Designing for adaptive lighting environments : embracing complexity in designing for systems

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Designing for Adaptive Lighting Environments

embracing complexity in designing for systems

by Remco Magielse

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PROEFONTWERP

ter verkrijging van de graad van doctor aan de Technische Universiteit Eindhoven, op gezag van de rector magnificus, prof.dr.ir. C.J. van Duijn, voor een commissie aangewezen door het College voor Promoties, in het openbaar te verdedigen op maandag 14 april 2014 om 16:00 uur

door

Remco Magielse

geboren te Bergen op Zoom

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"I'd rather be a comma, than a full stop."

Coldplay, "Every teardrop is a waterfall" Mylo Xyloto. CD. Capitol Records. 2011

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Dankwoord

Succesfully completing a doctoral dissertation is, in my opinion, a social effort. Therefore, I wish to dedicate a few lines to those who have contributed to the succesful delivery of this dissertation. I am extremely grateful and honored that so many people have invested time and energy in this project, and in my personal development.

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I strongly believe balance in life is essential. I cherish the moments where I *don't* have to think about work. I consider myself lucky with a fantastic group of family and friends that help me to achieve this balance in life.

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Jessie, jij maakt me een beter mens. *Look at the stars, look how they shine for you, and everything you do.*

About this dissertation

In the year 2009, Eindhoven University of Technology (TU/e) launched a research program with the title '*i-Lighting the World* '. With advances in Solid State Lighting technologies (SSL), and in specific Light Emitting Diodes (LEDs), this technology can be used to replace contemporary lighting technologies, and bring about a revolution in lighting. LEDs are small, durable, are low power, and can be easily and with high precision controlled by microcontrollers. This makes it possible to control lighting systems via intelligent control algorithms. Furthermore, it opens up possibilities to rethink the role lighting plays in everyday life.

Within the i-Lighting the World program two projects were defined, *Natural Lighting Solutions* (NLS), focusing mainly on the application domain of well-being, and *Adaptive Lighting Environments* (ALEs) focusing on investigating novel light behaviors and interating with lighting systems.The projects are a collaboration between six different faculties of the TU/e; each faculty allocates one doctoral candidate to one of the projects. For the ALE project this is a collaboration between the faculties of Industrial Design (ID), Computer Science (CS) and Electrical Engineering (EE). Specifically the ALE project, is a collaboration between Paola Jaramillo Garcia, Ph.D.-student from the faculty of EE, Sunder Aditya Rao, Ph.D.-student from the faculty of CS and myself, Ph.D.-student from the faculty of ID.

In this dissertation I present the work that was performed within the ALE project as part of my Ph.D. The book is accompanied by an online appendix, found at http://www.adaptivelighting.nl. I have chosen an online appendix as this allows me to present different forms of media: e.g., data files, video, spreadsheets. To bridge the gap between this physical dissertation and the online appendix, selected figures in this dissertation have been enhanced with augmented reality. This content can be accessed using the application 'Layar', which is freely available for smartphones and tablets running iOS or Android (via get.layar.com). The 'ar'-symbol on the right indicates when additional content can be accessed using Layar. When you open the application, position the image in the center of your view, and press the screen to scan the image. The cover of this dissertation can be scanned via Layar to bring you directly to the online appendix. Please feel free to try this.

Overall, the dissertation is divided in three parts (Part I: Incubation, Part II: Nursery, Part III: Adoption) that follow the specific approach I used for the ALE project. Prior to these three parts I introduce the design challenge that is addressed in this project. After these three parts, a final chapter is included in which I reflect on the project, its outcomes, and its relevance for the design of adaptive lighting environments.

1. Design challenge & approach

1. Introduction

In this dissertation I explore *how to design for adaptive lighting environments*. Recent advances in Solid State Lighting (SSL), and in particular Light Emitting Diode (LED) technology bring about a revolution in lighting technologies. LEDs are small, durable semi-conductors that are now able to produce light of sufficient quality to illuminate an environment. As they are semi-conductors, they can easily be controlled through networks of microprocessors to which sensors can be attached. This makes it possible for designers to develop interactive and intelligent lighting applications. These new opportunities lead to new design challenges. I focus my attention on three aspects regarding the design of adaptive lighting environments (ALEs). First, I explore how to design *meaningful lighting behaviors* for ALEs. Second, I investigate the *implications on social settings* of ALEs. Third, I explore and design *novel interaction concepts* for ALEs.

From a broader perspective, ALEs can be considered a class of socio-technical systems. This type of system represents a composition of people and (interactive) technologies with interdependent relationships between them. Designing for socio-technical systems typically entails complex challenges. This complexity is a result of the nature of these socio-technical systems: It is not possible to have a definitive and complete overview of the system at any point in time, there are many stakeholders involved and there is no single correct solution to a design challenge (Frens & Overbeeke, 2009; Rittel & Webber, 1973; Stolterman, 2008).

In order to deal with the complex nature of the design research challenge I use a research-through-design approach (Gaver, 2012; Koskinen, Zimmerman, Binder, Redstrom, & Wensveen, 2011; Zimmerman, Forlizzi & Evenson, 2007). More specifically, I use the Growth Plan (Ross & Tomico, 2009), which is an approach for the development of highly interactive products and systems. The Growth Plan consists of three phases: *Incubation*, *Nursery*, and *Adoption*. In these phases interactive (research) prototypes are explored, conceptualized, developed, and evaluated in real life contexts. This approach is particularly suitable to investigate innovative, interactive technologies and their implications on the behavior of people in a holistic, integrated way.

This chapter has the following structure: In Section 2 a more elaborate overview of the design challenge is provided. In Section 3 an overview of the effects light has on people is provided. In Section 4 an overview is presented of contemporary lighting systems and applications. Section 5 zooms out of the domain of lighting and considers challenges when designing socio-technical systems at large. In Section 6 the theoretical foundations and the Growth Plan as research-through-design approach for this project are presented.

