Shared control in office lighting systems

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Tatiana Lashina

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Contents

Summary

Occupant-controlled lighting has been explored already for several decades that resulted in a vast scientific evidence underpinning its benefits. It enables to adjust lighting systems to the diversity of lighting preferences of office users of different age, conducting tasks with different lighting requirements that cannot be satisfied with a fixed lighting level. Personal control has been shown to be associated with higher perceived lighting quality, higher office appraisal, more pleasant mood, higher motivation and improved subjective well-being, higher job satisfaction, higher organizational commitment, and lower intent to turnover. All this evidence has been demonstrated for lighting control in a single user situation in which control was affecting the individual workplace of that user. With the wide-spread open plan offices today where there is no direct mapping between the luminaires grid and the desks arrangement, and the desks are positioned close to each other it is no longer feasible to offer personal control that would affect only the individual desk. Lighting control could be offered in open office spaces by combining luminaires into luminaire control groups affecting clusters of desks underneath and controlled by several occupants occupying these desks. This form of control has been referred to as shared lighting control.

The question arises whether some of the benefits known for personal control could apply to shared control or whether the potential conflict among office users, preferring different lighting conditions, would overshadow the benefits of control. This is the central question of the current thesis.

To explore the experience of users with shared lighting control the first step was taken to design a user interface (UI) solution for controlling lighting conditions in an office that would be easy to interpret and to use by office

occupants. To achieve this goal an iterative user-centered design process was used that involved proposing four user interfaces concepts, evaluating them in an expert review, redesigning the UI and evaluating it within the context of the total light management system using the Wizard-of-Oz methodology. After most of the study participants gave positive feedback to the UI offering direct control of the lighting conditions, this UI was chosen to be used in the two subsequent field studies exploring the shared control.

To address the central research question two field studies have been conducted lasting respectively for three and a half and five months to compare the experiences of the participants with and without lighting control, whereby control was offered to them in the form of shared control. These studies demonstrated that in the condition with shared control the satisfaction with the lighting conditions was higher and that the frequency and the degree of conflict has been on average very low. The analysis of the social behavior revealed that individuals have been self-conscious of the presence of others in the office and deployed strategies meant to avoid conflict due to control of lighting. This finding advocates in favor of the system design that facilitates making environmental changes in a manner that is least disruptive to other space users.

Compared to the first field study the second study included daylight regulation and it evaluated three shared control strategies, “control set-point”, “memorizing” and “forgetting”. The results did not deliver evidence that would support the benefits of the control strategy “control set-point”, in which the user selected light level was treated as a set-point for daylight regulation. The results showed that when the system remembered the last level set by the user it resulted in a smaller amount of user actions and the resulting lighting conditions in the office better reflected individual preferences compared to the “forgetting” strategy in which the system was resetting overnight to its default state.

The first field study showed that individuals feel the nuisance of losing control over lighting stronger after control has been taken away compared to the satisfaction gain felt when they initially got control. This phenomenon is known in behavioral economics as the loss aversion cognitive bias and has been observed in other fields of technology innovations, like GPS navigation and mobile phones. This has implications for promoting beneficial effects of shared lighting controls in open office environments and appeals for the support from certification and regulation bodies like WELL.

The observed social dynamics in the conducted studies and the evaluation of the different control strategies demonstrate that there is a potential for further improvements in how shared control could be offered to office users to further increase its benefits.

1 Introduction

For hundreds of thousands of years, we, humans, evolved while spending most of our time outside and being part of nature [1]. This has attuned our biology from how our bodies store and use energy derived from food to how we react to our environment and how our environment affects our biological system. These days we are creating our own environments where we live and work. On this quest, as we progress along fulfilling higher levels in our hierarchy of needs [2], in the design of our indoor environments we are shifting the focus from the functional performance of buildings to how buildings can support and even enhance our well-being, including our mental health [3].

These trends are noticeable in the latest developments of the architectural design, spanning from hospitals with developments like healing environments [4] to the human-centric design of office spaces [5]. The industrial age of the 20th century created the dispiriting matrixes of office cubicles artfully ridiculed in the comedy of Jacques Tati *Playtime*. The workplace innovation [6, 7] spanned around the global office scene since around the beginning of the 21st century. It has transformed the modern office, introducing many environmental elements aiming at invigorating knowledge workers, spending the vast amount of time in office environments [8, 9, 10, 11]. As multinational corporations are fiercely competing to attract best talent, flag-ship offices with design lounge areas for socializing and coffee bars started to pop-up on the office buildings scene.

In her book ‘I wish I worked there’ Kursty Groves identified characteristics of the best office space designs she identified around the world, visiting offices of the companies representing the wealthiest and most recognized brands

[12]. Those design elements she categorized into the four categories of facilitating mental STIMULATION, REFLECTION, COLLABORATION and PLAY. A prominent example of a mentally stimulating environment, Kursty describes in her book, was created in the UK headquarters of Virgin (Figure 1). There, different meeting rooms had different themes in terms of its interior design, including color combinations. A *random meeting room generating* software application was offered to employees. For the purpose of the mental stimulation the application facilitated choosing different meeting rooms on different occasions.

Figure 1. A meeting room at Virgin headquarters (Groves, K., & Knight, W. (2010). I wish I worked there!: A look inside the most creative spaces in business. Chichester, England: John Wiley & Sons).

As real estate developers started to ask questions how to increase value of their buildings by among other aspects improving the environmental conditions for the occupants more need was created for research addressing office building comfort. These trends influenced the developments in office lighting, which is the largest sector in professional lighting industry [13].

These are the reasons why the focus context of the current thesis is office lighting.

1.1 Human-centric office lighting

Within the framework of human-centric design of buildings the design of lighting environments similarly experiences a strong advancement of human-centric lighting [13]. Peter Boyce has been leading in the research field of human-centric lighting and he defined it as "lighting devoted to enhancing human performance, comfort, health and wellbeing, individually or in some combination [15]." In early ages of this field the exploration of how lighting can support human visual performance for optimal productivity started with the classical experiments in Hawthorne Works plant [16]. Since then, a lot of research has been conducted exploring the questions of what contributes to the quality of luminous environments. This line of research has looked at the optimal workplace illuminance, directionality of light versus uniform light distribution, the influence of the incoming daylight, individual light level preferences of the occupants and the provision of lighting controls, the influence of the color temperature of light, the influence of the space wall illuminance and how it is related to the task at hand, among other aspects. This research that explored the determinants of lighting quality has been outlined in detail in several publications by Veitch and Newsham [17, 18].

Apart from static parameters of lighting within the human-centric lighting it has been recognized that evolutionary we have been exposed to constantly changing lighting conditions. Outside daylight conditions do not typically follow a predefined pattern and are very diverse [19]. Its spectral composition varies from light containing a large portion of the frequencies in the blue part of the visible spectrum. On the other side is the warm color light with dominant components towards the red visible spectrum that typically could be observed during hours around the sunset and sunrise as a breathtaking red colored sky. Apart from the variations in the spectrum, daylight demonstrates changes of the light intensity and directionality, both highly impacted by the weather conditions dynamics. Building architectural elements bring this dynamic inside office spaces with windows and skylights, that can be designed to either protect from direct sun glare or to bring in the interplay of light and shadow. The latest innovations in kinetic facades went even further by creating dynamic sunscreens that change in response to outdoor conditions including daylight, like in case of Aedas Architects' Al Bahar Towers in Abu Dhabi [20]. Despite the intuitive expectation of the beneficial effects of the dynamic changes of daylight, the psychological effects of this are not yet fully understood [19, 21].

The latest high-end office luminaires, commonly known as tunable white LED luminaires, have been designed to recreate the dynamic nature of daylight inside offices. These solutions artificially generate spectral and lighting intensity changes to optimally stimulate the human biological clock via exposure to the blue spectrum high intensity activating lighting in morning hours, while exposing office users to warmer lower intensity lighting in the afternoon [22]. Tuning the lighting spectrum to support concentration at work has been motivated by intentions to support alertness that is even more challenging in office spaces of night-workers, e.g., police, firemen, harbor control.

When triggering lighting changes in office spaces as part of automatic lighting control either as part of daylight regulation or due to occupancy changes it is important to be mindful about the potential distraction it could cause the occupants particularly in the context of concentrated office work. In this context understanding of the noticeable light changes plays an important role as system designers choose the parameters related to the speed of dimming but also to the perceptible dimming steps and how they vary dependent on the lighting output range [23, 71].

1.2 Occupant-controlled office lighting as part of human-centric lighting

An important piece of research within the human-centric lighting has been conducted to understand individual differences of people related to the experience of lighting conditions. An example that many would recognize relates to different light level preferences often causing disputes among people of the same household to agree which light level to choose. This recognition of differences led to developing lighting control solutions for tuning the lighting conditions in accordance with individual preferences. These control solutions evolved beyond the traditional on and off switches. They enable users to set the lighting dimming level, to vary the color temperature of lighting and even to use more sophisticated user interfaces to orchestrate lighting scenes resembling stage lighting shows. The latter applications have originally been brought in as part of lighting systems like Philips Hue for creating colored lighting atmospheres in home environments [24].

To promote evidence-based design choices for office buildings that enhance the wellbeing of their occupants and create incentives via building certification programs, a set of criteria is specified in the WELL Building Standard [25]. Some elements promoting a high standard of occupant comfort have already been included in earlier building sustainability assessment standards like BREEAM [26]. For example, provision of occupant-controlled lighting has been one of the BREEAM assessment criteria contributing to the total assessment points a building design could earn.

Within the academic field of office lighting perception, personal control of lighting has been recognized, based on the vast empiric evidence elaborated further in this thesis, as a beneficial feature for private offices and for settings where the user is controlling lighting affecting an individual workspace. Following the trend of workplace innovation when many offices were converted into open office spaces between 2005-2015 the question arose whether occupant-controlled lighting would still be beneficial in multiuser offices. This has become the core part of this research work. This question is explored within the context of the office lighting system that balances two goals: providing comfortable conditions to office occupants and ensuring optimal energy use. Although energy use is an important aspect deserving thorough consideration, the research described in this thesis focuses primarily on the user experience.

To make a distinction between different forms of occupant-controlled lighting, personal control will refer to the control of lighting that affects an individual workplace. Occupant-controlled lighting that is offered in multiuser offices where luminaires control groups, that can be as small as one luminaire, inevitably affect neighboring desks will be referred to as shared control.

1.3 Occupant-controlled lighting as part of the office lighting system

A lighting system is a lighting control solution that regulates the light output of the luminaires in an office space based on an algorithm that uses input from sensors. The sensor inputs could, for instance, include occupancy sensors used to switch on and off lighting dependent on the presence of people in an office space. This is a common energy efficiency measure to prevent lights from staying on while the space has been vacated. Next to occupancy, illuminance level sensors are typically used to estimate desk illuminance, that is composed of incoming daylight and artificial light falling on the desk surface, to optimize the luminaires’ output by maximizing the use of daylight. This is done in so-called daylight harvesting solutions that typically make use of a predefined set-point that determines the target desk illuminance based on office lighting guidelines. Following the European guideline this setpoint is typically defined at the horizontal illuminance level of 500 lx for lighting at workstations in open office spaces [50]. As incoming daylight varies throughout the day, the daylight harvesting algorithm controls the luminaires output to maintain a near-constant level of 500 lx on average at the desk level.

For the full environmental control of lighting conditions some office spaces deploy a combination of automatically controlled lighting and window blinds. These solutions are referred to as total light management systems. These solutions control the blinds based on an external light sensor, measuring the illuminance on the building façade, and using models for calculating the blinds angle that corresponds to experiencing blinding glare due to direct sunlight [27, 28]. This is done to automatically control the slats’ angle for two reasons: to protect occupants from glare by preventing direct sunlight from entering the space and to reduce the thermal load.

Although lighting control systems have been intended to address both energy efficiency and occupants’ comfort there are still opportunities to improve their deployment in office buildings. It has been demonstrated that fully automatic building environment control systems tend to have a lower acceptance by the building occupants compared to the acceptance of semi-automatic or manual systems [30]. It has been observed that occupants of buildings with automatic control having limited or no user control tend to report low indoor environmental satisfaction and sick building syndrome symptoms [31]. A field study conducted by Heschong Mahone Group in California in 123 office buildings with daylight harvesting lighting control reported that in 50 buildings the daylight harvesting controls did not function and among those in 35 buildings those controls were intentionally disabled due to occupants' complaints [33]. Another study of buildings with lighting installations that deployed daylight harvesting reported that at 4 out of 6 sites the control systems have been deactivated due to user complaints [86, 87].

It has been shown that in semi-automatic lighting installations in which controls were provided, poor usability decreased the use of controls and the primary users of the controls were expert users [33]. To counter these negative effects, often leading to frequent occupants' complaints, manufacturers of these systems have been reported to install placebo controls that create an "illusion of control" [35, 37]. Despite anecdotic evidence that placebo controls decreased the number of complaints, some studies reported that ineffective placebo controls have even worse satisfaction than no control [36].

Another challenge for lighting control systems is created by the fact that typically these systems have low granularity of control zones that typically cover multiple desks. This makes adaptation to individual preferences very challenging. A common approach to controlling conditions in multi-user spaces is to use setpoints and ranges of environmental parameters that would satisfy the majority of occupants. This leads to unsatisfactory conditions for individuals whose preferences deviate from the most preferred settings. As was demonstrated by Boyce, one fixed illuminance level cannot satisfy 100% of occupants and leaves at least 37% of users dissatisfied [39].

On the other side of the spectrum, fully manual systems tend to demonstrate poor performance in terms of energy efficiency, since occupants tend to use controls only sporadically, forget to switch systems off when no longer needed and do not dim lights even when incoming daylight is abundantly available [33]. When controlling manually, occupants tend to react to discomfort only after it has already been present for some time [31]. This explains why fully manual control was shown to result in higher occupant dissatisfaction with specific sources of brightness and glare compared to semi-automatic and automatic control [30].

In view of the arguments above, semi-automatic systems have been means to achieve both benefits: improved occupant comfort via manual control that leads to higher user acceptance; and improved energy efficiency via sensor-based control that optimizes energy use. The ultimate challenge is in combining the strengths of the two and overcome the pitfalls that were reported by understanding their interplay and its effect on end-users. In view of the arguments above and the increasing adoption of the sensor-based lighting control the current thesis considers shared lighting control in the context of a semi-automatic office lighting system.

1.4 Justification for providing occupant-controlled lighting

Contrary to what has been said about the diversity of individual preferences regarding lighting conditions, there are only few offices these days offering lighting dimming controls of any kind to office users. Many modern offices deploy automatic smart lighting control solutions including occupancy-based control and daylight harvesting, however, occupant-controlled lighting systems are rare. The reasons for this are not only economic. Facility managers have been cautious towards providing end-user controls, having concerns related to the potential misuse of them or they saw controls might cause conflict among office users with an inevitable raise of complaints [41]. Since several decades research has shown these concerns are largely exaggerated notwithstanding the evidence of the many benefits of the dimming controls. This section focuses on the evidence supporting several arguments in favor of providing dimming controls. It starts with the recognition of the broad range of preferred illuminances different individuals have. It further explores how preferred illuminances are impacted by different lighting designs, variation of daylight admitted into an office space, different types of tasks, including extensive use of computer screens, the range of illuminances enabled by a lighting system, the default dimming level provided and age.

1.4.1 Preferred illuminances and factors affecting illuminance choices

Since occupant-controlled lighting got its place as one of the contributors to office occupant comfort in the field of human-centric lighting, it is good to take a more detailed look at its underlying benefits. The primary reason of providing lighting dimming controls is recognizing the fact that individual preferences of people are very diverse. In the same office with daylight access and artificial lighting there would be occupants feeling that the lighting level is too low and there would be those feeling the opposite way. It has been shown in a windowless laboratory experiment that occupants conducting similar tasks when provided dimming controls would select a wide range of lighting levels [38]. In a US field study in a renovated office with minimal daylight access restricted by blinds 57 participants were controlling their desk illuminances with dimming control of the direct component of the direct/indirect luminaires and the range of experienced horizontal desk illuminances varied from 252 lx to 1176 lx [39]. A similar study in a laboratory windowless office in Canada with office lighting installations where office workers were controlling the lighting level in the last quarter of the working day reported similar ranges: 188 lx to 1478 lx for direct parabolic-louvered luminaires and a desk lamp and 116 lx to 1442 lx for direct/indirect luminaires [40]. Another UK study in four actual office buildings with daylight access with 45 occupants reported individual desk horizontal illuminances to range from 91 lx to 770 lx for occupants in similar working conditions carrying out similar tasks [41]. Similar wide ranges of horizontal illuminance levels were shown in other office studies [42, 43, 44].

A relevant component of the lighting installation within the discussion of the preferences range is the maximum illuminance provided. This has been explored in two studies in North America and delivered a graphical representation of the percentage of occupants unable to achieve their selected illuminance against the maximum lighting level of the installation (Figure 2). It shows that according to the data of these two studies, to cover 100% of the preferences selected by different occupants the maximum dimming level must be at least more than 800 lx which exceeds the maximum average desk illuminance level of 500 lx provided by most office lighting installations today.

Looking at the diversity of lighting preferences shown in the studies highlighted in this section, it is logical to conclude that one fixed lighting output would not satisfy preferences of all office occupants. Analysis of the data from the two studies, reference 7 and reference 11 in Figure 2, determined how many occupants would be close to their preferred illuminance level at different illuminance levels provided by a lighting installation in an office.

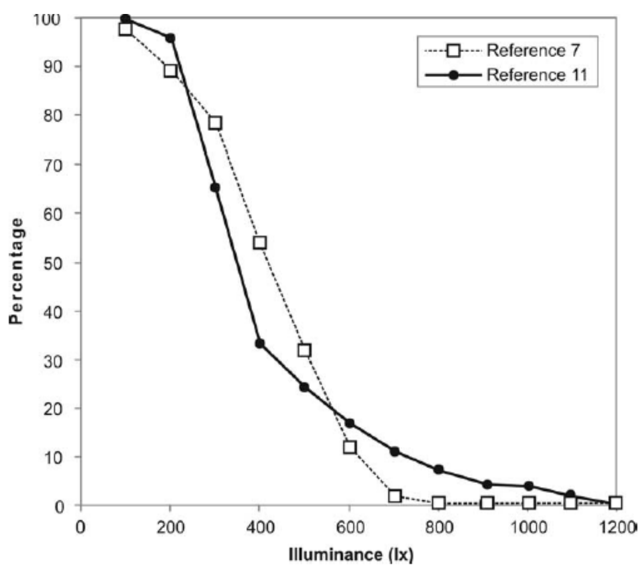

Figure 2. Percentage of participants who are unable to achieve their selected illuminance plotted against the maximum illuminance provided by the installation based on the data of the reference 7 study [68] and reference 11 study [45] (Boyce, P R, Veitch, J A, Newsham, G R, Jones, C C, Heerwagen, J, Myer, M, & Hunter, C M (2006, December). Occupant use of switching and dimming controls in offices. Lighting research & technology, 38(4), 358-378. https://doi.org/10.1177/1477153506070994. SAGE Publications).

In the reference 7 study, 47 participants worked for one day in a windowless office performing a series of visual performance tests and simulated office tasks, like typing, proofreading, creative writing, behind a computer screen [68]. The lighting conditions for every participant were chosen by another participant and the range of desk horizontal illuminances was between 0 lx and 800 lx. At the end of the day the participant who worked in the experimental office was asked to adjust the lighting conditions to the level that she or he desired. From these desired illuminances a calculation was made to derive the percentage of occupants within 100 lx of their preferred illuminance at any fixed level of illuminance. These results are illustrated in Figure 3 with the graph corresponding to the “Reference 7” dotted line.

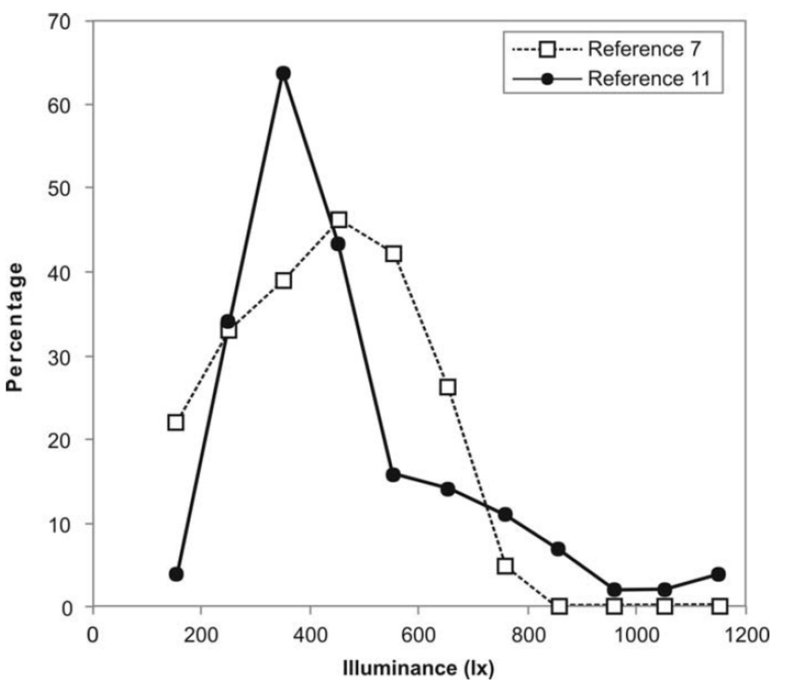

Figure 3. Percentage of occupants within 100 lx of their selected illuminance plotted against a mean illuminance for a fixed lighting output installation in a space with little or no daylight for the reference 7 study [68] and reference 11 study [45]. (Boyce, P R, Veitch, J A, Newsham, G R, Jones, C C, Heerwagen, J, Myer, M, & Hunter, C M (2006, December). Occupant use of switching and dimming controls in offices. Lighting research & technology, 38(4), 358-376. https://doi.org/10.1177/1477153506070994. SAGE Publications).

The second field study, reference 11, was conducted in cubicle offices in Albany, New York, and involved two lighting installations, one offering switching lighting control and another having dimming control. The participants of this study spent one day conducting experimental tasks in the study cubicle, 33 of them had the switching control condition and 57 had the dimming control. The participants could control lighting during the one day of the study the way they liked. Based on these study results, the calculation of the percentage of occupants within 100 lx of their preferred illuminance at any fixed level of illuminance is shown in Figure 3 with the solid line labelled “Reference 11”.

These results demonstrate that the two studies found an optimal illuminance level corresponding to the maximum number of occupants within 100 lx of their selected illuminances, provided the lighting installations used. These maximum percentages reach 45% and 63% and these peaks corresponded to 450 lx and 350 lx desk illuminance levels respectively. This analysis concluded that even at these optimal levels a substantial number of occupants were more than 100 lx away from their preferred lighting level [39].

Not only individual preferences drive differences in what light levels office workers choose, the light distribution created by a given lighting installation and the room characteristics have been shown to influence the occupants’ choices. A Canadian study in cubicle offices had 3 types of lighting installations: one in which the participants could control a custom designed luminaire delivering light on the vertical partition surface, another office had overhead direct luminaires and the third type had a combination of direct luminaires and desk lamps [40]. The study showed that the participants having these different lighting installations made different illuminance choices and created different luminous patterns in these three conditions. In the condition with the vertical partition surface being illuminated the participants controlled the luminaire to increase this vertical surface luminance.

In the US study mentioned above (reference 11 study [Boyce PR, Veitch JA, Newsham GR, Myer M, Hunter C. Lighting quality and office work: A field simulation study, A report for the Light Right Consortium, September 2003.45]), two conditions have been compared, the switching control condition, that had a suspended direct/indirect luminaire above the cubicle providing a fixed light output and in which the participants could control a desk lamp, and the dimming control condition, that had a suspended direct/indirect luminaire above the cubicle with a fixed indirect output and a user controllable direct component [39]. Figure 4 shows the frequency distributions of the chosen mean desk illuminances in the two conditions demonstrating very different pattens. In the switching (desk lamp) condition, a higher percentage of the participants made choices that led to high mean desk illuminances whereas in the dimming condition the opposite was occurring, and the majority made choices leading to low mean desk illuminances.

These studies demonstrate that assessing the luminous environment only by means of average horizontal desk illuminance is limited and that in fact the user experience of lighting is more complex and includes more aspects of the lighting distribution in a space like vertical illuminance and vertical to horizontal illuminance ratio.

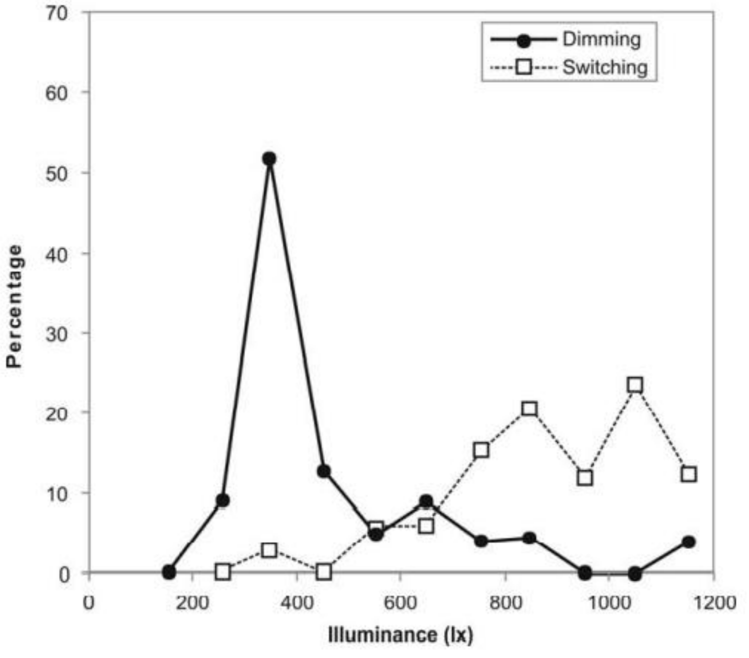

Figure 4. Chosen mean desk Illuminance frequency distribution for the switching (desk lamp) and dimming (direct/indirect luminaire) conditions. (Boyce, P R, Veitch, J A, Newsham, G R, Jones, C C, Heerwagen, J, Myer, M, & Hunter, C M (2006, December). Occupant use of switching and dimming controls in offices. Lighting research & technology, 38(4), 358-376. https://doi.org/10.1177/1477153506070994. SAGE Publications).

A study in Dutch offices involving 170 participants demonstrated that they on average added 800 lx of artificial lighting to various daylight levels throughout the year [46]. The behavior of selecting lighting dimming levels observed in the study revealed a morning, midday and afternoon effect demonstrating that people do not maintain a constant work plane illuminance, which is a chosen strategy in most daylight harvesting systems. The authors of the study concluded that vertical planes and illuminance ratios are more important for creating a comfortable luminous environment than horizontal illuminance.

Similar results have been obtained in the Finnish study involving 20 participants working in a daylit office [42]. In this study it has also been observed that some subjects increased the artificial lighting level in response to increasing daylight level which is seen to be driven by the desire to avoid large brightness differences at the back of the room and near the windows and has to do with a high vertical to horizontal illuminance ratio.

Since in the last two decades, with a wide spread of computer screens, the primary task area shifted from the horizontal plane to the vertical, it can be expected that the vertical illuminance on the computer screen would gain more attention within the field of satisfaction with the luminous environment. However, the vertical plane of the computer screen is a light-emitting surface that also reflects the light caused by daylight and generated by the lighting system and in this respect different than the horizontal desk plane that only reflects light.

Regarding the influence of the daylight on the illuminance choices the results of different studies are inconsistent. Contrary to the Dutch and Finnish studies mentioned above, other studies did not find similar tendencies to increase artificial lighting in response to increasing incoming daylight [41, 48]. Some studies reported that in the presence of daylight in the office occupants were less likely to switch on electric lighting [49, 74, 76]. Other studies showed that occupants were adding on average light levels lower than those that would deliver 500 lx contribution on their desk [77, 78, 79, 80].

