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Do Lighting Control and User Interface Designs Matter to Occupant Behaviour?

The case of optimal lighting use in non-residential buildings

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The case of optimal lighting use in non-residential buildings

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ABSTRACT

The lowering of energy use from artificial lighting in buildings is vital to reaching the goal of reducing CO_2 emissions. Hence, changes in individuals' behaviours regarding lighting use have received increased attention. Feedback on energy use has often been used to change individuals' behaviour. However, it is not clear to what extent this approach can be applied for non-residential buildings, where individuals' use of lighting may differ from that at home. In this type of building, other types of interventions may be required.

This thesis addresses the possible significance of (i) lighting control and (ii) user interface designs for effective use of lighting, referred to as 'optimal lighting use', of occupants in non-residential buildings. The main objective was to explore individuals' responses to different designs of controls and interfaces, and thereby the effects on lighting energy use.

Individuals' use of electric lighting with six different controls was investigated through field measurements in 18 single-occupant offices. A self-report diary and electronic measurement using a data logger were used to collect the data during a one-year period. The self-reported data were found to correlate with the logged data, suggesting that the diary was a suitable tool for measuring lighting use with different lighting controls. Generally, the results based on the logged data showed that use of electric lighting varied among the individuals using the different controls and indicated the potential of combining manual/automatic dimming controls with manual on/off or occupancy switch-off controls to achieve optimal lighting use.

Further, different designs of everyday interfaces for lighting controls (i.e. light switches) were investigated. In controlled environments, laypersons' perceptions of ten different lighting switches with regard to particular characteristics were assessed by questionnaires and found to be different among the switches. Field observations were subsequently conducted for 30 days for each of the original and alternative switches using a data logger in a public toilet in a hospital. The switches' characteristics (oversize, simplicity as well as affordances) were found to affect whether individuals used lighting optimally. Also, occupants' use of lighting with different light switches

in a dining room and a dayroom, regarded as shared environments, located in patient wards, were investigated. The self-reported questionnaire showed that satisfaction with lighting, affective-related beliefs and general lighting-use behaviours were important in influencing optimal lighting use by individuals. Further, measurements from data loggers revealed that the different designs of the switches had a significant influence on lighting and energy use.

This thesis contributes by providing information on different methods for investigating optimal lighting use and its relevant factors. The findings should facilitate the design of interventions to reduce energy use from lighting. In addition, the user perceptions employed to define the interfaces' characteristics could contribute to the development of guidelines for designing user interfaces for lighting controls with respect to users' viewpoints.

Keywords: characteristic, design, energy reduction, energy-saving behaviour, lighting control, light switch, lighting use, non-residential building, perception, user interface

POPULÄRVETENSKAPLIG INTRODUKTION

Att reducera energianvändningen för belysning i byggnader är viktigt för att uppnå målet att minska koldioxidutsläppen. Ett sätt att nå målet är om vi kan förändra människors beteende vilket kan ge en stor energibesparing. Feedback rörande energianvändning har ofta använts för att förändra beteende, men effektiviteten hos detta tillvägagångssätt är mer ifrågasatt för applikationer som rör offentliga byggnader där människors sätt att använda belysning kan skilja sig från hur man gör hemma. Därför kan andra typer av insatser krävas i sådana byggnader.

Den här avhandlingen tar upp betydelsen av ljusstyrning, användargränssnitt och design för effektiv användning av belysning i offentliga byggnader, något som kallas 'optimal belysningsanvändning'. Huvudsyftet har varit att undersöka människors reaktion på olika typer av ljusstyrning och olika utformningar av gränssnitt och därigenom effekterna på hur mycket energi som används för belysning.

Vi har undersökt hur människor använder olika typer av ljusstyrning i en studie med sex olika typer av styrning i 18 cellkontor. För datainsamlingen användes frågeformulär och dagböcker som de deltagande själva fyllde i, men vi loggade också elektroniskt när man befann sig i rummet och hur mycket energi som användes till belysning. Den självrapporterade informationen samvarierade med de elektroniskt loggade data, vilket tyder på att självrapportering med hjälp av dagbok är en lämplig metod för att undersöka hur människor använder belysningen på arbetsplatsen när man använder olika styrsystem. Vidare visade det sig att användningen av belysning varierade mellan beroende på vilken typ av ljusstyrning man hade i sitt kontor. Resultatet tyder på att det finns en potential i att kombinera manuell/automatisk dimming med manuell till/från eller automatisk frånvarostyrning för att uppnå optimal belysningsanvändning. Då har vi möjlighet att spara energi.

Vi har också undersökt vilken betydelse själva utformningen av strömbrytare har. Vi undersökte först hur olika utformning av strömbrytare uppfattades. I en försöksmiljö bedömdes 10 olika strömbrytares särskilda egenskaper med hjälp av speciellt

utvecklade frågeformulär. Det visade sig att det förelåg stora skillnader i upplevelse mellan de olika strömbrytarna. Därefter genomfördes observationer i en sjukhusmiljö på en publik toalett där olika strömbrytare installerades. Det visade sig att vissa egenskaper som överdriven storlek, enkelhet samt ”hur lättförståelig strömbrytarens design var” (affordances) hade en inverkan på individernas optimala belysningsanvändning. Vidare undersöktes strömbrytare i en matsal och ett dagrum på två vårdavdelningar. Med ett frågeformulär fick vi en bild av hur nöjd man var med belysningen och hur man såg på möjligheterna att själv styra belysningen. Dessa faktorer visade sig vara viktiga för att påverka en optimal belysningsanvändning medan energimätningarna visade att strömbrytarens utformning påverkade belysnings- och energianvändning de studerade offentliga miljöerna.

Den här avhandlingen bidrar med olika metoder för att undersöka optimal belysningsanvändning och ger kunskap om viktiga faktorer som påverkar vårt sätt att använda belysning på ett optimalt sätt. Detta kan underlätta planeringen när man vill genomföra åtgärder i den offentliga miljön som syftar till att minska energianvändningen för belysning. Arbetet ger också ett bidrag till kunskap som kan användas för att beskriva vilka egenskaper som är viktiga när man utformar strömbrytare. De använda metoderna kan också användas när man utvecklar ljusstyrningsanordningar för att få en uppfattning om människors upplevelse av de olika användargränssnitten.

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LIST OF PUBLICATIONS

This thesis is based on the following papers. The papers are referred to in the text by Roman numerals and appended at the end of the thesis.

I Self-report diary: A method to measure use of office lighting
P. Maleetipwan-Mattsson, T. Laike and M. Johansson
Leukos, Vol. 9 No. 4, pp. 291-306 (2013)

II Optimal office lighting use: A Swedish case study
P. Maleetipwan-Mattsson and T. Laike
Facilities, Vol. 33 Iss. 9/10 (2015), http://dx.doi.org/10.1108/F-01-2014-0004

III The effects of user interface designs on lighting use
P. Maleetipwan-Mattsson, T. Laike and M. Johansson
Journal of Engineering, Design and Technology (Submitted)

IV Factors affecting optimal lighting use in shared hospital environments: A case-study
P. Maleetipwan-Mattsson, T. Laike and M. Johansson
Building and Environment (Submitted)

The author's contribution to the papers:

Paper I The design and planning of the study were done by Thorbjörn Laike and Maria Johansson. Data collection, data analysis and interpretation of the results obtained were carried out by the author under the supervision of Thorbjörn Laike and Maria Johansson. The author was responsible for contact information for the research project. The paper was written by the author under the supervision of Thorbjörn Laike and Maria Johansson.

Paper II The design and planning of the study were done by Thorbjörn Laike. Data collection, data analysis and interpretation of the results obtained were carried out by the author under the supervision of Thorbjörn Laike. The author was responsible for contact information for the research project. The paper was written by the author under the supervision of Thorbjörn Laike.

Paper III The design and planning of the three studies presented in the paper, data collection, data analysis and interpretation of the results obtained were done by the author under the supervision of Thorbjörn Laike and Maria Johansson. The author was responsible for contact information for the research project. The paper was written by the author under the supervision of Thorbjörn Laike and Maria Johansson.

Paper IV The design and planning of the two studies presented in the paper, data collection, data analysis and interpretation of the results obtained were done by the author under the supervision of Thorbjörn Laike and Maria Johansson. The author was responsible for contact information for the research project. The paper was written by the author under the supervision of Thorbjörn Laike and Maria Johansson.

Other related publications by the author:

Design features supporting optimal use of electric lighting: Testing a conceptual framework for human interaction with lighting control devices in hospital environments.
P. Maleetipwan-Mattsson, T. Laike and M. Johansson
Proceedings of ARCH12, Gothenburg, Sweden (2012)

Perceived outdoor lighting quality (POLQ): A lighting assessment tool.
M. Johansson, E. Pedersen, P. Maleetipwan-Mattsson, L. Kuhn and T. Laike
Journal of Environmental Psychology, Vol. 29, pp. 14-21 (2014)

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INTRODUCTION

Background

Energy use in the building sector is known to be one of the main contributors of global greenhouse gas (GHG) emissions. Direct emissions increased by 26% between 1970 and 1990 and then remained at 1990 levels (IPCC, 2007). In the European Union, residential and commercial buildings are responsible for 40% of energy consumption and 36% of CO_2 emissions (European Commission, 2015a). Lighting appears to be one of the major energy uses (Yun, Kim & Kim, 2012). In Sweden, for example, lighting accounts for significant percentages of total electricity consumption in buildings: 23% for offices, 35% for schools and 26% for hospitals and healthcare facilities (The Swedish Energy Agency, 2010). According to the European Commission (2015b), the EU has set a target to achieve at least 27% reduction in energy consumption by 2030. Thus, reduction of lighting energy use in buildings will be vital in efforts to reach this target.

Occupant behaviour is well-known as having a crucial impact on building energy use (e.g. Nisiforou, Poullis & Charalambides, 2012). In relation to lighting, there is much evidence that energy goes to waste because of occupants' behaviour. One of the most obvious cases is leaving the lights on unnecessarily, especially in non-residential buildings (e.g. Mahdavi, Mohammadi, Kabir & Lambeva, 2008; Masoso & Grobler, 2010). According to Nisifourou et al. (2012), people may not behave in the same way in non-residential buildings as they would at home. In addition, Stern (2000) noted that determinants of individual behaviour are likely to be different from those of household behaviour. Turning lights off when the space is unoccupied and/or sufficient daylight is available could translate into ~10-30% of savings in building electricity use (Junnila, 2007).

Besides various efforts made to reduce energy use in buildings (e.g. development of new building codes and use of passive architecture, smart glazing and energy-efficient lighting) (Masoso & Grobler, 2010), use of lighting controls, i.e. occupancy sensors and/or manual/automatic/daylight dimming, has been proposed as a strategy for

substantial lighting energy savings (Dubois & Blomsterberg, 2011). However, it may not be straightforward to determine the energy savings associated with the use of lighting controls. This is because, as was noted by Yun et al. (2012), different lighting controls are likely to produce different occupant behavioural patterns; in line with Steg & Vlek (2009), the controls could be regarded as contextual factors that may directly affect occupants' behaviour. Conversely, according to Junnila (2007), occupants' behaviour can significantly affect lighting control use, impacting on energy savings.

Given the important influence of occupant behaviour on lighting control use, building occupants should be made aware of their lighting use with lighting controls as well as encouraged to reduce unnecessary use of electric lighting. The potential for reducing building energy use based on occupant behaviour at an individual level has received increasing attention (e.g. Nisifourou et al., 2012; Murtagh et al., 2013). Changes in individuals' behaviours have been suggested to have a potential long-term impact on building energy reduction (Scherbaum, Popovich & Finlinson, 2008) and can be applied to both new and existing buildings with low or no cost and without the need for high-tech knowledge; in most cases, the potential of behavioural change is higher than that of technological solutions (Masoso & Grobler, 2010).

Various behavioural change interventions have been designed to reduce energy use. According to Steg and Vlek (2009), effective intervention strategies should be targeted to relevant factors identified for the behaviour of interest. For instance, when the behaviour is significantly related to individual-based factors, such as attitudes, interventions can aim to promote attitude changes. In contrast, when environmental factors contribute to the behaviour, an environmental intervention could be tried.

To date, feedback on energy use, such as displays of energy use (e.g. AECOM/Ofegem, 2011 as cited in Murtagh et al., 2013) and an energy audit on the internet (Directorate-general for energy European Commission, 1999) have been used to encourage energy-saving behaviours among building occupants. However, these kinds of feedback rely on continuous interaction with the environment and are typically applied to occupants of residential buildings. Despite its effectiveness for energy reduction, it has been questioned whether feedback can be used effectively in office buildings where individuals' perceptions of responsibility for energy use may be weaker than in residential buildings (Murtagh et al., 2013). Moreover, feedback may not be suitable for use in public buildings, which are typically visited by a large number of occupants for a relatively short period of time, and therefore individual feedback on energy use is hard to provide.

It has been suggested that simple and easy-to-use lighting controls and user interfaces could help to achieve energy savings along with satisfying occupants in office buildings (Galasiu & Veitch, 2006). Individuals may be motivated to carry out energy-saving behaviours (e.g. switching lights off when leaving the space and/or dimming the lights when there is sufficient daylight) if simple and easy-to-use controls and interfaces are available. Analysis of such factors may shed light on the potential of lighting control and user interface designs for facilitating energy-saving behaviours, and thereby energy reduction in non-residential buildings. As Gärling (2005) has stressed, the most important strategy to support people's environmental behaviour is likely to be the design of environmental features that in themselves facilitate environmentally benign activities.