2. Designing for adaptive lighting environments

When this project commenced, the design brief was broad. The general line of reasoning was that LEDs offer possibilities to novel lighting applications. The lighting systems that were envisioned would have many benefits. However, this vision of adaptive lighting environments – environments that intelligently adapt to specific situations – needed to be created. This resulted in the main question for this project: *how to design for adaptive lighting environments?*

2.1. A brief history of artificial lighting

The most important source of natural light on Earth is the Sun, on which we have been dependent for centuries. Daily rhythms were structured around the presence of natural light (Bowers, 1988). Early forms of artificial lighting were based on fire: e.g., torches, candles. Typically, this meant that after sunset, people would stay indoors (Schivelbusch, 1995, p. 81; O'Dea, 1958) and gather around a single artificial light source (cf. Bowers, 1988. p.12). Artifical lighting in those days was expensive, dirty, and dangerous (Bowers, 1988; Boyce, 2010). For centuries, mankind has been developing increasingly advanced technologies to generate artificial light. These advances in technology have transformed our daily routines: Working days could be lengthened, and outdoor activities could extend into the night. As a consequence, artificial lighting is deeply interwoven into the daily lives of people (in the Western world). Since artificial lighting is cheap and readily available indoors, we now spend large part of our time indoors. Our daily rhythms are no longer structure by natural light: Lighting technologies have transformed our lives.

2.2. A new lighting technology

Recently, SSL technology has advanced significantly, which makes this technology increasingly popular. SSL technologies generate light through electroluminescence and the best-known type is LED. Other types of SSL are Organic Light Emitting Diodes (OLED) or Polymer Light Emitting Diodes (PLED). LEDs are semi-conductors that are optimized to produce monochromatic light as current passes through a p-n junction (Dupuis & Kramer, 2008). They are interesting as a new lighting technology, as they are small, durable, low-power, energy efficient, and have a life expectancy that exceeds traditional light sources (Bourget, 2008; Holonyak, 2000; Krames et al., 2007; Kume, 2012; Schubert & Kim, 2005). In addition to these 'traditional' benefits, LEDs are interesting due to their nature as semi-conductors and fast response time: This allows LEDs to be controlled easily and precisely via digital electronics and computing technologies. This makes all the benefits of computing technology directly available to the development of intelligent lighting applications. Essentially, the LED can be considered a portable and programmable light source to which sensors can be attached. This opens up a complete new design space for intelligent and adaptive lighting environments.

2.3. How to design for adaptive lighting environments

Considering LEDs as programmable light sources entails many implications for the way light can be used in the future. It enables the design of intelligent behavior for light sources: Sensors can acquire data from their surroundings, software algorithms can process these data, and the light source can be programmed to act intelligently. Furthermore, as LEDs are small, durable, and operate on low power, they can become embedded into (portable) products and environments. Yet, (intelligent) behavior may even extend beyond single light sources, as light sources become connected to each other to form lighting systems. Such a network of lighting technologies may interoperate with other systems. The combination of all these factors, entails a revolution in our view on artificial lighting systems. This means that lighting conditions can be adapted to diverse contextual parameters, which means that new knowledge and insights are required to deal with the question "*how* to design for adaptive lighting environments?" In order to structure this investigation, I identify three sub-challenges to investigate the main challenge.

- As lighting technologies can be embedded and can become context-aware they can be programmed to behave in personalized, adaptive and anticipatory (ways Aarts & Marzano, 2003). This implies that lighting conditions can be adapted to contextual information acquired through sensors. This means that it needs to be explored in what way lighting conditions should adapt to contextual factors, which leads to the first design challenge: *how to design meaningful lighting behaviors*?
- As was pointed out in the previous paragraph, artificial lighting systems have led to social and societal changes. This means that, next to the design of novel lighting behaviors, the implications of such systems on social settings in daily life need to be investigated. Not only will lighting conditions adapt to contextual factors, people will also adapt their behavior to such systems. Lighting systems will no longer be static, separate entities, but they will adjust dynamically to changes in the context of the user. This requires investigation towards *the implications on social settings of adaptive lighting environments*.
- Furthermore, the new possibilities of ALEs need to be made available to people. This allows designers to *explore and design novel concepts regarding the interaction between people and ALEs.*

Given these design challenges, I then define ALEs as lighting systems that – via information acquired through sensors – adjust their state to fit to specific contextual factors. This change of state may be induced via computational intelligence, or it may be directly set by users as they interact with the ALE. The shift from static lighting conditions, to lighting systems that behave in adaptive ways, changes the way people behave; people adapt their behavior. ALEs thus imply that behavior from both the system and its users adapt.

2.4. Involved stakeholders

This project took place in an environment where I collaborated with multiple people. Though all the texts in this dissertation are my own, I present and discuss work that was performed in collaboration with others. This paragraph provides a general overview of the project setting. A detailed description of the contributions of others to this project is presented in the acknowledgements at the end of this dissertation.

The project itself is interdisciplinary, which means that I collaborated with two other Ph.D.-students (Sunder Aditya Rao, Paola Jaramillo Garcia) on the project. The project is part of the Intelligent Lighting Institute (ILI) of the TU/e. Within the ILI there are other projects that are centered around the topic of intelligent lighting. Finally, I have been involved in educational activities as lecturer and coach: I have supervised one intern and coached diverse student-projects. All the work in this dissertation has been reviewed and evaluated by me, but that it might be performed by others. Whenever this is the case, I explicitly specify the contribution of others to this dissertation.

3. Light & people

As was mentioned in section 2, lighting technologies have transformed society. However, lighting also has more direct effects on people. To develop an understanding of the effect light has on people, I first review related work in the lighting domain. Research in this field can be divided in four categories: research towards the *visual*, *physiological*, *psychological* and *behavioral* effects of light (Begemann, Van den Beld, & Tenner, 1997; Boyce, 2010; Knoop, 2006; Van Bommel & Van den Beld, 2004; Veitch, 2001). In real life these effects are all intertwined, connected and dependent. For the sake of clarity, I separate these effects of light and discuss these individually. This exemplifies the complexity of designing a static lighting environment, let alone the design of dynamic and interactive lighting environments.

3.1. Visual and physiological effects of light

Light first and foremost allows us to visually perceive the world around us, via photosensitive receptors in the eye. The well-known rods and cones are photoreceptors in the eye that are responsible for scotopic and photopic vision; i.e., seeing under dark and well-lit conditions, respectively. Research towards the visual effects of light has led to the development of manuals (Rea, 2000) and guidelines (NEN-EN 12464-1:2011) for the design of lighting environments. Leading factors in lighting design currently are *visual performance* and *visual comfort*. Visual performance can be explained as matching the light in the environment to the person and the task. Visual comfort is explained as providing a pleasant lighting context (Boyce, 2010). Overall, there is a large body of research available, which provides a rather detailed understanding of the interaction between people and light. Veitch (2006) summarizes that the most influential aspects to take into account are: the (1) age of the person, the (2) size of the task being performed, the (3) contrast ratio between task lighting and background lighting, and (4) the illuminance level on the task.