The European Lighting Standard EN 12464-1 specifies the quality aspects of lighting for working environments [50]. It includes lighting requirements specifications for the type of work and the visual tasks office spaces are designed to support. These requirements are based on the evidence from studies that investigated visual performance and how it is affected by lighting characteristics like illuminance levels. A relevant question to consider within the context of occupant-controlled lighting is whether occupants consistently select different light levels for different tasks.

One study investigated this question by giving the participants two tasks that were different in nature and difficulty, a paper-based task, and an on-screen task [43]. For the paper-based task the visual difficulty varied between a 14-point print at a luminance contrast of 0.88 to 6-point print at a luminance contrast of 0.68. For the on-screen task the visual difficulty varied between a dark-background display and a bright-background display. The study participants selected different illuminances: higher illuminances for the paper-based tasks and lower for the screen-based tasks but there was no difference in selected illuminances for the levels of difficulty within each task.

Other studies demonstrated that office workers rarely adjust lighting levels for different tasks and, in offices without occupancy triggered lighting switches, they typically control lights at the start of the day and rarely throughout the day [39, 41]. These findings suggest that many typical office tasks would not be challenging enough from the visual performance point of view to trigger occupants' control behavior.

Office lighting recommendations evolved based on the accumulated evidence from visual performance studies. In the 40's and 50's the recommended light level for office work demanding visual tasks was 500 lx [51]. As computer-based tasks entered the workplace and the number of office tasks executed using computer screens, also referred to as video display units (VDUs), started to increase, new recommendations started to appear [57]. In the paper on the “Determinants of lighting quality II” Veitch and Newsham indicated that ambient lighting required for a paper task becomes a veiling luminance on a computer screen that has a self-luminous vertical surface [18].

Various studies report office workers choosing lower illuminance levels than 500 lx when conducting office tasks behind a computer screen [67, 68, 69, 70]. A UK study of office workers in 14 open-plan offices reported that the higher the percentage of the performed computer-based tasks was the lower working plane illuminance they had chosen (Figure 5) [58]. The Dutch study of Begemann did not demonstrate this effect of using VDUs since the participants in that study did not lower the lighting level for VDU tasks [46].

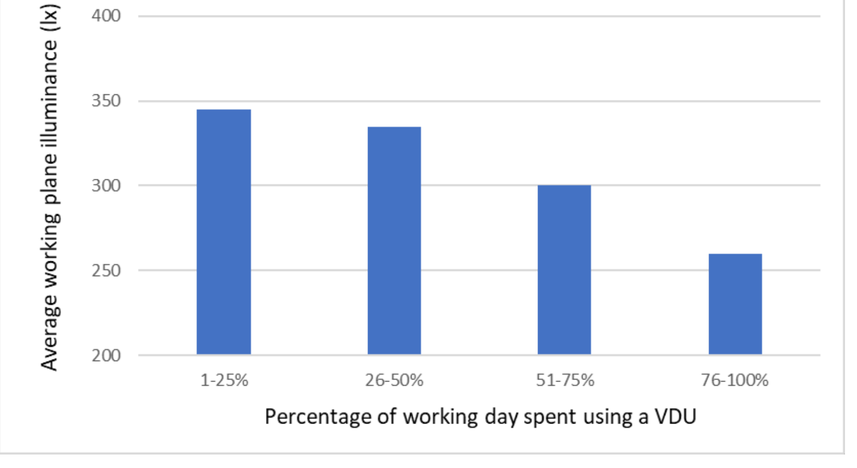

Figure 5. The relationship between average working plane illuminance and time spent using VDU. Reproduced after Moore T, Carter DJ, Slater AI. A field study of occupant controlled lighting in offices. Lighting Res. Tech. 34, 3 (2002) pp 191-205, https://doi.org/10.1191/1365782802lt047oa. SAGE Publications.

Fotios and Cheal pointed at the fact that different studies of illuminance preferences have been reporting different results [72]. Some report central tendencies of illuminance choices greater than 500 lx and others less than

500 lx. They observed that those studies had different experimental installations that offered different illuminance ranges leading to different choices the participant made (Figure 6). They pointed at the potential bias arising from the tendency to make choices close to the middle of the range, a phenomenon demonstrated before for choices of loudness and sweetness.

These observations have been confirmed by an experiment designed to explore the illuminance choices made sitting in front of an experimental booth representing an office [72]. In this study the experimenter was adjusting the range of the available illuminances so that each participant was making choices for 3 conditions offering the following ranges: low range from 48 to 1037 lx, middle range from 83 to 1950 lx and high range from 165 to 2550 lx. The analysis of the results demonstrated that the preferred mean illuminances tended towards the middle of each stimulus range.

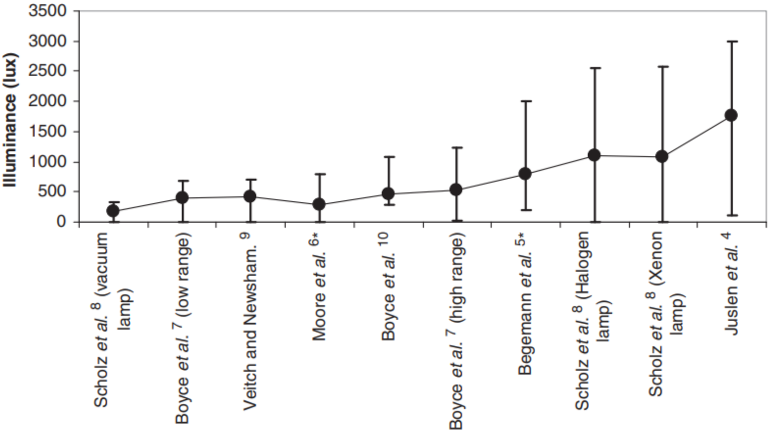

Figure 6. Illuminance ranges and central tendencies of preferred illuminances reported by different studies. Reproduced after Fotios, S., & Cheal, C. (2010, December). Stimulus range bias explains the outcome of preferred-illuminance adjustments. Lighting Research & Technology, 42(4), 433-447. https://doi.org/10.1177/1477153509356018. SAGE Publications.

A later study explored the influence of the illuminance range and the starting point of the dimming controller on the illuminance choices of the participants [73]. It confirmed the earlier findings that the lower range led to lower chosen illuminances and vice versa. The study showed that the low starting point led to lower illuminance choices and the high starting point led to higher illuminance choices. This result was later replicated in the study exploring options to influence the occupants' choices of the illuminance level to increase energy saving [74]. Interestingly, the results of Uttley et al [73] showed no difference in ratings of satisfaction when using the high illuminance range compared to the satisfaction after using the low illuminance range.

Apart from the various external factors influencing the illuminance preferences there are also characteristics of the end-users that play a role. One of these characteristics that has been experimentally explored is age. Physiologically it is known that with age the transmittance of the eyes' lenses diminishes. It has been shown that there is a strong relationship between visual acuity and visual performance and that visual acuity generally deteriorates with age [52]. It is important to consider that a lot of research on visual performance was conducted deploying tasks related to reading printed text on paper. More recent studies involving reading tasks on a mobile device screen demonstrate the importance of the luminance contrast between text and background for older people and showed no significant difference for different illuminance levels [53]. The relationship between age and illuminance preference is equivocal in view of research that did not show an effect [54] and research showing that older workers prefer higher illuminance [55, 56]. As average age of office population increases it is important to take it into account when designing office lighting environment control. Occupant-controlled lighting is a good way of enabling tuning the lighting environment to the needs of office occupants having different requirements.

1.4.2 The benefits of occupant-controlled lighting beyond user satisfaction with lighting conditions

Research demonstrated that having control over the environmental conditions in a workplace increases psychological comfort and reduces stress [59]. It has also been shown that the experience of control by users influences user satisfaction, technology acceptance and intention to use technology [60].

Two experiments in a simulated office in the US demonstrated that occupants had a preference for having personal control for lighting, rated their office lighting more favorably and this had a positive indirect effect on the attractiveness of their office space, mood, motivation and subjective well-being at the end of the day and lighting conditions that improved the visibility positively affected performance [61].

A field study in a Canadian deep-plan office with cubicles arrangement explored the use of individually controllable workstation specific luminaires and compared it to conventional lighting with zonal on-off switching [62]. It showed that occupants who had individually controllable lighting demonstrated significantly higher environmental satisfaction and office appraisal. The study also showed an indirect link with higher job satisfaction, higher organizational commitment, and lower intent to turnover.

1.4.3 The energy saving benefits of occupant-controlled lighting

The energy use of the lighting installation depends on the output range delivered by the system, the dimming level used when the system is on and the time the system stays on. Occupant controls can influence the latter two aspects and as such several studies investigated the energy use of the lighting installations with and without occupant controls.

A laboratory study in Canada investigated the energy use of the lighting installation in a private office where the participants were prompted to control the dimming level from the computer every 30 minutes [64]. The maximum output of the lighting installation was delivering 700 lx on the desk and the maximum daylight contribution was 500 lx. The study demonstrated 25% energy reduction compared to the lighting installation that would deliver a fixed 500 lx desk illuminance.

Another field study monitored the performance of a lighting installation in open-plan offices on four floors of an office building for one year [65]. The installation had occupancy, daylight harvesting and individual dimming controls. System data was used to derive the energy saving for every control type compared to when the luminaires would work at full power. This comparison showed that occupancy sensors would have saved about 35% of energy, daylight harvesting would have saved about 20% and individual controls about 10%.

A meta-analysis of 88 published studies reported that the average lighting energy saving potential of occupancy sensors is 24%, of daylight harvesting 28%, of occupant dimming control 31% and that mixed strategies allow to achieve 38% of savings [66].

Several studies explored the influence of the starting dimming level on the illuminance choices and showed that a lower starting level would lead to lower illuminances selected [73, 74]. This had no effect on the satisfaction ratings suggesting that higher energy saving could be achieved by offering a low starting illuminance level when offering dimming controls.

1.4.4 Shared control in multi-user offices

Most studies that investigated the use of occupant-controlled lighting in offices were conducted either in the context of an individual office or experimental lighting installations with workstation specific lighting. Since the 90's a major change in the office layout design was brought in under the wave of workplace innovation. This changed small 2-3 person offices into open bullpen offices in Europe and modified cubicle offices in the US into open-plan offices with low partitioning.

These office layouts, that became widespread, make it challenging to provide individual lighting controls affecting individual desks. The reason is that these office layouts are typically realized by refurbishing existing offices that already have existing lighting infrastructure or the lighting infrastructure typically gets installed first before the desks' layout is known. The way to provide lighting control in this type of open-plan offices typically involves defining control zones, that can be as small as just one luminaire, where control actions with the controller assigned with a zone affect the entire control zone. affecting clusters of desks. Users typically are given controllers in this context to control the dimming level per control zone thus affecting multiple desks underneath the luminaire(s) of one control zone. As it has been introduced already, this type of occupant lighting control is referred to as shared control as opposed to personal control in which only one individual desk gets affected.

The main question with respect to the shared control, especially in view of the broad range of lighting preferences occupants typically demonstrate (see Section 1.4.1), is whether it offers benefits to office occupants or rather introduces disadvantages since people might develop conflicts and have difficulties in agreeing amongst each other which light level to select.

A study that investigated the effect of shared lighting control was conducted in 14 office buildings in the UK, where 7 sites had offices with lighting controls and 7 sites were without controls [41, 58, 79]. The conducted survey showed that those users who had lighting controls (N=191) demonstrated higher satisfaction with the amount of light on their desk, rated the importance of lighting control higher, had greater perceived control and had a higher degree of satisfaction with lighting control than users who had no control (N=161).

1.5 How occupant control is used and what factors influence its use

1.5.1 Perceived and measured light and perceptible dimming steps

Another element relevant for lighting level control is related to perceived light versus measured light. It has been shown that the relationship between the measured lighting brightness and the brightness perceived by humans is nonlinear and follows a Stevens's power law that links a physical stimulus and the perceived increase in the sensation caused. This power law follows the squared power relationship, meaning that the measured brightness will be equal to the perceived brightness to the power two. The consequence is that at low light levels the perceived light is several times higher than the measured light, thus a lamp dimmed to 5% of its maximum measured light level corresponds to 22% perceived light level (Figure 7). The underlying phenomenon is the pupil dilation at lower light levels determining the amount of light entering the eye.

This illustrates that at the lower part of the dimming scale the changes in illuminance produce larger perceptible effects than at the higher part of the dimming scale. This relates also to the recommended perceptible steps for dimming as specified in EN 12665, which is a sequence 0-20-30-50-75-100-150-200-300-500-750-1000-1500-2000-3000-5000 (in lx) [71]. It shows that the perceptible differences at higher illuminances have larger steps than perceptible differences at lower illuminances.

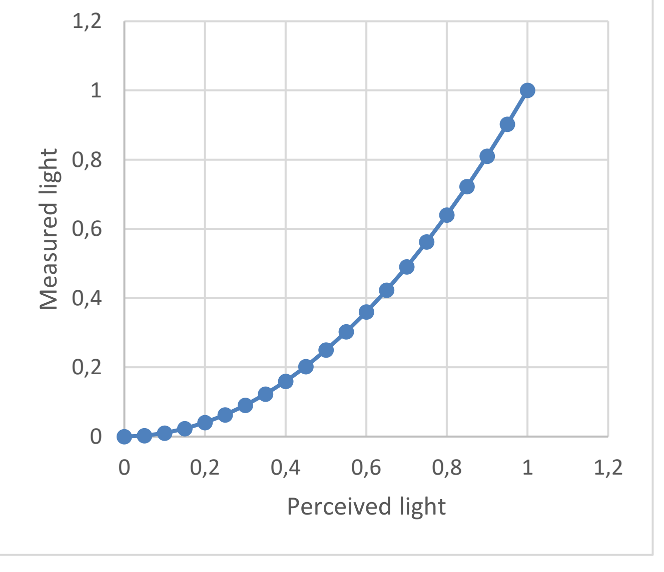

Figure 7. The square law relationship between measured and perceived light. Reproduced after IESNA Lighting Handbook, 9th Edition, (New York; IESNA, 2000), 27-4.

1.5.2 The frequency of using controls by office workers

One of the key questions related to using lighting controls by occupants is how often they would use controls when those are available. Would occupants consistently use controls when lighting conditions change, e.g., due to daylight dynamics, and especially when the illuminance level becomes insufficient to optimally support the visual performance? Would they consistently use controls when they no longer need lighting to stay on as is the case when they leave an office?

Evidence is rather consistent in demonstrating that lighting control use has a low frequency and does not consistently follow changes in lighting conditions. It has been shown that also in comparison to the use of other environmental controls, like the adjustment of window blinds, the use of lighting controls has a lower frequency [82]. Several studies showed a coherent pattern of controls being used to set the light level at the start of the working day and a low frequency of using controls during the day [39, 41, 74, 76, 82].

Several studies also demonstrated that the way occupants use lighting control does not demonstrate a consistent pattern in terms of which light levels the same individual would choose throughout the day, 25-50% choose a different light level [64, 47, 42].

A study in 14 UK office buildings explored factors that influenced the frequency of the use of lighting controls [58]. It showed that the luminaires control group size influenced the frequency with larger control groups associated with lower frequency of using lighting controls. They also showed that in offices with systems having pre-set switch-on levels the occupants were using lighting controls less.

The usability of the available lighting controls has also been shown to impact how they are used. It has been demonstrated that when controls are difficult to use, occupants would choose levels that reduce the need for using controls with the consequence of a higher energy consumption [86, 87].

In terms of the switch off behavior it has been shown that the majority of office occupants do not switch off lights making a strong case for automating switching off lighting using occupancy sensors [72, 41]. The occupancy sensors based switching off functionality has become part of standards like the ANSI/ASHRAE/IES Standard 90.1-2019 [84] in the US ensuring all new office buildings to have this as part of their infrastructure. The newest edition of the European norm EN12464-1:2021 mentions several recommended ways for achieving energy saving one of those being responding to occupancy patterns [85].

The evidence supporting the observed low frequency use of controls provides one of the pieces of the puzzle of optimal control strategies for office lighting. It is important to realize that when given control it will not be exercised consistently and thus needs to be complemented with sensor-based automatic control. The infrequent moments when occupants would use lighting controls offer the opportunity to collect data on their choices to construct a better model of their preferences. This enables a feedback loop, involving the environmental characteristics detected via sensors and user control actions, that could be used to better optimize office lighting conditions for the occupants.

1.5.3 Factors that affect the use of shared controls

Specific to the context of shared controls in open-plan multi-user offices only the study in the 14 UK office buildings explored factors that are of influence on the use of lighting controls [58]. A typical characteristic of an open plan office is that there is no direct mapping between the luminaires grid and the layout of desks underneath. The strategy to provide lighting control in these offices has been to combine several luminaires into control groups so that the luminaires could be controlled by adjusting the output of the whole group. Exploring 14 office buildings having different control group sizes, that varied between 1 and 6 luminaires, the UK study demonstrated that the larger the control group size was the fewer switching actions were observed. The study showed that smaller control groups were associated with higher energy efficiency and less perceived conflict among occupants [81]. Smaller control group size was shown to be associated with higher perception of control [89]. Study participants who had control rated the ability to control lighting over individual desks higher than those who did not have control.

It has been observed that the location of controls can discourage the use of them [88] and would influence the frequency of using controls [58]. The participants in the study of Maniccia et al. appreciated when controls were provided on their desks and when those controls were removed it led to fewer adjustments [82]. Remotely sited controls have been shown to be associated with a lower frequency of use and with a higher output selected [88, 58]. Locally sited controls were shown to be associated with a greater degree of control [89]. It was shown that the higher perceived degree of control was associated with a higher level of satisfaction with lighting conditions [79].

1.6 Research objective

In the previous sections it is shown that occupant-controlled lighting offers many benefits to office users. These benefits are underpinned by many studies particularly in the context of a private office or an office situation where lighting is workstation specific and affects an individual desk. In view of the wide spread of open plan offices, that are inherently multi-users spaces and where the lighting installation is affecting desks of multiple users, there is interest to understand whether benefits of offering dimming controls would be preserved and would not be overshadowed by potential conflicting preferences. There is very limited evidence on occupant controls for multi-user offices. Only the UK study already mentioned above reported extensive comparison of the user experience in existing multi-user offices with and without controls [41, 58, 79, 81, 89]. To further expand the understanding of how users experience occupant controls in multi-user spaces and how this experience is influenced by the social dynamics the current thesis focuses on the following main research objective:

Compared to a lighting installation with a fixed set-point, a lighting system with shared lighting control enabling occupants of an open plan office to adjust lighting output of luminaires affecting their desks can improve satisfaction with lighting conditions without creating impeding conflict.

To be able to study the experience of conflict, which requires time for the social dynamics to evolve and would not be realistic to study in a lab study, the approach to the main question is to study it in a realistic office setting to ensure the high ecological validity. A field study in an actual office space with office occupants using the space during working hours as their primary office for a prolonged period offers the right context to conduct this exploration. The drawback of the field study is that it makes it challenging to control different factors that could be of influence, like the amount of daylight admitted into the space, which can be easily excluded in a windowless lab space.

Since in open plan offices there is commonly no direct correspondence between the luminaires of the lighting system and the desks, typically luminaires will be combined in control groups. The size of the control group, as was mentioned already, would have influence on the frequency of using control, the energy saved, the conflict experienced, etc. Evidence shows that the smaller the control group size the more beneficial it would be for user satisfaction and energy efficiency. To demonstrate this effect of positively influencing satisfaction with the lighting environment, the experimental lighting system will be configured in such a way to create control groups as small as possible. In this context local adjustment of illuminance does not imply adjustment at an individual desk, but adjustment of the individual surrounding that will be defined by the area affected by the luminaires control group.

In the context of the current research, one of the factors influencing the experience of the luminous environment is the control of lighting output based on the incoming daylight through daylight harvesting. This lighting control varies the dimming level automatically based on incoming daylight. This lighting control strategy can potentially influence how satisfied office occupants are with their lighting conditions. In the context of the shared lighting control, it can influence how users would experience the system even in a more profound way since it might lead to situations in which the system makes dimming changes after the light level has been set by the user. This could give office occupants a false perception that they get overruled by the control system, although the automatic changes get triggered purely by daylight changes and might accidentally occur shortly after a user has made a control action. Another factor that potentially influences the user experience is whether the system is memorizing or forgetting the light level set by the user by resetting it at the end of the day. To be able to explore the main research objective and at the same time gain understanding of the influence of daylight harvesting and memorizing or forgetting strategies the research will involve two phases. Firstly, the experience of conflict and of the lighting environment will be studied by comparing the "no control" and "control" conditions without deploying daylight harvesting to exclude its influence on the user experience. Secondly, the study will be repeated and compare the "no control" and "control" conditions including "control" conditions using daylight harvesting, the conditions using memorizing and forgetting strategies.

As was mentioned in previous chapters, studies showed that usability problems with dimming controls had negative influence on the satisfaction with the smart lighting control solutions and were the reasons why dimming controls were used less frequent or primarily by expert users or even sabotaged. To avoid these pitfalls prior to conducting the study addressing the main research objective, a user interface will be created by means of an iterative design process involving several iterative steps to ensure that the control solution does not create any usability obstacles for the study participants to control lighting.

1.7 Thesis outline

Chapter 2 demonstrates the iterative process of designing the user interface the users would perceive as easy-to-use for controlling office lighting conditions where the user interface is part of a semi-automatic smart lighting system. The smart lighting solution is the total light management system that automatically controls office lighting based on incoming daylight and controls window blinds to prevent glare. The system considers user preferences derived from user control actions done by users when they adjust lighting conditions using the user interface. As part of the iterative design process different user interface options, for offering control of the combination of artificial lighting and incoming daylight, have been proposed and evaluated first in an expert review and later with office users. Based on the feedback received in the expert review and the evaluation with office users the user interface was redesigned based on received feedback. This process enabled to identify the best user interface choices that were well understood by users to prevent usability difficulties with the user interface in the follow-up studies.

Chapter 3 starts with the introduction of the larger field study that formed the basis for addressing the research questions elaborated in Chapter 3 and Chapter 4 as well as two separate publications co-authored by the author of the current thesis. Chapter 3 further presents the results of the two field experiments that address the main research question. Both experiments were conducted in the same open plan office space but involving two different groups of participants each consisting of 14 office workers. Both field experiments started with conditions in which no dimming controls were provided to the participants. After the subjective measurements were done in the "no control" conditions the participants were offered dimming controls in the "control" condition and could adjust the luminaire output of the zone they could control. The zoning of the luminaires was done to offer the smallest zones possible, including three luminaires per zone, in the study office space. The study reports two surprising outcomes that were not anticipated during the study design. Firstly, the participants of both experiments demonstrated a conflict avoidant behavior that became apparent from the interviews conducted with every participant individually. Secondly, the study showed that the participants experienced the impact to be stronger after they lost dimming controls in the last “no control” condition of the first experiment than the effect of gaining control when transitioning from the “no control” to “control” condition. Both experiments demonstrated most of the participants preferred “control” to “no control”.

Chapter 4 elaborates on the details of the second field experiment that involved 3 different “control” conditions: one using memorizing strategy, another using the forgetting strategy and the third one where daylight harvesting was implemented by using the user defined set-point as target illuminance for adjusting artificial lighting based on incoming daylight. Similar to the results of the first field experiment the second experiment demonstrated a higher satisfaction with the lighting environment in the “control” condition compared to a fixed light level of the “no control” condition. The comparison of the “memorizing” and “forgetting” conditions showed a difference in the dissatisfaction with the amount of daylight in favor of “memorizing”. It has also been observed that in the “memorizing” condition fewer user actions were performed and the resulting lighting conditions better reflected individual preferences.

In Chapter 5 of the thesis the results of the project are discussed to highlight the significance of the findings in view of prior art, their strengths, and limitations. Finally, the thesis ends with the recommendations for follow-up research.

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2 User interaction with a smart lighting system

This chapter is based on:

Tatiana Lashina, Sanae van der Vleuten-Chraibi, Dzmitry Aliakseyeu, Jolijn de Jongh-Teunisse, Paul Shrubsole & Tess Speelpenning (2021): User interaction for personalized total light management, Intelligent Buildings International, DOI: 10.1080/17508975.2021.1902258

In Chapter 1 it has been discussed that the potential energy savings of automatic lighting control in office buildings has been shown to be undermined by amongst others the poor usability of the user interface provided. To explore solutions with a potential to improve user satisfaction with these systems, an iterative user-centered design was conducted to propose personalized system behavior and an easy-to-use user interface (UI) for controlling the lighting conditions in an office. The steps included defining the semi-automatic system behavior that implicitly derives user lighting preferences from user interaction with the system. Four control options were evaluated in an expert review. Based on the received feedback a redesigned UI was subsequently evaluated as part of the total light management (TLM) system in a Wizard-of-Oz study. The results showed that the UI offering direct control of lighting dimming level and the position of the blinds offered higher level of usability than the UI with indirect control in which a user defines the desired illuminance from a combination of artificial lighting and daylight.

2.1 Introduction

Total light management (TLM) systems that combine automatic control of blinds and lights receive attention due to their potential to cut lighting energy costs with 30–60%, depending on the climate, in commercial buildings [1]. The main feature of the TLM system is that it balances daylight and artificial lighting, while pursuing several goals: maximizing daylight to save on lighting electricity, maintaining comfortable indoor lighting conditions while protecting from direct sun glare and reducing solar heat gain in a building. Despite the energy saving potential of automatic blinds, they have a poor reputation among end-users and due to sabotaging or non-optimal usage have been shown to save up to 50% less energy than expected [2, 3, 4]. These studies emphasize the importance of user satisfaction and comfort for a successful deployment of these systems. Another study has shown that 50% of the controllers of the automatic blinds installed in an office building were permanently kept in a manual mode by office employees [5]. Studies showed that when blinds are operated in the manual mode they would be lowered when there is glare, but seldom raised back to allow daylight in after the glare is gone [6]. This way of using blinds undermines the whole purpose of automatic control that strives for a combined benefit of energy saving and user comfort. An overview of different studies, demonstrating serious user satisfaction drawbacks of semi-automatic blinds is given in [6, 7].

This chapter reports the process and results of the iterative user-centered design conducted to propose a user interface (UI) for semi-automatic control of indoor office lighting conditions that is easy-to-use and enables personalized system behavior derived from user interaction with the UI. The topics covered in the current chapter are:

- the automatic TLM system behavior and explorative interview results focusing on user needs related to indoor office lighting,
- the proposed behavior of the personalized TLM system based on user preferences derived from user actions with the UI,
- evaluation results of the four UI concepts in an expert review,
- Wizard-of-Oz study evaluation results of the redesigned UI,
- the final UI proposal for semi-automatic TLM control.

2.2 Semi-automatic system behavior

This section describes the sensor-based continuous closed-loop control of a typical TLM system, then it highlights user needs and expectations with respect to office lighting and blinds derived in an explorative study and finally it defines the TLM system behavior personalized in accordance with user preferences implicitly derived from user interaction with a lights and blinds control UI.

2.2.1 TLM system behavior

The main goal of the TLM system is to balance daylight and artificial lighting, while maximizing energy efficiency and maintaining comfortable indoor lighting conditions. A TLM system automatically controls blinds and lights via a sensor-based continuous closed-loop control. This is done in a feedback loop, as shown in Figure 8. The interior photosensor, calibrated to estimate the desk illuminance, measures the inside light level in a space, which is then compared to an interior setpoint. The interior setpoint is a system's predefined average desk illuminance that is often defined by local norms and regulations. For example, office lighting in Europe is regulated in accordance with the European norm NEN-EN 12464-1 [8], which prescribes that an office lighting system should be able to deliver on average 500 lx illuminance at a desk surface for typical office tasks. In a TLM feedback loop, a deviation from the interior setpoint leads to blinds and lights' adjustments to minimize this difference. For glare detection, an exterior glare photosensor measures vertical illuminance on the building façade and compares it with an exterior threshold. Exceeding the exterior threshold would lead to the calculation of the glare cut-off angle and height of the blinds to control blinds to protect occupants from direct sun glare. This calculation is done using the existing models that take geographic latitude and longitude of the building, date, user position, space geometry, as input [9].

