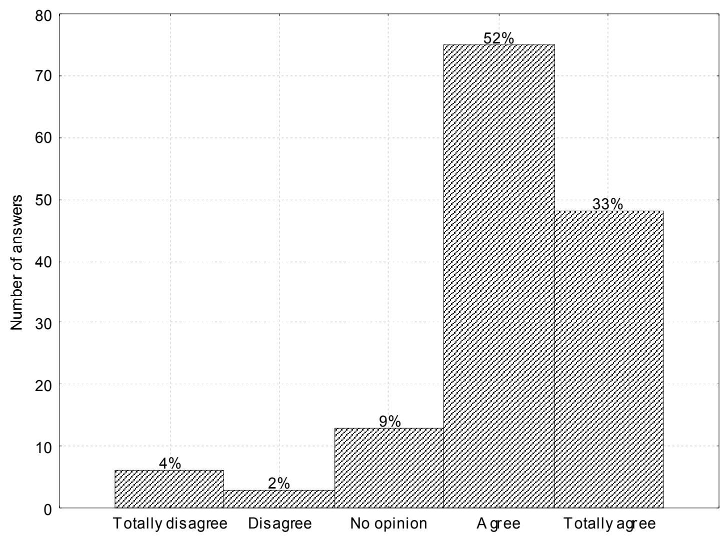

Figure 21. Average answers to the statement: “Good lighting has an influence on my work.” “After” questionnaires in studies A, C, D, E and F. (% indicates the percentage of the given answers)

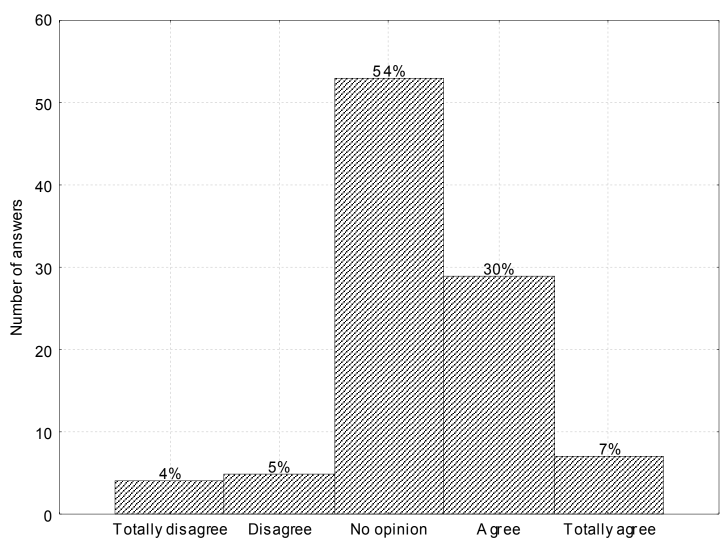

Figure 22. Average answers to the statement: “I would like to control the lighting at my task area myself.” “After” questionnaire in studies D, E and F, where lighting system was not controllable by users. (% indicates the percentage of the given answers)

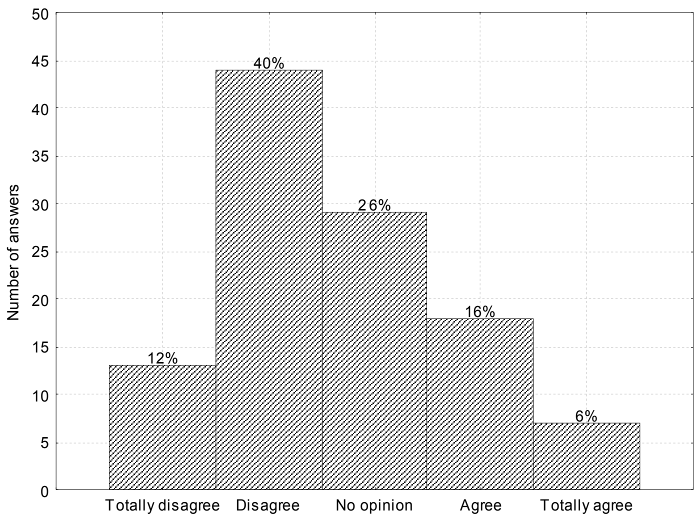

Figure 23. Average answers to the statement: “I am bothered by reflections from luminaires.” “After” questionnaires in studies A, D, E and F, where there was no daylight.

The questionnaires also included some performance-related questions. Figure 24 shows the results and questions in studies A, C, E and F. Average answers are between “no opinion” and “agree” (that new lighting helps). The spread here is wide, meaning that some employees felt that lighting does not help at all while some agreed strongly. Productivity was not measured in study C and employees rarely used task lighting. However, 41 per cent of them answered that task lighting helps them to perform better, and most of them wanted to keep additional task lighting.

Table 10 shows the answers to some lighting-related questions before and after the change in studies E and F. As can be seen, the answers are in favour of the new lighting installation, which in both cases increased task illuminance. However, differences between “before” and “after” answers are not very large. Clearly most of the subjects felt even before the change that “lighting level is sufficient for their work”. In both studies, some productivity or absenteeism improvements occurred at the higher illuminance. Also, afterwards, both groups on average felt that new lighting helped them to do their work better (Figure 24). This indicated that questionnaires used in these studies seem not to be a very reliable way to measure whether employees will benefit from the lighting change or not.

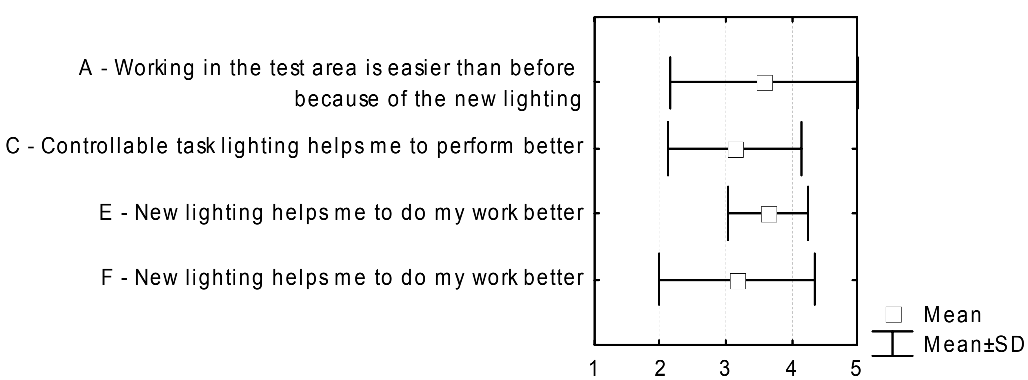

Figure 24. Mean of the answers to the lighting-related statements in different study places. (1- Totally disagree, 2 - Disagree, 3 - No opinion, 4 - Agree, 5 - Totally agree.)