If designs of lighting controls and user interfaces can be identified that encourage individuals to save energy in non-residential buildings, they doubtless will require less cognitive effort from the occupants compared to systems using instructions (see Nordman, Granderson & Cunningham, 2012) and also less engagement than using feedback (see Murtagh et al., 2013). Hence, people would be more likely to actually carry out energy-saving behaviours. Further, when people are motivated to perform energy-saving behaviours, they tend to stick to the behaviours with little or no other incitement. In the long term, this would be a great achievement for sustainable energy use (Gardner & Stern, 2002).

Given the significance of lighting control and user interface designs in influencing energy-saving behaviours in non-residential buildings, more studies are needed to investigate whether and to what extent different designs can positively affect optimal use of electric lighting by occupants in such buildings. To aid further design improvements, studies of different designs regarding the users' viewpoints and specific contexts of use are also desirable.

This thesis is based on four appended papers concerning the effects of lighting control and user interface designs on occupants' use of lighting in non-residential buildings, i.e. office and hospital buildings. The term "optimal lighting use" (Maleetipwan-Mattsson, Laike & Johansson, 2012) is used to describe occupants' use of lighting with lighting controls and user interfaces to achieve energy savings and provide comfort for individuals. The term here refers to the use of electric lighting that is (i) on only when needed, (ii) off when not needed, and (iii) the lighting level is adjusted to meet individuals' preferences or demands.

Previous research

Research in environmental psychology has investigated tools to change people's behaviour or encourage them to adopt new attitudes and behaviour to reduce the environmental impact (Gardner & Stern, 2002; Steg & Vlek, 2009). Regarding design, Pierce and Roedl (2008) have highlighted the need for finding ways to design products that both actively promote behavioural change towards energy reduction and are easily adapted to everyday life. As Werner and Carmalt (2006) have stated, occupants will make behavioural choices that affect the efficiency of design solutions.

Up to now, studies investigating different lighting control and user interface designs in non-residential buildings and their potential for energy reduction have mostly been carried out in office environments (see e.g. Galasiu & Veitch, 2006; Dubois & Blomsterberg, 2011) but few studies have focussed on how designs may affect occupants' responses concerning optimal use of electric lighting. Apart from lighting controls and user interfaces, the effects of design features on energy saving related behaviour and its relevant factors have been studied previously for kettles (Sauer & Rüttinger, 2004), stairwells (Swenson & Siegel, 2013) and the built environment (Joh, Nguyen & Boarnet, 2012; van Loon & Frank, 2010).

A number of prior studies are summarised in the following sections, focussing on aspects relevant to the thesis.

Occupant behaviour

In the studies carried out in office environments, methods such as observations by time-lapse photography (Hunt, 1979) and observations by human (Boyce, 1980; Maniccia, Rutledge, Rea & Morrow, 1999), interviews (Escuyer & Fontoynont, 2001) and use of data loggers (e.g. Love, 1998; Moore, Carter & Slater, 2003; Masoso & Grobler, 2010; Yun et al., 2012) were used to determine occupants' use of electric lights with lighting controls and user interfaces and thereby lighting energy use. However, these methods were often not effective in practice (Love, 1998) and hampered by problems concerning the participants' acceptance (Boyce, 1980). Tso and Yau (2003) applied a self-report diary to measure energy use in households and proposed it as a cost-effective approach, especially when a large sample size is required. According to Bell, Greene, Fisher and Baum (2001), self-reports are also easy to manage and do not impinge on the privacy of occupants. However, the validity of this method has been questioned and needs further study (Steg & Vlek,

2009). In a study of occupants' use of manual lighting controls in offices (Maniccia, Rutledge, Rea & Morrow, 1999), self-reported data revealed that occupants do not always give an accurate description of their actual behaviour.

Regardless of the type of method used, one of the most common findings of previous studies was that occupants generally use switching and/or dimming controls to set their preferred lighting in their offices once at the beginning of the day and then the lighting is rarely adjusted manually again until the end of the day (Hunt, 1979; Boyce, 1980; Moore et al., 2003; Boyce et al., 2006; Yun et al., 2012). It should be noted that these studies were conducted in different countries and investigated different types as well as combinations of lighting controls and user interfaces. According to Boyce et al. (2006), the above finding may imply that individuals use lighting controls to set their preferred lighting in offices but only change the lighting setting when necessary. Further, Lindelöf and Morel (2006) suggested that occupants' low frequency of switching and dimming activities could be due to the location of the lighting control at the door (out of arm's reach) rather than close to the desk.

Although the aforementioned studies illustrate infrequent occupants' use of manual lighting controls, a number of studies (see Galasiu & Veitch, 2006) have reported that the majority of occupants want the ability to manually control lighting through a user interface. In other words, lighting controls are more acceptable to occupants when combined with an interface that allows occupants to manually override the system. Occupant controlled general lighting has been found to be associated with occupant behaviour that can contribute to energy reduction (i.e. choosing low illuminance levels as preferred) (Moore, Carter & Slater, 2002). However, the latter study noted that occupants may use lighting controls in a way they find easiest but not necessarily in accordance with the intended design of the control systems.

To make the most optimal use of electric lighting with lighting controls, Jennings Rubinstein, DiBartolomeo and Blanc (2000) have suggested that building occupants should be given information about and insight into lighting controls, so that they can most effectively use the controls delegated to them and understand the consequences of their behaviours. Because occupants generally interact with the controls through user interfaces, according to Nordman, et al. (2012), users able to understand the interfaces are likely to comprehend the intended design of the control systems and most optimal modes of interaction.

Reducing energy use through design

Reports in the literature have shown the effects of small-scale design features on occupant energy-saving behaviour, and thereby energy reduction in buildings. Swenson and Siegel (2013) studied changes in stair use in a two-to-three storey office building through an interactive environmental intervention and found that decorating stairwells with interactive paintings could encourage occupants to use the stairs rather than the elevator. As a consequence, this could bring about energy reduction from elevators. In a series of studies (Sauer & Rüttinger, 2004), different designs of kettles were tested and found to affect water and energy use. The studies' results suggested that design modifications of size and integrated user support are effective in encouraging users to save water and energy. Moreover, it should be noted that user perceptions of design features play a crucial role in affecting behavioural outcomes (e.g. Nasar, 2008) and that the relationship between designs and behaviour may be mediated by individual-based factors, such as attitudes, affects or norms (Steg & Vlek, 2009).

Concerning lighting control and user interface designs, studies have so far considered critical characteristics that have potential to achieve energy-savings and satisfy occupants (see Galasiu & Vietch, 2006). A number of studies (see Dubios & Blomsterberg, 2011) have shown that manual/automatic/daylight dimming and occupancy switch-off controls can substantially reduce energy use in office buildings. However, use of a combined daylight dimming with occupancy switch on/off control was found to be associated with higher energy use compared to a manual switch on/off control when tested in field studies (Gentile, Dubois & Håkansson, 2012; Gentile, Laike & Dubois, 2013). The studies also found that use of a daylight dimming system cannot guarantee occupant satisfaction. Based on a study conducted in single-occupant offices, Jennings et al. (2000) noted that types of work task affected individuals' occupancy patterns in offices, and thereby the energy savings potential of lighting controls.

According to a comprehensive review of the lighting control systems literature (Galasiu & Veitch, 2006), complex lighting controls could provoke increased energy use and dissatisfaction among occupants. When occupants find controls difficult to use, they tend to choose lighting levels that minimize the need to use the controls, resulting in unnecessary energy use for lighting. Hence, easy-to-use lighting controls are likely to be more effective from both energy-saving and individual satisfaction points of view. Further, optimal use of both simple and more complex control systems may be improved by designing simple and easy-to-use interfaces.

The role of effective design of user interfaces for lighting controls has been discussed in the literature. As outlined by Liedberg and Sperling (1982), everyday user interfaces, i.e. light switches, must be designed in accordance with national building codes as the design and position of switches should be accessible for all people. Switches must also be designed to have quite large push buttons to improve coordination and allow the switches to be operated with the palm. Nordman et al. (2012) considered standardisation of the design of lighting control user interfaces but found no existing standard related to the design of the interfaces. However, principles for designing user interfaces had been preliminarily set out by standards organisations or technical committees. Nordman et al.'s study summarised many relevant aspects, including visual elements and characteristics of the interfaces, and stressed the importance of designing the interfaces for all people regardless of type (age) and ability besides energy savings.

Mediating factors

According to Steg and Vlek (2009), attitudes, affects or norms may mediate the relationship between designs regarded as product characteristics and users' behaviour. It is well-known that attitudes can have a strong influence on behaviour. So far, a number of studies have shown the influence of attitudes on energy-saving travel behaviours, i.e. no car use downtown (Kaiser & Gutscher, 2003) and walking and/or biking for transportation (de Geus, Bourdeaudhhuij, Janne & Meeusen, 2008; Dill, Mohr & Liang, 2014). Also, a meta-analysis of determinants of pro-environmental behaviour (Bamberg & Möser, 2007) identified the importance of attitudes in influencing such behaviour.

Besides attitudes, the literature shows the influences of norms, self-efficacy and habits on energy-saving behaviour. Norms reflect the extent to which behaviour is perceived as common thing to do or socially approved/disapproved (Cialdini, Kallgren & Reno, 1991; Ajzen, 1991). In particular, norms could be relevant for behaviours that occur in a place where people share the same physical environment (Gifford & Nilsson, 2014). Based on a study conducted in university shared dorm rooms, Chao and Lam (2011) noted that people motivated to behave in a socially desirable way would be more likely to turn off the table lamp when leaving the room. Similar to attitudes, self-efficacy or perceived behavioural control has been found to significantly influence energy-saving travel behaviours, such as biking and/or walking for transportation (de Geus et al., 2008; Carlson et al., 2012; Dill et al., 2014), as well as other pro-

environmental behaviours (Bamberg & Möser, 2007). Concerning habits, which are often considered as a crucial factor influencing future behaviours (e.g. Ouellete & Wood, 1998), a study of car use (Verplanken & Aarts, 1999) found a stronger influence of habit on behaviour when compared to behavioural intention.

There have also been reports that individual-based factors in particular, attitudes and self-efficacy or perceived behavioural control can be influenced by the physical environment. Dill et al. (2014) identified the importance of physical environment characteristics (i.e. number of street intersections, low traffic streets, presence of sidewalks and bike lanes) in influencing the frequency of biking and walking due to their influences on attitudes and perceived behavioural control. Lee and Shepley (2012) also identified perceived safety in the environment as an important factor affecting attitudes and perceived behavioural control influencing behavioural intention and walking behaviour among adults. Moreover, Corraliza and Berenguer (2000) investigated the influence of interaction between the situation (physical environment) and environmental attitudes on pro-environmental behaviour, including switching off heating in unoccupied rooms and buying energy-saving light bulbs and appliances. This study suggested that situations (physical environment) perceived as facilitatory can positively affect people who already have pro-environmental attitudes to carry out such behaviour.

In addition to the physical environment, the social environment has been suggested to possibly influence energy-saving behaviours (e.g. Murtagh et al., 2013). According to Moore et al. (2002), some occupants may avoid using lighting controls owing to fear of conflict with other occupants who share the same lighting. Evans (2003) pointed out that there is a link between individuals' self-efficacy and social interaction and that such interaction could be influenced by design features of the physical environment. So far, studies examining the role of social environment in influencing walking (Carlson et al., 2012) and biking for transportation (de Geus et al., 2008) have found that it affects walking but not biking behaviour. Owing to these inconsistent findings, the role of social environment in influencing people's behaviours towards energy savings remains unclear.

Theoretical departure

The following theories relating to individual- and environmental-based factors as well as designs of lighting controls and user interfaces that may influence human behaviour were employed to develop a conceptual framework for this thesis.

The theory of affordances (Gibson, 1979) has widely been used to describe behavioural relationships between objects/physical environments and individuals. As defined by Gibson (1979, p. 127), *"The affordances of the environment are what it offers to the animal, what it provides or furnishes, either good or ill".* Concerning affordances of objects, Gibson described that objects afford possible behaviours through visual perception: when looking at the objects, individuals know what can be done with them and what they can be used for. With an emphasis on product design, affordances are referred to as *"the **perceived** and **actual** properties of the things, primarily those fundamental properties that determine just how the things could possibly be used"* and signal to users to know what to do with objects (Norman, 1998[1988], p. 9). Affordances are also considered as a universal principle of design (Lidwell, Holden & Butler, 2010) and can be used as an evaluation tool to examine whether an object is used in accordance with its intended design (Maier & Fadel, 2009).

However, in some cases, affordances may not be dependent on the objects solely but can be subject to individual characteristics, such as age, size and height, of the perceiver (Gibson, 1979). To overcome this limitation, two principles of universal design (UD), which refers to *"design for people of all ages and abilities"* (Story, Mueller & Mace, 1998), were considered to represent affordances (i.e. functions and properties) as well as usability of the objects: (i) perceptive information – *"the design communicates necessary information effectively to the user regardless of ambient condition or the user's sensory abilities",* and (ii) simple and intuitive use – *"use of the design is easy to understand, regardless of the user's experience, knowledge, language skill or current concentration level"* (Story et al., 1998, p. 34). These two principles concern the ability of objects to communicate with users regarding their intended design and can thus be considered to represent affordances.