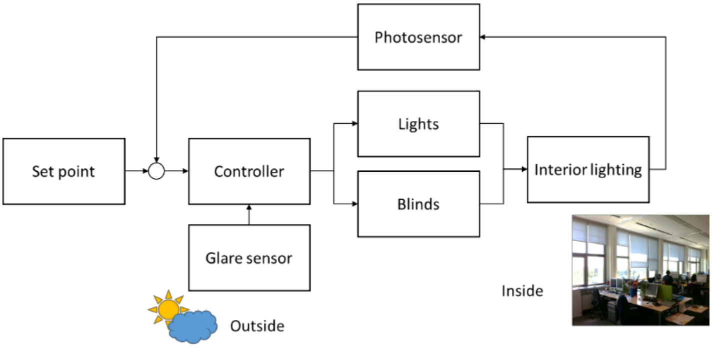

Figure 8. Integrated blinds & lights control feedback loop.

The automatic mode of a TLM system is generally complemented by a manual mode in which users can manually adjust electric lights' dimming level and blinds' height and slats angle. For this purpose, a user controller often offers a switch between the automatic and manual modes, as shown in the example in Figure 9. In the manual mode, the settings defined by the user would determine the status of the system. In the automatic mode, the user control actions override the system status only temporarily, disabling the automatic mode for a predefined timeout. After the timeout, the system returns into the automatic mode. Typically, events defined at the building level would overrule the system status leading to, e.g., raising the blinds at the end of each day or at high wind speed.

2.2.2 Explorative interviews

To explore user needs and expectations from office lighting and blinds, explorative interviews were conducted with 24 occupants who were present on each day of one week in an eight-story office building having the Somfy controllers of the automatic exterior blinds installation (Figure 9). The participants were occupying 2-3 person offices. During the interviews the participants were asked to explain how they typically used blinds in their office, what in their view were the functions of the Somfy controller elements and how they used them. About half of the people could not explain the difference between the manual and automatic modes. Similarly, to the study of Meerbeek et al [5], people, who consciously used the automatic mode, explained their choice to be a compromise between their need to be protected from glare and avoiding spending too much time on adjusting the blinds in the manual mode. It became apparent that satisfying diverse needs with respect to lighting and blinds control would be a challenge. This relates to a variety of individual preferences people have for light levels [10, 11], daylight admission and protection from glare [12, 13]. Despite that, most office systems nowadays exhibit behavior that does not change in relation to user preferences. Interior lighting levels are typically determined based on a fixed setpoint that would put only a fraction of office occupants within 100 lx of their preferred desk illuminance [14]. User preferences for lighting conditions vary not only individually but also contextually, that includes the activity and time of the day [15, 16]. Preferred light levels could be influenced by closeness to the window and the amount of daylight admitted into a space [17].

Figure 9. Somfy blinds UI: the switch on the right toggles between automatic and manual modes, while the up/down arrows on the left open and close blinds, move them up and down and the middle button stops the moving blinds.

2.2.3 Personalization of the lighting control

To better align automatic TLM system behavior with user needs, opportunities were explored for tailoring system behavior to satisfy user preferences. Most existing TLM systems operate using a feedback loop that compares the light level measured in an office space to the predefined set-point. Typically, user actions in the manual mode of a TLM system temporarily override the automatic behavior but do not have impact on it. In order to adjust automatic behavior of the system controlling lighting and blinds, an alternative approach is proposed that derives user preferences based on user control actions. In actual office context occupants have different motivations to control lighting level of luminaires and to control the amount of incoming daylight with blinds and these user preferences are argued to require a user preferred range of inside illuminance rather than a set-point. To explore this semi-automatic system behavior that gets adjusted based on user control actions, the analysis was conducted using two use cases described below that cover common situations for office desk work but do not include, e.g., meeting room or conference room tasks, like giving a presentation.

Use case 1

The first use case is a situation of working in an office when it is dark outside. In this case, the lighting conditions are primarily defined by available artificial lighting that would be typically capped in an office at 500 lx corresponding desk illuminance. As was already mentioned, users would have different preferred artificial lighting levels. Below a certain minimum light level, the user would consider the light level to be insufficient for performing visual tasks. As such, the range below the minimum required light level could be labeled ‘the discomfort range’. The range from the minimum required light level and beyond would signify a range in which the user would consider the available light level to be sufficient for performing visual tasks. The maximum of this range would correspond to light levels the user would consider too bright and can experience as visual discomfort. The range between the minimum required and the maximum level determines the boundaries of the lighting conditions that are sufficient for visual comfort without introducing discomfort. This range was labeled User Comfort Range (UCR).

Use case 2

To determine factors influencing the maximum boundary of UCR, another use case offers relevant considerations. In this use case, the office has plenty of daylight falling into the room on a clear sky sunny day. On such an occasion admitted daylight would easily reach more than 1000 lx at desks located close to the window. Even in the absence of direct glare, the ambient lighting brightness then can become too excessive creating visual discomfort for office visual tasks; especially those performed using an electronic display as several studies showed highlighted in section 1.4.1. In this scenario, due to the abundance of daylight, a way to regulate inside lighting conditions would primarily involve decreasing the incoming daylight by means of adjusting blinds' height and slats' angle until the light level would become acceptable.

User comfort range

As daylight admitted into an office space varies throughout the day, the range between the minimum required and the maximum acceptable levels would determine UCR (Figure 10). If a system would maintain the light level to be within UCR, it would satisfy user needs in a variety of situations that lie in between of the two extremes described in the use cases 1 and 2.

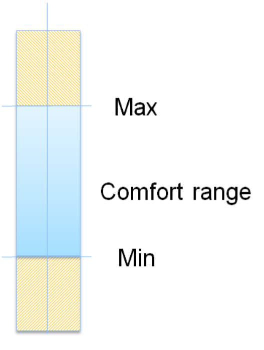

Figure 10. The User Comfort Range defined between the minimum required (Min) and maximum acceptable (Max) light levels.

Using the UCR, initially the system starts operating with predefined Min and Max UCR values that are, for example, based on the range recommended for office work. As the user interacts with the system, the Min and Max values of the UCR get adjusted to better fit his or her preferences.

In accordance with UCR, when the admitted daylight decreases causing indoor illuminance to go below the Max of UCR, the system would be triggered to start opening the blinds to maintain the state "desk illuminance lx ≤ Max”. As the incoming daylight decreases further, and the desk illuminance starts dropping below the Min of UCR, the system would start adding artificial lighting to maintain the state “desk illuminance lx ≥ Min”.

When the desk illuminance is above the Min and the user opens or closes the blinds, the system would adjust the maximum of UCR to become equal to the average desk illuminance at the moment of the user adjustment. Conversely, when the user would adjust the artificial lighting, while the illuminance level is below 500 lx and the blinds are open, the Min of UCR would get adjusted.

The exception to this system behavior is the case of a direct sun glare. In this case, the associated visual discomfort overrules the behavior of maintaining the UCR.

2.3 UI evaluation of initial concepts

After defining the semi-automatic system behavior, the next step was to design the UI for office users to control lighting and blinds. To do that several user interface directions were ideated and sketched in the form of the four concepts shown in Figure 11. The style for the visual presentation was deliberately chosen to be ‘sketchy’ and unpolished to encourage feedback by potential users [18]. To evaluate and improve these initial ideas an expert review study was conducted. The study involved 12 experts, half of those had their background in user experience and interaction and another half in lighting perception and application. During the expert review sessions, first, the context and purpose of the evaluation was explained. Then the image of each of the four concepts was shown to the expert and she or he was asked to think out loud how one would use the UI in the image to change lighting conditions in an office. During this process additional questions were asked on the usability of the UI elements and ideas for improving those were shared. After the four concepts were discussed, a comparison was made to identify concepts that would most optimally support control of office lighting conditions but be self-explanatory to enable ease of use.

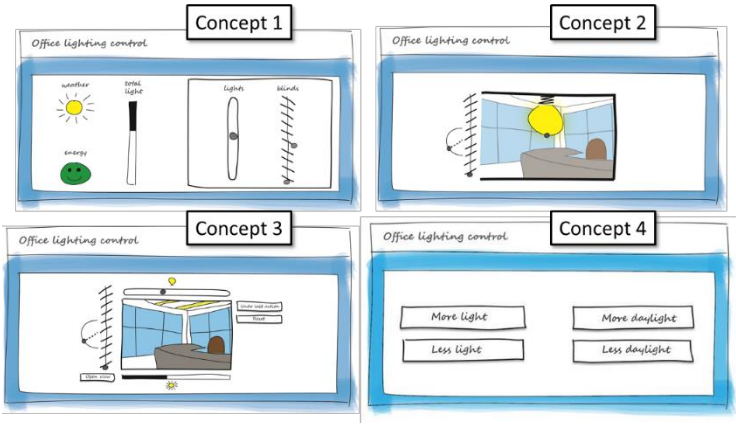

Figure 11. Initial concepts evaluated in the expert review.

In concepts 1 and 3 an indicator showing the total amount of inside light, created by the combination of artificial lighting and daylight, was introduced. The experts found this indicator to be difficult to interpret. In particular, the total light indicator (the horizontal slider at the bottom) and the lighting dimming slider (the horizontal slider at the top) in concept 3 were easy to confuse with each other. A suggestion was made to replace the total light indicator with a slider that could be used to adjust the inside light level.

Partially the frustration with automatic control, as mentioned in section 1.3, is caused by the lack of user understanding why a system behaves in a certain way. Existing UIs typically do not facilitate this understanding. In concept 1 the attempt to address this was by showing an energy indicator, a green smiley, to convey when the system was operating in an energy saving mode. Experts reacted positively to this energy indicator and found it important for communicating that the system aims to balance energy efficiency and user comfort. For this UI element, the idea was to only show it if a user would make an energy efficient choice and show nothing otherwise. In this way, the system encourages energy-efficient choices and respects the fact other choices could be made from visual comfort considerations.

Concept 2 explored a different interaction technique for adjusting artificial lighting by using a pinching gesture on the visualization of the bulb. This concept was criticized to be not self-explanatory since in most cases it was interpreted to be an image rather than an interactive UI element.

Concept 4 presented a rather extreme example. In this UI the user has no direct controls, e.g., of blinds height, but only buttons for requesting more or less artificial lighting and daylight. It is then up to the system to adjust lights and blinds accordingly. Experts were rather critical to Concept 4. They argued that users would have a variety of reasons for controlling lights and blinds, e.g., for opening an outdoor view or covering the window for privacy. These control actions would be impossible to do using the UI in Concept 4. The experts suggested that in these situations there should be a possibility to switch into a manual mode that would not affect the automatic system behavior.

Based on the feedback received, the elements of the four concepts were combined to produce a set of improved UI designs for further usability evaluation.

2.3.1 Redesigned UI

The redesigned UI, resulted from feedback of the expert review, included three elements: a total light controller (The Total Light Bar), a controller for blinds and a controller for artificial lighting (Figure 12).

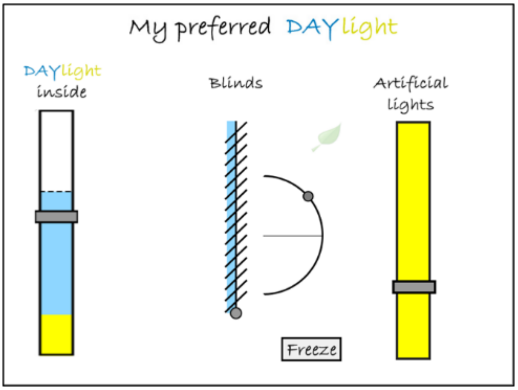

Figure 12. UI redesigned based on the expert review.

The Total Light Bar contains a sliding knob indicating the average work plane illuminance created by a combination of incoming daylight (blue part of the bar, referring to an association with a blue sky) and artificial lighting (yellow part, referring to a warm color temperature of artificial light sources, as preferred in the Northern part of Europe). The same color coding is used in the title of the UI screen saying, 'My preferred DAYlight' ('DAY' written in blue and 'light' in yellow). The dotted line above the slider knob in Figure 12 indicates that not all available daylight is admitted into the room and could be increased by further opening the blinds. By controlling the sliding level, the user instructs the system to increase or decrease inside illuminance and the system determines whether to achieve that by manipulating blinds or artificial lighting. The Total Light Bar functions as the light level controller and as feedback showing the current ratio of artificial lighting and daylight.

The improved blinds' controller consists of the two interactive elements: one for the blinds' height and the other for the slats' angle. These are indicated with the two gray circular handles, for changing the height and the angle. The slats' orientation in relation to the inside of the window is clarified with a blue daylight stripe. The artificial lighting controller is shown as a yellow slider with a gray knob controlling the luminaires' dimming level from minimum to maximum luminaire output.

The experts agreed that to increase users' acceptance of the automatic system behavior, it is important to provide the information on the environmental conditions to help users understand why certain automatic adjustments are taking place. This is, for example, the case in situations like that of direct sun glare, when the system would automatically close the blinds. To make it explicit, a glare indicator showing the blinds slats' angle range, within which users would experience direct glare, was added to the UI (Figure 13).

The energy-efficiency indicator got a more neutral green leaf representation to avoid suggestion of judging the user's choices.

To allow user control that would not affect the UCR and temporarily disable automatic system behavior, a 'freeze' button was added. The freeze mode was intended to lock the state of the lights and blinds and disable automatic adjustments in exceptional situations including those of opening blinds to reveal an outside view or to cover the window for privacy. Unfreezing would happen anytime the user would again start making changes to the UI. This is to promote automatic control for energy efficiency while allowing manual control for exceptions.

2.4 Redesigned UI evaluation

The next step of the iterative design process was to get qualitative feedback on the user interface design from potential users. At this stage the intention was to evaluate the UI and its interplay with the TLM system behavior. In an ideal case such an evaluation would need to be conducted in an office space having a TLM installation where the participants could experience the UI as part of the TLM system. Because such a system was not available at the time of conducting the study, an alternative was chosen to use a simulation and the Wizard-of-Oz approach for the evaluation [19]. In this approach, a researcher would push the knobs to generate the intended system reactions following the choices made by a study participant acting as the end-user.

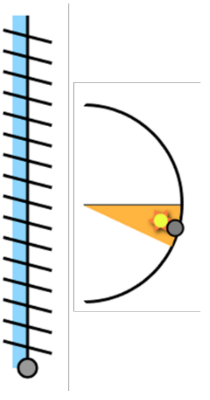

Figure 13. Indicator of slat angle range causing direct glare.

2.4.1 Materials

The study was carried out in a laboratory office. This lab was constructed as an actual office space with a purpose to prototype and test different lighting technologies for office use. Since there were no automatic blinds in the lab a projection screen was used to simulate the blinds' behavior and outside daylight conditions during the test, while the actual windows of the lab were closed using manual curtains. The projection displayed a photographic image of a window and could show different blinds' settings, including blinds fully raised up, blinds fully closed, blinds with slats opened at 90° or 45° (Figure 14). One image showed a clear sky and two showed a clouded sky. The lighting in the room could be controlled by the participants with the "artificial lights” slider of the UI (Figure 12), running as a web application on a tablet. The lighting in the room was delivered by five LED strips installed in the ceiling. The LED strip closest to the projection screen was used to simulate the incoming daylight. The image displayed on the projection screen was changed during the test by a researcher present in the room, using a laptop. The experimental set-up is shown in Figure 15.

2.4.2 Participants

Fourteen participants took part in the study. All of them were office workers recruited at High Tech Campus in Eindhoven. 12 out of 14 participants had blinds in their own office, of which 8 were automatically controlled. The other four participants had internal manually controlled blinds. 9 participants had their offices with windows located on the southern facade of the building, one had windows facing east, and four had windows facing north. All participants signed an informed consent prior to participating in the study.

Figure 14. Images used to simulate blinds states displayed on the projection screen.

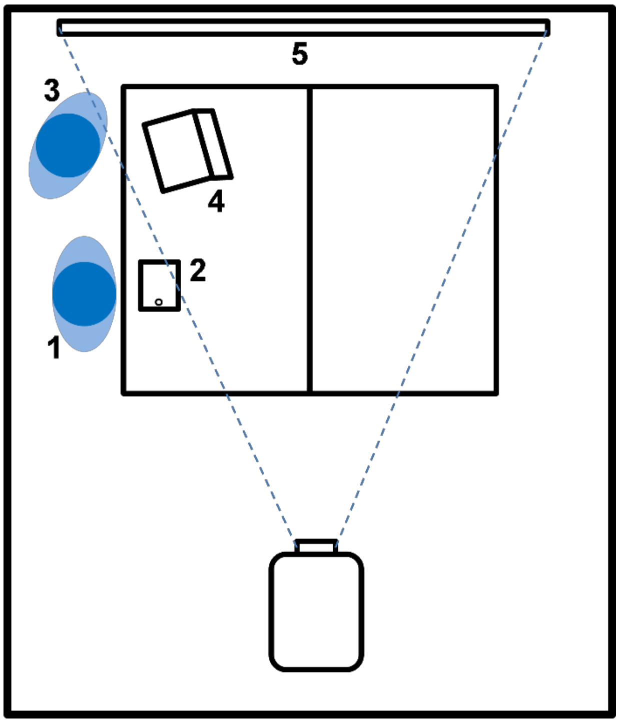

Figure 15. Experimental set-up in the laboratory office: 1. Participant, 2. Tablet with interactive UI, 3. Researcher, 4. Laptop with audio recorder, 5. Projection screen.

2.4.3 Procedure

Fourteen experimental sessions were conducted. During each session two researchers were present: one leading the evaluation and interacting with the participant, and the other assisting by controlling the projection screen.

The sessions were set up as semi-structured interviews guided by a researcher. The audio recordings of the interviews were made to later transcribe them for conducting content analysis. The study sessions contained the two parts: initially a usability walk-through evaluation of the UIs was conducted that was followed by simulating a set of prepared scenarios, demonstrating selected office use situations that were discussed with the participants. These scenarios were selected to illustrate the semi-automatic behavior of the TLM system in common office situations when occupants would have a motivation to adjust aspects of the inside lighting environment. The following three scenarios were included: the user increases inside lighting level and the system subsequently partially opens the blinds and decreases lighting to maintain the level set by the user in a more energy efficient way, the user opens the blinds and experiences direct sun glare that is indicated in the UI and the user closes the blinds to reduce outside distraction and needs to use the "freeze" button to prevent automatic opening of the blinds by the system. When interacting with the UIs, the participants were asked to "think out loud" [19] and share their spontaneous reactions to their experience with the UI.

The usability walk-through evaluation included the two UI options for controlling the office lighting. One option was the Total Light Bar for controlling inside lighting level and the other option presented the UI with separate sliders for the lights and blinds (Figure 16). In the second UI the blinds and lights sliders were functional control elements, and the Total Light Bar was not interactive but was used for feedback on the inside light level. Each experimental session started with giving the participants the 'Total Light Bar UI' prototype they could freely explore (Figure 16 a). After that, each participant was asked to perform the following three common lighting control tasks: create more light inside the office, create less light in the office and create more view to the outside. In the next step, the second UI with the blinds and lights sliders was given to the participant to conduct the same tasks (Figure 16b). Finally, the participants were asked to perform the three tasks again, but now they were free to choose one of the two UIs to do that.

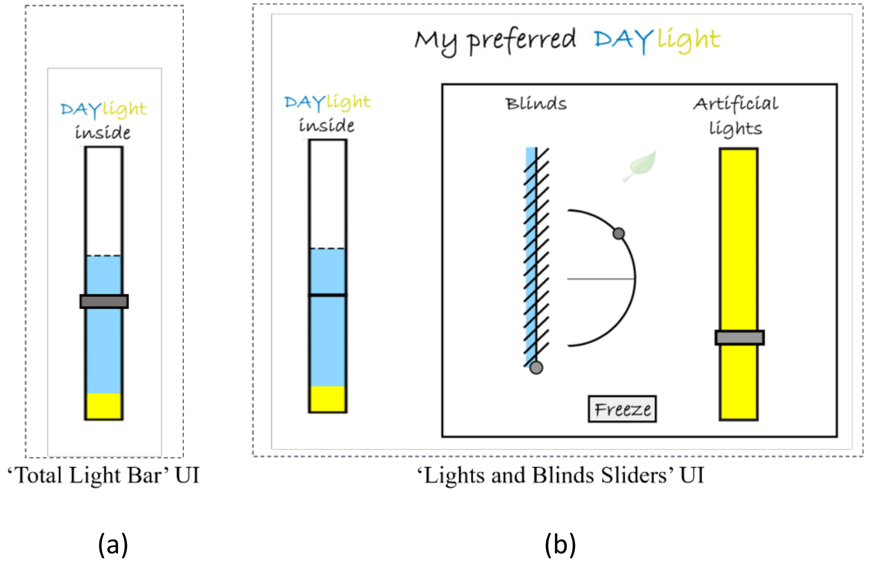

Figure 16. Two UIs used in the usability evaluation.

In the second part of the evaluation, four office scenarios were explored with the participants. Every scenario was introduced with a short description of the situation and the participant was asked to perform a given task using the 'Lights and Blinds Sliders' UI (Figure 16b). In response to the user action, the conditions inside the room were changed by the researcher controlling the projection. Finally, the participant was asked to give an interpretation of the environmental changes that took place and whether the reaction of the system was in accordance with the expectations. On average the sessions took one hour per participant.

2.4.4 Usability evaluation results

The intention of the Total Light Bar (Figure 16a) was to offer an easy-to-use way of selecting the user preferred inside illuminance and letting the system figure out how to achieve that by controlling the artificial lighting and blinds. However, during the test it became apparent that people were not thinking in terms of the resulting illuminance level on their desk, but rather were looking for lights and blinds control they were familiar with. It turned out that the Total Light Bar did not offer a straightforward way to complete the third task, which was to increase the view to the outside. For that task the Total Light Bar UI was not providing a practical way of achieving the desired result. 9 out of 14 participants could not understand how to use the Total Light Bar. The color coding of artificial lighting and daylight was often misinterpreted and the same was the case for the dotted line indicator. The participants' feedback was that the Total Light Bar did not provide proper means to successfully complete the experimental tasks. Conversely, the 'Lights and Blinds Sliders' UI (Figure 16b) did not pose any difficulties. All the participants could successfully complete all the tasks by using this UI. The feedback they gave was that these controls offered a familiar way of dealing with lighting and blinds. This gave the feeling of being in control instead of relying on the system as it was the case with the 'Total Light Bar'. When they were free to choose the UI, the participants used the 'Lights and Blinds Sliders' UI in 37 out of 42 cases (three tasks performed by 14 participants).

Feedback on the simulated scenarios

This section describes the scenarios tested in the second part of the evaluation and presents the resulting feedback from the participants.

Scenario 1

The following explanation was given to introduce the scenario 1, "The blinds are closed. It is partially clouded outside." These conditions are reflected in "Initial state" in Figure 17. The participant was asked to increase the lighting level inside. The UI changed its state to look like "After user action" state in Figure 17. In response to this change, it was explained that the system would gradually open the blinds and would dim the lights, as shown in the "After 10 min" state in Figure 17. This was supported by projecting the relevant window image (Figure 14) on the projection screen and controlling the LED strip above the projection screen.

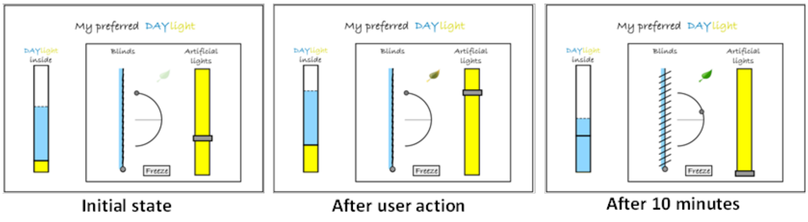

Figure 17. Scenario 1 states.

Feedback for scenario 1

Most participants reacted that daylight should be prioritized over artificial lighting, due to believed health benefits and the importance of an outdoor view. The convenience of automatic control was appreciated by most participants. However, they felt it was also important to have the option to override the automatic behavior. Several participants proposed to automatically adjust the blinds gradually preferably unnoticeable to office users to prevent distraction. The fact that the system was aiming to provide the desired amount of light in an energy-efficient manner was positively perceived.

Scenario 2

The following explanation was given to introduce the scenario 2, "It is a sunny day with plenty of daylight coming inside. Due to this high sunlight intensity the blinds are partially closed to prevent direct glare." The UI reflected these conditions, as shown in the "Initial state" in Figure 18. The participant was asked to further increase the amount of daylight falling in and increase the outdoor view. The resulting state is shown in the "After user action" state in Figure 18, where it could be noticed that the resulting state of the blinds corresponded to direct sun glare. The participants were not explicitly told about the resulting glare, since the question was whether the UI was conveying it properly so that the participants could derive it themselves.

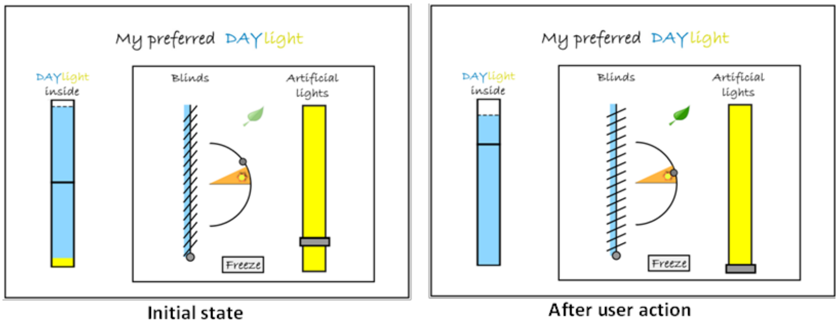

Figure 18. Scenario 2 states.

Feedback for scenario 2

12 out of 14 participants interpreted the glare symbol the way it was intended and commented it was useful to see at which angle direct glare would be experienced. 6 out of 14 participants tried to use the blinds' height adjustment after they had adjusted the blinds' angle.

Scenario 3

The following explanation was used to introduce the scenario 3, "There is a lot happening outside causing distraction." The participant was asked to close the blinds and increase the lighting level. In cases in which after closing the blinds and increasing the lighting the participant did not use the "freeze" button, the conditions changed "automatically" by the facilitating researcher who dimmed the lighting and changed the projection to the open blinds' image. In this scenario the experimenter would hint the participant to try using the "freeze" button and after the participant used the "freeze" its functionality was discussed.

Feedback for scenario 3

12 out of 14 participants understood the function of the “freeze” button. Some of the participants said to associate the “freeze” with the inside temperature or air conditioning. An alternative was suggested to use a padlock symbol instead. To automatically unfreeze based on a timer triggered by a user action with the UI was perceived not to be useful by the participants. Several of them proposed to have an automatic unfreeze of the system at the end of each day for convenience.

Additional feedback

12 out of 14 participants did not see added value of having the Total Light Bar for providing feedback. Most of the participants had difficulties understanding different elements of the Total Light Bar. The participants expected that the physical changes in the environment, like the luminaires’ output changes and the blinds’ height and slats’ orientation changes, would provide sufficient clues on the changes in the office environment.

11 out of 14 participants understood the leaf symbol. However, the change of the color and transparency of the leaf was not always noticed. It was suggested to relocate the leaf symbol and position it further away from the ‘freeze’ button to prevent confusion between the two.