Table 10. Average before and after answers to some lighting-related questions concerning the lighting change in studies E and F. (1 totally disagree; 5 totally agree)

	Study E			Study F		
	Before	After	After - before	Before	After	After - before
The lighting level is sufficient for my work	3,73	4,00	0,3	3,36	3,83	0,5
I need more light for my work	3,03	2,53	-0,5	2,91	1,96	-1,0
I would like to have less light than today	2,03	2,33	0,3	2,23	2,17	-0,1
I would like to have more light than today	3,21	2,63	-0,6	2,91	2,09	-0,8
I can see all colours well with the present lighting	3,83	3,86	0,0	3,86	3,87	0,0

The questionnaire results of the studies showed that

- Employees have a strong belief that good lighting influences their work.
- Most of the employees felt that glare was not a problem for them, although general lighting was provided by open luminaries.
- Thirty-seven per cent of the employees who do not have lighting control opportunities would like to have it.
- In those factories where the illuminance was increased, employees on average felt that the new installation helped them to perform better.

3.8.4 Discussion

The results of the questionnaires showed that the factors that are rated “important” are the ones that are also estimated to be a problem. Figure 19 shows that good ventilation and low sound level were estimated to be the most important factors in the factory environment, while Figure 20 shows that “warm (temperature)” and “quiet” were rated to be the most negative factors in the employees’ present environment. The questionnaire results and productivity results in studies E and F indicate that questionnaires are not a reliable way of evaluating whether someone will benefit from a lighting change or not. However, this does not mean that questionnaires are meaningless in evaluating lighting changes. For practitioners planning a lighting change, questionnaires could provide a means of obtaining information about the possible problems (open questions), using the questionnaires as a change-management tools. In this way, employees feel that their opinions have been heard.

4 Discussion

4.1 Preferred illuminances

4.1.1 General

Table 11 gives an overview of the results of studies A, B and C, where preferred illuminances were studied. As can be seen, there are some similarities, such as the use of uniform spread, meaning that practically all available values were sometimes selected by some employees. The differences in selected illuminances per daytime in all cases were small but still existed. There were annual differences in the use of task lighting in studies A and C. In the former, employees used lower illuminances during the summer period and in the latter task lighting was used less frequently in the summer.

The first difference between study results is the quite different use of controllable task lighting. In study A, it was always used; in study B, it was often used; and in study C it was rarely used. The second important difference between the results was the effect of preset (switch-on) illuminance values on the illuminance value selected. In study A, employees had preferred illuminance levels independent of the switch-on level or dimming speed, but in study B, the preset (switch-on) illuminance considerably influenced the illuminance selected. Employees in study B were not willing to control the task lighting as much as in study A. The third difference was the effect of the task in illuminances selected. In study A, employees selected more or less the same illuminances independently of the different assembly tasks they were working with, but in study C, illuminance as well the frequency of use of the task lighting varied between different work places having different tasks.

Table 11. Summary of the preferred illuminance level studies A, B and C [II(A), III(A), IV(A), V(B), VI(C)].

Study	A	B	C
Type of work	Luminaire assembly	Luminaire assembly	Luminaire assembly
Location	Finland	Germany	France
Controlling device	IR-controller	IR-controller	IR-controller
Task lighting	100lux….3000lux	100lux….900lux	300lux….1200lux
General lighting	100lux…380lux	200lux…300lux	0lux…300lux
Colour temperature	4000K	3500K or 4400K	4000K
Daylight	No	No	Yes, a lot
Use of task lighting	Always	>75% of the time	6.5% of the time
Selected task lighting scale	10%…100%	0%…100%	0%…100%
Differences in selected illuminance per daytime	small	small	small
Seasonal differences in the use of task lighting	Yes	Not studied	Yes
Individual week rhythms in selected illuminances	Yes	Not studied	Not studied
Effect of preset illuminance on the selected illuminance	No	Yes, a lot	Not studied
Effect of the dimming speed on the selected illuminance	Yes, a little	Not studied	Not studied
Effect of the colour temperature on the selected illuminance	Not studied	Yes, small	Not studied
Effect of the task on the selected illumianance	No	Not studied	Yes

There were differences in the methods employed in the studies conducted in this work in examining the preferred illuminances.

- Firstly, the studies were conducted in different locations and also in different countries. This means that the background of the workers were different. Even though three factories (A, B and C) belong to the same company, the laws and regulations are different in each country. Even more important than law-related issues is the culture. Factory cultures are not different just because of country, but also because of local things and the history of the site.
- The second difference is the lighting situation before the installation of the dimmable task lighting. In study A, there was constant task lighting before the change, but in study B only half of the places had task lighting before the change. In study C, no task lighting system existed before the change.
- The third important difference was the presence of daylight. There was no daylight in studies A and B. In study C, the skylights made the lighting very "dynamic" during the day.
- The fourth difference between the studies was the control possibilities of the task lighting. In study A, users were able to use considerably higher task lighting levels than in other locations. Study B was the only one where colour temperature was also changing.

The main similarities between the methods in studies A, B and C were:

- All factories were luminaire factories and the work was typical assembly work.
- Work was real work, not simulated.
- Task lighting was controlled via IR-transmitters and employees were allowed to do (or not to do) whatever they liked with the system.
- Data logging of the selected values was similar in all places.
- The most important similarity between these studies was that they were all very long user-behaviour studies. The total data-logging period was in all studies more than a year.

4.1.2 Activity using task lighting

The way in which the task lighting was used varied between study locations. In study A, the employees used task lighting always; in study B, most of the time; and in study C, rarely. The amount of daylight is most probably the main reason why users in study C used task lighting only rarely. The fact that, in study C, task lighting was used more actively when the amount of daylight was limited, especially in the early morning and late evening, supports this conclusion. Similar control behaviour (changes depending on daylight) has been reported among office workers (Hunt, 1979; Escuyer and Fontoynont, 2001; Reinhart and Voss, 2003). A possible reason for the limited use of task lighting in study C might be that, in study C, the employees did not have task lighting before and it was not in use in the otherwise similar production lines next to the study one. However, it is interesting that 41 per cent of employees in study C felt that task lighting helped them to perform better, and most of them wanted to keep the system. Familiarity with task lighting might also explain the differences in the way the task lighting was used in studies A and B. Another possible reason could be the change process. Employees in study A might have felt this new task lighting system to be more positive, because different peoples might have presented it to them in different ways, for example, or because of factory culture, and so used it very actively for that reason. It can be concluded that industrial assembly workers prefer to have controllable task lighting, and that, in the locations without daylight, they also use it actively.