Desmet and Herkkert (2007) have presented a framework of product experience relating to affective responses in human-product interaction. They noted that anticipation of interaction with the product as well as possible consequences of interaction can elicit affective responses from individuals. Affective responses can be influenced by characteristics of the individual (e.g. background, cultural values and

motives) and object (e.g. shape, texture, colour and function), the processes involved (e.g. perceiving and exploring) and context where the interaction occurs. These insights have implications for designs of lighting controls and user interfaces as different designs may trigger different affective responses, thereby influencing user behaviour.

Analogously, the human-environment interaction model (Küller, 1991) explains and discusses the roles of the physical and social environment together with individual-based factors such as attitudes and experience in influencing human perceptions and behaviour. In formulating the model, Küller developed several tools, i.e. semantic environmental description (SED) and social situation, for measuring the perceptions of the physical and social environment. By means of these tools, characteristics of the physical environment can be assessed and described in terms of eight dimensions, e.g. pleasantness, complexity, unity and originality, and characteristics of the social situation, e.g. social intensity, familiarity, and friendliness can be assessed (see Küller, 1991). Based on Küller's work, Sorte (1982) developed the semantic component description (SCD) to specifically describe and assess human perceptions of visual characteristics of common objects in terms of 11 dimensions, e.g. articulation, valence, scale, lightness and age.

Concerning individual-based factors, the theory of planned behaviour (TPB) (Ajzen, 1991), which was introduced to explain as well as predict human behaviour in specific contexts, has widely been applied to research work. So far, the TPB has been applied successfully for explaining different kinds of behaviours, including energy-saving behaviours, e.g. using energy-saving light bulbs (Harland, Staats & Wilke, 1999) and walking/biking for transportation (e.g. Dill et al., 2014). The TPB describes that behavioural intention and perceived behavioural control (PBC), which according to Ajzen, 1991, p. 183, refers to *"people's perception of the ease or difficulty of performing the behaviour"* are the proximal determinants of behaviour. Intentions are influenced by (i) attitudes towards the behaviour – *"the degree to which a person has a favourable or unfavourable evaluation or appraisal of the behaviour"*, (ii) subjective (social) norms (SN) – *"the perceived social pressure to perform or not to perform the behaviour"*, and (iii) PBC (Ajzen, 1991, p. 188).

The relative importance of TPB's factors seems to vary for different behaviours, groups of individuals (De Groot & Steg, 2007) and also different situations (Ajzen, 1991). For example, studies of walking and biking behaviour have shown that attitudes and PBC are more important in predicting behaviour compared to subjective norms and that the former two factors, especially PBC, could be influenced

by the built environment (see Dill et al., 2014). The latter finding may relate to the fact that the TPB also considers individuals' perceptions of environmental factors, as shown through PBC (Steg & Vlek, 2009). According to Ajzen (1991), new or unfamiliar elements in a situation or little information on behaviour may negatively affect PBC.

In addition to TPB factors, habits have been shown to be a significant predictor of future behaviours (e.g. Ouellete & Wood, 1998; Verplanken & Aarts, 1999). Usually, habits develop through behavioural patterns that are often repeated (Sauer & Rüttinger, 2004). Situational constancy is necessary for habit formation. However, habits may also develop in a specific situation and be limited to that situation (Verplanken & Aarts, 1999). Hence, habits can be characterised as either general or specific depending on situational constancy. Verplanken and Aarts (1999) have stated that general habits are particularly important because they may represent behaviours occurring in many different settings and have a significant impact on an individual's well-being, health or safety, the environment or the economy. Further, Verplanken and Aarts (1999) have discussed the issue of changing habits and creating new ones. They suggested that it is possible to break old habits as well as adopt new ones but repetition of effective interventions based on careful analyses of relevant aspects will be needed.

Conceptual framework

A conceptual framework (Figure 1) was developed and applied to describe the interaction between individuals and lighting controls and/or user interfaces, and possible factors that may mediate the effects of lighting control and user interface designs on optimal lighting use among occupants in non-residential buildings. Optimal lighting use was considered as electric lighting that is regulated to meet individuals' preferences and not regulated because individuals are satisfied with the existing lighting condition. This would therefore offer a simple means of reducing energy use in non-residential buildings and at the same time supporting occupant satisfaction with lighting.

Within this framework, the TPB and theory of affordances were integrated to link affordances of user interfaces with PBC, which together may positively affect individuals' optimal lighting use.

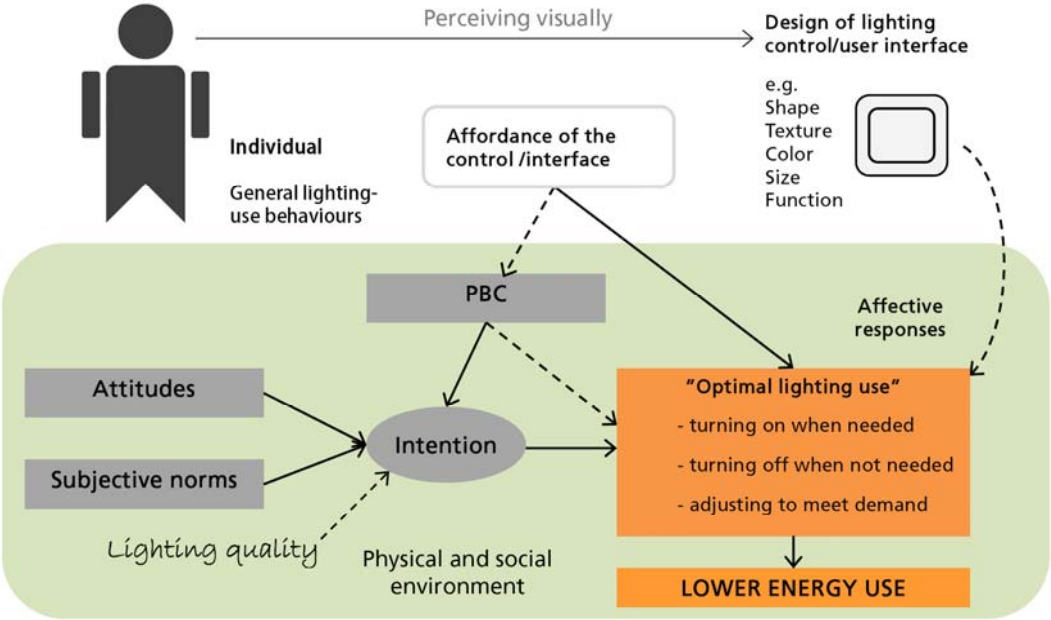

Figure 1 *Conceptual framework (adapted from Maleetipwan-Mattsson et al., 2012).*

Lighting control and user interface designs

Designs of lighting controls and user interfaces were assumed to be associated with behaviour both directly and indirectly. Since in general, occupants interact with lighting controls through user interfaces, the framework particularly focused on designs of the interfaces. As part of the framework, the interfaces' affordances were linked to behaviour via PBC. Here, affordances covered the two principles of UD concerning the usability of objects. The framework proposed that affordances would positively affect PBC by providing clear information about the optimal operation of the interfaces. In other words, affordances would support individuals in perceiving the ease of performing the behaviour of interest, i.e. using lighting optimally.

Apart from affordances, the framework further proposed that characteristics due to physical features, such as colour and shape of the interfaces, would evoke individuals' affective responses, and thereby prompt or hamper behaviour via visual perception. Based on Desmet and Hekkert (2007)'s insights, affective responses can be generated when people anticipate interaction with the interfaces and also possible consequences of the interaction. For example, anxiety about safety may dissuade individuals from using an interface to regulate lights due to anticipation of physical harm. On the

other hand, individuals may be keen to use the interface to regulate lights due to anticipation that using it can help to reduce energy use.

Physical and social environment

According to Desmet and Hekkert (2007), individuals' affective and behavioural responses could be affected by the context. An example of this would be when someone feels uncomfortable and avoids using interfaces in public buildings due to anticipation that using them can cause infection. Specifically, the framework considered physical and social contexts as possible factors influencing PBC. Based on Küller's work (1991), originality (the unusual or surprising) in the physical environment, familiarity (how common and well-known) and friendliness (positive or negative psycho-social atmosphere) in the social situation were assumed to facilitate PBC. Specifically, (i) originality in the physical environment was considered to represent a common location of the interface in the room, and (ii) based on Evans (2003), familiarity and friendliness of the social situation was considered to be closely related to social interactions among building occupants that may, therefore, positively affect PBC.

Individual-based factors

TPB factors and general lighting-use behaviours were considered as individual-based factors mediating the relationship between user interface designs and individuals' optimal lighting use in non-residential buildings. In accordance with the TPB, the framework proposed that individuals who express positive attitudes towards the behaviour, i.e. using lighting optimally (attitudes), perceive pressure from others to perform the behaviour (subjective norms, SN) and perceive that they can perform the behaviour easily (perceived behavioural control, PBC) are likely to have intention to perform the behaviour; these factors are linked to the physical and social environment in which the interaction between individuals and the interfaces occurs. Hence, the intention and PBC would lead to the actual behaviour. The framework further proposed that general lighting-use behaviours of individuals could also be a determinant of actual behaviour, in addition to the intention and PBC.

Objectives

The main objectives of the work described in this thesis were to explore occupants' responses to (i) different designs (types) of lighting controls and (ii) different designs of user interfaces at an individual level, and the effects of the occupants' responses on energy used for lighting in non-residential buildings. Use of lighting and perceptions of lighting quality in relation to the use of the controls were the main focus when analysing the responses to different designs of lighting controls. Besides use of lighting, perceptions of design characteristics of the interfaces that visually communicate with users, particularly affordances, were also examined for the responses to different designs of the interfaces.

Concerning the responses to different designs of lighting controls, the questions asked were as follows:

- In what ways can measurements of individuals' optimal lighting use with lighting controls be done effectively? (addressed in Paper I).

- How significant are lighting control designs in affecting
  - (i) individuals' perceptions of lighting quality?
  - (ii) individuals' behaviours in relation to optimal lighting use?
  - (iii) energy usage? (addressed in Paper II).

Concerning different designs of user interfaces for lighting controls, the questions asked were as follows:

- How significant are user interface designs in affecting individual perceptions of design characteristics, and thereby optimal lighting use? (addressed in Paper III and Paper IV).

- Which design characteristics encourage optimal lighting use among occupants? (addressed in Paper III and Paper IV).

- Which individual-based and physical and social environment factors are important in mediating the relationship between user interface designs and occupants' optimal lighting use? (addressed in Paper IV).

OUTLINE OF THE THESIS

The thesis describes the following empirical studies divided into four papers dealing with different parts of the conceptual framework, as shown in Figure 2. The methodological emphasis of the thesis is on measurements of individuals' responses to designs of lighting controls and user interfaces that could affect lighting energy use in empirical cases. Both subjective and objective measures were employed to collect the data. It was expected that this would gather sufficient information for understanding occupants' optimal lighting use with lighting controls and user interfaces. The quantitative approach was considered suitable for the data collection and analysis to examine the effects of lighting control and user interface designs. In line with Robson (2011), the responses measured were converted into numbers.

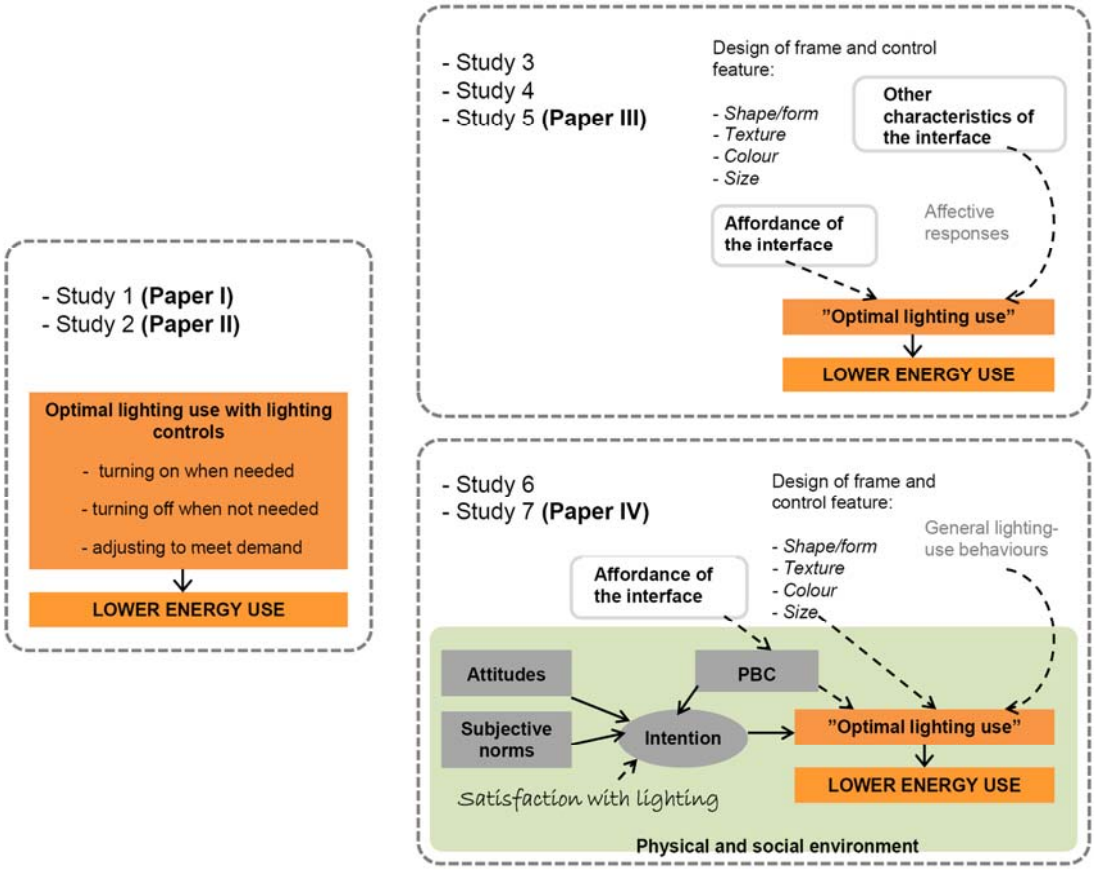

Figure 2 *The studies in relation to the conceptual framework.*

Empirical studies

Study 1 (Paper 1) was a methodological study conducted in 18 single-occupant offices equipped with different types of lighting controls to examine data on lighting-use-related behaviours and energy use obtained from a self-report diary compared to electronic measurement using a data logger (logged data). This methodological study provided an extensive assessment of suitability and reliability of the self-report method (diary) for measuring occupants' lighting-use-related behaviours and energy use. Study 2 (Paper II) was a case study of field measurements carried out in the same setting as Study 1 to determine optimal lighting use with different lighting controls. Individuals' use of lighting with the controls, energy use and perceptions of lighting quality were examined. This case study provided a basis for establishing optimal lighting use with lighting controls for individuals. In relation to the conceptual framework, studies 1 and 2 dealt with aspects concerning behavioural responses to different designs (types) of lighting controls and their effects on energy use.