2.4.5 Proposed UI design for TLM

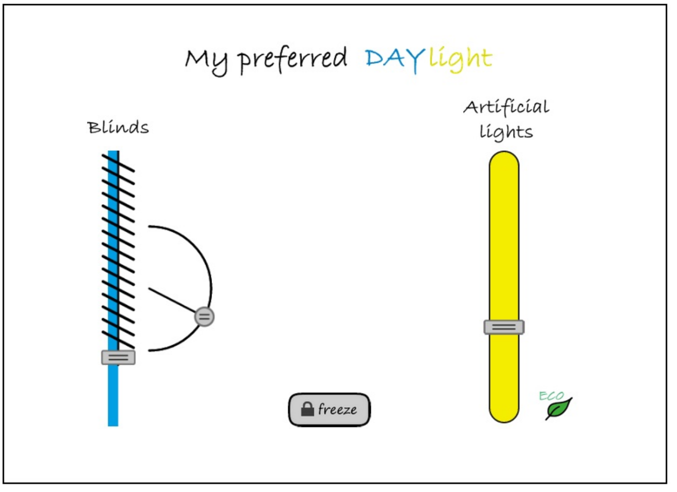

Figure 19. Redesigned UI.

Since the participants expressed a clear preference for the 'Lights and Blinds Sliders' UI it was decided to use this UI as the direction for the final TLM UI proposal (Figure 19). The look and feel of the sliders' knobs was improved by making them slightly larger and adding grip lines. The behavior of the leaf was simplified to only show it when the lighting dimming level would be below a predefined threshold and remove the symbol when it would be above that. A padlock symbol was added to the 'freeze' button to facilitate the intended interpretation of its function.

2.5 Discussion

This work was started by becoming aware of studies demonstrating that many TLM solutions installed in offices suffer from poor usability and low user acceptance. As a result, these systems often fail to realize their intended benefits in terms of improving comfort for office users and achieving forecasted energy savings.

To come up with a solution proposal that would address this challenge, the user-centered design was deployed starting with the exploration of how office users typically deal with office lighting, daylight, and outdoor view and what their needs and expectations are in this context. Integral to this user-centered design process were the iterations of validating different UI concepts. This aimed at identifying the UI that would best address the user needs with respect to office lighting environment control and facilitate user acceptance of the automatic TLM system by promoting user understanding of the system behavior and supporting it with an easy-to-use UI.

The main result of the study is the proposed UI design that integrates with the proposed semiautomatic system behavior. This system behavior takes user preferences into account and subsequently controls the dynamic indoor lighting conditions influenced by daylight.

Several studies demonstrated that among different modes of the existing TLM systems, including the options of fully automatic, semi-automatic and manual control, semi-automatic and manual control resulted in a higher level of user satisfaction than automatic control [20, 21]. However, in the study of Vine et al. [20] in the manual mode more office workers were dissatisfied due to experienced glare suggesting that automatically controlling blinds for glare could offer a better approach. As has been highlighted in section 1.5.2 several studies showed that when environmental controls are available, they were used by occupants only sporadically [15, 20, 22, 23, 24]. From this perspective, semi-automatic control offers benefit from both perspectives: it improves user-satisfaction by providing manual control and automatically takes care of the dynamically changing environmental conditions.

The study participants positively responded to the system behavior prioritizing daylight to artificial lighting due to believed health benefits. This daylight preference was demonstrated in studies before [6].

Although previously it has been reported that office users would prioritize their comfort to energy saving [19, 26], the current study participants were positive about the system controlling for energy efficiency while taking user preferences into account. However, this response of the participants could be due to the social-desirability bias that is difficult to avoid when exploring sustainability aspects by means of an interview. Another potential explanation of this result is that the way simulated scenarios were presented to the participants made it easier to interpret the system behavior compared to an actual office lighting system that would make it less apparent.

In view of the evidence showing low acceptance of the automatic control systems [4] one way to improve it is to provide information to users explaining automatic system actions. In the proposed UI it was, for example, achieved with the visualization of the blinds angle range that results in direct glare (Figure 13). The participants of the study found this information helpful to clarify the system behavior.

It should be acknowledged that even in case a TLM automatic behavior is designed with attention to usability and user needs it would remain challenging if impossible to cater to exceptional situations like control for outside view or privacy. These user needs that go beyond inside illuminance control, present challenges to TLM control systems that are designed to implicitly learn user preferences from user control actions. A possible solution is to offer possibilities for dealing with these exceptions, for example, by introducing a user control mode that does not affect automatic system behavior. Such feature was offered to the study participants in the form of the “freeze” button. Although most of the study participants understood the purpose of this UI feature, there is still room to further improve it to increase its ease of use. These situations also further emphasize the importance of manual override in lighting systems to support different user needs that was previously advocated [6].

The current paper focuses on the iterative user-centered design of the UI for the TLM system. The proposed design requires further validation within a TLM system in an actual office that would present a more complex environment, e.g., multiuser open office context that could not be fully reconstructed in the simulation of the reported Wizard-of-Oz study. The limitation of the simulated study was that the participants got instructions to perform specific tasks with the UI in response to described conditions, whereas in an actual office environmental discomfort like direct glare would motivate to make blinds and lights adjustments. Questions remain whether office users would still be able to use the UI, when the need arises, without the supporting instructions and how the UI can support multiple users in open offices. The initial step of validating lighting control using the proposed UI in a multi-user open plan office is the topic of Chapter 3 and Chapter 4.

2.6 Conclusions

Based on the studies conducted as part of the iterative design process the semi-automatic system behavior is proposed for the control of interior office lighting including the UI for controlling artificial lighting and blinds. Within the proposed approach, individual user preferences could be taken on board through the User Comfort Range (UCR) that spans from the minimum required illuminance to the maximum illuminance before it would cause discomfort. The UCR concept describes the method of deriving the user preferences from the users' interaction with the UI controlling office lighting and blinds.

The studies conducted to validate several conceptual UI ideas demonstrated the following learnings:

- Office users do not operate using the notion of desk illuminance when dealing with office lighting conditions. This is the reason why UI concepts, like the Total Light Bar, that are based on defining the desired desk illuminance were less favored by the study participants and they generally showed poor understanding. The study participants preferred familiar concepts of office lighting and blinds and found the associated controls for lights and blinds to be much easier to use and understand.
- The reasons for using blinds in the office go beyond influencing the inside illuminance level by controlling the amount of daylight admitted inside. It is also motivated by protecting from glare, opening the view to the outside and closing the windows for privacy.
- Most of the study participants understood the direct glare range visualization and found it useful for interpreting what the system was doing. This approach helps users to understand and thus develop a more accepting stance towards automatic system behavior.
- Another element of increasing acceptance of TLM systems was found in the possibility to make automatic adjustments so that the changes would be unnoticeable to office occupants. This would cause no or

minimal distraction to office users and in this way contribute to a more favorable attitude of users towards the system.

- The study participants demonstrated a positive attitude towards the system behavior that maximizes daylight admission to optimize energy use by artificial lighting. As such, if the UI highlights this attribute of the system behavior, for example, via an “eco” symbol as in the proposed UI (Figure 19), it positively affects the users’ perception of the system.

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3 The role of conflict when sharing lighting control

This chapter is based on:

Lashina, T., Chraibi, S., Despenic, M., Shrubsole, P., Rosemann, A., & van Loenen, E. (2019, January). Sharing lighting control in an open office: Doing one's best to avoid conflict. Building and Environment, 148, 1-10. https://doi.org/10.1016/j.buildenv.2018.10.040

As it has been highlighted in Chapter 1 occupant control for office workstation specific lighting was studied already for several decades, whereas this form of lighting control for multi-user offices is a relatively young field of research. The proliferation of open offices in the last decade makes it vital to understand the benefits and drawbacks of occupant-controlled lighting in multi-user spaces.

This chapter presents the results of two field experiments that explored the experience of conflict and the social dynamics among open office users to whom shared lighting control was offered. The study data revealed that in multi-user spaces, individuals are self-conscious of the presence of others and deploy different strategies to avoid conflict due to control of lighting. The chapter discusses the implications these findings have for the design of multi-user lighting control.

The results showed that individuals felt the nuisance of losing control over lighting stronger after the lighting controllers had been removed compared to the satisfaction gain felt after they initially got control, known in behavioral economics as a loss aversion bias. This has implications for promoting beneficial effects of shared lighting control in open office environments.

3.1 Introduction

This introduction provides the description of the larger study that created the context for the research described in Chapter 3 and Chapter 4 as well as two separate publications co-authored by the author of the current thesis. Because the current thesis highlights only a part of the research that has been conducted it is relevant to describe the scope of the complete study in order to help the readers put all elements into the intended perspective.

3.1.1 Prerequisites for initiating the study on shared controls

As has been discussed in section 1.4.4, since the ‘90s, a big shift took place in the office space design going away from small 2-3-persons offices and towards turning many office spaces into open offices like bullpen arrangements and offices with low partitioning. At the same time a big trend in lighting systems began to emerge that was often referred to as “smart lighting”. The smart lighting systems started to couple sensing solutions to luminaires that comprised such systems and adding connectivity solutions for aggregating sensor data to be used in controlling the whole system. The development of occupancy and daylight regulation controls has been an intrinsic part of this smart lighting systems development as discussed in section 1.3.

One solution that emerged as part of this development has been Coded Light [1]. Coded Light enables each luminaire of a lighting system to transmit modulated light imperceptible to the human eye while illuminating. This modulated light encodes a luminaire identifier detectable with a camera of a mobile device, like a mobile phone, running the decoding software. After detecting the luminaire identifier, an application running on the mobile device can send commands directed to the identified luminaire via a wireless communication channel to the control unit of the lighting system. This solution enables the software implementation of dimming lighting controls in an office space. Such implementation does not require installing any physical switches in the office because it can make use of the mobile phones carried around by every office user nowadays.

Despite the fact that technology wise elegant solutions, like Coded Light became available in the ‘10s of the current century, offering them to office occupants generated quite some concerns. For manufacturers of smart connected lighting solutions, also those having capabilities like Coded Light, it became relevant to understand whether the provision of dimming controls in open offices would improve the experience of office occupants or on the contrary would worsen it. Before that time, most office occupant lighting controls studies had been conducted in the context in which the study participants were controlling lighting in the workstation specific way, meaning that either the study was conducted in a single-occupant office, or the luminaire(s) were affecting only the desk of the participant and of nobody else. The overview of the evidence created by those studies is provided in section 1.4.

After the office layout, that first was comprised primarily of small 2-3-person offices, in most office spaces in Europe and to a lesser extend in the US, had been transformed into multiuser open offices, lighting in those offices had no longer remained workstation specific as it is discussed in section 1.4.4. Due to the arrangement of the luminaires grid in the ceiling of an open-plan office and its relationship with the desks grid therein, luminaires in open-plan offices typically affect multiple desks and occupant lighting controls are typically used by groups of users. Since occupants’ lighting preferences had been demonstrated to vary substantially (section 1.4.1), it would be logical to assume that this multiuser context potentially creates challenges for office occupants of selecting one lighting level that would satisfy everybody involved. As such, valid concerns had been raised related to the potential conflict occurring among the users of occupant lighting controls in open-plan offices. In the context of office lighting conflict is defined as inability of office occupants to achieve satisfactory lighting conditions affecting their individual working areas by means of lighting control provided in the office space. Analogous challenges had been identified for other office environment controls, for example control of air-conditioning. A control logic labelled "Logic for Building a Consensus" has been proposed and evaluated in an open-plan office with about 50 occupants in Japan [2]. The study reported no adverse effects of this solution on the occupants' satisfaction with the thermal environment and it showed the benefit of potential energy saving of 20%. There are a number of environmental factors that define occupants' comfort in office spaces, like lighting, temperature, noise, acoustics. The interaction between these factors and the need to influence them by exercising control in multiuser modern offices is the subject of ongoing research.

3.1.2 Study goals

The current study, comprised of experiment 1 and 2, focuses on the user experience of shared lighting control in the multiuser context of an open office. The goal is to explore the interplay between the known benefits of occupant controls demonstrated for workstation-specific lighting and possible drawbacks due to a prospect of conflict among multiple users of an open office. In order to resolve the question whether the provision of shared controls in multiuser open-plan office spaces would be beneficial or detrimental the following questions have been formulated to address:

Will the provision of shared lighting control in multiuse open-plan office increase the satisfaction of occupants with the lighting environment compared to their experience in an office with a lighting installation having a fixed setpoint?

How shared lighting controls in an open-plan office should be designed to increase the likelihood that occupants would experience the lighting conditions in a beneficious way?

How the study should be designed in order to evaluate the effect of shared lighting controls on the experience of occupants?

To what extent conflict, due to the control of lighting, will play a role and how it will affect the occupants' experience if open-plan office occupants get shared lighting controls at their disposal?

What patterns of behavior would emerge among the open-plan office users if they would get shared lighting controls at their disposal? The objective was to observe whether conflict would occur and among how many individuals, including the frequency and degree of conflict experienced. The study was to explore whether the conflict avoidance behavior reported in previous studies would manifest itself and to what degree and whether some individuals would seek consensus and look for a middle ground to set the light level respecting each other's needs.

3.1.3 The choices made for the study design

To address the questions of the study a number of study design choices have been made based on the evidence from literature and they will be explained in this subchapter.

One of the choices made was to conduct a longitudinal field study rather than a lab experiment. Apart from the reasons related to the high ecological validity of a field study design, the strongest argument was that in order to explore the potential negative effects of conflict, conditions had to be created for the conflict to be able to occur and a lab study would not be conducive to that. From this perspective a representative office in which occupants could interact with lighting and with each other during a prolonged period of time while using the office for their daily work activities offered the most suitable conditions to address the goals of the study.

Secondly, in order to compare the experience of the participants when they used shared controls to that when they did not have lighting controls, a combination of weekly short online surveys, paper diary booklets filled out by the participants weekly, interviews and extended online surveys at the end of each condition were used. The short surveys included the scales evaluating the perceived lighting quantity adopted from the UK study of Moore et al., 2004, [10], while the perceived lighting quality scale and the assessment of the experienced glare have been adopted from Veitch and Newsham, 2000,[21] (Appendix A). The extended surveys in addition included the environmental satisfaction scale adopted from Sundstom et al., 1994, [3], and the comfort scale of Osterhaus, 2005, [4] and Veitch et al., 2002, [5] for assessing the experience of temperature and acoustics whereas the air quality item was adopted from Veitch et al., 2007, [6] (Appendix B).

The mood of the participants was evaluated using the dominance, arousal and pleasure in every condition using the Russel and Mehrabian 3-factor scale [7]. The experience of conflict and the perceived degree of control and satisfaction with control of lighting has been assessed using the questions adopted from Moore et al., 2000, [13] (Appendix C).

The choices for the subjective experience evaluation scales mentioned above have been dictated by, on one hand, the variables that already demonstrated to impact the experience of the lighting environment. On the other hand, it was influenced by the motivation to keep the number of tasks feasible for the participants to complete since they were contributing to the study parallel to their daily work activities. Following this motivation, the scales to assess personality traits of the participants were not included, since at the moment of designing the study there had been no evidence identified that showed the personality traits' impact on the experience of lighting conditions. This is not to suggest that there could not potentially be an effect of personality on the office environment experience. For example, a recent paper just published in the proceedings of CLIMA 2022 has demonstrated the mediational effect of gregariousness on the experience of thermal discomfort [8].

Although controls are highly desired [15], the presence of other office users does affect the use of environmental controls. It was shown that users in private offices are more likely to use controls whereas users of open offices tend to rather deploy psychological coping strategies, like avoidance to use controls, despite discomfort [13]. The UK study of shared lighting control reported a strong correlation between the avoidance of using controls due to the fear of conflict and dissatisfaction with the degree of control [9-14].

The same study also showed that in a situation of conflict, some personalities avoid using controls while others continue to use them, suggesting dominant personalities. It was observed that control decisions were not taken to reach consensus but had a tendency to be taken by dominant individuals. An office occupant exhibits the dominant behavior in the context of shared lighting control if the output level of the luminaires affecting the desk of that user is actively influenced by the control actions of the dominant user and stays at the user's preferred level for most of the office use time. In contrast, the submissive behavior is when a user avoids actively using lighting control due to the presence of other office occupants despite being dissatisfied with the lighting conditions.

Despite higher satisfaction of users in offices with controls, the UK study showed that 30% of those users expressed dissatisfaction with controls, which the authors associated with poor usability and inability of users to make use of available controls. It was suggested that one of the reasons for not using controls was to avoid conflict with other office users.

The UK study on shared lighting controls showed that the more luminaires were included into the lighting control groups the less frequently occupants used the controls, more energy was used for lighting, more conflict was occurring, occupants were less satisfied and experienced being less in control. The offices of the UK study that did offer shared lighting control, were designed with different lighting control group sizes that varied from 1 luminaire per group influencing at least 2 desks to 6 luminaires per group. The study showed that in cases with smaller luminaire control groups, the level of conflict experienced by users was smaller, the controls were more frequently used, more energy was saved, and the users were more satisfied.

Contrary to the UK study that included offices with existing shared control installations, when preparing the current study there was freedom to decide how to combine luminaires into lighting control groups. Based on the findings of the UK study it has been decided to strive to achieve control groups with as few luminaires as possible. The specifics of combining luminaires into control groups will be further explained in subchapter 3.2.4.

When designing the field study special attention was paid to the design of the shared controls, definition of the lighting control groups of luminaires and the relationship between the controls and the lighting control groups of luminaires following the evidence from previous studies as outlined in subchapter 1.5.3. Local controls have been shown to result in lower luminaire output, controls being used more frequently, greater system awareness by the users, a greater perceived degree of control and less conflict experienced [13]. Following the evidence demonstrating that individual controls encouraged more frequent use of controls compared to, for example, wall mounted controls for shared use, every participant of the current study has got an individual lighting controller on his or her desk. These lighting controllers were implemented using an Apple iPod mobile handheld device running a software application with a user interface for dimming the corresponding lighting control group. When implementing the lighting controlling applications learnings from the usability evaluation study described in Chapter 2 were used to ensure its ease-of-use. Further details of the lighting controllers are provided in subchapter Light controllers.

3.1.4 Towards the building blocks of shared lighting control

Not all the results of the field study are included into the current thesis, since some have been published separately. This subchapter explains the total scope of the findings of the field study and provides an overview of the results included into Chapter 3 and Chapter 4 and gives references to the separate publications. The building blocks forming the field study findings with corresponding references and their relationship to the data collected in experiments 1 and 2 are visualized in Figure 20.

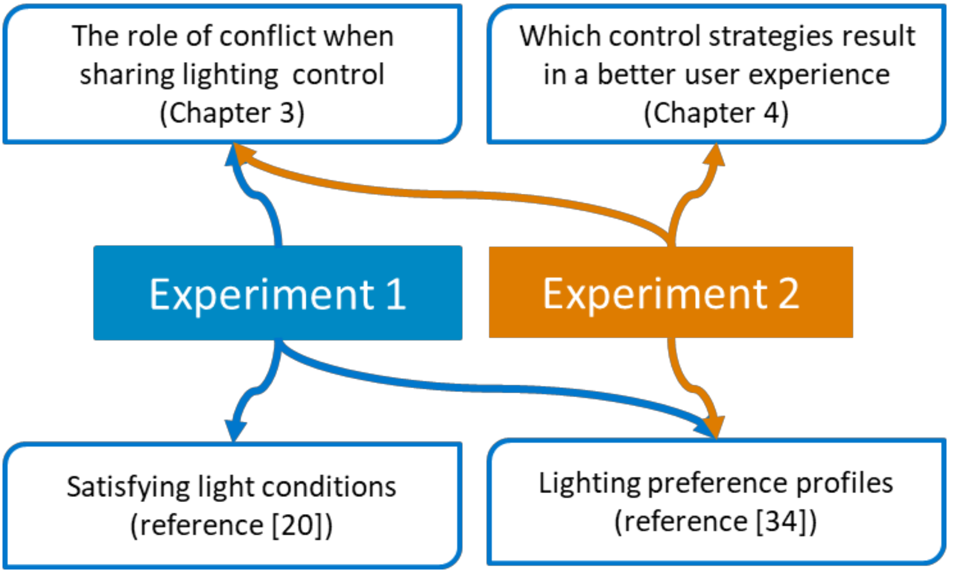

Figure 20. Overview of the field study findings.

A detailed description of experiment 1 with respect to how the participants experienced the lighting conditions, what illuminance choices they made and the illuminances they experienced has been published separately under the title “Satisfying light conditions: A field study on perception of consensus light in Dutch open office environments” [20] (Figure 20). The results demonstrated a significantly lower dissatisfaction with the light quantity on the desk as well as on the PC screen when shared controls were provided compared to when the participants did not have lighting control. Similarly, the quality of light has been rated significantly higher in the shared control condition compared to the condition without lighting control. Experiment 1 showed no effect of shared controls on the experience of glare, air quality, experience of noise and the mood of the participants, whereas the experience of temperature was significantly affected by the controls.

Because in experiment 1 several choices have been made for the lighting control strategy, like no daylight regulation and memorizing the user selected light level, it was decided to repeat experiment 1 and include new conditions with shared controls using alternative control strategies. This resulted in conducting experiment 2 in which 2 additional shared control conditions were included. One condition implemented a so-called “forgetting” strategy when the user defined light level had been forgotten at the end of each day instead of “memorizing” it as in experiment 1. Another condition was implemented to add daylight regulation of the light level selected by the user. Experiment 2 and its results highlighting which control strategies resulted in a better user experience will be elaborated in Chapter 4 (Figure 20).

The results of both experiment 1 and 2 with respect to the experience of conflict and the observed behavioral patterns related to the use of shared controls are discussed further in Chapter 3. Different studies show that control in general and specifically control over lighting is something individuals like to have as an antidote to not feeling in control [9, 15]. As mentioned in subchapter 1.3 a common practice related to thermal building controls is to mount placebo controllers to give an illusion of control to decrease complaints [16]. Several studies [17, 18] showed that, when controls are available, the frequency of using them is relatively low especially compared to sensor input based adjustments. At the same time, office users are typically very positive towards having occupant controls in case they might need to make a change [17, 19]. In the study of Moore et al. office users' self-rated importance of lighting control was evaluated [9]. The study showed a high mean score of 4.2 for the importance of being able to control lighting, rated on a 5-point scale ranging from 1 - unimportant to 5-important. In the current Chapter 3 (Figure 20) the outcomes of both experiment 1 and experiment 2 are reported with respect to effects on social dynamics among the participants, the perceived frequency and degree of conflict, the observed phenomena of conflict avoidance and loss aversion.

Despite the more positive assessments of the lighting conditions with shared controls compared to no controls, as it will be elaborated further in the current Chapter, some users were dissatisfied and were either experiencing a large degree of conflict or were unable to exercise shared controls in a satisfactory way. In order to look for possibilities for improving the experience of these users the analysis of the data of experiments 1 and 2 has been done to investigate the possibility of automatic profiling of the users and this work appeared in a separate publication under the title "Lighting preference profiles of users in an open office environment" [34] (Figure 20). This analysis shows that the users could be profiled according to the following characteristics: activeness, dominance, lighting tolerance and dimming level preference. Options are proposed to support users in achieving a higher level of satisfaction with the office lighting conditions with a semi-automatic control solution using automatically derived preference profiles.

3.2 Materials and Methods

3.2.1 Office layout

For the field study including experiment 1 and 2, an office, representative of widespread open plan European offices, was selected. This desks layout in the office is known as an open bullpen office or a low partitioning office layout (Figure 21). This office layout is gaining in popularity worldwide due to its costs efficiency [23]. In the open bullpen arrangement desks are lined up in clusters of 2 rows on both sides of a partitioning. The rows often stand perpendicular to the building windows façade. Desks in such open offices

Figure 21. Test office impression.

stand next to each other which decreases a perception of a workplace ownership [15, 32]. This contrasts with cellular offices and cubicles where desks have much more separation creating enclosed private office cells. The desks in the study office have been assigned to individual employees who were using the same desk during the whole study duration. This way of using desks was practiced in the whole building and the participants have been used to assigned desks.

3.2.2 Participants

The study execution has been conducted in two phases, which are referred further in the text as experiment 1 and experiment 2. The preparation and execution of experiment 1 took one year from January till the end of December in 2013. Similarly, the preparation and execution of experiment 2 took another year from January till the end of December in 2014. The preparation of experiment 1 included the steps of designing the study, preparing the study materials including the study system installation, inviting the participants to relocate into the modified study office and getting their commitment to contribute to the study by regularly filling out online surveys, keeping their office experience diaries and participating in interviews. In addition, office workers who were previously occupying the space had to be relocated into a different office. The study design has been prepared via consultations with experts in the domains of lighting application, lighting technology, cognitive psychology, statistical study analysis and questionnaire design.

The inclusion criteria for the participation in the study were not to be involved in lighting perception, lighting application and lighting technology research and spend at least 4 days a week in the office, excluding vacations periods. The participants of the study were equal in terms of their place in the organizational hierarchy. The department heads at the time of conducting the study were occupying separate private offices. Prior to the study the only office environment controls the participants had experience with were controls of the external blinds.

There were differences between the two samples of participants of experiment 1 and 2, and all participants in experiment 2 were different people than those who participated in experiment 1. The 14 participants of experiment 1 were part of the same administrative group from the Philips Research organization. This choice was deliberate to involve naïve users who had no professional expertise in the domain of neither lighting perception nor lighting technology. These participants knew each other well prior to participating in the experiment since they worked in the same department for at least half a year. They were mostly senior employees between 30 and 65 years old (mean=48.6, SD=9.49), including 3 females and 11 males.

Due to a new relocation of the building occupants initiated by the Philips Real Estate that took place after experiment 1 was completed, another Philips Research department moved into the study office. The members of this department were specialized in medical technology research. Because these new occupants were specialized in a different domain than lighting research, this department was invited to participate in experiment 2 and agreed to do so. Two members of the department turned out not to be eligible to participate in the experiment since they were spending too little time in the office. To replace these employees, two members of two other departments were invited to relocate into the study office for the period of experiment 2. In total 14 participants took place in experiment 2 and they were a mix of senior employees as well as students. These participants were less familiar with each other than the participants of experiment 1, since their department was formed several months prior to the study. The age ranged from 25 to 65 years old (mean=44.3, SD=11.58), including 1 female and 13 males.

Prior to conducting both experiments their protocols were reviewed and approved by Philips Research internal ethics committee. All participants signed an informed consent after familiarizing themselves with the study conditions that included explanation of the intent of collecting and processing the data, the duration of keeping the data and voluntary nature of the participation in the study.

3.2.3 Installation

To conduct the field study, an open office space in one of the Philips office buildings in Eindhoven was chosen. To prepare the test office space for the purpose of the study, an existing lighting installation was used. The office was equipped with 16 Philips TL5 49W lamps before the start of the study. These luminaires were modernized in view of the study goals with Philips DALI dimmable ballasts (Philips HF-Ri TD 1 28/35/49/54 TL5 E+) and combined light and presence sensors (Philips PLOS-CM-KNX) with a 30 min time delay at every luminaire. The advantage of using conventional luminaires was in the familiarity of the study participants with this type of office lighting. If instead new LED based luminaires would have been used, it could introduce a confounding effect induced by a different color temperature or lighting distribution.

3.2.4 Luminaires control zones

The open office arrangement, as introduced in Section 1.4.4, makes it impossible to offer lighting controls in a truly personal workstation specific manner. Following the common practice of offering lighting control in open offices, the luminaires in the test bed were combined into control groups. In view of the benefits of smaller control size groups, the smallest possible control group size was implemented. Smaller control groups including fewer luminaires lead to fewer users affected by the control group, which makes it potentially easier for members of the same group to reach a consensus. The top view of the test office layout is shown in Figure 22. As it can be seen the typical mismatch between the lighting grid and the desks grid was present in the office layout of the test office. The office had two lines of luminaires; each line comprised of 8 luminaires.