Additionally, light triggers processes in our body that activate us. In 1991, it was discovered that the human eye contains a third photoreceptor (Foster et al., 1991). This photoreceptor is not connected to our visual system – and thus does not allow us to see – but it is connected to another part of the brain. One of the main functions of this photoreceptor is that it synchronizes our circadian rhythm – our internal clock – to our physical surroundings via light with a wavelength between 470-480 nm (Dijk & Archer, 2009). It does so by regulating release and suppression of hormones melatonin and cortisol.

3.2. Psychological and behavioral effects of light

Besides the visual and physiological effects of light on people, there are also psychological and behavioral implications of light. Investigations of these effects have recently gained more attention. Presumably, this is that lighting technologies have advanced significantly and new lighting possibilities have become available. For example, luminaires that change the color temperature of light are now being installed in offices (De Kort & Smolders, 2010) and schools ("Beter leren met SchoolVision," 2013) as a specific light spectrum might be beneficial for specific tasks. Furthermore, the advances in LED technology have spurred many products that allow people to use colored atmospheric light sources in their homes. This means that from a technical point of view the possibilities are now available to easily provide people with different forms of light. In this section I address topics that are currently of interest to the research community and that are finding their way to (design) practice.

Psychological implications

There are various studies that indicate that specific lighting conditions alter how we feel and that it can be beneficial to us. The mechanism underlying many of these studies is that different lighting conditions influence the way we perceive an environment and that environments in which we feel pleasant elicit positive emotions (Veitch, 2001).

Various studies investigated the effect of lighting conditions on appraisals of environments. One of the first to demonstrate that our appraisal of environments is influenced by the lighting conditions were Flynn and his colleagues (Flynn, Hendrick, Spencer, & Martyniuk, 1979). They concluded that perceptual clarity, evaluative impressions, and spaciousness are determining factors for people. They identified that three lighting dimensions were responsible for these factors, namely light uniformity, brightness, and overhead versus peripheral lighting. Veitch (2001) extensively reviewed this work and argued that Flynn's sample size was too small and the results were never replicated, making it hard to assume these dimensions are generalizable. Later studies (e.g., Hawkes, Loe, & Rowlands, 1979) of a similar kind revealed only two dimensions: brightness and uniformity. A study by Veitch & Newsham (1998) revealed visual attraction, complexity and brightness as three relevant dimensions. These results are inconclusive. Veitch (2001) argues that various studies find *overall brightness* of an environment and the *light distribution* in an environment as important parameters. I find her reasoning convincing and take this as a starting point.

Another line of research investigated the effects of colored light on people. The general tendency is that red is considered to be arousing or activating, while blue is considered calming (Jacobs & Suess, 1975; Mahnke, 1996; Rajae-Joordens, 2011). However, results of color studies are also not always consistent (Valdez & Mehrabian, 1994). They contradict the physiological responses to light as the photoreceptor that suppresses melatonin is most sensitive light of blue wavelengths (which thus physically activates the human body). Various researchers (Elliot & Maier, 2007; Rajae-Joordens, 2011) argue that contradictory results are possibly a result of the different meanings that we have learned over time to associate to different colors: e.g., red is commonly used to signal us to pay attention or be careful (traffic lights/signs, warning indicators) and green/blue is associated with nature, sea, skies, which are generally calming environments. Furthermore, cultural meanings and symbolic interpretations of color (Mahnke, 1996) also mediate the way we relate to different colors. Whereas these investigations towards the psychological effects of light mainly considered variations in the hue-value, other evidence suggests that saturation (chroma) or brightness (value) are more important parameters that impact the psychological effects of light (Bellizzi & Hite, 1992; Gorn, Chattopadhyay, Sengupta, & Tripathi, 2004; Mikellides, 1990; Suk & Irtel, 2010). Rajae-Joordens (2011) furthermore argues that colored light should not only be regarded from the perspective of arousal, but that also valence should be taken into account. This means that the “intrinsic attractiveness” of an environment affects the way colored lighting is perceived. In other words, if the environment is perceived as pleasant the color might have calming effects, otherwise, the color might have negative effects. Veitch (2001) argues along similar lines that environmental appraisal – what we think of the environment – and affect – how this makes us feel – are interconnected. What I conclude from these studies is that the contextual factors of the lighting environment are important to consider when investigating the effect of light.

In recent years, various scholars investigated beneficial effects of lighting conditions that enhance human performance and well-being. Such studies, for instance, investigate the implications of a specific light spectrum (i.e., warm or cool white light) or different light levels on objective measures of performance and subjective measures (e.g., feelings of alertness and vitality). Results show that bright light in the morning, with a ‘cool’ white spectrum is found to reduce feelings of sleepiness and increase productivity. This can also be used to reduce winter depression (Eastman, Young, Fogg, Liu, & Meaden, 1998). The general hypothesis is that high levels of illumination activate and increase performance of people (Campbell & Dawson, 1990; Myers & Badia, 1993). Though many of these studies are targeted at night-shift workers or sleep-deprived participants, Smolders et al. (2012) focus on the beneficial effects of light under normal conditions. Their results show that higher levels of illumination increase objective performance and subjective feelings of vitality under normal circumstances. This implies that a lighting system can be designed in ways to boost performance throughout the day (de Kort & Smolders, 2010; Smolders, de Kort, & Cluitmans, 2012; Smolders & de Kort, 2011). These findings make compelling cases for products such as alarm clocks that enhance the experience of waking up with light ("Wake-up Light," 2013) or lighting systems that adjust lighting conditions to the activities of school children, allowing them to perform optimally (Barkmann, Wessolowski, & Schulte-Markwort, 2012; Sleegers et al., 2013).

Based on the results of these studies I conclude that it is possible to change the way people feel via specific lighting conditions. Results show that even human performance and comfort may benefit from specific lighting conditions. However, contextual factors need to be taken into account, as they may influence the experiences.