4.1.3 Day, week and seasonal rhythms in the preferred illuminances

Even though there were differences between the selected lighting levels at different times during the day in studies A and B where there was no daylight, these differences were so small that no strong conclusions can be drawn. Since the study periods were of several months duration and the differences small, this might not be a very fruitful area for further research. In study C, where there was daylight, slightly higher illuminance levels were actually used during midday and late evening than at other times. Similar results have been reported in the office environment (Tops et al., 1998) but also evidence of using lower lighting levels in an office environment when more daylight is available exists (Escuyer and Fontoynont, 2001). However, office environment with windows cannot be compared with industrial conditions with skylights. Higher selected illuminance levels at midday (Approx. 100 lux difference compared to early morning and late evening) in study C might also be because the amount of daylight was high, and to detect any difference participants on average set the illuminance level higher. During midday, the use of task lighting was not very active. Those who were using lighting at that time might have been those who preferred on average higher illuminance. A higher level in late evening, together with more active use of task lighting, may relate more to an actual need for more task lighting.

Seasonal differences in the selected task illuminance levels in study A are a more interesting area, since the differences were bigger than the time-of-day differences. In study C, the amount of daylight can explain why task lighting was used more actively during the winter period than during the summer period. The results of study A indicated that, in wintertime, higher lighting levels were preferred than during summertime. This is opposite to that reported in the office environment with windows (Begemann et al., 1997). More long-term studies are needed in order to draw conclusions regarding the seasonal differences in selected illuminance levels.

The interesting rhythm-related aspect was week rhythms in selected illuminance levels followed by two individuals in study A. These rhythms were different, but the fact that they existed at all is interesting. Something in the weekly rhythm seems to affect the lighting levels selected. There were no week rhythms in the work itself. So, at least for some persons, something in the weekly free-time pattern influenced their lighting preferences. Unfortunately, it was not possible to study the reasons for this.

4.1.4 Individual differences in the preferred illuminances

In all cases, it was obvious that practically the whole range of available task lighting illuminances was used. This means that the task lighting levels employed varied per person as reported for office workers also (for example, Begemann et al., 1997 and Boyce et al., 2006). Thus by giving industrial workers controllable lighting and monitoring their selections does not lead to results where strong conclusions can be drawn from preferred lighting levels. The "preferred" lighting level seems to be strongly influenced by the range of available illuminances. This is especially the case if the maximum illuminance given by the task lighting is low. Study A indicated that employees have personal illuminance preferences and that these preferences vary between individuals. These results are also supported by the activity results of study C, where some employees used task lighting regularly and some rarely.

There was no correlation between the selected illuminance and age or frequency to use task lighting in study C. Correlation between age and selected illuminance in study A was very weak and negative indicating that older workers tend to use less light than younger ones.

These results indicate that the amount of task illuminance industrial assembly workers prefer is not related to age. Individual preferences are stronger than age-related needs, at least under the conditions used in studies A and C, where participants had an opportunity to use higher illuminances compared to present standards (A >3000 lux, C>1000 lux). Although, based on literature, older participants can be estimated to benefit from higher task lighting levels, since it would compensate the spectral absorbance (Weale, 1988), older people are more sensitive to glare (Vos, 1995), which might reduce the preferred illuminances of the older participants in studies A and C. Older workers might have been also more expert at the tasks, which might have compensated for the decrement in vision. It is also important to note that these results do not tell if older participants would have benefited from selecting higher levels than they did, it only says that age did not have a marked effect on preferred task illuminance in these studies.

4.1.5 The effect of the task on preferred illuminance

In studies A and C, the tasks in different workstations were different. In study A, employees were assembling different luminaires at the different workstations. Although the luminaire assembly work itself was quite different, it always involved the combination of several rather similar tasks. This could explain why employees who were working at several assembly tables tended to use rather the same task-lighting illuminances independently of the workstation and task. In study C, tasks were much more limited since they were working in the assembly "line". Visual and physical tasks were different at each workstation. This might explain why both the preferred illuminance and the frequency of use of task lighting varied between workstations in study C.

4.1.6 The effect of switch-on illuminance and colour temperature on the selected illuminance

A major difference between the results of studies A and B was that, in study B, the preset illuminance levels did influence the selections, while, in study A, they did not. The reason behind this could be familiarity with the task lighting system. In study A, all employees also had task lighting before the study. In study B, the most occupied half of the workstations (luminaire assembly tables) was without task lighting before the study. Also, some cultural factors and change process might have had an effect. Presentation of the task lighting system and training of the participants to use it was made by different persons (native speakers), and estimating differences in presentation or training is not possible. Another difference between studies A and B was the use of different colour temperatures in the case of study B. The fact that users selected slightly lower illuminances when colour temperatures were higher could indicate some energy-saving potential. The reason for this might be that employees felt that brightness was higher when colour temperature was higher. However, when controlling luminaires by IR remote control, it is usual to look at the luminaires whilst doing so to see whether something is happening. Does the pushbutton work? It might be that the luminaire with the 4400 K setting was seen as being brighter than the same luminaire set to 3500 K. This "brightness" difference might have created the illuminance difference when workers were actually aiming for more or less the same value. Some early studies provided evidence that, the higher the colour temperature of lighting, the higher its perceived brightness (Harrington, 1954; Alman, 1977). But also, some studies carried out more recently, show that this connection does not exist (Boyce and Cuttle, 1990; Hu et al., 2006). It might be that the connection is more complicated than just colour temperature – colour rendering might also have an effect (Fotios, 2001).

4.2 Lighting and productivity

4.2.1 The reasons behind the performance improvements

The mechanisms of the lighting change model [I] were used in planning the productivity studies. When a lighting installation is changed, a positive impact on human performance might take place due to improved visual performance, visual comfort, visual ambience, interpersonal relationship, biological clock, stimulation, job satisfaction, problem-solving, the halo effect, and/or change process. Because of the study design, some of the mechanisms can be excluded when considering the reasons behind the productivity change. Table 12 provides an estimation of the mechanisms that could be the reason in each study of this work. "Visual comfort" was not intentionally improved in any of the cases. However, since in each case some kind of lighting change took place, visual comfort might have changed too. But this change was limited, and in no case was the glare produced by the general lighting reduced; only localised lighting was added. "Solving problems" (no record of "before" complaints) can be excluded in all studies. The same is true for "Visual ambience" and "Interpersonal relationship" in most of the cases. Only in studies B and E did visual ambience change remarkably (task lighting was added in the area where there was none before), and only in study E were employees face to face with colleagues during the work process. On the other hand, "Visual performance" and "Stimulation" cannot be excluded from any study, because, in all cases, the amount of task lighting was increased, as was the amount of light reaching the eye. The problem in estimating the influence of visual performance on task performance (for example, using the Relative Visual Performance Model (Rea and Ouellette, 1991)) was that all tasks were actually a series of visually different tasks carried out by different employees. However, it can be estimated that, since task illuminance in all studies was several hundreds of luxes, visual performance was already in the saturation area, where changes are small, but still exist. The biological clock has to be taken into account in studies where employees are working in changing shifts (studies D and E), because the amount of light might have influenced their circadian adaptation to the shifts.