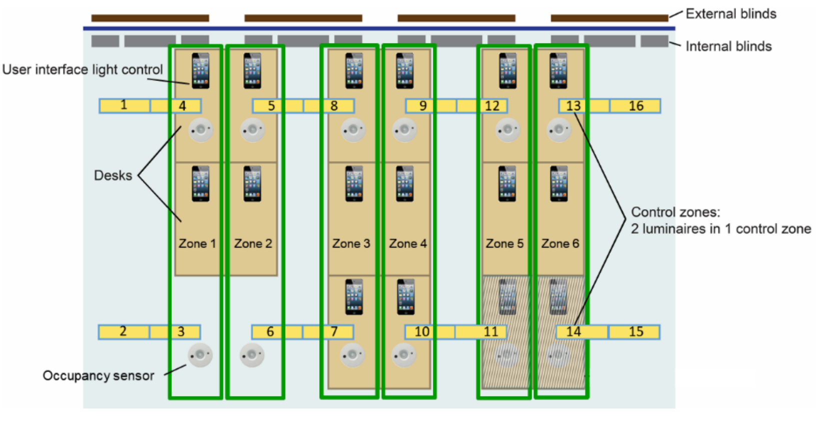

Figure 22. Top view of the test office floor plan.

Although the intent has been to give the participants equal level of lighting control, the middle desks presented a challenge since they situated in between the two lines of luminaires. If controls would be distributed per luminaire to every user, the users sitting in the middle, in between the luminaires' lines, could feel less entitled to change the light level of the luminaires above their neighbors on their left and their right. Their neighbors' desks were located below the luminaires creating a more obvious link between their desk and a luminaire. To resolve this asymmetry and give the participants equal sense of control, every two luminaires from each luminaire line were combined into control groups of luminaires that are further referred to as control zones indicated by bold vertical rectangles in Figure 22. In this arrangement luminaires 3 and 4 belonged to zone 1, luminaires 5 and 6 to zone 2 and so on. Each luminaire control group was assigned to the closest row of desks below it, creating 6 groups of 2-3 users per luminaire control zone. Four luminaires adjacent to the walls on both sides of the office were excluded from the control zones. Their light output level was fixed at 60% to maintain sufficient wall illuminance and prevent a possibility of having dark walls in the office. Well-illuminated office walls were shown to positively influence overall space appraisal and helped avoid sharp contrast that could occur due to incoming daylight [33].

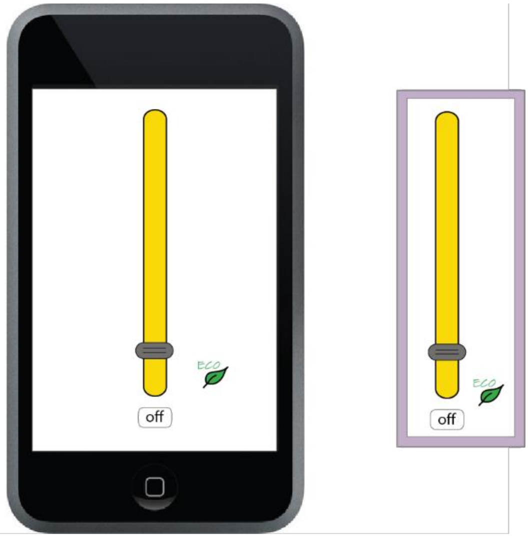

Figure 23. User interface for light control, iPod application (left)
and PC widget (right).

3.2.5 Light controllers

For the participants to experience lighting control during the study each study participant received a personal controller on their individual desk in one of the “control” conditions. The controllers were implemented as an application running on a handheld Apple iPod device and were placed in a docking station on each participant’s desk. Each participant got an individual short explanation of the purpose of using the controllers, security measures built-in in case an iPod would be taken away, and the actions to take in case any technical problems would occur. The explanation of how the controllers were assigned to the control zones and how they were controlling the luminaires in the space was not provided, since the intention was for the participants to discover it on their own.

The lighting control application displayed a slider for dimming lighting in the whole range from off up to the maximum luminaire output as illustrated in Figure 23. The learnings from the user interface evaluation study described in Chapter 2 have been taken on board when designing the lighting dimming application to ensure its ease-of-use. Controllers belonging to the same control zone were acting in an identical manner. A user action made on any of the controllers of the same control zone would set both luminaires of that control zone at the user selected dimming level. After that all controllers would display the new set value on the user interface.

During the study, every participant had an assigned desk, and every desk controller was hard coded to be connected to a particular control zone. The occupancy-based lighting control in the test bed was implemented for the whole space, the way most occupancy control systems operate. This means that when the first person would enter the space all luminaires of the lighting system in the space would be switched on. The occupancy-based control would turn all the lights in the space off 30 minutes after the last person would vacate the space.

3.2.6 Blinds

The test bed area allowed for a good admission of daylight into the space. The office was located at the southern façade of the building, on the fourth floor offering an unobstructed view due to the absence of either high trees or neighboring high buildings. Daylight in the space periodically created a challenge for adequate management of direct sunlight, i.e., glare. In the office, both internal and external blinds were available for office occupants to deal with glare and regulate daylight intensity inside the space. Internal blinds were manually controllable motorized Somfy blinds, controlling four clusters of window blinds separately using four provided remote controls. The external blinds offered two modes of control: automatic and manual control using the physical controllers mounted on the windowsill (Figure 9).

3.2.7 Conditions in experiment 1 and 2

This section explains the designs of experiment 1 and 2. The study participants were kept as naïve as possible about the actual purpose of the study to avoid response bias. This was done by stating that the study aimed at exploring their experience of the office space in a broad sense including aspects such as temperature, air quality, lighting, and noise.

In experiment 1, data was collected from the start of September till mid-December of 2013. The study was designed as a within-subject experiment with an ABBA reversing the order of conditions (Figure 24). The experiment was initiated with a reference “no control” - condition 1 in which the participants did not yet get the lighting controllers. All luminaires were set at their full output delivering on average 500 lx on the desk surface, which was calibrated when it was dark outside, and all blinds closed. Three full weeks of data were collected while the participants experienced this fixed light level condition. After the baseline condition, the iPod controllers were brought in and attached to the respective docking stations on every participant’s desk, initiating 7 weeks of the “control” conditions 2 and 3. Conditions 2 and 3 were identical in terms of their set-up. At the start of each "control" condition, the luminaire light output was initially set at a default level of 60%, which corresponded to on average 300 lx on the desks without daylight. After a user would change this level, the system would remember it until the next change made by a user. This system behavior was labelled as a "memorizing" shared control mode.

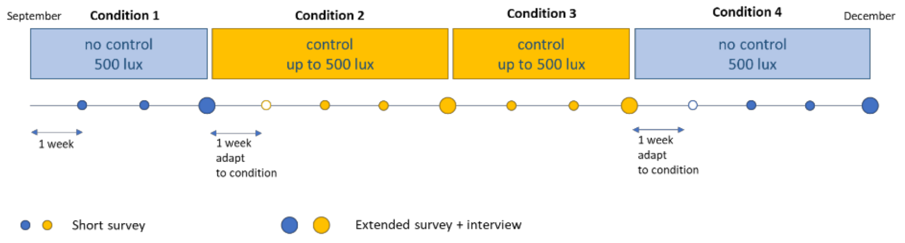

Figure 24. The order of the experimental conditions in experiment 1.

For the analysis of the data, the first week of the "control" condition 2 was excluded. Due to the novelty of the controllers, users played with light levels in the first week substantially more than in the rest of the "control" period. Finally, the "no control" condition was repeated during the last 3 weeks of the experiment 1 during which the iPods controllers had been removed. This was the last condition 4. This study design helped to balance the number of sunny and cloudy days occurring in "no control" and "control" conditions. At the same time, the ABBA design helped to demonstrate the difference between switching from the "no control" to the "control" condition (from A to B) and the withdrawal of them (from B to A).

In 2014, the second experiment was conducted, using the same test office and with the same modernized lighting installation. The office space at the time of the study consisted of 16 workstations. However, two office workers could not participate in the study but continued to use the study office since they belonged to the department occupying the office during the study. This is the reason why in comparison to experiment 1, two additional desks were part of the office, which are marked with a diagonal stripes pattern in Figure 22 (bottom right).

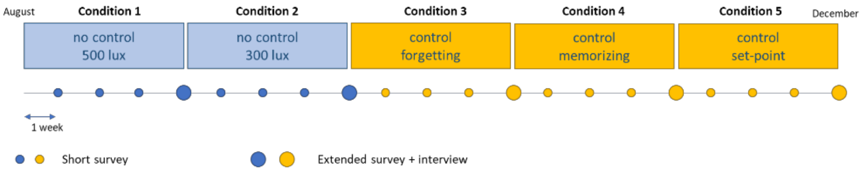

Figure 25. The order of experimental conditions in experiment 2.

In experiment 1, automatic luminaire output regulation based on incoming daylight was intentionally deactivated. Daylight regulation could potentially act as a confounding variable diluting the main purpose of the experiment. After experiment 1 was completed, the intention was to repeat the experiment but this time to include the daylight regulation, since most systems in the field are daylight regulated. Validating shared controls including the daylight regulation would improve the ecological validity of the study.

Experiment 2 was designed to measure lighting quantity and quality satisfaction, experience of conflict and preference for “control” or “no control” by letting the participants experience 5 different conditions (Figure 25). Condition 1 and condition 2 were “no control” conditions where light output of the luminaire was regulated to maintain 500 lx and 300 lx average illuminance on the desks, respectively. Conditions 3, 4 and 5 were “control” conditions, where similarly to experiment 1, the participants received iPod dimming controllers on each individual desk. In condition 3 at the end of each day, the system would go back to the default 60% luminaire output level. The users could change the luminaire output to their liking at any moment each day. This system behavior was labelled as “forgetting”. In condition 4 the last dimming level that was selected by a user on a particular day would be restored the next day, and this system behavior was called “memorizing” (similar to the “control” conditions 2 and 3 of experiment 1). In condition 5 the user was controlling the set-point of the lighting system. The set-point defined the target desk illuminance the system was maintaining by regulating corresponding luminaires’ output in response to available daylight. Each condition of experiment 2 consisted of 4 weeks, from which the first week was meant for the participants to adjust to the new study condition. The data was analyzed for the subsequent 3 weeks of each condition.

During the conditions of the study, short and extended online surveys were administered to collect subjective responses of the participants. Short surveys were completed on a weekly basis and included questions assessing perceived lighting quantity, quality, and glare (Appendix A). Extended online surveys included extra questions in addition to the short surveys questions (Appendix B) and they were completed at the end of each condition. In addition to the extended surveys at the end of each condition an interview was conducted with each participant. Extra questions assessed the importance of having control over lighting and, in “control” conditions, the frequency and the degree of conflict due to the use of the lighting controls (Appendix C). These questions have been adopted from the UK study of shared control [13] that has been discussed in section 1.5.3. The conflict assessment scale was included as a quantitative measure of assessing the subjective experience of conflict to complement interview data. The importance of having control over lighting was included to assess how and whether it would change as the participants experienced the 4 conditions of the study without and with lighting controls.

3.3 Results

3.3.1 Analysis of subjective responses

The subjective data collected from the surveys was ordinal scale data. The use of the ordinal scale data and the relatively small sample size motivated to use nonparametric Wilcoxon signed rank test for the comparison of the responses received in different experimental conditions. The mean of the frequency and degree of conflict responses in the "control" conditions was compared with the middle of the scale using one-sample Wilcoxon signed rank test. For the hypothesis testing a significance level $\alpha=0.1$ was used due to the relatively small sample size [36].

The data was firstly analyzed for differences between the weeks within each condition. Since the differences between weeks were negligible, the data was aggregated by taking an average per condition per participant.

3.3.2 Frequency and degree of conflict experienced

To explore the nature of conflict experienced between the participants during the study, the data on the frequency of conflict and the degree of experienced conflict due to lighting controls with other users of the space, was collected via extended surveys during the "control" conditions.

The frequency of conflict was evaluated by the participants on a 7-point scale from 1 – never to 7- frequently. In experiment 1, the users assessed the frequency of conflict with a mean of 2.32 and a standard deviation of 1.26 in Condition 2 and Condition 3 combined. The obtained mean of 2.32 was compared to the middle of the scale 4 with a one-sample Wilcoxon signed rank test and delivered the p=0.0006 meaning the difference is significant. The frequency of conflict in experiment 2 had a mean of 1.64 and a standard deviation of 1.44. The mean of 1.64 was compared to the middle of the scale 4 with a one sample Wilcoxon signed rank test and delivered the p=0.00007 meaning this difference is also significant. The means of the frequency of conflict for each participant for both experiment 1 and 2 are shown in Figure 26.

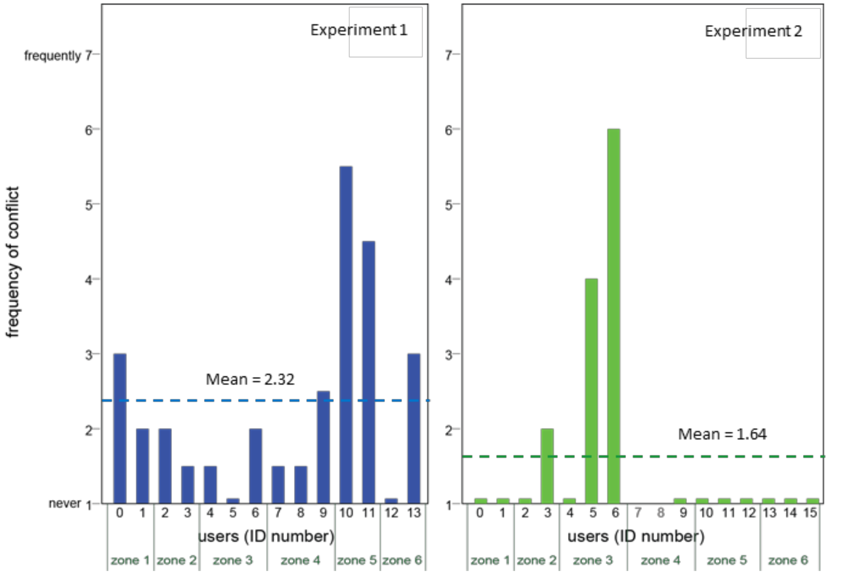

Figure 26. Frequency of conflict responses in experiment 1 (left) and experiment 2 (right) from [26]. In experiment 2 users 7 and 8 did not participate in the study.

The degree of conflict was evaluated on a 7-point scale from 1- no conflict at all to 7 – very high conflict. The degree of the experienced conflict was assessed by the participants in experiment 1 with a mean of 1.61 and a standard deviation of 0.60. In experiment 2 the mean for the degree of conflict was 1.36 and the standard deviation was 0.89. In both cases the comparison of the obtained mean with the middle of the scale 4 concluded the difference is significant (p<0.00001). The mean degree of conflict per participant in both experiment 1 and 2 is shown in Figure 27.

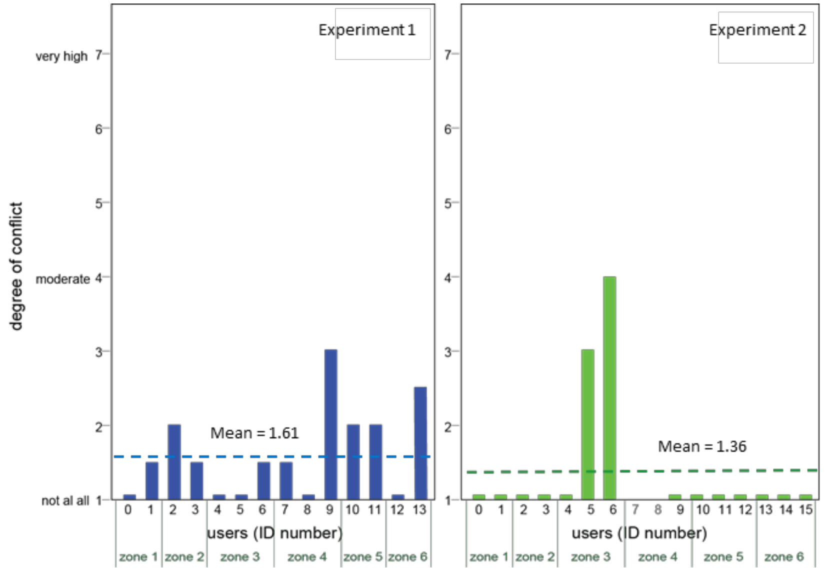

Figure 27. Mean degree of conflict in experiment 1 (left) and experiment 2 (right) from [26]. In experiment 2 users 7 and 8 did not participate in the study.

Some participants did indicate they tended to avoid using the controls: 2 out of 14 in Condition 2 and 3 out of 14 participants in Condition 3 (experiment 1). The two participants who indicated to avoid using controls in both condition 2 and 3 where the same people. Participants had different reasons for this avoidance:

- Fear of upsetting other occupants
- Changing a light level when others were present almost always led to remarks (though rarely to complaints)
- The maximum light output maintained in the zone was the preferred setting
- Once the level was set it was ok and people did not complain

3.3.3 Conflict avoidance

When lighting controllers were distributed to the participants to offer lighting control in the multi-user study office, it was hypothesized that the participants would discuss their preferences in an open way with their neighbors. It was expected that the participants would agree on a light level that everybody would find acceptable, within their control zone, in view of potential individual preferences differences. After the first series of interviews, it was discovered that the participants never discussed their preferences with their neighbors. The same response was given by the participants in all subsequent interviews of both experiment 1 and 2 during the “control” conditions. More surprisingly, most participants knew well what their neighbor’s preferences were either because they observed which lighting levels were selected by their neighbors or because sometimes their neighbors made a comment stating which level they preferred. It became apparent that people deployed various strategies to do their best to avoid conflict with their neighbors.

The analysis of the face-to-face interviews revealed patterns of behavior demonstrating how people tried to avoid conflict with neighbors. Several participants shared to mainly make light changes when their neighbors were not around, like early in the morning when their neighbors did not

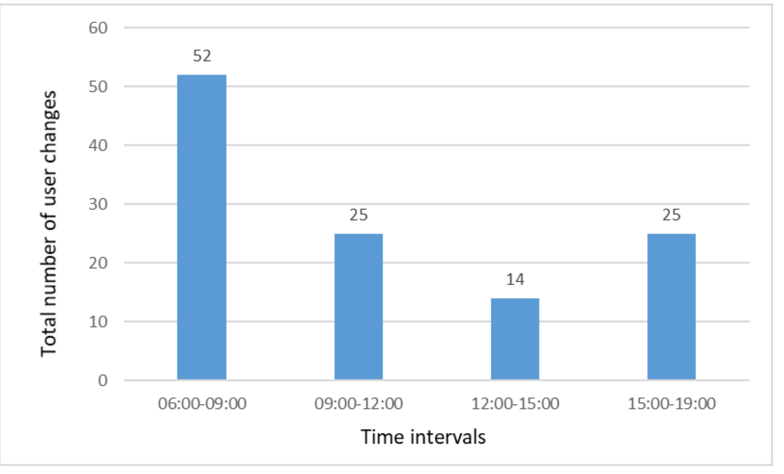

Figure 28.Distribution of the number of changes throughout the day (experiment 1).

yet arrive. This is also reflected in the logged user interface data of experiment 1, showing the distribution of the total number of changes throughout the day in conditions 2 and 3 (Figure 28). As shown in Figure 28, nearly half of the total number of changes were made early in the morning before 9:00 AM. In experiment 2 most changes occurred between 9:00 AM and 12:00 AM (Figure 29). At other moments throughout the day the participants indicated to prefer making changes when other neighbors sitting in the same control zone or the neighboring zones were away. The participants shared that when their neighbors would arrive at their desk, they would often not notice a change.

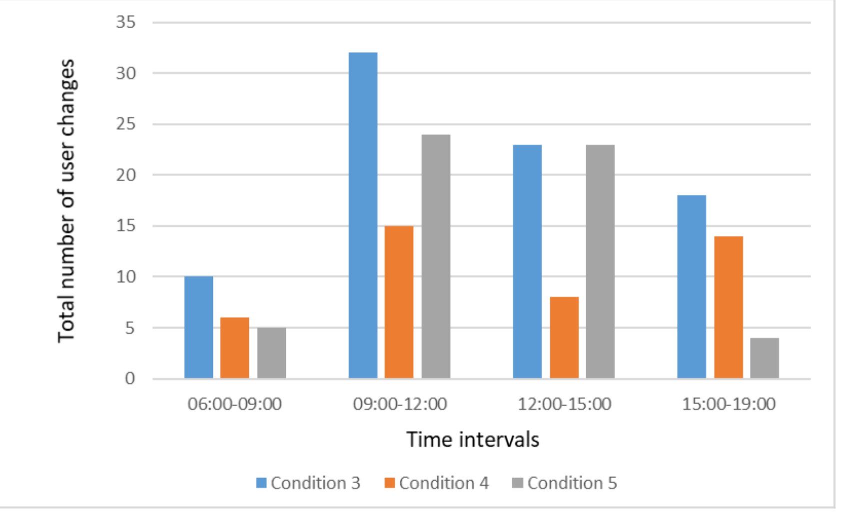

Figure 29. Distribution of the number of changes throughout the day in conditions 3, 4 and 5 (experiment 2).

After the controllers were introduced, the participants experimented more extensively with the controllers. The number of control actions was initially relatively high and decreased from slightly more than 4 changes per user per day during the first day of experiment 1 to around one change and stabilized at that level for subsequent weeks as shown in Figure 30. During the phase of getting familiar with the controllers, participants noticed that moving the slider relatively fast led to their neighbors noticing the change, since they would sometimes make a neutral remark like, 'Something happened to the lighting.' On the contrary, when changes were made by moving a slider relatively slowly, nobody made any remarks. Based on these observations some participants were changing the light level by moving the slider relatively slowly or in multiple small steps, so that it would not be noticed by the neighbors present in the office.

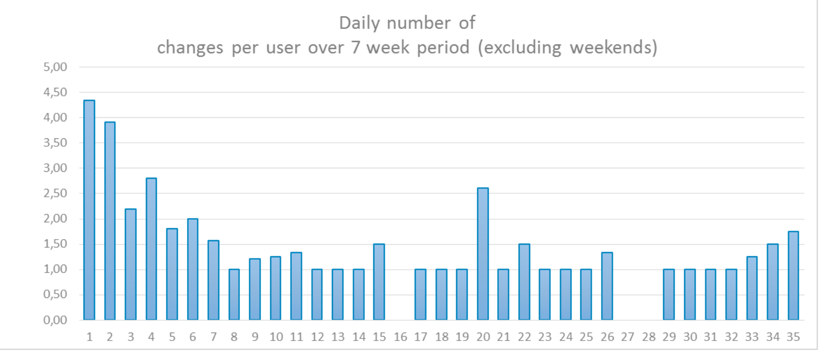

Figure 30. Average daily number of control actions per user (experiment 1).

3.3.4 Incidence of conflict

In the current section the submissive and dominant behaviors of the users are discussed as they were derived based on the survey data and face-to-face interviews data. In [34] the sensor data and user actions log data were analyzed to demonstrate possibilities of deriving the submissive and dominant behaviors profiles automatically.

In both experiment 1 and 2 neighboring participants with conflicting light level preferences were identified. This happened in the control zone 3 in experiment 1 and in the control zones 1 and 3 in experiment 2, in both experiments there were 6 control zones in total (Figure 22). The classification of the zones for both experiments based on objective and subjective measurements is given in [34]. In experiment 1, zone 3 included 3 users, 1 of those (user ID 4) preferred a relatively higher light level whereas 2 others preferred a lower one. The participant with a higher light level preference expressed in the surveys to be unsatisfied with the light quantity and quality. This participant also expressed a preference for an office without lighting controls when asked at the end of the study to make a choice between an office with “control” or without. Although unsatisfied with the lighting condition, this participant did not discuss the situation with the neighbors from the same zone and chose not to change the light level in the control zone when set by other zone users.

In experiment 2, a similar behavior was observed in zone 1, accommodating two users. One of the users (user ID 0) shared through the surveys to be dissatisfied with the light quantity and quality. In the interviews that user shared that his zone neighbor (user ID 1) preferred a lower light level. After the controllers were introduced, his zone neighbor had set his preferred light level, accompanied by the statement - 'This is the way I like the light level to be.' Aware of the conflicting preferences, the more submissive user did not use the light controller to adjust the lighting for the remainder of the study, despite of his own dissatisfaction with the zone lighting.

These two cases demonstrate a situation in which users have rather different light level preferences compared to their neighbors. To avoid conflict, the dissatisfied users chose neither to change the light level nor to discuss the situation with their neighbors. This behavior was labeled as a submissive behavior since the dissatisfied users subordinate their own comfort to that of their neighbor(s), because they are concerned it could lead to conflict.

In experiment 2, two users within zone 3 (user IDs 5 and 6) had opposite light level preferences, however, did not get involved in a submissive behavior. Being aware of the rather different light level preferences, the users chose to set their preferred light levels when their neighbor was away from the desk. Both users were aware of the situation and described it using similar details. Surprisingly, even these users chose not to discuss the situation openly with each other but were engaged in an implicit conflict. These two users were using their controllers more frequently than what was typical for users of other zones during both studies. They both felt they were forced to use the controllers more often than they would otherwise prefer. In an interview one of these users said that the ideal way of interacting with the lighting system would be to communicate the personal light level preference initially to the system, whereafter the system should maintain this light level automatically. Several other participants indicated that they expected limited interaction with a lighting system would be required. These users expected a certain level of intelligence from the system that would enable the system to get some limited user input to learn users' preferences and then to maintain the preferred lighting conditions for the users with only sporadic corrections from the users. The intelligent semi-automatic form of deriving user preferences with machine learning has been explored in [34] based on the data of experiment 1 and 2 and is also the topic of another study described in [35].

Other participants of the study did not report conflict and did not report high levels of dissatisfaction with the lighting conditions. In many of these cases the lighting preferences of the neighbors were similar. The rest of these participants were tolerant enough to the choices of their neighbors or less active in using the controllers.

Control actions were not always made to cater for own interests. Behaviors were observed where participants, for example, changed the light level in the afternoon because their neighbors preferred more light in the afternoon to compensate for the afternoon dip (experiment 1, zones 5 and 6). In yet another example, a participant (experiment 2, user ID 14) said when other neighbors in the control zone would be present, the participant would deliberately change the light level to a medium slider position. This strategy was explained as a way to respect other people's preferences by avoiding selecting any of the two extremes.

3.3.5 Preference for "control" or "no control"

After having experienced "control" and "no control" conditions, the participants were asked to make a hypothetical choice between having a desk in an office with controls as experienced during the study or a desk in an office without controls. In experiment 1, one user (user ID 4) opted for an office without controls whereas in experiment 2 three users (user IDs 5, 11 and 14) opted for "no control" (Figure 31). In both studies, users who opted for a "no control" office were either users who demonstrated a submissive way of dealing with opposing lighting preferences or users that were engaged in an implicit conflict.

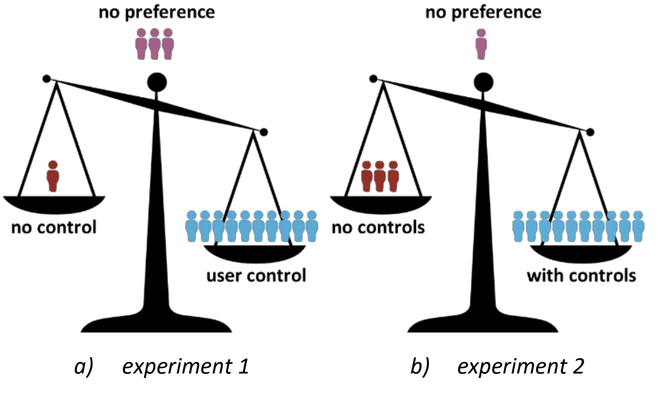

Figure 31. A choice for "no control" versus "control" in a) experiment 1 and b) experiment 2.