Study 3 and Study 4 were conducted in controlled environments to examine the effects of different designs of everyday interfaces, i.e. light switches, on user perceptions with regard to particular design characteristics, including affordances. In addition to Study 4, the individuals' general lighting-use behaviours were examined in relation to their perceptions of a commonly used on/off switch regarding its ability to reduce energy use. This was carried out to preliminarily determine the significance of this individual-based factor in influencing optimal lighting use. Afterwards, in Study 5, field observations were conducted in a public toilet to examine the effects of different designs of interfaces on optimal lighting use. Together, the latter three studies investigated occupants' use of electric lighting in relation to their perceptions of the switches' characteristics to identify the characteristics that may encourage optimal lighting use in public buildings, as reported in Paper III. The studies provided a basic approach for understanding how design may encourage energy-saving behaviours addressed in the framework concerning the perceptions of user interfaces' designs and their relation to optimal lighting use as well as energy reduction.

Study 6 was conducted in a dining room and a dayroom located in separate patient wards at a hospital to examine the importance of individual-based factors (i.e. TPB factors and general lighting-use behaviours), affordances of light switches and originality in the physical environment in affecting optimal lighting use. In addition to Study 6, the importance of familiarity and friendliness in the social situation were

examined. In the same settings, Study 7 was conducted to further examine the effects of different light switch designs on occupants' use of electric lighting. Together, the two studies investigated possible factors affecting occupants' optimal lighting use in shared environments where occupants have the ability to manually control the lights, as reported in Paper IV. Overall, the studies helped to elucidate the important factors that affect occupants to use lighting optimally in shared environments, considering all parts of the framework.

The specific methods and statistical analyses applied to the studies included in this thesis are summarised in Table 1 and presented in detail in the appended papers.

Table 1 *Methods applied in the studies included in this thesis.*

	Paper I	Paper II	Paper III			Paper IV	
	Study 1	Study 2	Study 3	Study 4	Study 5	Study 6	Study 7
Question(s) asked	In what ways can measurements of individuals' optimal lighting use be done effectively?	How significant are lighting control designs in affecting optimal lighting use?	How significant are user interface designs in affecting individual perceptions of design characteristics, and thereby optimal lighting use? Which design characteristics encourage optimal lighting use among occupants?			Which factors are important in mediating the relationship between user interface designs and optimal lighting use?	Which design characteristics encourage optimal lighting use?
Setting	18 single-occupant offices in an office building		Lecture halls	A controlled laboratory	A public toilet in a hospital ward	A dining room and a dayroom located in respective patient wards at a hospital	
Access to daylight:	Through glazing windows		Not applicable	Not applicable	No access	Indirect through glazed windows (daylight entered to each room via a glass roof over the indoor court next to the room)	
Participant	15 office occupants 6 males, 9 females, age 29-62	18 office occupants 9 males, 9 females, age 29-62	111 students 77 males, 34 females, age 18-30	50 students or staff at the university 25 males, 25 females, age 17-64	Not applicable	42 staff and patients at the wards 9 males, 31 females, age 20-69	Not applicable
Lighting control/user interface studied	6 types of lighting controls ranging from fully manual on/off to fully automatic on/off and dimming controls		Pictures of 4 light switches projected onto a large screen	9 light switches, 1 occupancy sensor with a manual override switch	Original and3 alternative switches	Original and 2 alternative switches	
Data collection method or instrument	A self-report diary form, A data logger	A data logger, A self-report questionnaire	A self-report questionnaire	A self-report questionnaire	A data logger	A self-report questionnaire	Human observation, Data loggers
Measured variables	Lighting-use-related behaviours Light-on time, Occupancy time	Lighting-use-related behaviours Light-on time, Occupancy patterns and time, Energy usage, Perceptions of lighting quality	Perceptions of light switches	Perceptions of light switches	Optimal lighting use	Perceptions of light switches and the environment, TPB's factors, General lighting-use behaviours, Optimal lighting use	Lighting-use-related activities, Use of lighting and energy usage
Statistical comparison	Correlational, Between groups	Between- and Within groups	Within groups	Within groups	Between groups	Correlational	Between groups
Statistical test	Spearman's rho, Pearson's *r*, Paired samples *t*-test	One-way ANOVA, Kruskal-Wallis test, Independent- and Paired samples *t*-tests	Exploratory factor analysis, PCA, One-way repeated measures ANOVA	One-way repeated measures ANOVA Pearson's *r*	Kruskal-Wallis test, Mann-Whitney U test	Spearman's rho, Logistic-regression	Kruskal-Wallis test, Mann-Whitney U test, Chi-squared test for independence
Expected outcome	Energy reduction by lighting control and user interface designs						

Ethical considerations

All studies were carried out in line with Swedish Research Council guidelines (source: Good Research Practice, report no. 3:2011 in the Swedish Research Council's report series), which lay down requirements for information, consent and confidentiality. The compilation of information and treatment of all data preserved confidentially; no sensitive information was recorded and all information on individuals was unidentifiable.

For studies 1 and 2, which took place in offices, the research team informed the company board members and obtained permission to conduct the studies. The intervention used for office lighting was designed by experts to ensure professional standards of the systems. A meeting was arranged during which the office occupants were approached and informed of the studies' background, aims and implementation procedures. The occupants were told that occupancy and use of lighting in their respective offices would be measured electronically by a data logger throughout the study period without disturbing normal activities and that they would be asked to complete questionnaires and lighting use diaries once every two months. It was explained that participation in completing the questionnaires and diaries was voluntary and the occupants could drop out at any time without giving any explanation. The occupants signed a written consent to take part in the studies.

For studies 3 and 4, which took place in controlled environments, the participants were approached and informed about the studies' objectives and procedures. The participants gave their consent to participate in the studies. For studies 5 to 7, which took place in a hospital regarded as a public building, the research team undertook a meeting with the property management company responsible for healthcare institutions in the county and obtained permission to conduct the studies. Meetings were arranged with the heads and staff of the two patient wards where the investigated environments were located to inform people about the studies' background, objectives and implementation procedures and reassure them that the studies would not disturb normal activities in the wards and it would not be possible to obtain individuals' identities. Users of these facilities (staff, patients and visitors) were informed that use of lighting would be measured in relation to occupancy in the facilities by data loggers and/or human observations. The users were approached to participate by answering a questionnaire; participation relied on a person' consent and was voluntary.

Moreover, it should be noted that by using data loggers, information on occupancy and electricity use in the investigated environments could be captured without jeopardising the occupants' privacy or anonymity of the data (i.e. such techniques cannot identify or distinguish individuals). Data loggers have widely been used for studies tracking energy use in buildings in relation to occupant behaviour in many applications; besides measurements of occupancy and actual use of lighting, data loggers have been used to track energy used for heating, ventilation and air conditioning, and other electrical equipment in buildings (Masoso & Grobler, 2010).

PAPER I

Study 1: A methodological study

The aim of this study was to test whether a self-report diary was a suitable and reliable approach for measuring occupant behaviours in relation to lighting use with lighting controls and energy usage in offices compared to electronic measurement. The focus was on the extent to which the diary could be used considering occupants' involvement and length of participation in the study.

Method of Study 1

The study was conducted in 18 single-occupant offices located on the fourth floor of a seven-storey office building in central Stockholm, Sweden. The occupants of these offices had individual control over their office spaces. All offices had access to daylight through two or four glazed windows. Ceiling luminaires in the offices were controlled by different kinds of lighting controls, ranging from fully manual on/off to fully automatic on/off and dimming controls. User interfaces for lighting controls were either wall-mounted or pull-cord switches.

The diary form (see Paper I) was designed for each occupant to report regulation of general lighting (i.e. the luminaire) and a desk lamp. Fifteen occupants (six males and nine females ranging in age from 29 to 62 years, mean age = 47 years) participated in completing the diary forms and 59 forms were returned. The occupants were then categorised into two groups as *full participation* occupants or *occasional participation* occupants. Throughout the study period, a data logger measured the occupants' use of the luminaires and occupancy in their respective offices.

Differences between the self-reported and logged data were examined for four variables: (i) regulation of the luminaires, (ii) movements (categorised as occupancy/vacancy), (iii) light-on time (hours), and (iv) occupancy time (hours).

Main results of Study 1

The diary form appeared to be successful in obtaining self-reported data on occupants' use of lighting and movements, except for data on use of daylight, which were missing from about 25% of the returned forms. Concerning occupants' manual controls of the luminaires and desk lamps, the self-reported data revealed that most occupants usually switched the lights on manually at the beginning of the workday but then the lights were rarely switched off manually until the end of the day. This self-reported switching behaviour was found for both wall-mounted and pull-cord switches. The self-reported data also showed that daylight was usually allowed into the offices but only a few occupants adjusted window blinds and curtains when they sat in their respective offices during the day.

In general, correlation between the self-reported and logged data was found to be stronger for the first three occasions on which the occupants were asked to fill in the diary than for the later occasions, with the exception of the correlation for occupancy time, which was found to be non-significant on all occasions. The correlation analyses showed that light-on time and occupancy time obtained from all self-reported data, to some extent, were related ($r = 0.42$, $n = 51$, $p < 0.01$), but when considering just the full participation occupant group, only a weak relationship between light-on time and occupancy time was detected. There was no significant relationship between light-on time and occupancy time obtained from all logged data. Moreover, *t*-test analysis revealed no significant differences in mean values between all self-reported and logged data for light-on time and occupancy time.

Discussion and conclusions of Study 1

This study found that the self-report dairy form was able to obtain useful data regarding the occupants' use of lighting and movements in and out of their respective offices during the day. Overall, the results indicated that the form was a more reliable and suitable tool for measuring individuals' regulation of electric lighting (ceiling luminaires) with different lighting controls as well as user interfaces and light-on times than measuring occupancy in offices for participants with either low or high involvement in the study. The diary form appeared to be unreliable for measuring occupancy time, although there was a strong relationship between self-reported and logged data for occupancy/vacancy in the offices.

Concerning long-term studies, the correlations detected for the full participation occupants indicated that as the number of occasions where participants were asked to complete a self-report increased, the less reliable the self-report became for measuring lighting use with lighting controls. Moreover, it was found that the mean value of light-on time obtained from the self-reported data was slightly higher than that obtained from the logged data, suggesting that people may overestimate light-on time when using the self-report diary.

As an example of using the diary form, mean values of the light-on and occupancy times obtained from the self-reported data were used to calculate energy use for lighting with manual on/off controls. The energy use was then compared to mean values of light-on time obtained from the logged data. For all occupants, full participation occupants and occasional participation occupants, respectively, the energy use was found to be overestimated (between 2% and 8%) when using mean values of the self-reported light-on time and underestimated (between 6% and 31%) when using mean values of the self-reported occupancy time compared to using mean values of light-on time obtained from the logged data[1].

To conclude, this study showed that the self-report diary could be an effective method for studying occupants' use of lighting in offices at an individual level, especially when a large sample size and/or a nonintrusive method are required. The concluding findings were as follows:

- The diary form offers a useful tool for determining occupants' switching patterns with lighting controls during the day.

- The diary form was more reliable for measuring occupants' regulation of electric lighting and light-on time than their occupancy/vacancy in the offices.

- The diary form could be employed to measure light-on time, and therefore estimate energy used for lighting, although caution should be exercised as people may overestimate their light-on time.

[1] It was assumed that energy was used by manual on/off controls.

- The diary form provides a reliable way for measuring electric lighting use with lighting controls as well as determining lighting energy use for both low and high involvement participants in short- rather than long-term studies.

For future studies, the design of the diary form could be improved to obtain information on dimming activities and provide participants the opportunity to freely report movements and reasons for changing their lighting use with lighting controls. Moreover, different environmental and social contexts may have an effect on the suitability and reliability of the diary form, and thus use of the form should be examined in different types of offices and organisations.

PAPER II

Study 2: A case study of field measurements

This study aimed to examine occupancy, use of electric lighting, energy usage and perceptions of lighting quality in different seasonal periods, considering occupancy and daylight hours as key factors determining optimal lighting use with different types of lighting controls for individuals. The main hypothesis was that use of electric lighting and perceived lighting quality would vary among individuals with different lighting controls. Further, long daylight hours in spring-summer would replace use of electric lights, and therefore would positively affect optimal lighting use by individuals using different lighting controls.