In Table 12, study A has been divided into two columns because the reasons behind the 4.6 per cent productivity increase compared to the reference group (first column of table 12.) and correlation between the illuminance and productivity (second column of table 12.) might be different. When considering the productivity increase in study A compared to the reference group, the reason behind the productivity increase might be a change process or related to job satisfaction. The users were given a new task lighting system, and, according to the questionnaires, they were also very happy with it. For example, improved ratings of mood and satisfaction (Newsham et al., 2004) and higher ratings of quality and comfort (Boyce et al., 2000) have been reported in office-work-related laboratory studies with individual lighting control compared to the situation without control. The halo effect has to be taken into account also. Although it was not stated that the new task lighting system would improve productivity, the users may have believed it would, and this belief may indeed have boosted their productivity. "Stimulation" could also be a reason for the higher productivity in study A compared to the reference group. The ways stimulation may have influenced performance in study A are, for example, that being influenced by higher lighting levels during the daytime can reduce the impact of possible sleep loss on sleepiness levels and performance (Phipps-Nelson et al., 2003) or that higher lighting levels in the morning also increase the morning cortisol level (Scheer and Buijs, 1999; Thorn et al., 2004), perhaps allowing a "fresher" start to the working day.

Table 12. Estimated reasons behind the productivity increase per study. (No –mechanism can be excluded, [X] – might have an effect (but is estimated not to be an important reason in this study), X – very likely has an effect).

Study	**A**	**A**	**B**	**D**	**E**	**F**
Type of work	Luminaire assembly	Luminaire assembly	Luminaire assembly	Electronics assembly	Machine maintenance	Luminaire assembly
Location	Finland	Finland	Germany	Netherlands	Netherlands	Netherlands
Number of subjects	21	21	25	35	26	42
Localised lighting	100lux….3000lux	100lux….3000lux	100lux….900lux (a)	No	50lux/1700lux	0lux/700lux
General lighting	250lux	250lux	250lux	800lux/1200lux	300lux	500lux/350lux
Change localised lighting	User´s selection	User´s selection	User´s selection	No	Regular changes	Increase once
Change general lighting	No	No	No	Regular cahnges	No	Decrease once
Shifts	Morning	Morning	Mor/ (Eve)	Mor/Eve/(Nig)	Mor/Eve/Nig	Mor /(Eve)
Measuring period	2 years	1 year	8 months	2 x 2 months	5 months	before/after
Reference group	Yes Productivity	No	No	No	Yes absenteeism	Yes Prod. & absent.
Productivity change	4.6% (b)	r=0.14 (c)	5.7% (a)	Morning 3% Evening 3% Evening 7%	3%	5.5% (d)
Absenteeism change	Not measured	Not measured	Not measured	Not measured	-17% (d)	-2.5% (d)
Visual performance	X	X	(X)	X	X	X
Visual comfort	No	No	No	No	No	No
Visual ambience	No	No	(X)	No	(X)	No
Interpersonal relationships	No	No	No	No	(X)	No
Biological clock	No	No	No	X	X	No
Stimulation	X	X	(X)	X	X	X
Job satisfaction	X	No	No	No	X	X
Solving problems	No	No	No	No	No	No
The Halo effect	(X)	No	No	No	(X)	(X)
Change process	X	No	No	No	(X)	(X)

(a) 3500K and 4400K task lighting were varied in study B. Productivity was higher when the colour temperature of the task lighting setting was higher.
(b) 4.6% increase compared to reference group, which did not have controllable task lighting
(c) r=0.14 correlation between lighting level and productivity.
(d) Statistical testing has not been done for productivity results of study F and absenteeism results of studies E and F
(they are before and after results and might have been influenced by some other variables)

On the other hand, the weak correlation results between illuminance and productivity in study A can only be explained by visual performance or stimulation. Biological clock, problem solving and interpersonal relationships were not relevant in study A. Illuminance was selected by participants and there were no changes in job satisfaction, halo effect or change process depending on the level they chose and differences in visual comfort and visual ambience were minor.

In study B, productivity was 5.7 per cent higher when a higher colour temperature was in use (4400 K / 3500 K). Improved visual performance is unlikely to be the reason, especially when the selected illuminance levels were slightly lower when a higher colour temperature was in use. Colour temperature changes naturally affect the visual environment, but it is not likely that this kind of change would greatly influence productivity. A cooler colour temperature can be more effective via a photo-biological pathway (Brainard et al., 2001; Hattar et al., 2002; Mills et al., 2007), resulting, for example, in higher cortisol levels in the early morning. However, here too the difference in colour temperature was actually quite small and is unlikely to be the only reason. It is possible that a productivity increase is attributable to visual performance, visual ambiance and stimulation.

In study D, a higher illuminance level (1200 lux) was accompanied by an increase in productivity during nearly all the shifts in summer and winter compared to lower illuminance level (800 lux). There was no localised lighting, and task illuminance was influenced only by general lighting. Since only the level of the general lighting was varied between shifts, visual ambience and visual comfort are very unlikely reasons. Partly for the same reason (varying lighting levels per shift), and because many of the workers were even unaware of the study and its methods, "The halo effect", "Job satisfaction", "Solving problems" and "Change process" can also be excluded from the list of likely reasons. There was no face-to-face communication during the work, which means that "interpersonal relationships" cannot be used to explain the results. During the night shift, the higher lighting level could have helped to change the internal clock (biological clock), but the most obvious reasons are related to "visual performance" and "stimulation".

The productivity change in study E is relatively weak, since even though the result was 3 per cent, repairing times of every error types are not very clearly pointing to same direction. Work was very free in the way it was performed, and the location of the work as well as the way of working varied. The lighting level was changed periodically, so actually only visual comfort and "Solving problems" can be really excluded from the list of reasons. On the other hand, the absenteeism results seem to be relatively strong. However, as this result is a "before-and-after" result, it is not strong on its own.

Study F is a typical before-and-after study. The lighting was changed once, and things were monitored before and after. In this type of study, none the variables can ever be controlled totally, even though the use of a reference group helps. Also, the reasons for the productivity increase and absenteeism decrease might vary. However, the results of this study are encouraging, since, together with the productivity and absenteeism improvements, considerable energy savings were also achieved (39 per cent).