3.3.6 Loss aversion

Participants were asked once a week to evaluate the light quantity on their desk, screen, and due to daylight. The assessments of light quantity were converted into a dissatisfaction scale, where the extremes of too little (1) and too much (7) were translated into dissatisfied (3); the just right (4) response was translated into satisfied (0), scores 2 and 6 translated to score 2, scores 3 and 5 translated to score 1. The descriptive statistics of the “no control” (Cnc) and the “control” (Cuc) dissatisfaction data of experiment 1 is shown in boxplots in Figure 32.

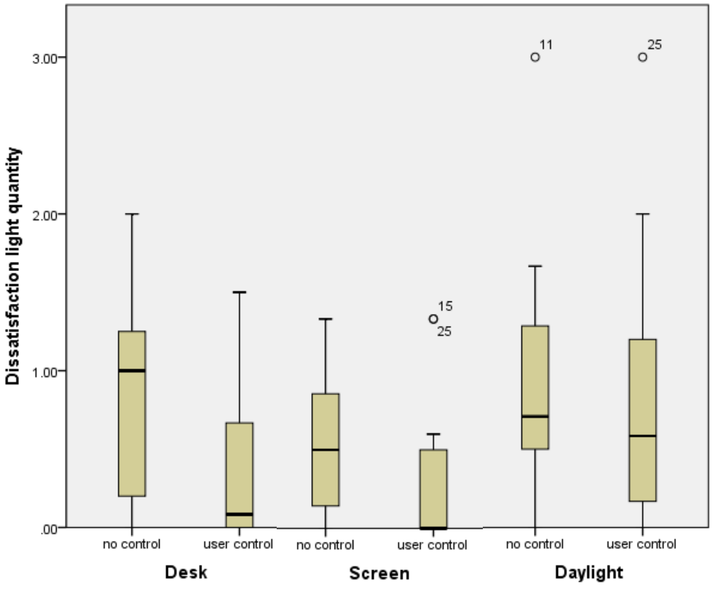

Figure 32. Boxplots of dissatisfaction with light quantity in “no control” and “user control” conditions, ranging from 0-satisfied to 3-dissatisfied.

Statistical analysis using the non-parametric Wilcoxon Signed Ranks test found a significantly lower dissatisfaction with the light quantity on the desk ($p=0.029$, effect size $ES=-0.58$) as well as on the screen ($p=0.047$, effect size $ES=-0.53$) in the user “control” situations (Table 1).

Looking at the 4 conditions of experiment 1 separately, as explained in Section 3.2.7 and illustrated in Figure 24, the descriptive statistics for the lighting quantity dissatisfaction data is given in Table 2 including median scores and standard deviations (SD).

Table 1. Wilcoxon Signed Ranks Test results for "control" versus "no control"

	Dissatisfaction with quantity of light (0=satisfaction, 3=dissatisfaction)		
	On desk	On screen	Daylight
Z	-2.179(a)	-1.988(a)	-1.246(a)
Asymp. Sig. (2-tailed)	0.029 *	0.047 *	0.213

a. Based on positive ranks.
Wilcoxon Signed Ranks Test

Table 2. Median dissatisfaction scores with quantity of light for the 4 sub-conditions

	Dissatisfaction with quantity of light (0 = satisfaction, 3 = dissatisfaction)		
	On desk	On screen	Daylight
Condition 1 (n=47)	0.49 (SD=0.688)	0.43 (SD=0.617)	1.09 (SD=1.080)
Condition 2 (n=42)	0.43 (SD=0.630)	0.38 (SD=0.661)	0.90 (SD=1.055)
Condition 3 (n=41)	0.24 (SD=0.489)	0.27 (SD=0.549)	0.76 (SD=0.994)
Condition 4 (n=41)	1.10 (SD=1.068)	0.71 (SD=0.844)	0.76 (SD=0.943)

Table 3 gives the results of the Wilcoxon Signed Ranks significance testing for the 4-subconditions. The data shows a small difference in the median scores between condition 1 (“no control”) and condition 2 (“control”) and this difference showed to be insignificant. The second “control” condition 3 did show a significant difference with the first “no control” condition 1 for quantity of light on the desk. It can be noticed that the median dissatisfaction score in condition 4, second “no control” condition, raised substantially higher compared to condition 3 demonstrating a significant difference with both conditions 2 and 3 for quantity of light on the desk. As such a larger effect on the dissatisfaction with the lighting quantity on the desk was observed after controls were removed than after they were introduced.

Table 3. Wilcoxon Signed Ranks Test results for the 4 sub-conditions

Comparison between		Dissatisfaction with quantity of light (0 = satisfaction, 3 = dissatisfaction)		
		On desk	On screen	Daylight
Conditions 1-2	Z	-0.237b	-0.773b	-0.847b
	Sig.	0.812	0.440	0.397
Conditions 1-3	Z	-2.240b	-1.583b	-1.561b
	Sig.	0.025 *	0.113	0.118
Conditions 1-4	Z	-1.260c	-0.510c	-1.513b
	Sig.	0.208	0.610	0.130
Conditions 2-3	Z	-2.271b	-1.089b	-0.855b
	Sig.	0.023 *	0.276	0.393
Conditions 2-4	Z	-1.917c	-1.635c	-1.282b
	Sig.	0.055	0.102	0.200
Conditions 3-4	Z	-2.505c	-1.807c	-0.183b
	Sig.	0.012 *	0.071	0.855

In experiment 2, the dissatisfaction with light quantity and quality was analyzed by aggregating data for 2 “no control” conditions and 2 “control” conditions, excluding data of condition 5 due to the unpredictable participants’ response to the system behavior in this condition. In view of the explorative nature of the study, $\alpha=0.1$ was used and the data showed a significant effect indicating a lower light quantity dissatisfaction on the desk (Wilcoxon signed rank test with $p=0.092$) and higher light quality assessment (p=0.096) in the "control" conditions. It is important to notice that in experiment 2 after the controllers were removed no further measurements were conducted. As such it was not possible to see whether the effect of loss aversion would also manifest itself in experiment 2 and yet the data during the "control" conditions showed a similar trend as in experiment 1.

The participants gave a median score of 4 on a 7-point scale to the importance of controlling the lighting over their desk before they had controls in experiment 1. The importance increased to 6 after the participants experienced the controls and it stayed at 6 in both conditions 2 and 3 (Figure 33). In the last "no control" condition 4, the importance of having control scored higher than in the initial "no control" condition 1. As one participant commented in an interview: "Before, I did not know what difference it would make to have controls. After I have tried them, I do not want to be without anymore".

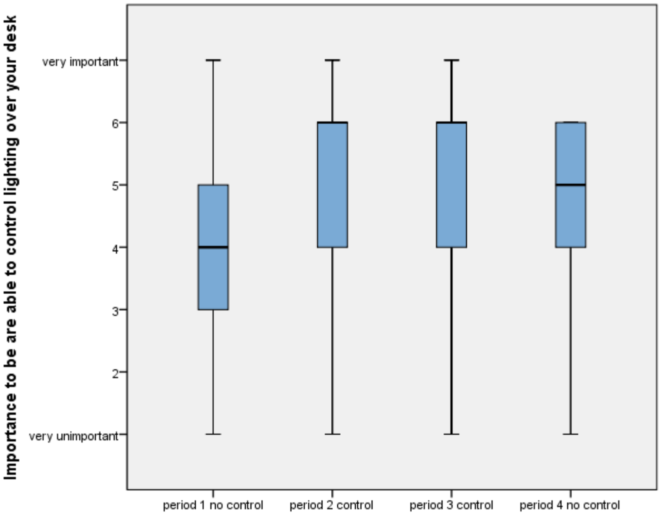

Figure 33. Ratings of the importance to control lighting.

3.4 Discussion

3.4.1 Conflict avoidance

Although previous research shows that some users avoid using controls out of conflict avoidance considerations, this study revealed that even dominant individuals avoid having an open discussion of their lighting preferences with their neighbors and do not proactively search consensus. A surprising outcome of the study is that none of the 28 participants openly discussed their preferences with neighbors to find a mutually acceptable light level.

The study explored what strategies users deployed to avoid conflict. One strategy observed was making a change in absence of neighbors. Another strategy was making a change by moving the slider slowly or using small incremental steps, so others would not notice the light output change.

In several cases, strategies were proactively deployed by users to remain on good terms with their neighbors, like selecting a less extreme dimming level when others would arrive or setting the level their neighbors preferred in the afternoon.

Interestingly, similar strategies were observed with respect to dealing with daylight by means of blinds control. Individual daylight level sensitivities and preferences showed to be diverse, resulting in a variety of, sometimes conflicting, daylight requirements. Participants who were less sensitive to high daylight levels did not expect the blinds to be completely closed on bright, sunny days. Some of them even had an explicit desire for blinds to be completely open at the lower end to allow for an outside view. Other participants indicated experiencing a quite severe disturbance from daylight. For these participants the blinds position was often not ideal due to other office users who preferred the blinds not being completely closed. Some also indicated that they did not want to completely close the blinds, to make sure their colleagues would not sit “in the dark”.

During the study the external blinds were monitored via a webcam installed in a building facing the building façade where the test bed was running. The webcam images revealed that the blinds had a tendency to be closed more on sunny days and to be opened more on cloudy days.

3.4.2 Incidence of conflict

By means of in-depth interviews and surveys data it was explored in which situations conflicts did occur among the neighbors. The study exposed the behaviors the study participants engaged in when there was a difference in lighting preferences: the submissive behavior and the implicit conflict behavior.

As mentioned in section 3.2.2 the two samples of participants of experiments 1 and 2 were different. The participants of experiment 1 were more familiar with each other than the participants of experiment 2. This could be one of the reasons why several more cases of conflict were observed in experiment 2. Therefore, more participants opted against controls and the participants were less active using the controllers than in experiment 1.

The participants of the study were using individually assigned desks. Flex unassigned desks would offer more flexibility to possibly swap a desk in case of a conflict. The use of lighting controls in an office with flex desks needs further exploration.

It was observed that even in cases in which individuals did experience conflict (even relatively frequently) the degree of experienced conflict was hardly ever above average. There are two possible explanations to that. The test office chosen for this study faced southward such that daylight often exceeded the contribution of artificial lighting. In view of sufficient daylight and other environmental factors, dissatisfaction with the light level possibly was not critical enough to cause a high degree of conflict. Another possibility is that the participants were giving a more socially desirable response to the degree of conflict question. This possibility is supported by the results showing that some participants who experienced a conflict situation tended not to opt for an office with controls. This aspect could be further explored by deploying objective measurements rather than subjective.

3.4.3 Loss aversion

Experiment 1 allowed to make a comparison between the subjective lighting ratings observed after the controllers were introduced and after the controllers were removed. The results show a much smaller change in the lighting quantity satisfaction scores observed after the controllers were given to the participants than after they were removed from the desks. This effect resembles what is known in behavioral economics as loss aversion. Loss aversion demonstrates the human propensity to experience a loss psychologically in a much more powerful way than a gain. In other words, it looks like after the participants got the controllers initially it mattered to them much less than when the controllers were removed at the end of experiment 1. The differences between the ratings given to the importance to control lighting in conditions 1 and 4 of experiment 1, support this observation. Due to time constraints during experiment 2, no measurements could be conducted after the controllers were removed and thus it was not possible to see whether this loss aversion effect could be replicated.

3.5 Conclusions

3.5.1 Conflict avoidance

The study shows that most people, including dominant individuals, are very conscious of a potential conflict with neighbors and use different strategies to avoid conflict. This finding has implications for the design of multi-user control solutions in buildings. After the user initiates an environmental change with a user interface, a system response that leads to rapid, clearly noticeable parameter change is not appreciated due to its disruptive effect on other users of the space. Based on the study data, choices that enable users to make environmental changes in a way that is hard to notice by others would be more comfortable for office users and thus promote the use of controls. A recommended strategy is to introduce a mode on the UI in which a user action would always lead to a gradual change of light, to make it barely noticeable to other users of the space.

3.5.2 Loss aversion

The observations made in experiment 1 show a stronger effect on the dissatisfaction with lighting quantity after the controllers were removed compared to when they were introduced. The assessment of the quantity of light on the screen and on the desk rose towards “too much” rating after the controllers were removed despite the fact that it was the last condition with less sunny days and a lower external lux level than during the preceding conditions. This observation is discussed in section 3.4.3 as an instance of the loss aversion cognitive bias. The study data supports previous findings indicating that even in multi-user office spaces most users perceive lighting shared control in a beneficial way. The loss aversion effect observed suggests, however, that the nuisance of having no control over lighting will be felt stronger after people lose it than the satisfaction gains when people first get it. In this respect, the occupant-controlled lighting rather belongs to a category of hygiene factors, than 'wow' effect creators.

3.5.3 Implications of the findings

In multi-user spaces, people are generally self-conscious of the presence of other individuals. System design needs to facilitate making environmental changes in a manner that is least disruptive to other space users.

Although offering control enhances satisfaction and most users prefer control over no control, there is always a risk of creating conflict due to instances of opposing preferences. Solutions that help resolve conflict in multi-user context need to be further explored.

By demonstrating the loss aversion effect, it is shown that despite all benefits occupant control is rather a hygiene factor. To bring the benefits of occupant-controlled lighting to office users its application needs support from certification and regulation bodies like WELL, since occupant control would have hard time promoting itself.

In Chapter 4 the results of experiment 2 related to the comparison of the 3 different strategies of providing shared control to office users, including "memorizing", "forgetting" and the control strategy including daylight harvesting with a user adjustable set-point, are described.

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4 Which control strategies result in a better user experience when sharing lighting control

This chapter is based on:

Lashina, T., van der Vleuten-Chraibi, S., Despenic, M., Shrubsole, P., Rosemann, A., & van Loenen, E. (2019, February). A comparison of lighting control strategies for open offices. Building and Environment, 149, 68-78. https://doi.org/10.1016/j.buildenv.2018.12.013

This chapter presents the results of the second field experiment exploring the experience of shared control in a multi-user open office. The experiment showed that despite users having diverse lighting preferences, provision of control even in a multi-user office resulted in a higher satisfaction with the lighting environment than in an office with a fixed light level.

This experiment 2 evaluated three shared control strategies. The results did not deliver evidence of benefits of the control strategy “control set-point” in which the user selected light level was treated as a set-point for daylight regulation. The results showed that when the system remembered the last level set by the user, the “memorizing” condition, it resulted in a smaller amount of user actions executed using shared control and the resulting lighting conditions in the office better reflected individual preferences compared to the “forgetting” strategy in which the system was resetting overnight to its default state. The results were significant only with respect to satisfaction with daylight in favor of the system remembering the light level set by the user.

4.1 Introduction

4.1.1 "Control" versus "no control"

To explore the effects of offering shared control in multi-user open offices two field experiments have been conducted and they are described in Chapter 3. An elaborate exploration of the social dynamics among the study participants, including their experience of conflict, dominant or submissive behaviors, conflict avoidance and loss aversion, is provided in the previous Chapter and in [15].

Experiment 1 focused on the social dynamics among the open office users and their experience of conflict due to lighting control. The data of experiment 1 showed that in the shared control condition the level of satisfaction with the lighting quantity and quality was higher, majority of users preferred "control" to "no control" and the frequency and degree of conflict in "control" condition was low.

In experiment 1 daylight regulation of the luminaires output with respect to incoming daylight was deliberately excluded since it could potentially act as a confounding variable affecting the experience of conflict which was initially the focus. Current standards like ANSI/AHRAE/IES Standard 90.1-2016 [16] prescribe using daylight regulation in new and renovated lighting installations, to increase energy efficiency of modern buildings. Due to these measures, daylight regulation becomes nowadays a widespread lighting control feature in office buildings. Due to this wide adoption of daylight regulation in offices it was relevant to repeat the original experiment 1 exploring the benefits of shared control but this time to include daylight regulation into the experimental design. To do that a second experiment 2 was designed to include experimental conditions with and without shared control in which daylight regulation was applied to the extend it was possible. This part of experiment 2 is the focus of the current chapter.

The primary objective of experiment 2 was to compare the experience in the “control” and the “no control” conditions replicating experiment 1 described in Chapter 3. In view of the results of experiment 1 and prior shared control study mentioned in section 1.4.4 there has been a chance that also in experiment 2 lower dissatisfaction with lighting quantity on the desks and higher lighting quality appraisal will be observed in the “control” conditions compared to “no control”. The difference with experiment 1 was in adding 2 modifications of the “control” condition behavior. Besides the “memorizing” behavior described in the previous chapter, one added “control” condition deployed the “forgetting” of the last user selected light level and resetting it to default at the end of each day and the other control behavior added daylight regulation with the set-point corresponding to the user selected light level. The secondary study objective was to compare the user experience in these 3 “control” conditions.

4.1.2 Motivation for different strategies of shared control

It is a desired behavior when a smart lighting control system learns user preferences and then maintains the light level accordingly. The users expect that controlling light should involve minimum effort from their side. As mentioned in section 1.5.2 studies showed that the actual frequency of user control actions when lighting controls were provided was low and primarily used at the start of the day and rarely being adjusted in the course of the day despite of changes in the lighting environment conditions [11,18–21]. This evidence indicates a consistency between the expectations people have about how frequently they would prefer to use control and the actual frequency of use observed.

Also the shared control UK study previously mentioned [4,8–12] explored differences between systems that had to be switched on by users themselves upon arrival and systems that were automatically activated, e.g. upon occupancy detection, and had a default pre-set switch-on level. The study showed that when a system had a pre-set switch-on level it discouraged system users to make any adjustments to the default light level [9].

For automatic activation of the lighting system, upon presence detected in an office, different choices could be made. One possibility is to reset luminaire's output to a chosen default light level at the end of each day. This behavior is further referred to as "forgetting", since the system "forgets" the user selected light level at the end of each day. In another approach it is possible to initially activate a system at a chosen default light output but after a user changes the default level with a controller, a lighting system can remember this light level until the user changes it again. This system behavior is referred further as "memorizing", since the system keeps the user selected light level in its memory and restores the user selected light level when user presence is detected.

In view of the observations and findings mentioned above, it was hypothesized that from the user perspective "memorizing" would result in higher user satisfaction with the system. This is because "memorizing" removes a need to make daily light level adjustments, which is in line with user expectations and with the actual frequency of use of lighting occupant control. Moreover, since it was shown that default pre-set switch on level discourages users to make any adjustments there is a risk that in case of “forgetting” the default light level would prevail most of the time. As such one of the study goals is to validate whether “memorizing” system behavior results in higher user satisfaction than “forgetting”.

In daylight regulation the luminaires’ output is controlled dependent on incoming daylight to deliver the electric light contribution to achieve the total desk illuminance in accordance with the setpoint. In a shared control condition, the user is modifying the set-point of the corresponding luminaires and after the set-point is adjusted it can be treated similarly to the set-point of “no control” conditions as just explained. Since daylight regulation of a lighting system with a fixed set-point enables energy saving of 28% on average as discussed in section 1.4.3 the expectation is that also the combination of the shared control and daylight regulation would lead to energy saving. However, the effect on the user experience could be negative as users observe the system automatically adjusting the lighting level when the incoming daylight level increases in case the reason for this automatic behavior is unclear to office users. The exploration of this daylight regulated form of shared control in comparison to “memorizing” and “forgetting” system behaviors is part of the secondary objective.

4.2 Materials and Methods

4.2.1 Test bed and participants

In experiment 2, the office was hosting office employees representing several research departments, as detailed in subchapter 3.2.2, who were using the test bed as their daily office during the duration of the study. Prior to the study, most participants did not share an office together but worked in different office spaces. Due to a relocation of teams within the office building, the participants were moved into the test office. The office after the relocation included 16 workplaces, of which 14 were occupied by the participants of the study. Two out of 16 office users were not eligible to participate in the study since they were not spending the required time in the office due to the nature of their work (refer to subchapter 3.2.2 for the inclusion criteria). These 2 users were not asked to fill out experimental surveys, but both received lighting controllers and could use them like other study participants. In the test office desks were assigned to individual employees by their department managers, and this assignment remained the same during the experiment. Twelve participants were members of the same research group working on different research projects and thus not all of them were collaborating daily. Two participants relocated into the test space for the purpose of the study and belonged to other groups within the same organization.

The desks, luminaires and sensors arrangements are illustrated on the office plan in Figure 22. To measure energy consumption by every luminaire, PlugWise meters (FW 2.36+) were attached to every luminaire, and they reported data per luminaire on an hourly basis.

To assess the amount of light different desks were receiving during the study 8 HOBO data loggers (Onset U12-012) were used to record the desks illuminance every 5 minutes (Figure 34). The data loggers were attached to the vertical dividers on the desks using a horizontal mount to avoid the sensors being blocked by paperwork or the participants' body parts.

For controlling the amount of daylight entering the office the participants were offered motorized interior blinds with wireless remote controls placed on the windowsils each for one of the 4 windows in the office. The states of the blinds have been recorded every 5 minutes. The exterior blinds were controlled by the building management system for the entire building facade. Images of the study office blinds were captured every hour by the computer with a connected webcam installed in a neigbouring office building.

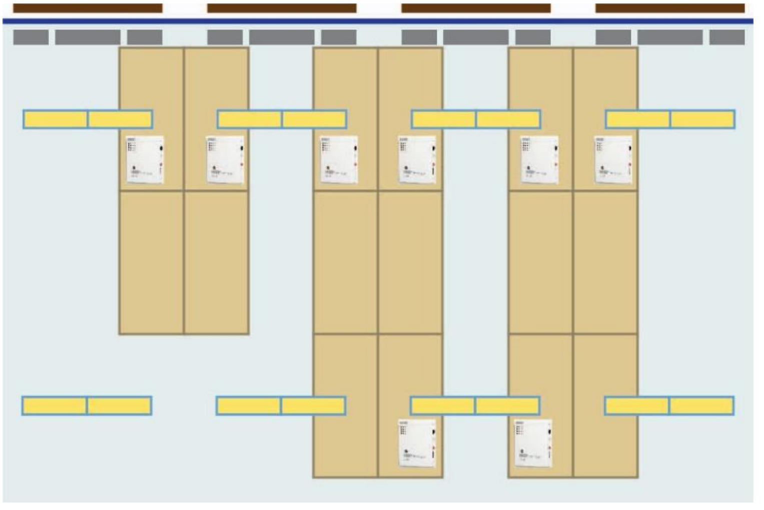


Figure 34. The layout of the office with the positions of the HOBO loggers.

4.2.2 Shared lighting control

During the experiment, the participants experienced two types of conditions. In the “no control” conditions the participants had no control over lighting. In the “control” conditions the lighting controllers were offered to the participants similarly to how it was done in experiment 1. In the “control” conditions each study participant received a handheld smart device (iPod Touch 5th generation), positioned in a docking station on the participant’s desk, running a light dimming application displaying a control slider depicted in Figure 35. These iPod controllers were commissioned to control the luminaires of their corresponding control zone (Figure 22). Each controller acted identical to other controllers of the same zone. This means that if the user would adjust the position of the dimming slider using the user interface

(Figure 35), the light output of all the luminaires belonging to the corresponding zone would change in response. All the iPod controllers within the same zone would display the luminaires output level of that zone at any moment. The user interface on the iPod controller offered extra functionality accessible via the exclamation icon. It offered the participants an option to provide environmental comfort feedback to facility management related to experienced temperature, ventilation, light level, and noise.

Figure 35. The user interface for controlling luminaires output used in experiment2.

The adjustments of the light level triggered by user actions controlling the slider occurred after the finger was released using a 2 second fade time between the previous light level and the new selected light level. This behavior was chosen to prevent too many abrupt lighting changes while controlling the slider that could be too distractive to other participants present in the office. A subsequent study has shown that a fading time close to 2 seconds is acceptable to more than 70% of the users [23, 24].

4.2.3 Experimental conditions

In experiment 1 the subjective experience of office lighting was compared in two cases, firstly, in the "no control" case in which 500 lx average illuminance was maintained on the desks and no lighting control was offered and, secondly, in the "control" case when the office users could control luminaires output from off to the maximum level. Experiment 2 was designed to again offer conditions without user control and conditions in which user control was available. The difference with experiment 1 was that the conditions without shared control deployed daylight regulation and the conditions offering shared control used daylight regulation to the extend it was possible. Moreover, to explore differences between different possible system behaviors when offering shared control, in accordance with the study objectives, three shared control conditions were included. This resulted in a within subject experimental design comprised of different experimental conditions offered sequentially to the participants of experiment 2 (Figure 25).

Condition 1 was a condition without control in which the system was adjusting the artificial light component dependent on incoming daylight to maintain the average 500 lx desks illuminance in the space. In condition 2, another "no control" condition, the light output was adjusted based on incoming daylight, but this time aiming to deliver on average 300 lx desks illuminance. In conditions 1 and 2 daylight regulation was implemented using the daylight harvesting (DH) algorithm of proportional control [25]. This DH control scheme was chosen based on the comparison to an alternative integral control that was shown to be more prone to underillumination [26]. The control of each zone of luminaires was based on the illuminance values from the ceiling sensors positioned along the windows (top line of occupancy sensors in Figure 22). It took into account the fact that the desks further away from the windows received less daylight. The difference in illuminance received at the desks closest and furthest away from the windows was measured to be on average 30 percent. The luminaire output levels of the luminaires along the hallway were compensated accordingly within each zone.

Conditions 3, 4 and 5 were “control” conditions in which iPod controllers were placed on every participant’s desk and offered a possibility to use the user interface displaying the slider (Figure 35) to control lighting dimming level between 1 and 100 % luminaire output within every control zone. Each controller was assigned an identifier that was permanently linked to a particular control zone of luminaires.

In conditions 3 and 4 initially the system was operating in automatic daylight regulation mode with a 300 lx setpoint, which was identical to the system mode in condition 2. After a user initiated a control action adjusting the artificial lighting level in conditions 3 and 4, the system would switch off the automatic DH mode and would go into a manual mode. In condition 3 the system behavior followed the “forgetting” strategy, meaning that at the end of each day the user-selected light levels in all zones were forgotten and the system was restored to the default mode in which the system was delivering 300 lx on the desks in a daylight regulating manner. In condition 4 the system behavior was implemented in accordance with the “memorizing” strategy in which the user-selected light level was remembered and restored every time the system was triggered by the occupancy sensors to switch on. In condition

4, after the first user light level adjustment in a zone, no longer DH was applied in that zone.

Condition 5 was the third condition offering shared control. This was an explorative condition to investigate potential benefits or drawbacks associated with applying daylight regulation to the dimming level selected by the user. In this system mode, after the user would select a certain luminaire output level with the slider, the system would act to maintain the resulting desk illuminance level, which was estimated based on the ceiling sensor readings. The illuminance level the system was maintaining was capped at 500 lx. The desk illuminance estimation was performed 30 secs after the last user action was performed. This delay was used since users tended to try out different levels before making their final choice. The user-selected light level was remembered overnight like it was done in the “memorizing” mode.

4.2.4 Subjective measurements

To compare the subjective experience of the participants in the 5 experimental conditions each condition was tested for 4 weeks as shown in Figure 25. The survey used to evaluate lighting quantity was adopted from [4] and the items of the subjective scale are shown in Table 4.