Method of Study 2

This study took place in 18 single-occupant offices at the same setting as used in Study 1. The offices were divided into six groups of three offices installed with six different lighting controls for ceiling luminaires (see Paper II).

A data logger (see Study 1) was used continuously to record data on use of general lighting (ceiling luminaires) and occupancy at intervals of two minutes for each office throughout the one-year period of study. Some data were omitted because (i) the occupants did not use the luminaires, (ii) there were errors found in the measurements, or (ii) there was an issue with the occupant's mobility throughout the entire study period. Out of the 18 office occupants (nine males, nine females, age range: 29-62 years), data were analysed from 15 occupants. Moreover, occupants were asked to rate the perceived quality of lighting in their respective offices using a questionnaire with a seven-point rating scale (after Küller & Wetterberg, 1993) after

15.00[2] on any working day except Monday and Friday, once every two months. A total of 105 questionnaires were distributed to occupants in the 18 offices; 57 questionnaires were filled-in and returned.

For each office, occupancy patterns, occupancy times, light-on times and energy used for lighting were calculated for each day using the logged data. Ratios of light-on times to occupancy times of 1 or below were deemed to indicate optimal lighting use (i.e. the lighting was used only when the occupant was in the office or was replaced by daylight). Data on occupants' perceptions of office lighting quality obtained from the questionnaires were analysed and presented in terms of hedonic tone and brightness. For all 15 office occupants included in the study, differences in the occupancy, use of lighting (i.e. ratios between light-on times and occupancy times), energy usage and perceptions of lighting quality between the data for the spring-summer versus autumn-winter were examined. Additionally, for each office, comparison of the mean ratios between the two seasonal periods was made. Among the offices, variations in the occupancy, use of electric lighting, and perceptions of lighting quality were examined.

Main results of Study 2

Using the data from all 15 office occupants included, a paired-samples *t*-test showed non-significant differences in the mean values of daily occupancy and perceptions of lighting quality, whereas there were significant differences in the mean values of use of electric lighting and energy usage between the two periods (Table 2).

In general, light-on times, ratios between light-on times and occupancy times, and energy used for lighting were found to be significantly lower in spring-summer than in autumn-winter. Using one-way ANOVA analysis, variations in occupancy were found among the investigated offices. Also, variations in the ratios between light-on times and occupancy times (which was found to range from 0 to 14.10) were identified for both the spring-summer ($F_{(14,621)} = 34.95$, $p < 0.001$) and autumn-winter months ($F_{(14,547)} = 88.56$, $p < 0.001$). Considering each of the 15 offices separately, there were significant differences in the mean ratios between the two

[2] All offices were likely to be in the shade of surrounding buildings at this time in spring-summer. In autumn-winter (except for September and October), the outside of the offices were totally dark at this time.

different seasonal periods for 11 of them. Moreover, mean ratios of about 1 and below were obtained for one office with manual on/off and dimming control in the spring-summer months and two offices with manual on/automatic off controls together with automatic dimming to 90% of the 500 lux setting in both periods.

Table 2 *Occupancy, lighting and energy use, and perceptions of lighting quality in single-occupant offices for spring-summer versus autumn-winter (n = 15).*

	Spring-Summer		Autumn-Winter		Δ	*t*
	M	*SD*	*M*	*SD*		
Occupancy time (h)	3.80	1.13	3.91	1.45	0.11	-0.83 ns
Light-on time (h)	5.31	2.15	7.57	2.61	-2.26	-3.93**
Light-on time : Occupancy time	1.57	0.91	2.48	1.94	-0.91	-2.95*
Energy used for lighting (Wh/h)	389.63	214.30	522.17	200.23	-132.54	-4.00**
Perceptions of lighting quality (7-point scale):						
- Hedonic tone	4.70	0.87	4.33	1.11	0.37	2.02 ns
- Brightness	4.47	1.16	4.36	1.21	0.11	0.99 ns

*$p < 0.05$, ** $p < 0.01$ (2-tailed)

For each hour, energy was used equally by manual on/off controls (75.87 watt-hours/hour (Wh/h)) and manual on/automatic off controls with no automatic dimming options (the values obtained from the field measurements varied among the offices, from 72.32 to 77.81 Wh/h). Offices with automatic on/off controls and algorithmic functions showed the highest energy use per hour (about 30% higher than that obtained with manual on/off controls). The energy use for manual or automatic dimming controls was found to be lower than for the other controls in the spring-summer months.

The perceptions of lighting quality were generally higher than the neutral point (point 4 on the 7-point scale). Two occupants using manual on/automatic off controls and the 90% dimming functions perceived lighting in their offices as having low hedonic tone and brightness in both periods. Kruskal-Wallis test analysis showed variations in the perceived hedonic tone ($X^2_{(16,\ n = 59)} = 38.18$, $p < 0.01$) and perceived brightness ($X^2_{(16,\ n = 60)} = 42.75$, $p < 0.001$) when considering both periods together.

Discussion and conclusions of Study 2

In this study, occupancy, use of electric lighting and perceptions of lighting quality for different types of lighting controls in the spring-summer and autumn-winter were investigated. Considering all 15 office occupants included, no differences were detected in their occupancy and perceptions of lighting quality between the two seasons, but their use of electric lighting in the spring-summer months was significantly less than that in the autumn-winter months.

Among the individuals using the different types of lighting controls, variations were identified for occupancy, use of electric lighting and perceptions of lighting quality. Use of electric lighting was found to be non-optimal in most offices regardless of the type of lighting control used. Some occupants constantly used lighting regardless of daylight availability. An increase in optimal lighting use in the spring-summer months was only observed in one office with manual on/off and dimming control and two offices with manual on/automatic off controls and the 90% dimming functions. However, the occupants of the latter two offices generally perceived low lighting quality, and thus optimal lighting use with the controls could not really be determined. Moreover, the study results highlighted the potential of using manual or automatic dimming together with occupancy switch-off controls to facilitate optimal lighting use, especially when occupants often have to leave their offices during the day. Instead of occupancy switch-off controls, manual on/off controls could be an energy- and cost-effective option when offices are occupied most of the day.

In conclusion, the results of this study showed the importance of considering occupancy patterns of individuals, their use of electric lighting and perceptions of lighting quality over different seasonal periods when determining optimal lighting use with different types of lighting controls. It should be noted that different lighting controls affect the energy used for electric lighting in different ways; thus, this issue should also be considered for determining optimal lighting use with the controls.

Some conclusions from this study are given below:

- Occupancy patterns, use of lighting and perceptions of lighting quality can vary among individuals using different lighting controls.

- Taking these factors into account when designing and selecting lighting control solutions could help achieve optimal lighting use.

- There are potential of manual overrides to support optimal lighting use with lighting controls.

It is also important that individuals are aware of their lighting use habits and motivated to reduce unnecessary use of electric lighting. Both behavioural changes and lighting control solutions are required to achieve optimal lighting use. Given the importance of individual behaviour, studies into individual factors that may possibly affect lighting-use behaviour, such as attitudes and perceptions on lighting controls, are desirable.

PAPER III

Study 3: Evaluation of light switches

The main objective of this study was to determine whether everyday user interfaces, i.e. manual on/off light switches, can be evaluated with regard to their design characteristics that visually communicate with individuals considering their context of use in public buildings. Additionally, the study sought to examine associations among the design characteristics and user perceptions of the switches. Mainly, it was hypothesised that different characteristics of light switches that visually communicate with the users and associations among them could be identified.

Method of Study 3

Principles for designing light switches for use in public buildings were used as an initial point of departure for describing design characteristics of the switches. Through a literature search, a total of seven design principles were proposed, namely, (i) visible and easy to identify, (ii) simple, (iii) suitable for use in public buildings, (iv) safe, (v) hygienic, and (vi) comfortable to use, and finally, (vii) able to trigger energy saving. A 30-item questionnaire (see Paper III) was then developed to assess user perceptions of light switches with regard to the seven principles proposed.

The participants comprised 70 civil engineering and 41 architecture students; all were Swedish (77 males, 34 females, mean age = 22.10 years, age range: 18-30 years) and in the first or second year of their study. The participants assessed four different light switches; each of the switches was presented in the form of a two-dimensional picture on a large screen on the wall of their lecture halls and the participants were asked to report their perceptions of the switches by means of a questionnaire. The 70 engineering students could only assess two out of the four switches owing to time restrictions, whereas the 41 architecture students responded to all four switches; 304 questionnaires were collected in total. The data from all the collected questionnaires were used to explore whether the design principles could describe characteristics of the interfaces that visually communicate with users. Associations between the

participants' perceptions of different characteristics were also examined. Furthermore, differences in the perceptions between the switches were examined among the group of architecture students (n = 41).

Main results of Study 3

The 30 items covered by the questionnaire were subjected to an exploratory factor analysis (the number of factors extracted was seven and missing data of about 5% were replaced by means of the respective variables). The data were deemed suitable for factor analysis (see Paper III).

As shown in Table 3, there were seven components. However, the seventh component was discarded because it contained residual items. Items weakly correlated with others in the same components ($r \leq 0.30$) were removed. Additionally, items with a factor loading of < 0.70 and also items that lowered the internal reliability of the scale were removed from components 1 and 2 to reduce the number of items from these components for which too many items were loaded. Three components were found to affirm the principles suggesting that light switches should be suitable for the context of use, hygienic and able to trigger energy saving. The principles that stated the switches should be simple, visible and easy to identify were re-categorised as 'affordances' and 'visibility' of the switches. The principles stating that switches should be safe and comfortable to use were grouped together into one component renamed as 'physical safety' of the switches. Cronbach's α for all components was ≥ 0.79, suggesting satisfactory internal reliability, except for hygienic use (Cronbach's α = 0.47).

It was found that the perceived affordances correlated strongly with the perceived suitability for use in public buildings of the switches ($r = 0.58$, $n = 263$, $p < 0.01$) and moderately with perceived visibility ($r = 0.37$, $n = 264$, $p < 0.01$) and perceived physical safety ($r = 0.42$, $n = 264$, $p < 0.01$). Moreover, perceived physical safety correlated moderately with perceived suitability ($r = 0.42$, $n = 264$, $p < 0.01$) and also perceived hygienic use ($r = 0.31$, $n = 273$, $p < 0.01$). One-way ANOVA analysis showed significant differences in the mean scores of the participants' perceptions among the four switches assessed for all six components (see Paper III).

Table 2 *Summary of exploratory factor analysis results (n = 304) (items in regular format included in the components: (1) affordances, (2) physical safety, (3) ability to trigger energy saving, (4) visibility, (5) suitability, and (6) hygienic use).*

Item	Rotated factor loading (Varimax)						
	1	2	3	4	5	6	7
This product is simple to use.*(1)	0.79						
*Instruction is needed in order to use this product.***	-0.78						
This product is complicated.	-0.76						
This product helps me understand how to use it.*(1)	0.76			0.30			
The control feature(s) of this product are easy to identify.**(1)	0.73						
*This product works just like I expect it to work.**	0.71	.034					
This product is easy to identify.**(1)	0.70			0.36			
Using this product makes me feel unsafe.	-0.57	-0.45					
*Using this product makes me overexerting myself.***	-0.52	-0.50					
*The way(s) in using this product are satisfying for me.***	0.50	0.36			0.33		
This product is suitable for use in the public spaces.(5)	0.49				0.38	-0.39	
I do not prefer this product to use in the public spaces.	-0.49						
*This product can be used without having to repeat any motion.***	0.48				-0.32	-0.35	0.36
Using this product causes pain.**(2)		-0.77					
This product threatens my safety.**(2)		-0.75					
*This product can be used without uncomfortable postures.***	0.30	0.59					
*It is safe when using this product.***	0.41	0.56					
This product makes me want to save energy.(3)			0.85				
Using this product makes me want to save energy.(3)			0.83				
Using this product by me can help to reduce energy use in the buildings.(3)			0.74				
This product is obvious in the room.**(4)				0.87			
This product is easy to see in the room.**(4)				0.85			
The design of this product is satisfying for me.					0.66		
The design of this product would look suitable in the public spaces.(5)					0.56		
It would be surprising to see this product in the public spaces.(5)					-0.51		
This product looks clean and hygienic.					0.48		
Using this product in the public spaces can cause infection.(6)						0.73	
Using this product makes me feel unclean.(6)						0.59	
This product can not contribute to energy saving in the public spaces.							0.77
Using this product can control the light effectively.							-0.37
Percentage of variance (Extracted)	21.60	10.77	8.42	7.64	6.98	5.97	3.98

* Items which were directly taken from Beecher and Parquet (2005), ** Items which were reformulated or modified from Beecher and Parquet (2005).

Study 4: Assessments of user perceptions

The objective of this study was to test whether user perceptions of different light switches could be differentiated with regard to their particular characteristics, including affordances. It was expected that users would differentiate between the different switches' designs with regard to the different characteristics.

Method of Study 4

User perceptions were assessed in a controlled environment, an empty room with an approximate area of about 9.60 m^2 (3.00 m x 3.20 m). Nine different light switches and an occupancy sensor with manual override available in the Swedish market (Figure 3) were assessed with regard to characteristics selected from Study 3: affordances, suitability and ability to trigger energy saving of the switches, which were considered relevant to the context of use in public buildings. In addition, part of the semantic component description (SCD) (Sorte, 1982) for describing visual characteristics of objects in the built environment was used to assess user perceptions. Five items, i.e. simple, dark, over-dimensioned, boring and old-fashioned, were selected. These items correspond to characteristics reflecting articulation, lightness, scale, valence and age of the switches, respectively.