The productivity results of the five studies described in this work support the results of old field studies (Ruffer, 1925 and 1927; Schneider, 1938; Goldstern and Putnoky, 1931; Bitterli, 1955; Stenzel, 1962a and 1962b; Crouch, 1967; Lindner, 1975; Carlton, 1980) and the results of newer studies made with simulated industrial tasks (Völker, 1999) in the sense that the studies suggest that increased task lighting can improve productivity.

4.2.2 Measurements that did not show an increase in productivity

Some measurements did not show a significant increase (or decrease) in productivity. In study A, different dimming speeds led to small differences in the selected illuminances, but this difference did not lead to differences in productivity. In study B, different switch-on values resulted in quite a large difference (550 lux/820 lux) in the selected illuminances but not in the productivity. In study D, the number of assembly errors was also measured under different lighting levels, but these results in study D were not significant. In study E, productivity changes were relatively weak. The possible reasons for no significant increases in productivity are:

1. The lighting change did not have an effect on productivity in these cases.
2. The way in which productivity was measured was not correct.
3. The statistical power of the study was not high enough. In some cases the probability for so-called "type II" errors might be high. So the amount of data etc. might have resulted in the risk of getting wrong "no effect" results.
4. Something was blocking the productivity improvements. Although lighting gave the employees the possibility of performing better by allowing them to see better, stay more alert, etc., it did not necessarily mean that they would in fact do so. The production speed of the process, habits, salary system, union-related reasons etc., could block the increase in performance.

Reasons 2 and 4 are not very likely in the case of study A, since the same way of measuring productivity also led to a significant increase in productivity (4.6 per cent increase compared to the reference group) in the same place. The fact that productivity did not increase might be best explained by reasons 1 and 3, as the change in illuminance was only 180 lux. A small change did not significantly affect productivity, or the measurement method employed was not able to detect small differences. The reason for no significant "amount of error" results in study D is likely 3 (statistical power). Even though there was a clear reduction in the number of errors, the number of these, even at the beginning of the study, was so limited that getting any significant results was very unlikely. It is more difficult to explain the results of study B. Higher illuminance levels did not increase productivity, while, at the same time, colour temperature changes did result in significant changes in productivity. The reason for this remains unclear, but it is not very likely that the measurement was wrong or that something was blocking an increase. As to the limited results of study E, statistical power should not be the reason, since the measurement period was very long and the amount of data was large. During the measurement period, there were several thousands of machine malfunctions. It is possible that, for example, the habits of the personnel were blocking the results. Another reason could be that the measurement of productivity in study E proved to be insufficiently sensitive for estimating performance, since repairing the machines was only part of the operators' work. The operators were also spending part of their time outside the test area, which might also have had an influence. Interestingly, the questionnaire results in study E showed that employees strongly believed that new lighting helped them to perform better.

These results show that an increase in productivity cannot be guaranteed when lighting is changed and task illuminance increased. Reason 4 above remains particularly true in many industrial working environments. Actually, reason 4 might have affected the results of all the studies conducted here.

4.2.3 Sustainability and generalisation

If lighting change influences productivity, as was the case in the studies described earlier, how long does that effect remain? If the reason for productivity improvement is visual performance, visual comfort, visual ambience, interpersonal relationships, biological clock or stimulation, the effects can be estimated to be long term, provided nothing else blocks or decreases performance at the same time. More psychological effects, such as job satisfaction, solving problems, the halo effect and change processes, might fade away over time, depending on the other actions on site.

Can the productivity results discussed earlier be generalised for other industrial work or for other kinds of working environments? Most of the studies (excluding E) were made with assembly workers. In the factories, the studied employees have specific tasks and they are used to always having to carry out similar work. In industrial work similar to assembly work, these results can be used directly. However, generalisation to other kinds of industrial work and to, say, office work, is more difficult. Such generalisation might be possible, however, for work that is repetitive. It is important to note that the approach used in the field studies as part of this work neglected to study several possible indirect effects of the lighting change. Because lighting conditions were changed periodically in some studies (D and E), possible longer-term effects, such as sleep or free-time quality, innovativeness, happiness, etc., cannot be detected. And even in studies (A, B, C and D) where these effects could have been present, the measurement of a possible longer-term effect other than productivity was not within the scope of this work and so was not undertaken.

4.3 Workers' opinions

The answers to general factory-environment-related questions used in questionnaires showed that the most important items in the factory environment generally were the ones that subjects felt most unhappy with within their own personal environment, such as quietness and ventilation. Ratings of the factory environment changed very modestly in studies E and F, where the same questions were asked before and after. The questionnaire results do not indicate that lighting changes in studies E and F made workers alter their opinions regarding their own working environment. It is also interesting to note that even before the change, the workers were, on average, happy or did not have an opinion regarding the illuminance levels in their workplace. However, the "after" questionnaires and productivity measurements showed that higher lighting levels were preferred and that these resulted in higher productivity. This indicates that the workers' feelings about the lighting level are not a very reliable indicator of whether or not they would benefit from a different illuminance level. People might have a general lack of imagination regarding lighting. Without knowledge that it could be different, people are not able to demand or wish better lighting.

Figure 21 shows that most employees feel that good lighting influences their work. They have the general belief that lighting has an influence on performance, as was similarly reported by Veitch et al. (1993)**:** "Brighter lights leads to greater productivity". This gives us reason to believe that employees have presumptions concerning lighting, which then might influence the success of the lighting change (the halo effect). Additionally, it indicates that lighting improvements are changes that will not encounter resistance from employees, as discussed in Chapter 2.2. However, the phrase "good lighting" is very general and does not define what actually constitutes good lighting. Since lighting changes are presumed to have a positive effect, additional benefits might be obtained if the users are involved in the process of change. Figure 20 shows that 37 per cent of subjects not having this opportunity would wish to have the opportunity to control the lighting,

In all studies, the general lighting installation consisted of open-reflector luminaires without protection at angles over 65 degrees. Nonetheless, the questionnaire showed that the employees were not bothered by reflections from luminaires, even in situations with higher illuminance levels.

4.4 Experiences of making field studies in industry

The lighting preferences of the workers were studied mainly by observing the use of controllable task lighting. A secondary and very subjective approach was to use questionnaires. Major individual differences in lighting preferences can be detected in both short-term studies and in laboratory studies, as discussed in Chapter 4. However, long-term studies provided interesting information concerning the way in which additional task lighting was used and illuminances selected at certain times when engaged in real work. These effects cannot be detected reliably in any other way. Monitoring the dimming voltages of the lamps was a good measurement technique because it avoided having to introduce sensors to the work area, which would have been disturbing. And in long-term studies, it is unclear even what these sensors would have measured. For example, some object casting a shadow could have been momentarily located next to a sensor. A possible risk with the approach selected in this work is the temperature behaviour of lamps. If lamps are cold when they are switched on, it will take some minutes until they reach their normal light output. This means that in cases where lighting is not actively used, as in study C, the selected illuminances are actually lower than measured by dimming voltages. However, this effect does not influence the differences between different workers or workstations. Questionnaires were found to be a relatively unreliable way of finding out employees' lighting preferences and whether or not they would benefit from the lighting change.