Table 4. Lighting quantity survey questions

Light quantity
Would you say that the amount of light on your desk is: too little – too much
Would you say the amount of light on your laptop/ computer monitor is: too little – too much
Think about the amount of daylight that reaches your desk, is this: too little – too much

Table 5. Lighting quality survey questions

Light quality
Overall, how satisfied are you with the lighting at your desk?
very dissatisfied - very satisfied
Please rate the lighting available to you for reading.
poor - excellent
Please rate your workstation on the amount of light for the work you did last week:
poor - excellent
How do you rate the acceptability of the lighting in this office?
completely unacceptable - completely acceptable
Lighting at my desk hindered me from doing my job well.
strongly disagree - strongly agree

The lighting quality subjective scale comprised 5 questions as shown in Table 5 and was based on the scale as described in [28]. The survey items were evaluated using a 7-point scale with higher scores corresponding to better lighting quality, except the last item that was reversed.

The first week of every condition was intended as a period of getting used to a specific condition thus corresponding subjective data was excluded from the analysis. Every 4 weeks in conditions offering shared control the short surveys were complemented with additional questions (extended survey in Figure 25) evaluating the perceived level of control and the level and degree of conflict due to the use of the lighting controls. The questions comprising these subjective scales can be found in Appendix C. Every condition was finalized by a face-to-face semi-structured interview with every participant. The interviews were intended to collect complementary participants' input on their experience of the controls, the office, and their interactions with other office users.

4.3 Results

In the results section, the analysis of the subjective data is shown, followed by the analysis of the objective data obtained from sensor logs.

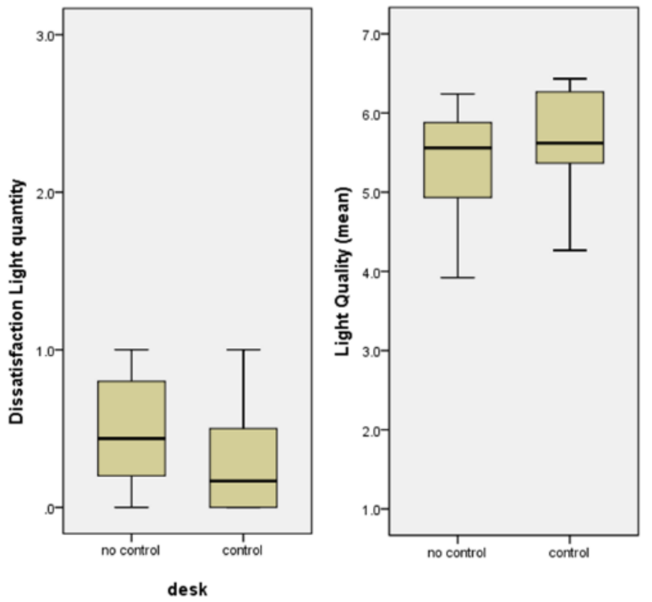
4.3.1 Analysis of subjective responses

The subjective data was analyzed by comparing data corresponding to the different conditions with each other. For the comparison of the responses received in different experimental conditions a non-parametric related samples Wilcoxon signed-rank test was used. This choice for a non-parametric analysis is motivated by a relatively small size of the sample used and the fact that the ordinal data collected did not satisfy the normality criteria. For the hypothesis testing a significance level $\alpha=0.1$ was used due to the relatively small sample size [32].

The data was firstly analyzed for differences between the weeks within each condition. Since the differences between weeks were negligible, the data was aggregated by taking an average per condition per participant.

4.3.2 "Control" versus "no control"

The analysis of differences between "no control" and "control" conditions was done by aggregating data of conditions 1 and 2 comprising the "no control" data set and by aggregating data of conditions 3 and 4 comprising the “control” data set. The data of condition 5 was not included due to the explorative nature of the condition. There were too many uncertainties in how the participants would experience the semi-automatic behavior of the system in condition 5.



a) b)

Figure 36. a) Dissatisfaction with light quantity ranging from 0=satisfied to 3=dissatisfied and b) Ratings of light quality on a 7-point scale with higher values for higher experienced light quality

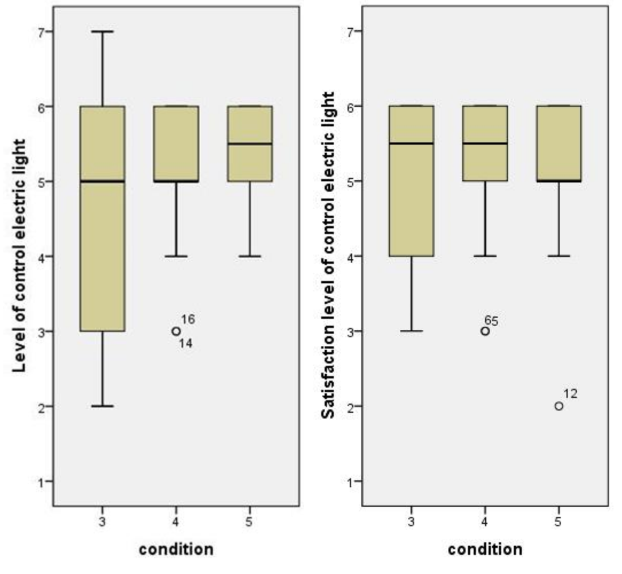
The assessments of light quantity were converted into a dissatisfaction scale, where the extremes of too little (1) and too much (7) were translated into dissatisfied (3); the just right (4) response was translated into satisfied (0), scores 2 and 6 translated to score 2, scores 3 and 5 translated to score 1. The descriptive statistics box plots for the “no control” and “control” data for dissatisfaction with lighting quantity on the desk are shown in Figure 36 (a) where the mean (M) for dissatisfaction with “no control” was M=0.46

(standard deviation SD=0.35) and for “control” was M=0.29 (SD=0.37). The difference between dissatisfaction with lighting quantity on the desk in “no control” and “control” conditions was assessed using non-parametric related samples Wilcoxon signed-rank two-tailed test using a significance level $\alpha=0.1$. The test statistics delivered a probability $p=0.092$ (moderate effect size $r=-0.45$) and thus according to the experimental data the difference is significant. The differences in dissatisfaction with lighting quantity on the screen and due to daylight did not show a significant effect. This result replicates the result obtained in experiment 1.

The resulting box plots of the lighting quality data are shown in Figure 36 (b), where the mean value for “no control” is M=5.36 (SD=0.7) and for “control” is M=5.65 (SD=0.59). The related samples Wilcoxon signed-rank two-tailed test statistics was calculated and delivered $p=0.096$ (moderate effect size $r=-0.44$). Based on the experimental data and the calculated statistics the difference is significant. This result replicates the result of experiment 1.

4.3.3 Level of control

During the control conditions (3, 4, and 5) the participants were asked to evaluate the level of control they had over lighting and their satisfaction with that experienced level of control (Appendix C). The subjective scores provided are summarized in the box plots in Figure 37.



a) *b)*

Figure 37. Perceived a) level of control on a 7-point scale from "no control" to "full control" and b) satisfaction with control on a 7-point scale from "very dissatisfied" to "very satisfied"

4.3.4 Comparison of shared control conditions

The weekly survey responses data was aggregated per condition per participant and treated per category of lighting quantity on the desk, screen and due to daylight. The resulting box plots for all 5 conditions are shown in Figure 38, where the y-axis represents the dissatisfaction levels from 0= satisfied to 3=dissatisfied, and the x-axis represents the conditions (from 1 to 5). As visible in the graphs, in general the dissatisfaction level with daylight was relatively higher than dissatisfaction with the amount of light on the desk and on the screen. The light quantity assessments for daylight had a tendency in the direction of too little while the amount of light on the desk and on the screen has been mostly assessed to be "just right".

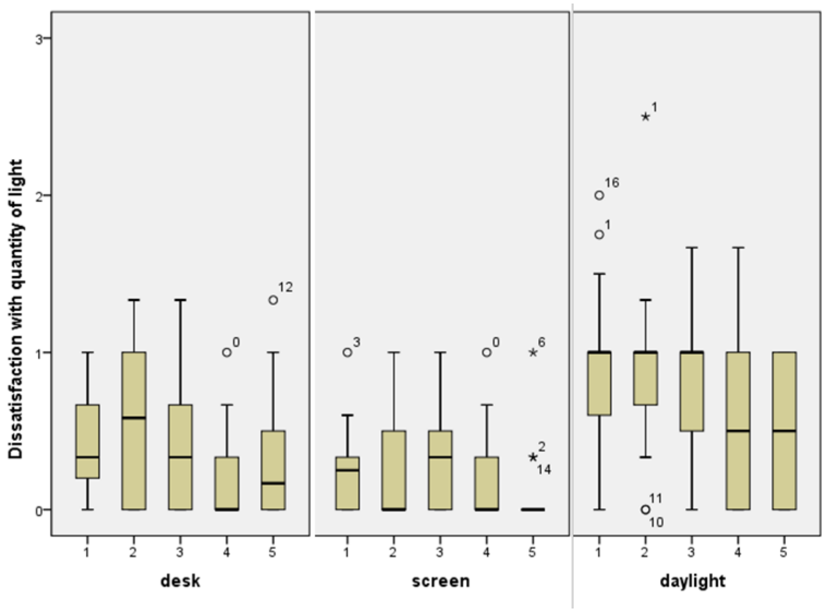


Figure 38. Boxplots of dissatisfaction with lighting quantity from 0=satisfied to 3=dissatisfied for the 5 conditions indicated along the x-axis (condition 1 = 1, condition 2=2, …, condition 5=5).

Although the median dissatisfaction values for "memorizing" condition 4 are lower than the median values in "forgetting" condition 3 (

Table 6) the analysis of the difference was not found to be significant for the amount of light on the desk (p=0.11) and on the screen (p=0.44), but it was found to be significant for the experienced amount of daylight (p=0.05, large effect size r=-0.52).

During the interviews the participants shared that the behavior of the system in condition 5 "control set-point" has been quite confusing and they did not understand why automatic lighting level adjustments were occurring. Some participants believed there was something wrong with this behavior of the system. In view of this feedback no further comparison has been done of the dissatisfaction with the amount of light in condition 5.

Table 6. Dissatisfaction with light quantity (median)

	(0 = satisfied, 3 = dissatisfied)		
	On desk	On screen	Daylight
Condition 3 (n=13)	0.33	0.33	1.00
Condition 4 (n=14)	0.00	0.00	0.50
Condition 5 (n=14)	0.17	0.00	0.50

The box plots based on the lighting quality evaluations data are shown in Table 7 and Figure 39. Despite a higher median value of lighting quality in “memorizing” condition 4 the difference with the “forgetting” condition 3 is not significant (p=0.12). For the same reasons as explained for the lighting quantity, no further analysis has been done for the explorative condition 5.

Table 7. Light quality responses (Scale from 1 to 7, higher scores = better quality)

	Condition 3 (n=13)	Condition 4 (n=14)	Condition 5 (n=14)
Median	5.40	5.83	6.03

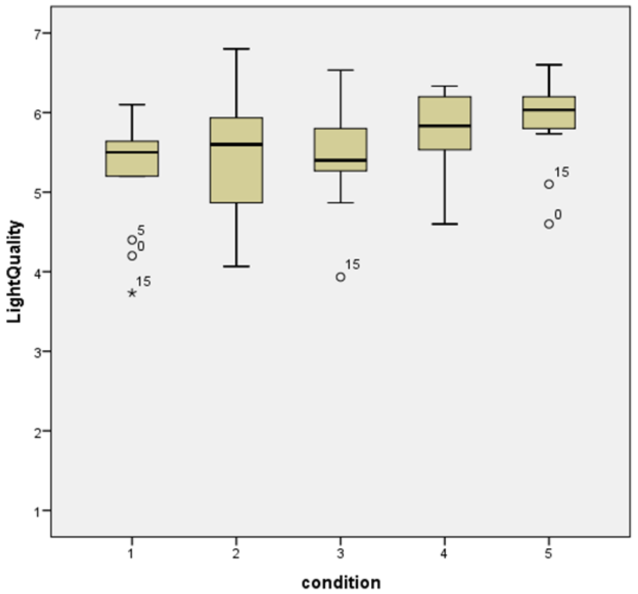


Figure 39. Box plots of lighting quality scores on a 7-point scale with higher values for higher experienced light quality

4.3.5 Objective results

In addition to the subjective data collected through surveys and interviews, logged data was recorded and analyzed and is reported in the current section.

Figure 40 shows the box plots of the number of changes made by the participants in conditions 3, 4 and 5. As it can be seen the number of changes in "memorizing" condition 4 (M=3.13, SD=2.47) is smaller than in the "forgetting" condition 3 (M=7.07, SD=4.70) and this difference is significant according to the related samples Wilcoxon signed-rank one-tailed test (p=0.0043, medium effect size r=0.48).

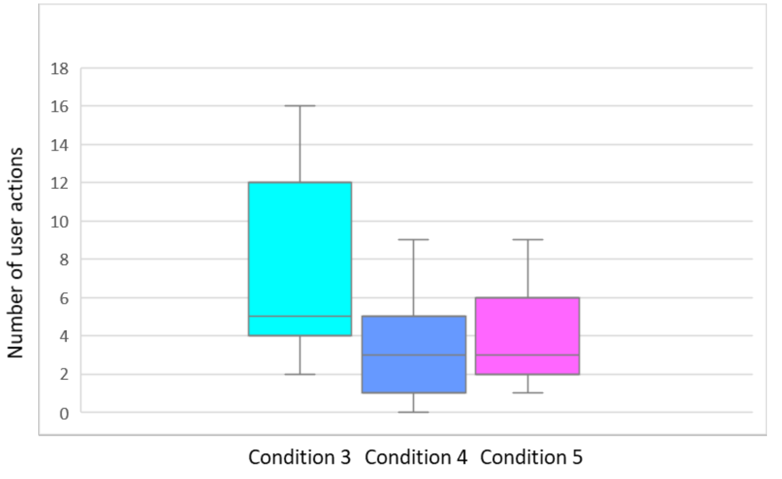


Figure 40. Box plots of total number of user changes per condition

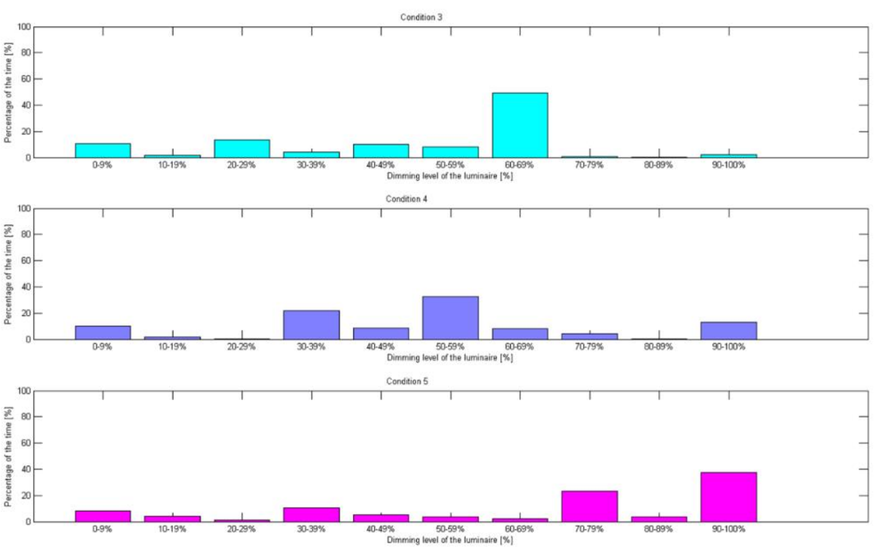


Figure 41. Histogram of the luminaires output

Figure 41 shows the histogram of the luminaires output level for the three “control” conditions. In condition 3 the maximum is at 60-69% luminaire output that corresponds to the system reset level at the start of every workday. In “memorizing” condition 4 the maximum is shifted to lower luminaire output levels of 50-59%. This is in line with results of previous research demonstrating a substantial proportion of luminaires output during the control conditions to be below the default 60% level [15, 28]. The histogram of condition 5, where the user-set light level was treated as a daylight regulation set-point, shows a relatively high proportion of luminaires output close to the maximum output level.

4.3.6 Energy consumption data

To measure energy consumption in the different conditions, hourly logged data of PlugWise meters at every luminaire was used. When luminaires were operating at constant maximum output delivering on average 500 lx on the desks the average consumption per luminaire per hour was 52 Wh. Based on this average a weekly energy consumption of the installation with 16 luminaires operating 24 hours 7 days a week would be 140kWh. This energy consumption corresponds to the unscheduled system mode when the lighting installation is delivering light at full output 24 hours per day 7 days a week, which is highly inefficient. In practice nowadays in many buildings a scheduled operating mode would be applied that switches lighting off outside typical working hours. For the scheduled operation when the lighting system would be “ON” from 6:00 AM to 8:00 PM on 5 working days per week the consumption of the test installation delivering 500 lx would be 58 kWh per week. Before the 5 conditions of the experiment were initiated, energy measurements were conducted while the system was operating for 3 weeks using occupancy control without daylight regulation and delivering 500 lx and then for another 3 weeks using occupancy control without daylight regulation and delivering 300 lx. Average weekly energy consumption was measured respectively to be 50 kWh in the 500 lx case and 34 kWh in the 300 lx case (Table 8). During the 5 experimental conditions energy use was measured and the average weekly consumption is shown in Table 8.

For the visual presentation of average energy consumption in different operating modes of the installation, the “500 lx, scheduled” mode was taken as a reference (Figure 42). The average weekly energy consumption of the other system operating modes was converted in percentages relative to the reference mode and is depicted in Figure 42 as purple bars. Figure 42 shows both the relative energy consumption in different system modes (purple bars) as well as the average inside light level of the combined daylight and electric lighting (blue bars), measured with the ceiling sensors. The inside light levels are also converted to percentages but using a different reference this time, which is the average inside light level in the “500 lx DH, occupancy” mode.

Table 8. Average weekly energy consumptions in different system modes

Operating mode		**kWh**	**%**	**month**
500 lx, unscheduled		140	241	N/A
500 lx, scheduled		58	100	N/A
500 lx, occupancy		50	85	June
300 lx, occupancy		34	57	July
500 lx DH, occupancy	(condition 1)	39	67	August
300 lx DH, occupancy	(condition 2)	31	52	September
Shared control, forgetting	(condition 3)	35	60	October
Shared control, memorizing	(condition 4)	37	63	November
Shared control + DH	(condition 5)	42	72	December

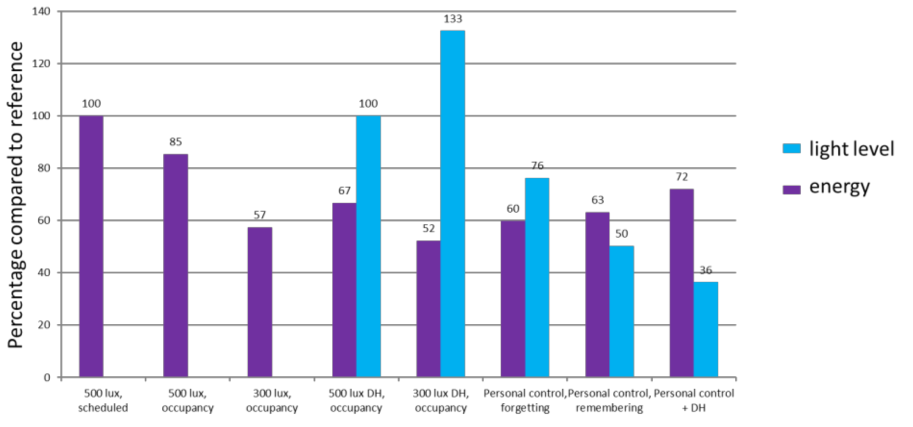


Figure 42. Average weekly energy consumption and average inside light level

4.4 Discussion

4.4.1 Control versus no control

In the context of the main research objective, exploring the effect of shared control on the satisfaction with lighting and the experience of conflict related to lighting control among open plan office occupants, experiment 2 was designed to replicate the "no control" and "control" comparison as in experiment 1 for collecting more evidence. The difference between the two experiments was in using additional lighting control strategies in experiment 2, one of those being daylight regulation.

Due to high costs of conducting a field study in an actual office, that is ideal to ensure the high ecological validity, some compromises had to be made that introduced limitations to the study. One of the limitations is the sample size of 14 recruited participants that is relatively small, qualifying the study to be merely explorative. Another compromise was made regarding the duration of the experiment that lasted from August till end December. Because of the 5 conditions that had to be tested in experiment 2 there was regrettably no room to counterbalance the order of the conditions, which was the case when conducting experiment 1.

Although explorative, experiment 2 is a second experiment in a series of two in which the two samples, each comprising 14 participants, did not overlap. The experimental data collected in experiment 2 showed, similar to experiment 1, lower dissatisfaction with lighting quantity on the desk and higher lighting quality assessment when control was provided compared to "no control". Similar to experiment 1, in experiment 2 most participants reported a low frequency and degree of conflict experienced due to control of lighting. 10 out of 14 users said to prefer shared control as experienced during the study to "no control".

At the moment of writing this thesis, most European offices have lighting installations delivering a fixed level of 500 lx average desk illuminance that is not user adjustable. The alternative lighting system behavior explored in the current study, that delivers by default 300 lx desk illuminance and allows users adjusting the light level up to 500 lx, is in accordance with the European norm NEN-EN 12464-1 [29]. It makes the system capable to deliver 500 lx for tasks that typically require higher illuminance levels, e.g., reading from paper, and makes the system adjustable in view of diverse individual preferences and needs.

4.4.2 Memorizing versus forgetting

In view of the prior evidence of the UK study [12] and experiment 1, a more positive assessment of the amount of light was expected in "memorizing" condition compared to "forgetting". Although median values obtained for lighting quantity dissatisfaction assessments in the "memorizing" condition were lower (more positive) than for the "forgetting" condition, the difference was shown not to be significant for both lighting on the desk and the screen but turned out to be significant for the amount of light due to daylight. Regarding lighting quality, the more positive median scores of the "memorizing" condition did not show a significant difference with the scores in the "forgetting" condition.

When looking at the logged data and the average number of changes per user per day, a significantly smaller number of changes was performed by users in the "memorizing" condition than in "forgetting". As mentioned before users tend to exercise lighting control only sporadically and not in accordance with lighting condition changes, e.g., daylight dynamics. Similarly, users expect to spend only limited effort to control the lighting system. Consequently, the system mode that requires fewer user actions would be more in line with user expectations.

The histogram of the luminaires output in the "forgetting" condition (Figure 41) shows that most of the time the luminaires were at their default 60% output setting, whereas in "memorizing" condition the luminaires output was more uniformly distributed. This reflects previous findings demonstrating that an availability of a pre-set switch-on level discourages users to use lighting dimming controls. The disadvantage of the "forgetting" mode is that the luminaires were about half of the time at their default output setting while in "memorizing" luminaires outputs were more diverse, better reflecting individual preferences of people in the space. At the same time the "memorizing" mode required fewer user actions than the "forgetting" mode.

The results speak in favor of the "memorizing" system mode having advantages for end-users with a caveat that in terms of subjective experience the experimental data demonstrated only limited evidence. Since implementing either of the shared control options in modern lighting systems is a matter of software choices and there is no difference in terms of costs there are good reasons discussed above to be in favor of “memorizing” over “forgetting”. This holds in particular for office spaces in which employees have either assigned desks or where the user’s location is known, and the last user-defined light level can be restored at the user’s current workplace.

4.4.3 “Control set-point” condition 5

During the interviews the participants said to notice that the light level was sometimes changing automatically in condition 5. This was described by the participants as confusing since for them it was unclear why luminaires’ output was changing automatically, especially after they would select a certain light level with a controller. Remarkably, users typically do not complain about automatic dimming of the daylight regulated lighting systems without end-user control. In view of this user feedback, it turned out to still be challenging to provide a semi-automatic control that would be positively perceived by office users. One potential improvement could be to pay more attention to the timing of the automatic lighting adjustments and to use the knowledge generated on the perceptible dimming speed to achieve lighting changes in such a way that they happen unnoticeable to office occupants [23, 24].

As it can be seen in Figure 39 the lighting quality assessments demonstrate an increasing trend of the average scores becoming higher the longer the participants had experienced the shared control conditions. A similar trend of increasing lighting quality scores was also observed during the shared control conditions of experiment 1. It could be that this progressive effect occurred since users were becoming more positive the longer they used shared control. Since both experiments 1 and 2 were conducted during the last two quarters of the year the daylight admission into the space has been decreasing as illustrated in Figure 42 and reflected in Figure 43 showing the decreasing trend of working hours when external daylight level exceeded 10K lx (commonly used as reference in northern Europe [31]) based on the study building weather station data. This effect of the diminishing daylight as the study was progressing could potentially play a role as well. To explore this time-based effect further a dedicated study design would be required.

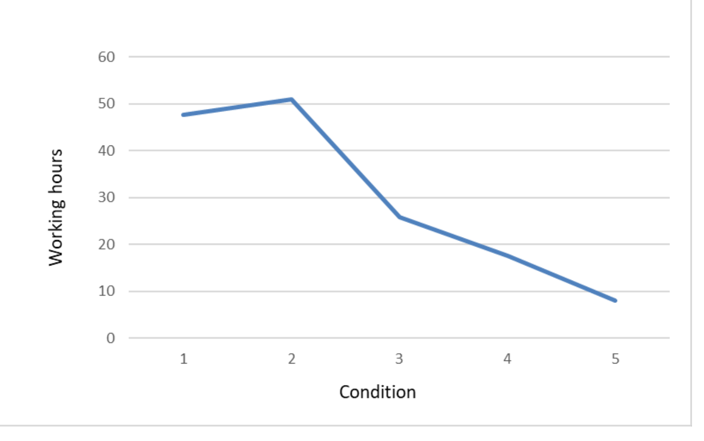


Figure 43. Working hours of daylight >10K lx in the 5 conditions of experiment 2, each condition lasted 3 weeks.

In view of the inside light level differences in the 3 shared control conditions the energy consumption cannot be compared independent of the admitted daylight. In absence of a reference space that would receive the same amount of daylight, the experimental data does not allow to make a comparison of the energy consumption in different shared control conditions. As such, the potential energy saving benefit of the “control set-point” mode requires further exploration.

4.4.4 Energy consumption

The control strategies deployed in experimental conditions used daylight regulation and thus the luminaires output of the lighting installation depended on the amount of incoming daylight. This is the reason why the comparison of the reported energy consumption provided in subchapter Energy consumption data should be viewed in a qualitative way. For a quantitative comparison an additional lighting installation running in parallel would be required receiving the same amount of daylight. The use of manually controllable blinds makes it even more challenging to ensure equal daylight admission. In view of these challenges, energy consumption could only be compared qualitatively.

4.5 Conclusions

4.5.1 Memorizing versus forgetting

The comparison of the “memorizing” and “forgetting” conditions showed more positive mean subjective evaluations of lighting quantity and quality in “memorizing”, although significant difference was only found for the amount of light due to daylight. It was observed that in the “forgetting” condition the default 60% luminaires output mode remained unchanged by users approximately half of time. In contrast, the logged data of the “memorizing” condition showed a more diverse distribution of luminaires dimming levels with respect to their relative proportion of time experienced, which better reflected user preferences. At the same time less user actions were made with controllers in “memorizing” than in “forgetting” which is in line with user expectations of using lighting control. The mean daily cloud coverage has been comparable for the two conditions and thus can be ruled out as a potential confounding variable.

4.5.2 Combining shared control with daylight regulation

In the explorative condition 5 “control set-point” the system treated the illuminance estimated on the desk, after the user selected a dimming level, as a new set-point for daylight regulation and controlled the luminaires output accordingly. In qualitative interviews users indicated to notice automatic changes to the luminaires output in “control set-point” condition and expressed their confusion about why these changes were taking place. The combination of these outcomes does not speak in favor of this system behavior and thus the experiment did not demonstrate good reasons for daylight regulating the user-selected light level the way it was offered in experiment 2. Potentially choosing the dimming speed of automatic lighting adjustments unnoticeable to most office users could make this system behavior acceptable but this requires further research.