Behavioral implications

In the previous section I showed that light can change the way we feel and has the potential to enhance our performance. In this section I argue that light also influences the way we behave, although the exact implications are dependent on contextual factors.

There are various indications that light has an influence on human attention, physical orientation, and movement through space. People tend to avoid darkness and move and orient their bodies towards brighter areas (Antonakaki, 2006; Taylor & Socov, 1974). When presented with a choice between two paths, people tend to take the path that is more brightly lit (Taylor & Socov, 1974), which for example is used in emergency lights to guide people towards exits. One possible explanation for this is that brighter areas in the visual field attract the attention of people (Hopkinson & Longmore, 1959). Hopkinson and Longmore called this 'human phototropism', named after the phenomenon that plants grow towards a source of light. Giusa and Perney (1974) corroborate these findings and showed that students paid longer attention to a task, when it was performed in the spotlight. This technique is widely used in theatre and stage lighting, where spotlights are used to direct the attention of the audience.

Furthermore, specific lighting conditions can be used to influence human social behavior. When people perceive an environment as being darker, they show more self-interested behavior and cheat more (Zhong, Bohns, & Gino, 2010). Although the authors do not present exact lighting conditions, they show that when people only perceive an environment as being darker (i.e., through using sunglasses) they exert more egocentric behaviors. The authors claim that due to darkness perceived anonymity increases, which explains the self-interested behaviors.

Results of other studies corroborate the conclusion that darkness negatively influences social behavior. Darkness is not appreciated as it is found to strengthen negative dispositions against others (Schaller, Park, & Mueller, 2003) and increases desire for personal space. In very dark conditions (1.5 lx) female subjects reported a larger personal space than in normal lighting conditions (600 lx) (Adams & Zuckerman, 1991).

However, dim lighting conditions (150 lx versus 1500 lx) are found to increase the likelihood of people to cooperate (Werth, Steidle, & Hanke, 2012). This is supported by earlier studies (Baron, Rea, & Daniels, 1992) that showed that under dim (150 lx) lighting conditions, people assigned higher performance appraisals to others. The same study revealed that warm-white lighting conditions made people resolve conflicts through collaboration rather than avoidance as compared to cool white lighting conditions. Furthermore, in dimmer lighting conditions (150 lx) people tend to disclose more information (speak longer) and also rate their own disclosure higher (Miwa & Hanyu, 2006). However, earlier findings (Gifford, 1988) conclude exactly the opposite and revealed that for written communication with a known friend, bright lighting conditions resulted in more self-disclosure and intimate communication. Miwa & Hanyu (2006) suggest that dim lighting conditions resemble the lighting conditions in which you speak to a friend and thus implicitly advocate a more intimate setting in which people tend to disclose more information. This reasoning can be supported by the findings of Baron et al. (1992) who conclude that relatively high illuminance (1500 lx) was more associated to business and hospitals settings, Carr & Dabbs (1974) who report that dimmer lighting conditions are rated as more intimate and participants found an intimate interview more inappropriate under dim than under brighter lighting conditions. Also findings regarding the influence of lighting conditions on sound levels strengthen this argument. Although intuitively one would say that dimmer lighting conditions lead to lower sound levels, the evidence is contradictory. Some studies support this hypothesis (Feller, 1968; Sanders, Gustanski, & Lawton, 1974), although these studies failed to rigorously control lighting conditions and measure sound levels. An empirical study by Veitch and Kaye (1988) revealed counter-intuitive results: In brighter light condition (1274 lx vs. 400 lx) participants produced lower sound levels in interviews. The authors argue that our intuitive assumption that dim light invokes lower sound levels is guided more by associations we have to places that are dimly lit than by the actual lighting conditions (Genereux, Ward, & Russell, 1983). For example, restaurants and theatres are typically places where the lighting conditions happen to be dim and the social norm is to speak in a low voice.

Comparing the results of these studies is difficult as the contexts in which they are performed are different. It might for example be that the task in the experiment affected the outcomes of the study: E.g., in Gifford's experiments participants were asked to write a letter. It might simply be that writing a letter is more comfortable in brighter lighting conditions, and thus make people communicate more intimately, whereas actual conversations between people might feel more intimate in dim lighting conditions. This would argue that human behavior under specific lighting conditions is dependent on contextual factors. Results of Werth et al. (2012) support this argument, as they conclude that people were more willing to cooperate on a task, when their partner was also cooperative. When their partners were not cooperative, lighting did not yield significant effects. A context of cooperation can thus be *enhanced* through lighting conditions, rather than *created* by means of lighting conditions. Furthermore, Smolders et al. (2012) showed that specific lighting conditions influence people, as only suggesting changes in lighting conditions is not sufficient to yield effects. Consequently, I conclude that to study the implications of light on real behavior of people, the conditions in which these experiments are performed should resemble the actual context.

In summary: In this section I showed that specific lighting conditions can change the way that we appraise an environment, that they can influence our feelings, and that in some cases they even induce behavioral changes. All these effects are mediated by contextual factors. This means that a designer cannot state that "if the lighting system behaves like X, people will feel and behave like Y." Instead, the influence of lighting behaviors needs to be investigated in-context to acquire conditional insights.

4. Innovative lighting products and systems

In the previous section I showed that lighting conditions can be used to influence the way we feel and the way we behave. The context is a modifying factor and should always be considered. However, it becomes even more relevant to study the implications of lighting conditions on human behavior when different lighting conditions become available to people. In this section I discuss technological advances regarding lighting technologies that are made in recent years. Better control strategies for lighting technologies offered designers new opportunities and flexibility to create dynamic lighting behaviors. These opportunities are used in new lighting applications that serve different goals: e.g., to preserve energy, enhance aesthetical experiences, or use light as a carrier of meaning. Even though new lighting technologies are applied in more contexts, I discuss these applications as they specifically make use of new lighting control strategies and they relate to the implications of light as discussed in the previous section.