The five productivity studies described in this work showed the difficulty of the field studies. Even though the mechanisms model was used in the study design, it was still not possible to limit the actual reason for productivity increase in one specific mechanism. However, using the model in the study design helped to reduce the effect of more psychological factors. Changing lighting conditions periodically or giving employees an opportunity for lighting control is necessary in order to be able to get rid of most of the intervening variables. Without this approach one single "before-and-after" study is just a single example, since so many other things are changing all the time in the real work environment. This is why no strong conclusion can be drawn from the results of study F, where a change was made only once. Another difficult issue with studying productivity in the real working environment is that something might be blocking the productivity improvements. Although lighting change would give employees the possibility of performing better by allowing them to see better, stay more alert, etc., it does not necessarily mean that they will. Production speed, habits, salary system, union-related reasons, etc., could block the increase in performance. To limit the effect of the Hawthorne effect on the study results, the productivity measurements of the studies was not discussed with employees. In three studies (A, B and F), productivity was measured per person, and there were differences. This at least shows that different productivity rates are possible in those cases. Going deeper into the discussion with employees about the possibilities of increasing productivity is not recommend in field studies because this really can spoil the results. This limitation just has to be taken into account when analysing the results. However, in lighting changes, studying the productivity aspects is naturally recommended and can show new ways of how lighting can influence productivity.

From the research point of view, measuring the productivity is possible in the industrial environment. All factories have their productivity indicators. However, during this work it also became clear that sometimes those indicators are not really measuring the productivity of a certain group, but are more general figures. This is a rather different problem to that described in the previous paragraph, where productivity increase was blocked in some way. The problem discussed here is that, even though a productivity increase happens, the measurements used in the factory would not necessarily be able to detect it.

5 Conclusions and recommendations

5.1 Lighting preferences of the industrial assembly workers

The lighting preferences of industrial workers vary; the age of the participants did not influence their preferences under the conditions used in studies A and C, where they were studied. Most of the participants in this work preferred higher illuminances than the minimum maintained illuminances required to meet the present European norm (EN 12464-1). It was found that many industrial employees preferred to be able to control the lighting themselves. The control behaviour in three study places was similar as regards the way that practically all available illuminance values were sometimes selected by some employees. This actually means that the so-called “preferred” task illuminance is heavily influenced by the range of available illuminance levels, and strong conclusions or clear “preferred” values based on one study cannot be drawn.

When the task of the assembly worker was simple, the task influenced the illuminance selected as well as the frequency to use of task lighting. However, in the case where the task was actually a series of smaller tasks or sometimes even a different task, no major differences in preferred illuminance levels were found.

It can be said that most of the industrial workers agreed with the very general statement “Good lighting has an influence on my work.” Questionnaire results also showed that most of the workers were happy with the illuminance increase made in their task area as a part of this work.

Individual, seasonal, weekly and daily rhythms in the selected illuminances all showed some statistically significant results. However, differences in daily rhythms were relatively small. Seasonal differences are more interesting; on average, industrial assembly workers used lower illuminances during the summer than during the winter, when there is no daylight available, and when daylight was available, they tended to use task lighting more rarely during the summer than during the winter. Individual rhythms are maybe the most interesting since they were very clear for two participants in study A. These workers had clear and not work-related week rhythms in the selected task illuminances. Concerning preferred lighting levels, the most interesting topic for future research are these individual rhythms, since they indicate that something else than working conditions and task might change the preferred lighting.

5.2 Lighting and productivity in the industrial environment

Based on the field studies carried out in this work, it can be said that lighting change can affect productivity in the industrial environment with industrial assembly tasks where task performance has an influence on individual performance. If productivity is related to human performance, it is possible by increasing task illuminance to increase productivity, even though the starting illuminance level is already in accordance with the norms governing the minimum requirements. Predicting the exact productivity effect and the lighting change needed is difficult. Starting conditions, the lighting installation, the work itself and the change management will all influence productivity. The direct productivity increase detected in this work was in the range 0 per cent - 7.7 per cent. The use of the mechanism model can help in the process of estimating the importance of different aspects and in aiming efforts in the lighting change in the right direction. Figure 4 shows one example. Among the mechanisms discussed earlier, “stimulation” seems to be the most interesting topic for future research, since the ways in which light affects human alertness, for example, are far from clear. This mechanism might have had a role in the productivity increase found in all the field studies presented in this work. Future research might be able to separate this mechanism from several different mechanisms based on affecting the pathway (Does the effect come via visual or biological pathways or via their combination?) the speed (How fast does the effect take place?) etc. This could be the focus of laboratory studies aiming to find the link between lighting and performance, since this issue cannot be separated in field studies. For future field studies of lighting and productivity, making longer-term studies by using the model of mechanisms as a tool for study planning is recommended when also taking into account constraints mentioned in Chapter 4.4. To be able to detect the longer-term effects of different lighting situations, a single setup should be kept longer than that of studies D and E. So, for example, a two-year study in which changes are made every second month and also sleep quality, general satisfaction etc. are measured, could add something to the results of this work.

5.3 Recommendations

Lighting change should be part of the strategic management process. Lighting change can create both direct and indirect productivity effects [I]. The indirect effects, such as well-being, innovation, alertness and absenteeism are themselves important goals. However, the direct effects, such as less time, more speed or higher output, are in many cases first targets, since they are easier to measure and turn into money. The following recommendations are given for lighting practitioners working on industrial lighting projects:

1. **Study the present conditions.** Inform those concerned that planning the lighting change is in progress. Give them an opportunity to exert their influence, use unofficial interviews and questionnaire with open questions, or give presentations in workers' meetings. The use of questionnaires with multiple-choice answers is not a reliable way of estimating whether or not users will benefit from a lighting change. The important questions to be answered are: What kind of lighting is there now? Are there complaints from users? Is something interfering with the productivity rate (speed of the machine, salary system etc.)? What and where are the tasks?
2. **Create a plan.** In the case where something is interfering with the productivity rate, try to find a solution, or take into account the fact that direct productivity results cannot be achieved. Use the mechanism model to evaluate the effects (direct and indirect) of the lighting change and to plan new lighting. Take into account the possible needs for presenting working areas to customers as well as the need for flexibility, together with good energy management. Consider using localised lighting and giving control of the lighting to the workers. Use norms and codes, but do not be afraid to make a better lighting installation than that resulting from following the minimums given by the norms.
3. **Make a change.** In the case where a lighting change seems to be a reasonable investment, do it by involving those concerned and follow up the process in order to be able to correct possible misunderstandings or installation errors.
4. **Evaluate the results.** This is important, because maybe something was forgotten during the design process that can be corrected later on. Also, designers and the other parties involved in the change need feedback to be able to learn from the process.
5. **Make corrective actions and/or close the project.**

The present Euro norm (EN 12464-1) mainly takes into account lighting requirements related to visual demands. The results of this work show that productivity can be improved by using higher illuminances than the minimum maintained illuminances required in the norm. Future norms should:

- Encourage lighting practitioners more strongly to use higher lighting levels than the minimums (or different light spectra), since the field studies presented in this thesis have shown that even small illuminance increases can result in an increase in productivity.
- Encourage lighting practitioners to use controllable task lighting or, at least, localised lighting, since these techniques are preferred by users and can also improve productivity and even reduce the use of energy.