Figure 3 *The assessed objects (from the left, switch no. 1 to 10).*

The participants were Swedish, 25 males, 25 females (mean age = 39 years, age range: 17-64 years). The participants assessed the ten interfaces that were placed on the wall at about1.20 m above the floor (a common push-button switch used in Sweden (no. 1) was placed first as a point of reference). From a distance of 1 m, each participant responded to each of the interfaces by filling in a questionnaire (see Paper III) with initial perceptions. The questionnaire was constructed to determine whether the interfaces were perceived differently with regard to each of the characteristics.

Main results of Study 4

One-way ANOVA analysis (n = 50) showed significant differences in the mean scores of the participants' perceptions among the ten interfaces assessed for all the items and characteristics.

Post hoc tests ($p < 0.05$) revealed that the mean scores of perceived simplicity, affordance and suitability for use in public buildings for the commonly used switch (no. 1) were significantly higher than for most of the other interfaces. This commonly used switch was also perceived as very boring. The double size switch (no. 2) was perceived to hold the most over-dimensioned attributes; there were significant differences in the mean scores between this switch and the other nine interfaces. Switch no. 2 was also perceived as having an affordance; however, the perceived affordance was significantly lower when compared to the commonly used switch. It should be noted that the participants' perceptions regarding lightness of the interfaces were significantly affected by the frames' colours. Moreover, there were no significant differences in the perceived ability to reduce energy use between all of the on/off light switches; the highest mean score of perceived ability to reduce energy use (M = 3.66, SD = 1.15, n = 50) was held by the occupancy sensor with manual override (switch no. 10).

Additional analysis and results

In addition, it was expected that general lighting-use behaviours would affect user perceptions regarding the ability of the interfaces to trigger energy saving, i.e. people who always carry out behaviours that contribute to energy savings would perceive no difference in such ability (measured by the item: 'Using this product can help to reduce energy use') between manual on/off switches and occupancy sensors with manual overrides. This hypothesis was tested by examining the possible association of general lighting-use behaviours with the perceived ability to reduce energy use of the commonly used switch as compared to that of the sensor with manual override. Thirty-five out of 50 participants reported their general-lighting use behaviours with four items (see Paper IV). It was found that the participants' general lighting-use behaviours correlated weakly and insignificantly with both the perceived ability to reduce energy use of the common manual on/off switch (r = 0.19, n = 34) and that of the sensor with manual override (r = -0.17, n = 34).

Study 5: Field observations

Based on the results of Study 4, Study 5 was conducted to investigate the effects of different light switch designs on occupants' optimal lighting use (in this case, switching on electric lighting when needed and switching it off when not needed). It was expected that several characteristics of light switches that positively affect occupants to use lighting optimally would be identified.

Method of Study 5

The study took place in a public toilet located in a patient ward in a hospital in Stockholm, where occupants had fully individual control over electric lights by means of a manual on/off switch (Figure 4). The toilet had no access to daylight and was intended for visitors, but staff and patients could also use this facility. Three light switches (see Figure 4) of different size and colour were selected for the test because user perceptions of them were found to be significantly different from those of the commonly used interface (switch no.1) regarding most of the characteristics studied in Study 4 (see Paper III). In particular, one of the switches was selected due to interest expressed in its oversized features. The switches were tested against the original switch, which was similar to the commonly used switch in Study 4.

A data logger was used to continually observe use of electric lights and occupancy in the toilet. It was likely that the occupants using the facility would switch on the lights when entering and then perhaps switch them off when leaving. Observations were first made for the original switch for 30 days and thereafter for the three selected switches one at a time for 30 days. The logged data were then checked at one-minute intervals. It was assumed that the toilet could generally be used by individuals for ≤ 5 minutes each time. Therefore, optimal lighting use was counted when it was seen that the lights were switched on and then off within this short period of time (the toilet was sometimes used continually for longer than five minutes but this rarely occurred and was excluded from the data analysis).

For each of the observed switches, the number of occasions when the lights were on-off within a period of five minutes was calculated as a percentage of total light-on occasions for each day. Differences between the observed switches in the mean percentages for the occasions when the lights were switched on-off within five minutes were examined.

Main results of Study 5

Kruskal-Wallis test analysis revealed significant differences in the mean percentages across the four switches: X^2 (3, n =120) = 8.09, $p < 0.05$. As shown in Figure 4, the highest mean percentage corresponded to the switch of double size (C). Further, Mann-Whitney U tests with a 2-tailed test of significance[3] showed a significant difference in the mean percentages between this switch and the switch with green frame (B). Moreover, when comparing the double sized switch to the switch with red frame (D), a difference in the mean percentages was found to be close to a significant level.

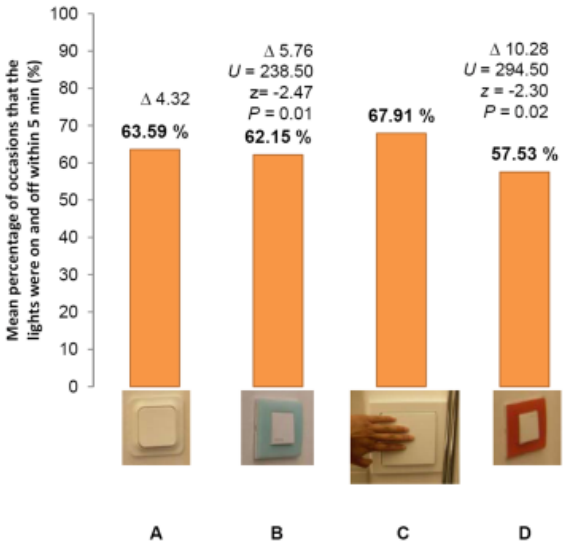

Figure 4 *Mean percentages for the switches observed: the original switch (A) and three selected switches B, C, and D.*

[3]a Bonferroni correction gave a stricter alpha level of 0.05/4 = 0.013

Discussion and conclusions of studies 3, 4 and 5

Taken together, the three empirical studies investigated differences in electric lighting use due to user perceptions of light switches' characteristics in public buildings. The results of Study 3 verified that light switches can be evaluated with regard to their design characteristics that visually communicate with users. In this study, six characteristics of light switches were identified using the design principles as a starting point. Moreover, the significant associations found between the design characteristics may indicate that these characteristics support each other's communication with users. The significant differences in the participants' perceptions found among the switches with regard to the six characteristics identified suggest that users differentiate between different characteristics in different designs of these everyday interfaces.

Study 4 revealed differences in the participants' perceptions of the different light switches with regard to particular characteristics, including affordances, thereby affirming that user perceptions of different designs of user interfaces can be distinguished with regard to design characteristics. However, it should be noted that no effect was detected for the perceptions relating to the ability to reduce energy use of the switches when the sensor with manual override was excluded from the comparison. The perceived ability to reduce energy use of the occupancy sensor was found to be relatively high. Based on Goodman (2009), this may be because the participants did not consider electrical losses caused by use of the sensor. The additional results, on the other hand, suggest that manual switches and occupancy switch-off sensors may be perceived similarly regarding the ability to reduce energy use by individuals who generally carry out lighting-use behaviours that contribute to energy savings. It should also be noted that the factor analysis' outcomes showed a significant association between affordances and simplicity of the switches. However, whereas an effect of double size was found for the perceived affordances, there was no effect found for the perceived simplicity (see Paper III). Further, colour features were found to affect the perceived suitability but had no effect on the perceived affordances.

Finally, the results of Study 5 suggested that different design characteristics of the switches had an effect on optimal lighting use in a public toilet owing to the significant differences in lighting use detected among the switches. Compared to the commonly used switch, the switch perceived as simple, very over-dimensioned and as having a relative affordance in Study 4 was found to affect occupants to switch off the lights more often when leaving the facility. This finding may imply that simplicity

and oversize of the switch (as measured by the SCD's items) could support an affordance in encouraging the behaviour. Regarding other characteristics of the switches, their potential to support affordances as well as optimal lighting use behaviour was questionable.

In general, it was found that an effect of different designs of light switches was more apparent for the participants' perceptions regarding the switches' characteristics than for the occupants' optimal lighting use. However, together the empirical results suggest that it is possible to identify characteristics of lighting control user interfaces that attract attention, and thereby encourage optimal lighting use among individuals and promote energy reduction in public buildings.

The concluding findings are as follows:

- Everyday user interfaces, i.e. light switches, were able to be evaluated with regard to their design characteristics that visually communicate with individuals.

- Different designs of light switches were found to affect the participants' perceptions with regard to the characteristics studied and the occupants' optimal lighting use.

- By combining oversize with simplicity of the switches, it was possible to support affordances to prompt occupants' switching off lighting when not needed.

Finally, it should be noted that optimal lighting use may be more dependent on individuals than design characteristics of the interfaces. This is supported by Study 5, which showed that differences in the occupants' optimal lighting use between pairs of the investigated switches were mostly non-significant. Additionally, it was often seen that once an occupant left the lights on, the lights remained on after the next occupancy.

PAPER IV

Study 6

The main objective of this study was to investigate the effects of characteristics (i.e. affordances) of user interfaces and individual-based factors (i.e. satisfaction with lighting, TPB factors and general lighting-use behaviours) on occupants' optimal lighting use in shared environments to determine the significant factors for this specific kind of context. Specifically, it was expected that (i) affordances of the interfaces would be associated with the behaviour via perceived behavioural control (PBC), and (ii) TPB factors as well as satisfaction with lighting and general lighting-use behaviours would in turn be associated with the behaviour.

Method of Study 6

The study took place in a dining room and a dayroom in two patient wards in a hospital, which was designed and built under the 1960s, in Stockholm, Sweden. The dining room and the dayroom were located on the seventh and eighth floors, respectively, and had access to indirect daylight through eight-glazed windows. General lighting in the rooms was provided by ceiling lamps that could only be operated manually using push-button on/off switches located at the entrances. During the period of data collection, the original switch or one of two alternative switches (See Figure 5) were present in each room.

Data on occupants' optimal lighting use as well as characteristics (i.e. originality in the physical environment, affordances of the switches) and individual-based factors (i.e. TPB factors, satisfaction with lighting and general lighting-use behaviours) were collected by means of a questionnaire (see Paper IV). Occupants of the two rooms, including staff, patients and visitors, were asked to answer the questionnaire on three occasions of data collection. A total of 42 questionnaires completed by 27 staff and 13 patients (nine males, 31 females, mean age = 44.15 years, age range: 20-69 years) were used to analyse possible associations of the variables studied with intention to use lighting optimally and associated behaviour.

Main results of Study 6

It was found that the perceived affordances of the switches correlated moderately with perceived originality in the physical environment (r_s = -0.40, n = 35, p < 0.05) and PBC (r_s = 0.37, n = 41, p < 0.05). Moreover, there was a strong, negative correlation between the occupants' satisfaction of lighting in the rooms and their intention to use lighting optimally (r_s = -0.59, n = 42, p < 0.01); this implied that the less the occupants were satisfied with the lighting, the more likely they were to use the lighting optimally (i.e. adjust the lighting to meet their preferences). There were no significant correlations of TPB factors: attitudes, SN and PBC) with the intention. However, a subscale measuring attitudes, i.e. affective related beliefs, was found to correlate strongly with the intention (r_s = 0.51, n = 42, p < 0.01). The behaviour of interest, i.e. optimal lighting use, was found to correlate moderately with the intention (r_s = 0.34, n = 42, p < 0.05) and general lighting-use behaviours of the occupants (r_s = 0.37, n = 38, p < 0.05).

In a logistic regression model for predicting the intention, satisfaction with lighting and affective-related beliefs were found to be significant predictors (X^2(2, n = 42) = 27.56, p < 0.001); the strongest predictor was affective-related beliefs (Odds Ratio, Exp (B) = 4.47). In a model developed for predicting the behaviour, the intention and general lighting-use behaviours were significant predictors (X^2(2, n = 42) = 10.59, p < 0.01); the strongest predictor was the intention (Odds Ratio, Exp (B) = 4.43).

Additional analysis and results

In addition, it was expected that familiarity and friendliness in the social situation in the rooms would be associated with PBC. The occupants' perceived familiarity was assessed by 4 scales: different, everyday, traditional, unfamiliar, whereas the perceived friendliness was assessed by another 4 scales: friendly, comfortable, sociable, respectable (Küller, 1978; 1991); the responses to these scales ranged from '1' = slightly to '7' = very. However, PBC was found to correlate weakly and insignificantly with perceived familiarity- (r_s = 0.10, n = 39) and perceived friendliness (r_s =0.23, n = 40) in the social situation.

Remarks on Study 6

The association found between the perceived affordances of the switches and PBC is notable because it shows a link between a design characteristic of these common interfaces and an individual-based factor of building occupants and that integrating the theory of affordances with the TPB can be useful for exploring whether the interfaces' designs can affect energy-saving behaviours. Moreover, the association found between the perceived affordances of the switches and perceived originality in the physical environment may underline the importance of the physical environment in affecting user perceptions of the interfaces.

Study 7

This study was conducted to investigate the effects of different designs of interfaces on occupants' lighting use in shared environments. It was expected that physical features of the interfaces would be associated with occupants' lighting use. It was further expected that critical features affecting occupants' lighting use could be identified.