4.1. Lighting control strategies

'Traditional' lighting systems are typically controlled by the power supply to the light source. A light switch makes or breaks the electrical circuit and as such turns a light source on or off. Dimming light sources is generally achieved by reducing the energy through the circuit, for example by having the energy pass through a variable resistor. There are also digital mechanisms to control light sources. The most used mechanism, especially for LED light sources, is Pulse Width Modulation, (PWM)[1]. PWM makes use of the very fast switching

[1] see Glossary at the end of this dissertation for further explanation.

time of LEDs by rapidly enabling and disabling it. The human eye cannot perceive this fast flickering and will see the average light intensity: I.e., it appears as though the light is dimmed. PWM is an example of low-level control. There are also standards that represent higher-level control: Digital MultipleXing (DMX)[1] ("USITT DMX512," 2004) and Digital Addressable Lighting Interface (DALI)[1] ("DALI Manual," 2001). DMX is the standard for theatre and stage lighting and architectural lighting. DALI is mostly used in the ballasts for light sources. DALI is slightly more complex, but it allows two-way communication between light sources and the controller. These standards separate the supply of power to the light source from the light control. Recently, wireless solutions entered the market: e.g., wireless DMX (W-DMX). There are also wireless standards that are not dedicated to solely the lighting domain. E.g., WiFi, Bluetooth and ZigBee are used in a variety of applications and devices, ranging from smartphones to household appliances to automotive, and are now also used to control light sources. The benefit of using wireless control is that one does not have to setup a complex wired infrastructure. A disadvantage is that, currently, wireless solutions are less reliable and slower than wired solutions.

4.2. Lighting applications

There are highly diverse lighting applications presented in literature (for a recent overview see "The Future Of Light," 2013). In this section I focus on three domains of lighting applications: energy saving, engaging and aesthetical experiences, and light as carrier of meaning.

Energy saving

A large domain in research and design practice of lighting applications is concerned with energy consumption. Lighting consumes a large part of the global energy bill (Mills, 2002). As LED is more efficient than other lighting technologies, this can already yield large energy savings. But by using intelligent control algorithms, also light 'waste', i.e., lights that are on when no one is using them, can be reduced, leading to even larger energy savings. This domain can roughly be divided between lighting for outdoors and indoors. In both cases the goal (generally) is to balance energy consumption with other lighting requirements or parameters of user comfort. For example, research investigates how to design intelligent algorithms to dim streetlights (Atici, Ozcelebi, & Lukkien, 2011), while maintaining feelings of safety (Haans & De Kort, 2012). For indoor lighting, there are roughly three strategies to save energy: daylight harvesting, occupancy sensing, or user-demand (Wen & Agogino, 2011). Daylight harvesting involves strategies to transport light into buildings, and to dim lights when sufficient daylight is present. Occupancy sensing involves dimming or disabling lights when no user activity is detected. User demand strategies provide users with control and take the preferences of these users as a starting point for the lighting conditions, and not the recommended standards, as user preferences are generally lower than these standards.

[1] see Glossary at the end of this dissertation for further explanation.

Engaging and aesthetical experiences

There is a large domain of lighting applications designed for engaging and aesthetical experiences that mainly leverage the psychological implications of lighting. Stage and theatre lighting is the most basic example of this: Lighting is used to emphasize the character or ambiance of a concert or show and as such engages the 'users' into the whole experience. There are also applications that use colored light and projections to reduce stress, for example the 'Ambient Experience' (Knoop, 2006; Marzano, 2005) or Nebula (Aarts & Marzano, 2003). Many art installations also use lighting to provide aesthetically pleasing experiences. There are light festivals all across the globe, where such installations are exhibited. Often, such installations visually transform elements of the building via projections, which are also referred to as 'media facades' (Boring et al., 2011). Furthermore, in retail environments lighting can be used to fit or strengthen a brand image (Schielke, 2010). For consumers, products are released that use the expressive possibilities of light: Philips has their Ambilight technologies (Diederiks & Hoonhout, 2007): Lights on the back of televisions extend the image into the surroundings. Not only does this reduce contrast between the television and its surroundings, it also immerses users more into the movie experience. In 2013, Philips released Hue (Bui, Lukkien, Frimout, & Broeksteeg, 2011; "Philips Hue," 2013). This system consists of a number of LED light sources in the form of traditional light bulbs and a so-called 'bridge' (depicted in Figure 1.1). Each light bulb contains a small microprocessor and a wireless transceiver. The bridge connects the light sources to the home network. Smartphones, tablets and other devices that communicate to the home network can be used to control the light sources wirelessly. Each light bulb contains RGB[1] and white LEDs. This makes it possible to generate a wide variety of light settings. Multiple light sources allow users to easily create lighting atmospheres in their home environment. In the domain of 'atmosphere creation', there are diverse projects that investigate tangible ways to create such an atmosphere for an entire room. M-Beam (Westerhoff, van de Sluis, Mason, & Aliakseyeu, 2012) is a circular object with an LED inside (Figure 1.1). Depending on the direction of the LED in space (upwards/downwards) and the distribution of the light (wide/small) the atmosphere for a complete environment is determined. The M-Beam uses the expressive qualities of a single object and scales this to the atmosphere of a complete environment. Another example is Carrousel (top-right in Figure 1.1) by Ross and Keyson (2007), which uses the motion and the shape of the device and translates this to system parameters for the lighting system. Carrousel not only uses the expression of shape, but also of motion and translates this to an atmosphere. Fonckel is a lamp (see Figure 1.1), based on the doctoral research of Ross (2008) that allows user to control the direction, size, and intensity of the light via gestures. Ross showed in his dissertation that the interaction with the lamp can be programmed in specific ways as to elicit specific experiences. He showed that when the lamp requires occasional help from the user, people feel helpful and when the lamp behaves submissive, people feel powerful.

[1] see Glossary at the end of this dissertation

Carrier of meaning

In other cases, light is used as carrier of meaning in order to provide people with new behavioral possibilities. For example, light can be used as display, in order to directly convey meaningful information to people. Appleby and Overbeeke (2009) present 'Newsflash', A kiosk-like stand, which allows visitors to browse through news-articles from different online sources in order to compare news from different perspectives. PicoTales (Robinson, Jones, Vartiainen, & Marsden, 2012) uses a small projector and a phone to display animated stories created by multiple users. SixthSense (Mistry & Maes, 2009) combines a wearable projector and camera to augment the world with information: E.g., in the supermarket, information about a specific product can be displayed when the user holds it in his hand. In these examples, the projected light *is* the information and as such influences behavior of people. However, there are also examples where light is used to convey abstract information in an aesthetically pleasing way. For example, AmbientROOM (Wisneski et al., 1998) and Home Radio (Eggen, Rozendaal, & Schimmel, 2003) convey information through dynamics in lighting. AmbientROOM presents