6 References

Alman, D.H., (1977) Errors of the standard photometric system when measuring the brightness of general illumination light sources. Journal of Illuminating Engeneering . Society. 1977; October: 55–62.

Aries M, (2005) Human Lighting Demands – Healthy Lighting in an office Environment, PhD thesis, Technische Universiteit Eindhoven, The Netherlands

Begemann SHA, van den Beld GJ, Tenner AD (1997) Daylight, artificial light and people in an office environment, overview of visual and biological responses. International Journal of Industrial Ergonomics 1997; 20: 231-239

Berson DM, Dunn FA, Takao M. (2002) Phototransduction by retinal ganglion cells that set the circadian clock. Science. 295: 1070-1073.

Bitterli, E. (1955) Licht und arbeit. Bulletin Schweizerischer Elektronischer Verein, 46(12), 559–563.

Black, J.S., Gregersen, H.B., (1997). Participative decision making: An integration of multible dimensions. Human Relations. 50(7), 859-878.

Boivin DB, James FO (2002) Circadian adaptation to night shift work by judicious light and darkness exposure. Journal of Biological Rhythms 17, 556–67.

Boyce PR. Observations of the manual switching of lighting. Lighting Research and Technology 1980; 12: 195-205

Boyce, P.R., Cuttle, C., (1990) Effect of correlated colour temperature on the perception of interiors and colour discrimination. Lighting Research and Technology. 22: 19–36.

Boyce, P.R., Eklund, N.,H.; Simpson, S.N. (2000) Individual lighting control: Task performance, Mood and Illumiance, Journal of Illuminating Engineering Society, Winter, 131-142.

Boyce, P.R., Veitch, J.A., Newsham, G.R., Jones, C.C., Heerwagen, J., Myer, M., Hunter, C.M., (2006). Occupant use of switching and dimming controls in offices. Lighting Research and Technology, 38(4), 358-378.

Brainard, G.C., Hanifin, J.P., Byrne, B., Glickaman, G., Gerner, E.and Rollag, M.D. (2001) Action spectrum for melatonin regulation in humans: evidence for a novel circadian photoreceptor. The Journal on Neuroscience 21 (16), 6405-6412.

Buchanan, T.L., Barker, K.N., Gibson, J.T., Jiang, B.C. and Pearson, R.E (1991) Illumination and errors in dispensing. American Journal of Hospital Pharmacy. 48, 2137-45.

Campbell SS, Dawson D (1990) Enhancement on night-time alertness and performance with bright ambient light. Physiology & Behavior 48, 317–20.

Cardy, R.L and Selvarajan, T.T., (2001). Management interventions. In book: handbook of industrial, work and organizational psychology, volume 2, Organizational Psychology, Sage

Publications, London, edited by Anderson, N., Ones, D.s., Sinangil, H.K., Viswesvaran, C., 346-376

Cotton, J.L., Vollrath, D.A., Lengnick-Hall, M.L., Jennings, K.R., (1988). Employee participation: Diverse forms and different outcomes. Academy of Management Review, 13, 8-22..

Daurat A, Forêt J, Benoît O, Mauco G (2000) Bright light during night-time: effects on the circadian regulation of alertness and performance. Biological Signals and Receptors 9, 309–18.

Duffy JF, Wright KP Jr. (2005) Entrainment of the human circadian system by light. Journal of Biological Rhythms. 20(4):326-338.

Eastman CI, Stewart KT, Mahoney MP, Liu L, Fogg LF (1994) Dark goggles and bright light improve circadian rhythm adaptation to night-shift work. Sleep 17, 535–43.

Escuyer S. and Fontoynont M. (2001) Lighting controls: a field study of office workers' reactions. Lighting Research and Technology. 2001; 33: 77-96

Fotios, S.A., (2001) Lamp colour properties and apparent brightness: a review. Lighting Research and Technology. 33,3, 163–181

Goldstern, N. and Putnoky, F. (1931) Die wirtschaftliche Beleuchtung von Webstuhlen; neue arbeitstechnische Untersuchungen. Licht und Lampe 22, 5-9 and 25-28.

Gooley J.J., Lu J, Fischer D, Saper CB. (2003) A broad role for melanopsin in nonvisual photoreception. Journal of Neuroscience. 23(18), 7093-7106.

Harrington, R.E., (1954) Effect of color temperature on apparent brightness. Journal of Optical Society of America. 44, 113–16.

Hu, X., Houser, K.W., Tiller, D.K., (2006) Higher colour temperature lamps may not appear brighter. LEUKOS, The Journal of the Illuminating Engineering Society of North America, Volume III - Number I - July

Hunt, D.R.G., (1979) The use of artificial lighting in relation to Daylight levels and occupancy. Building and Environment, 14, 21-33.

Locke, E.A., Alavi, M., Wagner, J.A., (1997). Participation in decision making: An information exchange perspective. Research in Personnel and Human Resources Management, 15, 293-331.

Love JA. (1998) Manual switching patterns in private offices. Lighting Research and Technology 1998; 30: 45-50

Maniccia D, Rutledge B, Rea M, Morrow W. (1999) Occupant use of manual lighting controls in private offices. Journal of Illuminating Engineering Society. Summer 1999: 42-56

Mayo, E. (1933) The human problems of an industrial civilization (New York: MacMillan) ch.3.

Mills, P.R., Tomkins, S.C., Schlangen, L.J.M. (2007) The effect of high correlated colour temperature office lighting on employee wellbeing and work performance. Journal of Circadian Rhythms. 5,2.

Moore TA, Carter DJ, Slater AI. (2003) Long-term patterns of use of occupant controlled office lighting. Lighting Research and Technology. 35, 43-59.

Newsham, G., Veitch, J., Arsenault, C., Duval, C., (2004), Effect of dimming control onoffice worker satisfaction and performance, IESNA Annual Conference Proceedings, Tampa, Florida, July 25-28, 2004, 19-41.