Method of Study 7

This study took placed in a dining room and a dayroom in two hospital wards, the same settings as in Study 6. Besides the original switches installed in the rooms, switches differing in colour or shape (see also Figure 5) selected from Study 4 were tested.

Data on occupants' lighting use in each room were collected by direct observations conducted by a researcher and electronic measurements using a data logger. Data collection was first made for the original switch. Afterwards, the selected switches were installed in the rooms one at a time; data collection for each switch started about one week after the installation. The researcher observed lighting-use activities concerning use of general lighting (ceiling lamps) of each occupant when s/he entered and left the rooms. For each switch and room, observations were conducted during non-visiting hours and visiting hours on a weekday and visiting hours on a holiday for about 12 hours in total, whereas a data logger was employed to continually monitor use of ceiling lamps for 30 days. The logged data were then scrutinised at one-minute intervals; use of the lighting was operationalised as the number of occasions that the

lighting was used, so-called lighting-use occasions (times) and energy usage (in kilowatt-hours (kWh)) per day. For each room, associations of different designs of the switches with occupants' observed lighting-use activities and data on lighting use were examined.

Main results of Study 7

Generally, it was observed that the occupants very rarely adjusted the lighting by using the switches. Chi-squared tests for independence revealed no significant associations between the different light switch designs and occupants' lighting-use activities observed in both the dining room ($X^2(2, n = 269) = 1.17$, $p = 0.56$ (2-sided), Cramer's V = 0.07) and dayroom ($X^2(2, n = 166) = 1.65$, $p = 0.44$ (2-sided), Cramer's V = 0.10).

In contrast, for the logged data, Kruskal-Wallis tests showed significant differences in mean values of lighting-use occasions among the different light switches placed in the dining room ($X^2(2, n = 90) = 14.89$, $p < 0.005$) and dayroom ($X^2(2, n = 90) = 10.16$, $p < 0.01$). Similarly, there were significant differences in mean values of energy usage for both the dining room ($X^2(2, n = 90) = 12.76$, $p < 0.005$) and dayroom ($X^2(2, n = 90) = 13.36$, $p < 0.005$). As shown in Figure 5 (a), the lowest mean values of lighting-use occasions and energy usage in the dining room corresponded to the original switch (A). Mann-Whitney U tests with a 2-tailed test of significance[4] showed a significant difference in mean values of lighting-use occasions between this switch and the switch with a red frame (C). Compared to the other two switches, the mean value of energy usage for switch A was significantly lower. Moreover, no significant differences in the mean values were found between switches B and C. As shown in Figure 5 (b), the lowest mean values of lighting-use occasions and energy usage in the dayroom corresponded to the switch with a red frame (E). Compared to the original switch (D) and switch F, mean values of lighting-use occasions and energy usage for switch E were significantly lower. No significant differences in the mean values were found between switches D and F, which had the same colour but different shapes.

[4] a Bonferroni correction gave a stricter alpha level of 0.05/3 = 0.017

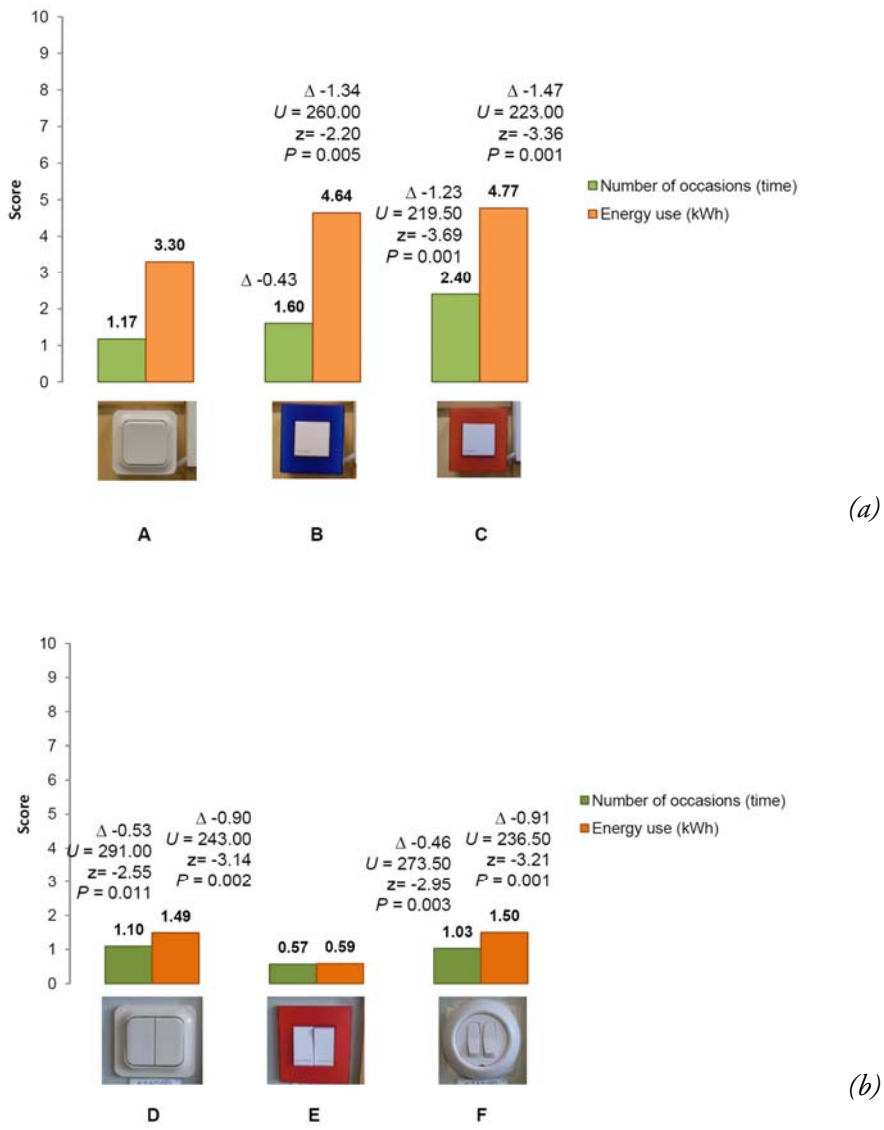

Figure 5 *Mean values for the original switches and the alternative switches in the dining room (a) and the dayroom (b) and comparison of the values.*

Remarks on Study 7

The results suggested that different design features such as shapes and colours of the switches had no significant effect on occupants' lighting-use activities observed by the researcher. However, effects were identified for lighting-use occasions and energy usage per day determined from data captured continually by data loggers. It should be noted that if the original switches are perceived as having high affordances (Maleetipwan, 2010), the results obtained from each of the two rooms appeared to

contradict each other regarding the effects of affordances on lighting-use occasions and energy usage.

Based on the Study 4 results, the original switches could be perceived to have more affordances than all the selected switches, except for switch F installed in the dayroom, the design of which was similar to ones used in Sweden since about the1930s. Moreover, switch E, which corresponded to the lowest mean values of lighting-use occasions and energy usage in the dayroom, was perceived as having few boring- and old-fashioned attributes in Study 4 compared to the other two switches in the room.

Discussion and conclusions of studies 6 and 7

Together, these two studies investigated the effects of user interface designs and individual-based factors on occupants' optimal lighting use in hospital shared environments and revealed important factors for optimal lighting use.

According to the results of Study 6, satisfaction with lighting, affective-related beliefs (which in this case concerned the importance of regulating lighting in the present environments) and general lighting-use behaviours were identified as individual-based factors that significantly contributed to occupants' optimal lighting use in the shared environments investigated. More specifically, the results implied that these individual-based factors played a more significant role than design characteristics (i.e. affordances) of the interfaces in affecting the occupants' optimal lighting use. As previously noted by Verplanken and Aarts (1999), habits may strengthen the affective component in attitudes towards habitual behaviours. It seems reasonable to assume that affective-related beliefs and general lighting-use behaviours may be related to each other. As a subscale for measuring attitudes, affective-related beliefs alone were found to be most associated with occupants' intention to use lighting optimally and had a significant influence on the behaviour. When combining affective- and outcome-related beliefs as attitudes, there was no significant association identified between this variable and the behaviour. Apart from attitudes, no associations of subjective norms and PBC with the behaviour were identified.

The Study 7 results indicated that different design features (i.e. shape and colour) of the interfaces had a significant effect on lighting-use occasions and energy usage per day in both investigated environments. The results also suggested that the effect of

different colours was larger than that of different shapes. However, it was not possible to identify specific characteristics relating to the colour and shape that could potentially promote energy reduction. It should be noted that the results from each of the two environments seemed to contradict each other regarding the effects of affordances. This may, to some extent, supports the Study 6 results, which suggested no significant influence of the perceived affordances of the interfaces on the occupants' optimal lighting use.

Overall, the results of these two studies imply that both individual-based factors and designs of user interfaces are important in influencing occupants' optimal use of lighting in shared environments. Hence, these factors in parallel should be considered when designing behavioural change interventions to reduce energy use in such environments.

The concluding findings are as follows:

- Affective-related beliefs were identified as being a strong predictor of behavioural intention to use lighting optimally, thereby suggesting the impact of affect on individuals' optimal lighting use in shared environments.

- Besides intention, occupants' general lighting-use behaviours were found to contribute to the prediction of optimal lighting use in this specific context.

- The effects of different designs of the interfaces on the number of lighting-use occasions and energy usage point to that careful consideration of user interface designs could help to encourage optimal lighting use among building occupants.

Since PBC addresses behavioural capability (Dills et al., 2014), which is a crucial factor behind whether individuals will regulate the lights, it is also worth considering the significant association between PBC and affordances of user interfaces.

CONCLUDING DISCUSSION

This work described in this thesis explores occupants' responses to different designs (types) of lighting controls and user interfaces at an individual level. The main motivation behind was to gain a better understanding of how designs of lighting controls and user interfaces can be used to persuade individuals to use lighting optimally in non-residential buildings. This is important as it could make a substantial contribution to energy savings in such buildings, and thereby reduction of GHG emissions. The responses to the controls' designs were operationalised as (i) perceptions of lighting quality, (ii) behaviours in relation to optimal use of electric lighting, and (iii) energy usage associated with use of the controls. Besides optimal use of the lighting, the responses to the interfaces' designs were operationalised as perceptions of design characteristics of the interfaces that visually communicate with users, particularly affordances. In addition, individual-based factors and characteristics of the physical and social environment were investigated in relation to the responses to the different interface designs.

Occupants' optimal lighting use and the effects of relevant factors

In this work, 'optimal lighting use' was considered as occupants' use of electric lighting with different lighting controls and user interfaces to achieve energy savings and provide comfort for individuals. This simple approach provided insights into how lighting is used in relation to occupancy and individual perceptions of lighting quality. This information could be used to communicate the effects of occupant behaviour on lighting energy use in relation to different designs of lighting controls and user interfaces.

Overall, this work showed that designs of lighting controls and user interfaces play a significant role in affecting perceptions and energy use behaviour. Moreover, the relationship between the designs and the behaviour seem to be mediated by individual-based factors (in this work, satisfaction with lighting, affective-related

beliefs and general lighting-use behaviours were identified as important variables influencing whether individuals use lights optimally). Concerning methodology, the work also demonstrated that a self-report diary was a useful instrument for measuring occupants' use of electric lighting and characterising energy usage with lighting controls. However, the diary form used needs to be improved to include dimming controls (see Paper I). Also, applying self-reports together with electronic measurements and/or observations can be useful for gathering information on actual occupant behaviour and lighting energy use in different types of indoor environments.

Behavioural outcomes

In the single-occupant offices, the individuals' lighting-use-related behaviours were captured by means of both a self-report diary and electronic measurement using a data logger. Generally, most of the occupants reported that they left the lights on when they left their offices during the day, especially for short periods. In line with the self-reported data, the logged data showed that most of the lights were usually left on unnecessarily (i.e. when offices were unoccupied) and were rarely adjusted manually during the day. The data captured in the offices were similar to those observed in the dining room and dayroom of the hospital wards, which showed that existing lighting conditions were rarely adjusted (switched on/off or dimmed) manually by individuals regardless of the length of their occupancy time.

In contrast, in the public toilet studied, it was found that in more than 57% of the total observed cases, individuals switched the lights off when leaving the facility. This may be due to differences in occupancy patterns between public toilets and single-occupant offices or shared environments. The office occupants may have intentionally left the lights on when leaving their respective offices for a short period of time because they felt it indicated they were present at work (Moore, Carter & Slater, 2003). Another possible reason is that the occupants may not have realised that energy savings could be made by just turning the lights off for short periods (Rea, Dillon & Levy, 1987). The occupants of the dining room or dayroom may have avoided switching off the lights because, according to Moore, Carter and Slater (2002), they considered other occupants. In contrast, occupants may have been more likely to switch off the lights when leaving the toilet because people usually do not come back to the facility within a short time. Taken together, the data obtained may imply that different environmental contexts affect occupants' use of electric lights

differently, and therefore have an important influence on an individual's energy-saving behaviour.

It was also observed that when an occupant did not switch the lights off when s/he left the toilet, the lights tended to be left on after the next occupancy. In this case, the occupant may have left the lights on because s/he believed that the toilet would be used again by others in the ward. Another possibility is that because automatic switch-off after occupancy controls are commonly in use in non-residential buildings today, the occupants did not manually switch off the lights because they relied on this kind of lighting controls. Analogously, office occupants with occupancy switch-off options usually left the lights on when they left their respective offices during the day. It can thus be assumed that habitual behaviour such as neglecting to manually switch off lighting owing to the use of occupancy-switch off controls could be formed among building occupants, and therefore could significantly contribute to unnecessary lighting energy use in non-residential buildings.