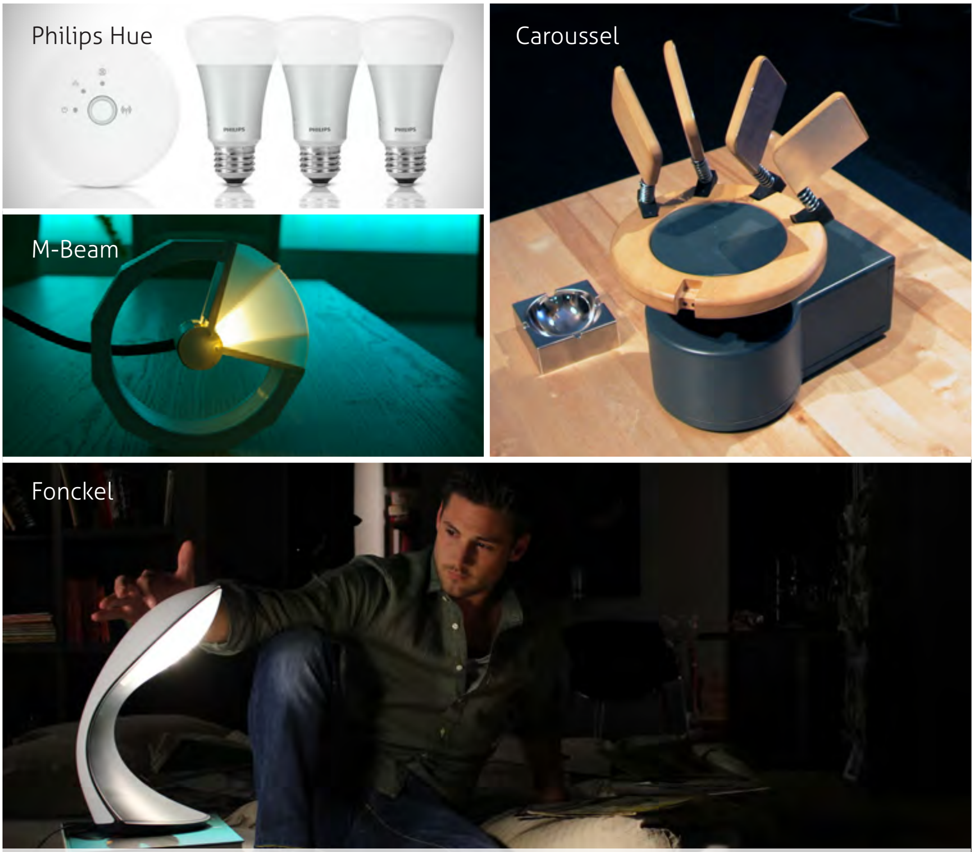


Figure 1.1 Examples of related work: Philips Hue ("Philips Hue", 2013), Caroussel (Ross & Keyson, 2007), M-Beam (Westerhoff, Van De Sluis, Mason, & Aliakseyeu, 2012), and Fonckel ("Fonckel", 2013)

information about the presence of others in the workplace via projected light on the wall. The Home Radio makes people aware of the activities that occur at home via soundscapes and colored projections. In these cases lighting is used as a modality to convey abstract information. However, light is also used to enhance existing streams of information. The 'follow-me-phone' (Appleby & Overbeeke, 2009) uses light to add an additional communication channel to auditory communication. This concept describes a set of communication devices to connect remote living rooms. Light on the local device shows the distance of the remote user to his device: This enables users to 'drift' in and out of conversations as they know whether others are close to the device and can thus hear them. Also in practical applications, such as keeping time in meetings, light can be used (Occhialini, Van Essen, & Eggen, 2011). Occhialini and colleagues designed a system where light changed color over time to indicate how much time has passed and how much time is left for a meeting. In this example, the lighting is used for aesthetical and illumination purposes, but it is enhanced to convey meaningful information to people. Light thus creates added value for people.

5. Designing for systems

Thus far, I argued that the design of adaptive lighting environments is characterized by both technological and social challenges. On the one hand, lighting has implications for the way we feel and behave and on the other hand, novel lighting technologies are designed in order to provide new possibilities to people. This balance between social aspects and technological aspects makes that adaptive lighting environments can be considered a socio-technical system. These types of systems represent a composition of people and (interactive) technologies with complex interdependent relationships between them, which leads to new design challenges (Frens & Overbeeke, 2009). In this section I argue that this complexity is a result of the nature of these socio-technical systems (Rittel & Webber, 1973; Stolterman, 2008). This complex nature has as a consequence that it is not possible to have a definitive and complete overview of the system at any point in time; there are many stakeholders involved and there is no single correct solution to a design challenge (Frens & Overbeeke, 2009; Stolterman, 2008; Zimmerman, Forlizzi & Evenson, 2007; Zimmerman, Stolterman & Forlizzi, 2010).

The field of industrial design is expanding towards designing for systems (Frens & Overbeeke, 2009). From a technology perspective a system mostly refers to the topology of technical components: e.g., the architecture of a computer system. However, in this dissertation I define a system as the composition of people and interactive technologies and the relations between them in a certain context, as is depicted in Figure 1.2 (cf. Benyon, 2013; Frens & Overbeeke, 2009). For this project in specific, I focus on interactive technologies as this is my main field of research. These technologies are characterized by the following parameters: They are electronic devices with computational power, they can change their state (i.e., they contain an actuator) based on information they acquire from their environment (i.e., they can be interacted with), and they are able to exchange information with other devices.

Other fields of research share similar ideas about systems as constructs of 'the social' and 'the technological': The field of socio-technical systems (STS), which is typically targeted towards workplaces, defines systems as the "complex interaction between humans, machines and the environmental" (Baxter & Sommerville, 2011, p.5). Kevin Kelly (2011) uses the term 'technium' to describe technology in its network of "culture, art, social institutions, and intellectual creations of all types," (p.11-12). Kelly approaches systems from a technology perspective, and argues to include social constructs. On the other hand, there are those that approach systems from a social perspective, and argue to include technology in their definition. For example, Latour (2005) and Law (1992) are known for their work on actor-network theory. They argue "networks are composed of not only people, but also of machines, animals, texts, money, and architectures" (Law, 1992, p.381). Pinch & Bijker (1984) also argue that technology needs to be considered as a social construct, and that technologies are successful due to technical superiority and their place in the social context. Also in design-research fields, visions on the interwoven structure of people and technology are widespread. Weiser (1991) presented *ubiquitous computing* (ubicomp) as a vision on the future of information and communication technology, where technology fades into the background and is seamlessly interwoven in our social lives. Where ubicomp mainly focuses on a work context, *ambient intelligence* (Aarts & Marzano, 2004) is focused towards the home context, which brings technology directly into the private life of people. Many of these fields aim to provide definitions to describe and analyze such systems. However, I need a working definition from a designer's point-of-view. Therefore, I use the description of Frens & Overbeeke (2009) of designing for systems, as they identify challenges from a designer's perspective. In the remainder of this section I further explore the complex nature of systems and the design challenges that follow from this.