Parsons, H.M. (1974) What happened at Hawthorne?, Science, 183, 922-932

Phipps-Nelson J, Redman JR, Dijk DJ, Rajaratnam SM (2003) Daytime exposure to bright light, as compared to dim light, decreases sleepiness and improves psychomotor vigilance performance. Sleep 26**,** 695–700.

Rea, M.S, and Ouellette, M.J. (1991) Relative Visual Performance: a basis for application. Lighting Research and Technology, 23, 135-144.

Reinhart C.F., Voss, K., 2003, Monitoring manual control of electris lighting an blinds. Lighting Research and technology, 35,3, 243-260.

Roethlisberger, F.J. and Dickson, W.J. (1939) Management and the Worker. Cambridge, MA: Harvard University Press.

Ruffer, W. (1927) Licht und Leistung, Licht und Lampe , 242-245.

Ruffer, W. (1925) Leistungssteigerung durch Verstärkung der Beleuchtung, Die Lichttechnik, 53-58.

Scheer, F.A.J.L. and Buijs, R.M. (1999) Light affects morning salivary cortisol in humans. The Journal of Clinical Endocrinology & Metabolism 84, 3395-3398

Schneider, L. (1938) Förderung der menschlichen Arbeitsleistung durch richtige Beleuchtung. Das Licht 8, 286-96.

Stenzel, A.G. (1962) Erfahrungen mit 1000 lux in einer Lederwarenfabrik, Lichttechnik 14. Jahrgang Nr. 1/1962, 16-18

Stenzel, A.G. (1962) Erfahrungen mit 1000 lux in einem Kamerawerk, Lichttechnik 14. Jahrgang Nr. 7/1962, 351-353

Thorn, L., Hucklebridge, F., Esgate, A., Evans, P., Clow, A., (2004) The effect of dawn simulation on the cortisol response to awakening in healthy participants, Psychoneuroendocrinology 29, 925–930

Veitch, J.A. and Newsham, G.R. (2000) Preferred luminous conditions in open-plan offices: Research and practice recommendations. Lighting Research and Technology, 32, 199–212.

Veitch, J.A., Hine, D.W. and Gifford, R. (1993) End-users' knowledge, beliefs, and preferences for lighting. Journal of Interior Design, 19(2), 15–26.

Veitch, J.A. (2001). Psychological processes influencing lighting quality. Journal of the Illuminating Engineering Society, 30(1), 124-140.

Wagner, J.A. (1994). Participation's effects on performance and satisfaction: A reconsideration of the research evidence. Academy of Management Review, 19, 300-312.

Weale, R.A. (1988) Age and the transmittance of the human crystalline lens, Journal of Physiology, 395, 577-587.

Vos, J.J. (1995) Age dependence of glare effects and their significance in terms of visual ergonomics, in W. Adrian (ed.) Lighting for aging vision and health, New York: Lighting Research Institute.

Wyon, D.P. (1996) Indoor environmental effects on productivity. In: Teichman. K.Y. (ed). Proceedings of IAQ 96-Paths to Better Building Environments. ASHRAE. Atlanta, 5-15.

Völker, S. 1999, Eignung von Methoden zur Ermittlung eines notwendigen Beleuchtungsniveaus, PhD Thesis Technical University Ilmenau.

Yoon IY, Jeong DU, Kwon KB, Kang SB, Song BG (2002) Bright light exposure at night and light attenuation in the morning improve adaptation of night shift workers. Sleep 25, 351–6.

Appendix 1.
English version of the before Questionnaire of study E

The purpose of this questionnaire is to gather knowledge how people working in a factory perceive their environment and what aspects are most important for the workers. Answers should represent the personal opinion of the employee. Answers are neither 'good' nor 'bad'. Please try to fill in all answers. Questions and answers are only used for this specific research. Answers will not be used to make known your personal opinion or preferences. All answers will be processed anonymous and will not be supplied to third parties.

Name: __________

Department: __________ Gender: __________

Function: __________ Age: __________

How long are you working in this factory? __________

	Yes	No
Do you wear spectacles?	❑	❑

1 Please indicate for yourself how important the next characteristics are in your factory environment

	Not important				Very important
Comfortable temperature	❑	❑	❑	❑	❑
Much light	❑	❑	❑	❑	❑
Uniform lighting	❑	❑	❑	❑	❑
Good ventilation	❑	❑	❑	❑	❑
Windows	❑	❑	❑	❑	❑
Decoration of the factory	❑	❑	❑	❑	❑
Low sound level	❑	❑	❑	❑	❑
Much space	❑	❑	❑	❑	❑
View	❑	❑	❑	❑	❑
Possibility to control yourself the settings of installations	❑	❑	❑	❑	❑
Presence of colleagues	❑	❑	❑	❑	❑

2 What is your general impression of your working environment?

	Very negative	Negative	Neutral	Positive	Very positive
Pleasant	❑	❑	❑	❑	❑
Interesting	❑	❑	❑	❑	❑
Bright	❑	❑	❑	❑	❑
Warm (temperature)	❑	❑	❑	❑	❑
Spacious	❑	❑	❑	❑	❑
Quiet	❑	❑	❑	❑	❑
Cosy	❑	❑	❑	❑	❑
Orderly; tidy	❑	❑	❑	❑	❑
Clean	❑	❑	❑	❑	❑
Nice	❑	❑	❑	❑	❑
Clearly structured	❑	❑	❑	❑	❑

3 In which shift (morning, evening, night shift) the next statements are mostly applicable for you?

	Morning shift	Evening shift	Night shift	Does not matter
I prefer to work during the …	❑	❑	❑	❑
I feel most tired during the …..	❑	❑	❑	❑
I feel most tired at the start of the ….	❑	❑	❑	❑
I feel most tired at the end of the …..	❑	❑	❑	❑
I feel most active at the start of the ….	❑	❑	❑	❑
I feel most active at the end of the ….	❑	❑	❑	❑

4 Lighting
Please indicate if you agree or disagree with the next statements:

	Totally disagree	Disagree	No opinion / neutral	Agree	Totally agree
The lighting level is sufficient for my work	❑	❑	❑	❑	❑
I need more light for my work	❑	❑	❑	❑	❑
I would like to have less light than today	❑	❑	❑	❑	❑
I would like to have more light than today	❑	❑	❑	❑	❑
I can see all colours well with the present lighting	❑	❑	❑	❑	❑
I am bothered by reflections of luminaires	❑	❑	❑	❑	❑
I would like to control the lighting at my task area myself	❑	❑	❑	❑	❑
Good lighting has influence on my work	❑	❑	❑	❑	❑

Remarks ____

____

____

____