Effects of lighting control and user interface designs

In Study 2, variations in the use of lighting and perceptions of lighting quality were found among the office occupants, thereby indicating that the lighting control design had an important influence. However, it should be noted that the variations in use of lighting were partly due to variations in occupancy patterns among the occupants. This study found that use of occupancy switch-off controls could bring about a reduction of light-on time and that the use of manual or daylight dimming controls could lower energy use per hour. These findings highlight the potential of combining dimming with occupancy switch-off controls for achieving optimal lighting use. As suggested by Jennings et al. (2000), occupants who leave their offices frequently during the day are likely to benefit the most from occupancy switch-off controls. However, manual on/off controls could be used instead of occupancy switch-off controls if occupants utilise their offices for most of the day; this may indicate that the specifics of user interfaces have an impact on occupants' optimal lighting use. Moreover, the study suggested that occupancy, use of lighting and perceptions of lighting quality of individuals should be taken into account when designing lighting controls in non-residential buildings.

In the offices investigated, the user interfaces for lighting controls comprised two kinds of wall-mounted on/off switches with different design features placed close to the door and one kind of pull-cord switch placed within arm's reach above the desk.

According to Lindelöf and Morel (2006), the traditional position of close to the office entrance is likely to affect occupants' use of manual controls within a short time after arrival or before departure. They have also pointed out that the traditional position is likely to dissuade occupants from using dimmable features to dim the lights; instead, occupants tend to only switch the lights on or off completely. However, in this thesis work, no difference in self-reported switching behaviour in the offices was found among the user interfaces with differences in design features and position (see Paper I). Generally, the occupants reported that they manually switched the lights on once at the beginning of the day and then did not do anything until the end of the day, when they manually switched the lights off upon departure. These self-reported switching patterns are similar to previous findings from observations of lighting-use behaviour in office environments (Jennings et al., 2000; Reinhart & Voss, 2003; Moore et al., 2003; Boyce et al., 2006).

Different designs of light switches were further investigated considering the context of public buildings because these everyday interfaces generally interact with a wide range of users. It was found that different designs of the switches affected the participants' perceptions with regard to the particular design characteristics and use of electric lighting in hospital wards in two distinct types of environment: (i) a public toilet, where a single occupant had full control over the environment as well as lighting, and (ii) a dining room and a dayroom, where occupants generally shared the environment and lighting.

The switch perceived as simple, having a relative affordance and oversized was identified as having the greatest positive effect on occupants' optimal lighting use in the toilet. This somewhat affirms the significance of designing simple and easy-to-use interfaces in reducing lighting energy use (Galasiu & Veitch, 2006). Moreover, oversize and simplicity of the interface could be identified as characteristics supporting an affordance to encourage optimal lighting use among building occupants. The characteristic of oversize agrees with Liedberg and Sperling (1982), who stated that light switches must have large push buttons to give an advantage in coordination and make it possible to manage the switches with the palm. In the shared environments, it remains unclear whether affordances due to colours and shapes of the switches affected occupants' use of electric lighting from ceiling lamps. Also, the effects of other characteristics on occupants' optimal lighting use in different environments need to be investigated further.

Overall, the findings show the possibility of identifying characteristics and physical features of the interfaces that facilitate energy reduction in non-residential buildings.

Moreover, light switch designs could affect users' perceptions regarding the physical safety, hygienic use and ability to reduce energy use of the switches; these characteristics may be related to affective responses, and thereby occupant behaviour in non-residential buildings. It should be noted that different designs could produce different effects on perceptions (e.g. colour features were found to affect the perceived suitability but no effect was identified for the perceived affordances).

Effects of individual-based and environmental factors

In Study 6, a number of individual-based factors mediating the relationship between designs of light switches and individuals' optimal lighting use in shared environments were identified, namely individuals' satisfaction with lighting, affective-related beliefs (in this case, the importance of regulating lighting in the present environment) and general lighting-use behaviours (see also Maleetipwan-Mattsson et al., 2012).

In the shared environments investigated, the individuals' satisfaction with lighting and affective-related beliefs were found to have a significant influence on their intention to use lighting optimally, whereas general lighting-use behaviours were found to have a significant influence on the behaviour. It seems reasonable to assume that the individuals who generally used electric lights in a way that contributes to energy savings were most likely to use lighting optimally in these particular environments. Moreover, the results of the additional analysis suggested that the participants who always carried out general-lighting use behaviours that contribute to energy savings were most likely to perceive no difference in the ability to reduce energy use between manual on/off switches and occupancy sensors with manual overrides. This may imply that people who generally carry out lighting energy-saving behaviours may not always rely on technological solutions (e.g. occupancy-switch off sensors) to reduce energy use.

No significant associations of perceived behavioural control (PBC) and subjective norms (SN) with occupants' optimal lighting use were identified in the shared environments investigated. The results concerning SN showed that the individuals perceived low social pressure to regulate lighting; this is consistent with the notion (Figueiro, 2004 cited in Galasiu, Newsham, Suvagau & Sander, 2007) that people generally do not feel responsible to manually control lighting in shared environments. However, different social contexts may affect SN, and thereby behaviour; for instance, people working in environmental conservation organisations may perceive high social pressure to use lights optimally in shared environments in their workplaces. Although

no association was identified between PBC and optimal lighting use, it is important that PBC was significantly associated with the perceived affordances of the interfaces. This is because an individual's ability to perform certain behaviour is likely to depend on the degree of PBC, which in this case was associated with the perceived affordances of the light switches used.

Moreover, the significant association identified between the perceived affordances and perceived originality (unusual or surprising) in the physical environment, which in this case may refer to a common position of lighting control user interfaces in the room, may highlight the potential role of the physical environment in affecting user perceptions of the interfaces. This finding differs from preliminary results (Maleetipwan-Mattsson et al., 2012), which showed a weak, non-significant association between the perceived affordances of light switches and perceived originality in the physical environment. Dill et al. (2014) have shown that the physical environment is important in influencing biking and walking behaviour because it influences PBC and attitudes. Thus, it is possible that the characteristics of user interfaces and the physical environment may have a combined effect in influencing PBC, attitudes, and thereby optimal lighting use in non-residential buildings. In addition to the aforementioned findings, no significant associations were identified between PBC and the occupants' perceptions regarding familiarity and friendliness in the social situation, suggesting a non-significant role of social interactions in influencing occupants' optimal lighting use in shared environments.

Interventions to reduce building energy use

Taken together, the results presented in this thesis demonstrate the importance of considering individual-based factors and lighting control and user interface designs when designing behavioural change interventions to reduce energy use from electric lighting in non-residential buildings. Based on these results, optimal lighting use should be encouraged by promoting affective-related beliefs towards the behaviour and by environmental interventions focusing on the designs of lighting controls and user interfaces. In particular, the interface design could be used to prompt occupants to switch off lighting rather than using reminder stickers on switch plates because, according to Rea et al. (1987), there could be an issue concerning user acceptance of such reminders. Considering the influence of general lighting-use behaviours on optimal lighting use, careful selection of the design would mostly benefit occupants who generally carry out energy-saving behaviours (e.g. switching lights off when a

room is unoccupied). It is also important to consider characteristics of the physical environment as well as positions of the controls and user interfaces as they may also affect occupants' perceptions and behaviour.

Environmental interventions should also be examined to determine the extent to which they can be successfully used to change occupant behaviour. This is particularly relevant in relation to the presence of habits, which can be resistant to behavioural changes (Sauer & Rüttinger, 2004; Steg & Vlek, 2009). According to Steg and Vlek (2009), people are very likely to leave out information that is not in line with their habitual behaviour. However, effective interventions to modify habitual behaviour can be designed by taking account of how habits are formed, supported and sustained. Concerning energy-saving behaviours, Swenson and Siegel (2013) have shown that decorating stairwells could increase stair use over elevator use among occupants of two-to-three storey office buildings and that the effects could be sustained for over 6 weeks. Also, the use of reminder stickers on switch plates has been shown to be effective in reducing lighting energy use in single-occupant offices in the long term (Rea et al., 1987).

Generally, the results indicate the potential of effective lighting control and user interface designs in encouraging optimal lighting use among occupants in non-residential buildings. In relation to habits, it was seen that some of the office occupants continued their habitual switching patterns throughout the one-year study period. This finding is particularly promising for optimal lighting use and energy savings if occupants habitually switch off lighting every time in unoccupied rooms or when daylight is sufficient in the room. Moreover, the results of the field observations in a public toilet seem to suggest that switching off lighting may also be dependent on habits; in this case, the facility was possibly used by the same group of staff and these users may have maintained their lighting-use habits.

General remarks

The work in this thesis attempted to investigate the role of lighting control and user interfaces designs in affecting individuals' use of lighting in non-residential buildings. The main finding was that the design can have a strong effect in encouraging occupants' optimal lighting use to achieve energy savings and provide comfort for individuals in such buildings.

One of the main concerns is that different designs (types) of lighting controls and environmental contexts could affect occupants' use of lighting differently. Another concern is that individuals' occupancy patterns play an important role in the effectiveness of lighting control solutions. Further, this work shows that lighting energy use could simply be reduced by designing simple and oversized user interfaces for lighting controls. It is also important to consider the role of the physical environment in affecting occupants' perceptions of the interfaces as well as individual-based factors that mediate the relationship between the interfaces and optimal lighting use.

A few remarks on the methodology could be made. First, the self-report items measuring the perception regarding hygienic use of the interfaces, affective-related beliefs and SN need to be further developed to improve the internal reliability. Second, only a limited number of lighting controls, user interfaces and types of environments were investigated to derive general conclusion regarding what designs encourage occupants' optimal lighting use in non-residential buildings. Moreover, the ability to generalise the results, particularly regarding perceptions of the interfaces' characteristics, may have been limited because the study was only conducted on Swedish participants; according to Desmet and Herkkert (2007), cultural differences can influence individuals' responses to products.

In further studies, it would be desirable to examine a greater number of lighting control and user interface designs together with individual-based factors with a larger sample size and in different environmental and cultural contexts. It would also be interesting to continue examining the effectiveness of different designs in encouraging building occupants to use lighting optimally (e.g. by systematically examining the effects of designs in relation to habits) and attempt to identify more design characteristics of the interfaces that positively affect the behaviour.

Implications

Implications for research

The effects of contextual factors on environmental behaviour have become a topic of interest in environmental psychology research (Steg & Vlek, 2009). In the work presented in this thesis, the theory of affordances and theory of planned behaviour (TPB) were integrated as parts of a conceptual framework to specifically link designs

regarded as contextual factors to an individual-based factor, i.e. perceived behavioural control (PBC), which together were hypothesised to influence optimal use of electric lighting among individuals in non-residential buildings.

According to the studies' results, there was (i) a significant association between affordances of the interfaces and PBC, and (ii) no significant influence of PBC on optimal lighting use. These findings may demonstrate that the framework is suitable for systematically exploring the relationship between contextual factors and energy-saving behaviour. Since, affordances cover all scales of the physical environment, the framework may be applied to studies on various scales of designs, from small-scale products to large-scale urban and regional environments. Further, the framework may be modified to include more characteristics of the physical environment that facilitate and/or constrain affordances or PBC, and thereby the behaviour. Although the thesis results showed no association of familiarity and friendliness of the social situation with PBC, the role of social environment should still be considered. There may be other aspects of the social environment related to the behaviour. Also, the social environment may be associated with the perceived affordances of situations (e.g. Church, Katigbak & del Prado, 2010).

Regarding the measurement of behaviour, some of the studies included in this thesis were conducted in line with previous suggestions for future research (Steg & Vlek, 2009) i.e. actual behaviour should be measured and more attention should be paid to the validity and reliability of self-reported data. Considering the methodology used to acquire individuals' use of lighting in non-residential buildings, our findings highlight the importance of multiple modes of measures (e.g. combining self-reports and measurements from data loggers). Moreover, the information on occupancy and electric lighting use derived from these studies can be applied to simulation techniques for refining individuals' behavioural patterns (e.g. occupancy and switching patterns), thereby contributing to more accurate prediction of energy demands and potential savings in non-residential buildings.

Implications for practice

There has been an increased interest in occupant energy-use behaviours owing to the need to make energy savings in all walks of life, and behavioural change is one approach proposed to reduce energy use in organisations (Scherbaum et al., 2008). The results of the present work may benefit this approach in two ways. First, the success of using the different methods in visualising occupants' optimal lighting use

suggests that these methods could be used to provide valuable feedback to both organisations and individuals. In particular, comparison of light-on time with occupancy time offers a simple way of evaluating how lighting is used by individuals. Second, the information on important factors affecting occupants' optimal lighting use, e.g. types of lighting controls, designs of user interfaces, occupancy patterns, lighting-use behaviours, perceptions of lighting quality and affective-related beliefs, would facilitate the design of effective behavioural change interventions to reduce energy use from lighting in non-residential buildings.

The concept of affordances has practical value as a useful tool for evaluating designs in relation to user experience (Maier & Fadel, 2009). Hence, it could be employed as a platform for practically examining user perceptions with regard to characteristics of lighting control user interfaces, which could aid design improvements with respect to users' viewpoints. The results of the empirical studies suggest that the interfaces' characteristics perceived by users are highly important in encouraging optimal lighting use, as well as affordances, implying that effective design of the interfaces could achieve substantial energy savings in buildings by affecting the perceptions and consequential behaviour of users.

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APPENDIX

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