5.1. Challenges when designing for systems

Figure 1.2 depicts a schematic overview of the definition I use of a system. The person figures represent (groups of) people. T represents interactive technologies. Interaction, depicted by the lines in the figure, refers to the relationship that is established between the actions of the person and the actions of the thing; the inter-action between the two (Norman, 2011). Interaction is bi-directional: People interact with technologies, but these technologies also mediate our behavior (Verbeek, 2005). Furthermore, people also interact with each other, and technologies communicate via technological networks. These interdependent relationships between the different components have consequences for the design of such systems: It is difficult to have a complete overview of the system due to the dynamic composition of the system. This entails new challenges for interaction design, as functionality of a product may extend beyond the

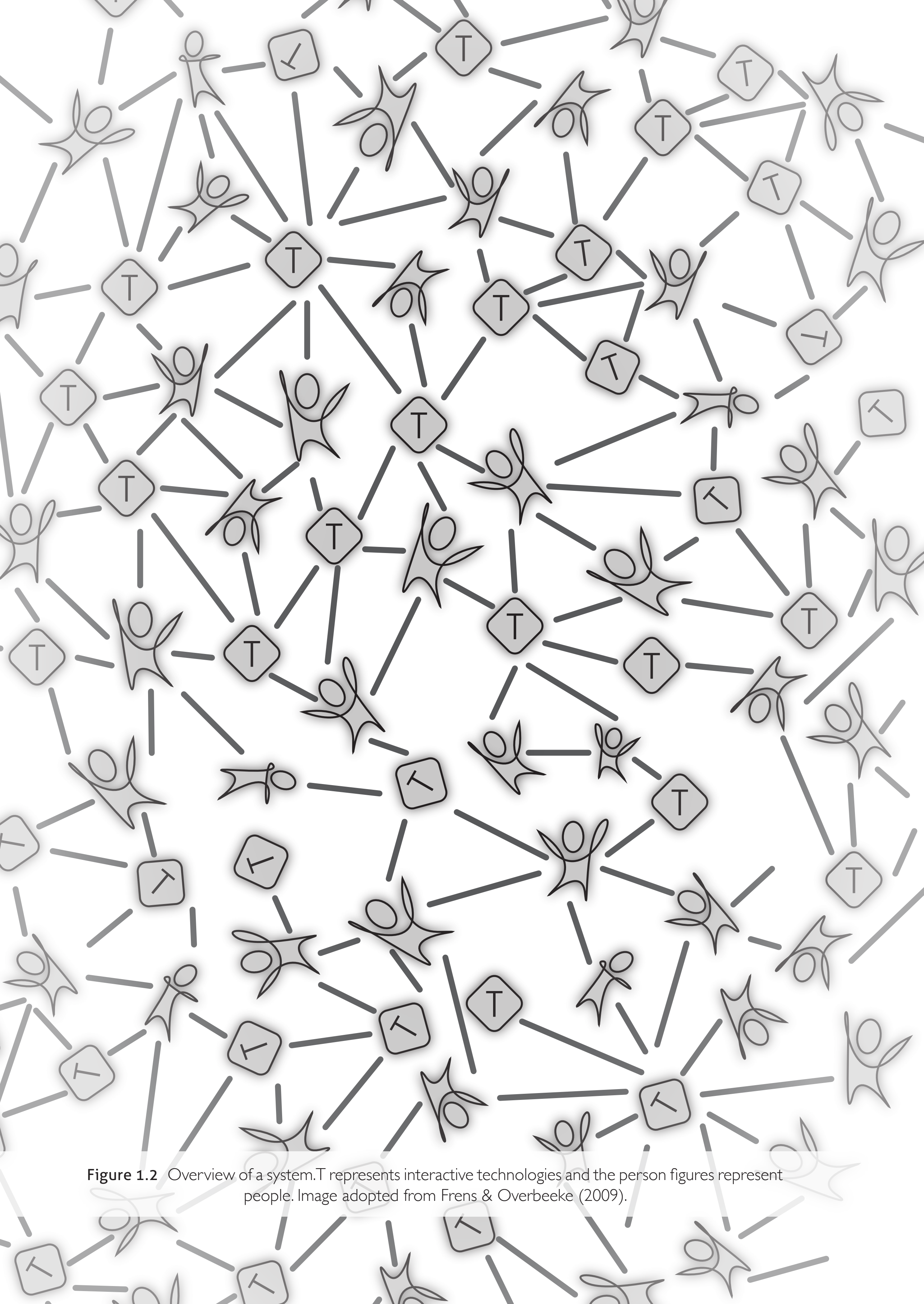


Figure 1.2 Overview of a system. T represents interactive technologies and the person figures represent people. Image adopted from Frens & Overbeeke (2009).

single product and may depend on other components of the system. Finally, in a system context, situations of conflict occur, as contradictory demands might have to be satisfied.

The interwoven relationships in a system make it difficult for a designer to have a complete overview of the system. In the first place, because it is difficult to determine the boundaries of the system. In the second place this is a result of the dynamics of daily life, which means that systems are dynamic: People perform different activities throughout the day, where they interact with different people and technologies. The role of a technology may shift between different contexts: E.g., contemporary smartphones are not only used to make phone calls, but can also be used to browse the Internet, listen to music, take pictures etcetera and this can even be shared with other technologies or people. The function of a system is not generic, but changes for different contexts. Since the functionality of systems may change throughout the day, this has implications for interaction design: The coupling between 'input' and 'output' changes. In- and outputs of the system may be of different modalities or may reside at different locations (Frens & Overbeeke, 2009). Ideally, one would like to design interaction opportunities that integrate *form*, *interaction,* and *function* (Frens, 2006). However, as technology and people have different roles in different contexts, it becomes difficult to design loci of interaction in such an integrated unity. Simply because the form, interaction and function may no longer be static. The audio-system in the car is an example of this blurred structure: Its most basic functionality it is used to listen to the radio. When the driver receives a phone call, this can be transmitted over the audio system. But the audio system may also act as output to the in-car navigation system. Following the unity of form, interaction, and function, one would argue that for each of the different uses of the audio-system, people require dedicated interaction possibilities.