4.5.3 Benefits of shared control

The comparison of the “control” and “no control” conditions revealed significantly lower dissatisfaction with lighting quantity on the desk and higher lighting quality assessment in “control” conditions. These results also show that although daylight regulation was introduced in the conditions of experiment 2, whereas it was absent in experiment 1, similar positive subjective experience of the “control” lighting conditions was observed in both experiments.

4.5.4 Implications of the findings

In experiment 2, similar to experiment, 1 it was shown that the availability of shared control in a multi-user setting of an open office resulted in a more positive lighting condition assessments, in terms of lighting quantity and quality. It showed that most users, 10 out of 14, preferred “control” to “no control”. Although the frequency and degree of conflict was in most cases extremely low, for the 3 individuals conflicting preferences with close neighbors negatively affected satisfaction. Since a similar fraction of the study participants had a similar negative experience with controls also in experiment 1 strategies to facilitate office neighbors having conflicting preferences require further exploration and are addressed in [14]. There is a potential for improvement of the shared control by automatically profiling users, making them aware of the preferences of their neighbors and offering dimming options that are less extreme and consider preferences of multiple users of the same control zone.

In terms of how to offer shared control, three strategies were evaluated: “forgetting”, “memorizing” and “control set-point”. The results did not deliver evidence of benefits of the lighting control strategy “control set-point” in which the user selected light level was treated as a set-point for daylight regulation. This strategy was perceived as confusing by the users. The results showed that “memorizing” the light level set by the users required less actions from users and the resulting lighting conditions in the office better reflected individual preferences compared to the “forgetting” control strategy. Since there are no additional implementation costs associated with the “memorizing” control, from the occupants’ benefit perspective it is recommended to deploy this strategy rather than the “forgetting” control in offices with assigned desks and offices where the occupants’ locations are known.

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5 Discussion

5.1 Introduction

In view of the existing literature on occupant control for lighting that was explored in Chapter 1, several benefits have been demonstrated in favor of providing lighting controls to office occupants. Most studies highlighted in the literature review have been conducted in the situation when the lighting installation was affecting an individual workstation of the user and there was no influence of the user control actions on the desks of other occupants. After the widespread deployment of open office spaces, that are multi-user by nature, only one study in the UK explored the experience of shared lighting controls in comparison to the experience of fixed lighting installations in 14 office buildings [2, 3, 4, 5, 6]. In the context of shared controls for open plan offices every person in an office is provided with an individual controller, however, when a person adjusts the dimming level with a controller the resulting light changes affect not only her or his desk but also the neighboring desks. In order to obtain insights into whether introducing shared controls would lead to a more positive experience with a lighting installation and whether this positive effect could be overshadowed by the experience of conflict among users, who might have opposing lighting preferences, two field experiments were conducted. Both studies were set-up as longitudinal field studies in such a way that the participants could experience both types of conditions without controls and with shared controls as they were using the office during the study. Subjective evaluations of the lighting conditions by the study participants were collected via survey questions together with more detailed subjective experiences collected via individual interviews at the end of every condition.

This study design enabled to collect insights into the subjective experience of each participant, the interaction with other participants and to compare the two situations: with and without shared lighting controls.

Before conducting the two field experiments, in view of previous research indicating the importance of the usability of lighting controls to encourage their use, an iterative user-centered design process was conducted. The goal has been to evaluate different user interface concepts, to go through several user interface design iterations and arrive at the final user interface design that did not create any difficulties for the users to make use of lighting control in the context of a smart lighting system.

This chapter discusses the main findings of the research conducted, it highlights the strengths and pinpoints the limitations of the methodology used and finally it provides recommendations for follow-up research to build further knowledge in the domain of shared lighting controls.

5.2 Main research findings and their significance

Compared to a lighting installation with a fixed set-point, a lighting system with shared lighting control enabling occupants of an open plan office to adjust lighting output of luminaires affecting their desks can improve satisfaction with lighting conditions without creating impeding conflict.

The comparison of the subjective assessments in the first field study, in which the participants experienced two "shared control" conditions and two "no control" conditions, revealed a significantly lower dissatisfaction with the lighting quantity on the desk and on the screen in the "shared control" conditions. Similarly, lighting quality assessments in the "shared control" conditions were more positive than in the "no control" fixed light level condition and this difference deemed significant. Similar results were obtained in the second field study after the subjective data of the lighting quantity on the desk and quality assessments was aggregated for the 2 “no control” conditions and compared to the data of the 2 “shared control” conditions. When the subjective experience of conflict was explored via subjective assessments of the frequency and degree of conflict on the scale between 1 and 7, the mean frequency of conflict per condition was between 1.64 and 2.64 and the mean degree of conflict varied between 1.29 and 1.71 where 1 corresponded to respectively “never” and “no conflict at all”. When asked which office they would prefer to choose, 10 out of 14 participants in both field studies preferred the office with “shared controls”. These results demonstrate that although some degree of conflict was introduced by bringing in shared controls, most of the occupants preferred the situation with controls and when they had controls the participants were more satisfied with lighting quantity and quality in their office.

Office occupants chose lighting control strategies and behaviors that are favorable for avoiding conflict with their neighbors.

A surprising result that was observed when the analysis of the face-to-face interviews was conducted is that, despite the expectations, the study participants never discussed their lighting preferences with their neighbors. This observation was consistent throughout all interviews and it was true for both participants groups of the two field studies. When looking at the details of how the participants were using controls, additional conflict avoidant strategies emerged that were utilized to avoid using controls openly in public. Thus, a number of participants admitted using controls when their neighbors were not around, for example early in the morning when their neighbors did not yet arrive or when they were away attending a meeting, getting a cup of coffee. The participants, who shared these stories, observed that when neighbors would return to the office, they would not show signs of noticing a difference in the lighting level.

After the controllers were given to the study participants, they experimented with them quite a lot during the first week that was also reflected in a high number of user actions, 4 changes per user per day, that later reduced. During this week the participants noticed that when they were controlling the slider of the controller relatively fast the neighbors would make a remark, signaling they noticed a change. However, when the change was made by moving the slider slowly, the neighbors would not show signs of noticing it. This finding is also related to the aspect of distraction by lighting changes made either automatically or by other users that was one of the findings highlighted in Chapter 2 and by the study exploring noticeable dimming speed [7].

Another behavior that was observed during the studies related to the conflict avoidance was the submissive behavior pattern. In these cases, the user would have a different lighting level preference than other users of the same zone, but out of the consideration of avoiding conflict the user would choose not to make adjustments to the lighting level.

Office workers would experience gaining lighting control in a less impactful way than they would experience losing control.

Due to the familiarity of office workers with not having lighting control in open plan offices, both field experiments 1 and 2 started with conditions in which the participants did not have control but experienced fixed lighting set-point conditions. In experiment 1, after experiencing the "no control" condition 1, the participants got lighting controllers for the period of 7 weeks, the two "shared control" conditions 2 and 3, and then the controllers were removed for the last "no control" condition 4. When the lighting quantity dissatisfaction subjective ratings were analyzed per condition the difference between dissatisfaction scores between condition 1 ("no control") and 2 ("shared control") was insignificant. In contrast, the dissatisfaction in the condition 4 ("no control") was significantly higher compared to that in condition 3 ("shared control"), reflecting a bigger impact of removing the controllers compared to that of getting the controllers. A similar dynamic was observed in the ratings of the importance to control lighting, it was rated higher in condition 4 ("no control") compared to the ratings in condition 1 ("no control").

This result is relevant in terms of its implications for promoting lighting control for multi-user spaces. The findings demonstrate that the provision of lighting control in multi-user offices does lead to increased satisfaction with the lighting conditions and the majority of occupants prefer control to no control. At the same time, the dynamic of the dissatisfaction ratings showed that the transition from "no control" to "shared control" did not create a "wow" effect but rather the dissatisfaction scores demonstrated a gradual improvement the longer they were used. In this regard evidence that the "shared control" improves satisfaction with lighting conditions is important since the effect of offering control would not be evident compared to increase in the dissatisfaction when the control would be taken away. From this perspective, shared control could be compared to workplace hygiene factors that are seen as maintenance factors leading to the increasing of dissatisfaction when they are not provided. This aspect emphasizes the importance of certification and regulation programs like WELL to promote the benefits of shared control in office spaces.

Memorizing lighting levels selected by users leads to fewer user control actions and lighting conditions that better reflect individual preferences than the conditions created when the system resets the luminaires output to a default level at the end of each working day.

The second field study compared the two strategies of offering shared control, the “forgetting strategy” in which the luminaires output was reset to a default level at the end of each working day and the “memorizing” in which the luminaires output selected by the users in each control zone was remembered until the users would change it. The results showed that in case of “forgetting” a large proportion of time the luminaires were at their default 60% output setting and in the “memorizing” condition the luminaires output was more uniformly distributed. This illustrates the effect that when a default lighting level is reset at the start of the day it discourages users to use the controls to change it to the level they prefer. It also shows the disadvantage of the “forgetting” mode since a large portion of time the luminaires remained in their default output mode while in the “memorizing” mode the lighting conditions better reflected the preferences of the office occupants. Another positive benefit of the “memorizing” strategy is that the users made fewer lighting adjustments in the corresponding condition compared to that of the “forgetting” strategy and this is in line with how users make use of control and how they prefer to use lighting control. When looking at the lighting condition dissatisfaction ratings the mean values obtained for the “memorizing” condition were lower than for the “forgetting” condition, although the analysis did not find a significant effect.

These findings advocate in favor of the “memorizing” strategy and can be deployed in open plan offices where users have assigned desks or in flex desks arrangements where the location of the user is known, for example in case of a reservation system, so that the preferences of the user could be restored at the desk used on a particular occasion.

A user interface directly controlling luminaire output is preferred to one controlling the combined desk illuminance resulting from the combination of the artificial lighting and incoming daylight.

Smart lighting systems that deploy strategies like daylight harvesting, that regulate luminaire output based on incoming light, or total light management, that control both artificial lighting and window blinds based on sunlight intensity outside and the light level inside, treat desk illuminance as a combination of daylight and artificial light. These systems operate with the notion of the set-point that is defined as a target illuminance on the desk resulting from this combination of daylight and artificial lighting. From this point of view, it makes sense to offer end-users of the system user interface controls making it possible to adjust the set-point. This approach has been validated by iteratively creating user interface designs and validating their usability with office workers. The interviews with the study participants revealed that office workers do not think of their lighting conditions in terms of daylight and artificial lighting contribution on their desk. Office users demonstrated a strong familiarity with controlling luminaires dimming level through luminaires controls and adjusting the blinds with the blinds controls and have a preference to use these controls to adjust their office lighting conditions. Since usability of controls has been shown to have impact on lighting systems acceptance and on the intended energy savings of these systems it is important to take the office occupant perspective when creating user interfaces for these systems.

5.3 Strengths and limitations of the research

5.3.1 Strengths

Conducting field studies

The main strength of the work conducted within this research are the two longitudinal field studies conducted in the actual offices used by office workers. This realistic set-up of the study, which gives it a high ecological validity, was essential to explore the social dynamics and how it changes after introducing shared controls and to answer the main question related to potential conflicts that could occur. Two groups of employees within the Philips Research organization, one administrative department during the first field experiment and the other a mix of several research departments focusing on healthcare research topics during the second field experiment, supported this research and relocated for the duration of the study into the experimental open office space.

Introduction and withdrawal of control

One of the relevant results described in Chapter 3 was obtained solely thanks to the changing of the order by first having no control and then introducing it while finally withdrawing control that resulted in the observed loss aversion effect. The difference in satisfaction with the lighting conditions observed is significantly more pronounced and higher after the lighting controls were removed than after they were brought in. The fact that this effect could be observed is important since it reflects the way office occupants value controls and the difference between their appreciation of the controls before they tried it out and after. This phenomenon has been observed in the past also in relationship to other technologies. Something that we currently can hardly believe, provided the proliferation of mobile phones these days, has been revealed in a video footage from 1999 with the reactions of Dutch interviewees showing that none of them reacted positively to the question of whether they wanted to have a mobile phone [9].

Combination of measurements deployed

In the two field experiments conducted as part of this research study various measurements have been deployed including subjective evaluations via regular surveys, in-depth interviews with the participants, objective measurements including desk illuminance and occupancy, logging of the user actions with the lighting controllers and measures of energy consumption. This set of measuring tools made it possible to conduct a multilateral analysis of what was going on in the experimental office during the duration of the field studies. For example, the identification of the submissive behavior and the implicit conflict cases became possible by matching the subjective survey responses and in-depth interview data.

Opportunities realized by the deployment of DALI dimmable ballasts

It was fortunate that it was possible to equip the lighting installation of the experimental office with the Philips DALI dimmable ballasts. This gave the needed flexibility to be able to program the system in such a way to achieve luminaires control zones that are as small as possible and at the same time providing equal level of control to the study participants. The same DALI programmable interface also enabled programming different lighting control strategies, like memorizing, forgetting and daylight harvesting with user-adjustable set-point, that have been evaluated in the second field study.

5.3.2 Limitations

The explorative nature of the field studies

The two field studies conducted as part of this research have an explorative nature. One element of this is that the sample sizes in the field experiments have been relatively low. This was intentional since the level of engagement with the study participants has been maintained to be very high, involving sending reminders for filling out the weekly surveys, regular in-depth interviews with the individual participants including reflections on the notes kept by the participants in their diaries and the survey responses for the corresponding week. This level of engagement enabled the collection of comprehensive data that was vital for the exploration of the social dynamics and the occurrence of conflict among the participants. It would be very costly and hardly possible to maintain the same level of engagement in a large-scale study. The results collected are valuable for understanding different patterns of interaction that could occur between office occupants and offer the needed insights for follow-up explorations. However, in view of the relatively small sample size of the studies the results can only be seen as indicative.

The range of offered illuminances

Both field studies described in Chapter 3 and Chapter 4 demonstrated a higher satisfaction with the office lighting conditions in the shared control conditions compared to the no control conditions (lower dissatisfaction with the lighting quantity and higher lighting quality assessment in conditions with shared controls). It needs to be acknowledged that the range of illuminances available in the study office was limited by the maximum output of the installed luminaires that was capped at 500 lx. As demonstrated in the studies of Fotios and Cheal the range of the illuminances made available in a study determines the range of the selected illuminances [1]. The study of the same research team showed no difference in satisfaction between the condition in which a lower illuminances range was available and the condition with a higher illuminances range [8]. In this light, the higher satisfaction with the lighting conditions observed in both field experiments is most likely related to the availability of controls and less likely related to the absolute illuminances the participants experienced on their desks.

Participants belonged to the same department unit

The participants of the two field studies conducted belonged to two different departments which are organizational units within the Philips Research organization. This could have an influence on the social dynamics among the participants since the participants were colleagues already for some time working closely and having a history of interaction with each other. As flex offices are receiving a large-scale adoption, occupants of those offices might have a lower degree of familiarity with each other. In flex offices dependent on the desk availability people could accidentally find an unoccupied desk and start working in an office with people they did not previously interact with. This could impact the way people make use of lighting controls, for example, by potentially exacerbating the conflict avoidant behavior, since people would have less knowledge of what reactions to expect from their neighbors. Alternatively, occupants could be less concerned about the potential conflict since there would be fewer social connections that could be jeopardized. Less familiar context could lead to a higher degree of reluctance of using controls since it could lead to a higher degree of self-consciousness and thus preferring control behaviors less obvious to others [10].

Cultural background

Since behavior has been shown to be related to the cultural background the replicability of the results could be limited by the specific set of cultural backgrounds of the studies participants [11]. During the first field study all the participants were of Dutch origin. The Dutch culture is distinctive in striving for a consensus decision-making that satisfies interests of different participating parties also known as the polder model. Although the second group of participants, who took part in the second field study, had about half of the people of non-Dutch origin, the behaviors observed were very similar to those of the first group. This possibly could be explained by the fact that even colleagues of other cultural origins living in the Netherlands for some time would assimilate and adopt communication strategies like those executed by people of the Dutch origin. Studies have shown that high-context cultures, like India and China, in which the communication is context dependent prefer the compromising and integrating conflict resolution style whereas low-context cultures, like the US, the UK and Sweden, prefer the explicit verbal communication also referred as the dominating style [11]. Dutch culture scores very high on the individualism dimension and is typically classified as the low-context culture where the communication style tends to be direct and transparent [12]. From this perspective one might expect an even higher degree of conflict avoidance if the study would be repeated in one of the high-context cultures and possibly a tendency to make choices that promote consensus to prevent conflict from occurring.

5.4 Recommendations for follow-up research

The studies conducted within this research have generated results that are in line with limited scientific evidence created so far on the subject of shared lighting control in open plan multi-user offices. Due to the nature of the field experiments conducted, for prolonged periods of time in the experimental office the participants used as their primary office, and due to a high level of engagement with the participants intricate social dynamics pattens have been uncovered. This exploration revealed various forms of conflict avoidance behavior deployed to avoid executing lighting control openly as a strategy to prevent potential confrontation due to the difference in lighting preferences. As in every scientific discovery process the more aspects are being explored the more questions it would generate and thus in this section new potent areas of research to be further followed-up upon are discussed.

Time-based effect of having control

As it has been discussed in Chapter 4, in both experiment 1 and 2 a time-based effect of using shared control has been observed. This effect manifested itself in that the subjective ratings of the lighting conditions provided by the participants showed a positive trend the longer the controls were used. In Chapter 4, potential causes of this effect are hypothesized, however, this effect has been observed during the study and has not been anticipated during the study design. Therefore, the study design is not suited to properly investigate this effect. A dedicated follow-up study would be relevant to conduct to explore the underlying causes for this effect.

"Control set-point" behavior energy saving

One of the control strategies explored in experiment 2 of the current research has been the "control set-point" strategy, in which the set-point used for daylight harvesting was tied to the last dimming level selected by the user. Due to the deployment of daylight harvesting the energy consumption of the lighting system in that mode was dependent on the daylight admission into the space. Due to this dependency on daylight the quantitative comparison of the energy consumption to that in other system modes was not feasible. This could be further explored in a follow-up study focusing on the energy saving benefits of the control strategies for lighting systems that include shared controls.

Flex office influence

The open plan office space where the studies have been conducted had fixed desks in that every participant had an individual assigned desk he or she was using on a regular basis. Nowadays flex office arrangements are gaining in adoption where the desks are not assigned but are used based on their availability leading to the situation in which office workers might use different desks on different days. In those arrangements other elements of the social dynamics will be at play and it is relevant to understand how it would influence the experience of the lighting environments in which shared controls would be offered.

One possibility is that since in flex office spaces desk reservation mobile applications have already been deployed [13] those applications could be extended with extra functionality that could extend beyond desk availability and offer desk recommendation based on similar lighting conditions preferences and even similar preferences for other environmental parameters [14]. Even in these flex offices the choices people would make when selecting an available desk would be motivated not only by the environmental preferences but would also include, e.g., proximity of colleagues people are working with, closeness to meeting and conference rooms. The constellation of these elements would create a hierarchy of priorities that would influence the readiness to accept environmental conditions that might have not a 100% match to their ideal environment. How these solutions could influence the satisfaction of office occupants with their office environment would be relevant to further explore.

Influence of high-context cultural background

As it has been mentioned already culture influences how people deal with conflict. High context cultures like those in India and China tend to communicate in such a way that prevents the occurrence of conflict. During the study, most of the participants had Dutch origin, which is characterized by a high level of individualism, direct communication and avoiding conflict style [11]. In contrast, if the study would be conducted in a culture that scores high on the collectivism, a compromising and integrating style to resolve conflict would most probably prevail. From this perspective it could be expected that people might adopt a strategy of deliberately selecting a light level in the middle of the scale, or a weighted average of users of one zone, to respect preferences of their neighbors. This style of using shared control was demonstrated by one participant of the current study who explained that the reason for selecting the middle of the dimming scale has been exactly to make it acceptable for his neighbors. It is relevant to explore whether more people would demonstrate this behavior regarding office lighting control if the study would be conducted involving the participants having a high context culture background.

Strategies to further Improve shared control experience

Despite the study results, that showed lower dissatisfaction with lighting quantity and more positive lighting quality assessment when “control” was provided, 3 out of 14 participants in both experiments 1 and 2 indicated to prefer having “no control”. These participants experienced conflicting lighting level preferences with their close neighbors and thus could not exercise lighting control to their satisfaction. Since this means that 20% of the participants in both experiment 1 and 2 were not satisfied with shared control further improvements of shared control are needed.

Potential ways to improve shared control via automatic profiling have been explored in [15]. Based on the objective measurements and subjective data collected in the two field experiments of the current study it has been shown that users could be profiled according to the four characteristics of activeness, dominance, lighting tolerance and dimming level preference. Using this automatic profiling, the five strategies are possible to improve the user experience and potentially prevent conflict. These are:

- Creating lighting conditions in the control zones based on the combination of the user profiles,
- Assessing the probability of conflict and, in case in which it is high, facilitating users by offering consensus lighting dimming choices,
- Requesting submissive and inactive users to submit their preferences,
- Making active and dominant users aware of the preferences of their neighbors,
- Suggesting an optimal assignment of people based on their lighting profiles to desks that would minimize the chances of conflict to occur.

These strategies have potential to further improve the user experience with shared controls. However, these strategies would require further validation and thus offer opportunities for follow-up research studies.

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Appendix A

Lighting quantity

The lighting quantity scale is adopted from Moore, T., Carter, D.J., Slater, A.I. A study of opinion in offices with and without user controlled lighting. Lighting Research and Technology, 36, 2 (2004) pp 131-146. Available from: https://doi.org/10.1191/1365782804li109oa.

The following set of questions is about the quantity of light at your workplace. Please answer these based on your experience in the past week.

Would you say that the amount of light on your desk is:

Too little	1	2	3	Just right	5	6	7	Too much

Would you say the amount of light on your laptop/ computer monitor is:

Too little	1	2	3	Just right	5	6	7	Too much

Think about the amount of daylight that reaches your desk, is this:

Too little	1	2	3	Just right	5	6	7	Too much

Lighting quality

The lighting quality scale is adopted from J.A. Veitch, G.R. Newsham, Exercised control, lighting choices, and energy use: An office simulation experiment, J. Environ. Psychol. 20 (2000) 219–237. doi:10.1006/jevp.1999.0169.

The following set of questions is about the quality of light on your desk. Please answer these based on your experience in the past week.

Overall, how satisfied are you with the lighting at your desk?

very dissatisfied	dissatisfied	somewhat dissatisfied	neutral	somewhat satisfied	satisfied	very satisfied

Please rate the lighting available to you for reading

poor	1	2	3	4 neutral	5	6	7	excellent

Please rate your workstation on the amount of light for the work you did last week:

poor	1	2	3	4 neutral	5	6	7	excellent

How do you rate the acceptability of the lighting in this office?

completely unacceptable	1	2	3	4 neutral	5	6	7	completely acceptable

Please rate the following statement:

Lighting at my desk hindered me from doing my job well.

strongly disagree	1	2	3	4 neutral	5	6	7	Strongly agree

Glare

The following questions are about glare. Please answer these based on your experience in the past week.

How much do reflections on the laptop/ computer monitor bother you?

extremely	1	2	3	4 neutral	5	6	7	not at all

How much does glare bother you? (By glare here we mean uncomfortable bright light in your eyes)

extremely	1	2	3	4 neutral	5	6	7	not at all

Appendix B

The following scales were used in addition to the weekly survey questions, forming the extensive surveys to be completed every 3 weeks.

Environmental satisfaction

The following scale is adopted from Sundstrom E, Town JP, Rice RW, Osborn DP, Brill M. Office Noise, Satisfaction, and Performance. Environment and Behavior. 1994;26(2):195-222. doi:10.1177/001391659402600204.

Please rate the following statements about your workspace:

I am proud to show my workspace.

strongly disagree	1	2	3	4 neutral	5	6	7	strongly agree

My workspace helps me get my work done efficiently.

strongly disagree	1	2	3	4 neutral	5	6	7	strongly agree

All things considered, I am very satisfied with my workspace.

strongly disagree	1	2	3	4 neutral	5	6	7	strongly agree

The physical layout of my workspace is well suited to the tasks I do.

strongly disagree	1	2	3	4 neutral	5	6	7	strongly agree

The following scale is adopted from W. Osterhaus, Discomfort glare assessment and prevention for daylight applications in office environments, Sol. Energy 79 (2005) 140e158 and from Veitch, J. A., Farley, K. M., & Newsham, G. R. (2002). Environmental satisfaction in open-plan environments: 1. Scale validation and methods. Institute for Research in Construction, National Research Council of Canada, Ottawa, RR-106.

The following questions are about your work environment.

In general, how do you judge the...

... temperature in this office?

too cold	cold	a bit cold	just right	a bit warm	warm	too warm

... acoustics in this office?

Too noisy	Noisy	A bit noisy	Just right	A bit quiet	Quiet	Too quiet

The following scale is adopted from Veitch, J. A., Charles, K. E., Farley, K. M. J., & Newsham, G. R. (2007). A model of satisfaction with open-plan office conditions: COPE field findings. *Journal of Environmental Psychology*, *27*(3), 177–189. https://doi.org/10.1016/j.jenvp.2007.04.002.

How satisfied are you with the temperature in your work area:

very dissatisfied	dissatisfied	somewhat dissatisfied	neutral	somewhat satisfied	satisfied	very satisfied

How satisfied are you with the overall air quality in your work area:

very dissatisfied	dissatisfied	somewhat dissatisfied	neutral	somewhat satisfied	satisfied	very satisfied

Appendix C

The following scale is adopted from Moore, T., D. J. Carter, and A. I. Slater. Conflict and control: The use of locally addressable lighting in open space office plan. *Proc. Of the Chartered Institute of Buidling Service Engineers* (2000).

Experience of conflict

Do you ever experience conflict with other users when trying to control the lighting?

never	1	2	3	4	5	6	7	frequently

How would you rate the degree of the experienced conflict?

no conflict at all	1	2	3	4 moderate conflict	5	6	7	very high conflict

Importance of lighting control

How important is it for you that you are able to control the level of electric lighting over your desk:

very unimportant	1	2	3	4	5	6	7	very important

Perceived degree of control and satisfaction with control

How much control do you feel that you have over the electric lighting above your workstation:

no control	1	2	3	4	5	6	7	full control

How satisfied are you with this level of control:

very dissatisfied	1	2	3	4	5	6	7	very satisfied

Curriculum Vitae

Tatiana Lashina was born on 17-04-1976 in Minsk, Belarus.

After finishing the secondary school Nr. 51, currently the gymnasium Nr. 29, with excellence in 1993 in Minsk, Belarus, she studied Radiophysics and Electronics at Belarusian State University in Minsk, Belarus. In 1998 she graduated Cum Laude within the System Analysis department on the subject “Development of the method and programming means for the photoelectric sensors signal correction”. In 2000 Tatiana graduated as PDEng in User-System Interaction at Stan Ackermans Institute with her final project of developing and validating the user interface conceptual design that had been implemented in SoundAgend 2.0 software of Philips USB computer speakers showcased at CES2003.

Since 2000 Tatiana is employed at Philips Research. Tatiana is the co-inventor of 56 patents and the co-author of 20 scientific publications published by international conferences and research journals. In 2017 Tatiana received Philips Research Bronze Patent Award. During her carrier at Philips Research Tatiana led various multidisciplinary, international teams developing novel interactive solutions exhibited at Philips Experience Lab, like Intelligent Shop Window, Interactive Mirror, Entertable and developing innovations for Philips products including first-of-a-kind Power over Ethernet office connected lighting solution, Interact IoT, Avalon and Intellispace Perinatal obstetric solutions.

From 2014 Tatiana started a PhD project in the Building Lighting group of Alexander Rosemann at the Unit Building Physics and Services in the Department of the Built Environment at Eindhoven University of Technology (TU/e). The results of this PhD project are presented in this dissertation.

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