Another consequence of the interwoven nature of a system is that multiple people interact with the system simultaneously, affecting the state of the system for others. This may introduce conflicting situations into the system. For example, what happens when two smartphones are connected to the audio-system and two phone calls are received? Or the system may be instructed to behave in ways that contradict with what the user intends to do: If the user mutes car audio-system, should phone calls still be received? I believe that in order to make systems successful, they should be sensitive to these conflicting situations and provide appropriate ways for people to structure and deal with these situations.

In conclusion: When designing for systems, designers are faced with interwoven, complex structures of people and technology. This means that it is difficult to have a complete overview of the system, and has consequences for interaction design, because a product's function may change over time. Additionally, conflicting commands may be provided to a system, as the in- and outputs to the system are dynamic. Designers need ways to deal with such design challenges.

6. Theoretical foundations

Throughout this chapter I argued that the design of adaptive lighting environments entails interaction design challenges. My perspective on interaction design is informed by the ideas of embodied interaction, as I agree with the proposition that the way people interact with technology should respect the whole human being with its perceptual-motor, emotional, cognitive, and social skills (Overbeeke, 2007).

In current design practice, interaction design is associated with the development of websites and/or applications for screen-based devices. Computing devices are often mistaken for 'computers', whereas I already outlined via visions of ubicomp and ambient intelligence, that objects in our surroundings can be equipped with computational power: In principle, every device can become a 'computer'. However, this does not imply that every device in the future will have a screen so people can interact with the device. Instead new possibilities for people to interact with these devices – that fit closer to our being in the world – need to be explored.

In this respect, embodied interaction (Dourish, 2004) approaches interaction design from a broad perspective that Dourish summarizes as 'being-in-the-world'. Dourish defines embodied interaction as "the creation, manipulation, and sharing of meaning through engaged interaction with artifacts" (Dourish, 2004, p. 126). Embodied interaction is constructed from a phenomenological and ecological perception perspective on the world. These perspectives argue that our world is inherently meaningful to us as we act in it. Computing devices should offer meaningful action possibilities, which are the possibilities that an object affords given its form and function, and the body and intention of the actor. The difficulty with contemporary interaction design is that action possibilities of electronics are not inherently meaningful to us: The "intrinsic link between functionality, appearance, and action" (Hummels & Lévy, 2013) that we have with objects in the mechanical world does not equate to the electronical world in which these devices operate. Therefore, the designer has to create action possibilities that allow people to grasp the capabilities of electronical devices. For personal computers the Graphical User Interface (GUI) is the main interaction paradigm that allows us to interact with these electrical circuits and access this digital world. Yet, these GUIs mainly rely on our cognitive skills, as we have to learn and remember actions and their consequences. Instead embodied interaction argues that our physical, social, and historical interactions in the world and with people can be capitalized in interaction design in order to facilitate this "creation, manipulation and sharing of meaning through engaged interaction with artifacts". Dourish consequently argues – and includes this as one of his design principles – that people (and not designers) in the end create and communicate meaning. It is therefore essential that design-research activities take place in the context in which they are to be used, as meaning emerges in use.

7. Research-through-design via the Growth Plan

In order to deal with the complex nature of the design challenge I use a research-through-design approach. More specifically, I use the Growth Plan, which is an approach for the development of highly interactive products and systems in context, consisting of three phases: Incubation, Nursery, and Adoption. In these phases, interactive (research) prototypes are explored, conceptualized, developed, and evaluated in real life contexts. This approach is particularly suitable to investigate innovative, interactive technologies and their implications on the behavior of people in an holistic, integrated way, this allows me me to deal with the complex nature of the question how to design for adaptive lighting environments.

7.1. Research-through-design

Research-through-design (RtD) is a method in which design action and scientific investigation support and invigorate each other in an iterative process (Frens, 2006; Hengeveld, 2011; Koskinen, Zimmerman, Binder, Redstrom, & Wensveen, 2011; Zimmerman, Forlizzi, & Evenson, 2007). As there is no generally agreed upon definition of what RtD actually is, or how it should be practiced (Forlizzi, Zimmerman, & Stolterman, 2009; Gaver, 2012) I address the elements of RtD that are important for this project.

I use a RtD approach to deal with complex (Stolterman, 2008) or 'wicked' (Rittel & Webber, 1973) design challenges. These are challenges without a clear problem definition and without a 'true or false' solution. Solutions for complex challenges cannot be hypothesized and accepted or rejected, but solutions can be good or bad depending on the perspective one takes (Gaver, 2012; Rittel & Webber, 1973). Also, due to a high number of stakeholders with (oftentimes) contradictory perspectives, these challenges are difficult to tackle using a reductionist approach (Hummels & Lévy, 2013; Stolterman, 2008): It simply is not possible to reduce the nature of the problem to some distinguishable and measurable variables.

Furthermore, a RtD approach has a holistic and constructive nature. It is holistic as it attempts to encompass the problem in its full complexity. Since RtD revolves around the development of (research) prototypes it is a constructive approach (Koskinen, Zimmerman, Binder, Redstrom, & Wensveen, 2011), where the designer intervenes with the context to study the implications in a possible future (Hummels & Lévy, 2013). Prototypes serve various goals in this process. First, they are physical, experiential hypotheses (Frens, 2006; Frens & Hengeveld, 2013). In an interdisciplinary project – which this project is – they form a medium of communication between disciplines (Stappers, 2007) and they support the disciplines to focus on integrated solutions. Second, (research) prototypes can be evaluated with actual users in realistic contexts, which is necessary to empirically investigate the user experiences of novel technologies (Battarbee & Koskinen, 2005). This allows designers to investigate the implications of their design rationale.

The research-through-design process is an odd one, as designers have to make decisions about possible futures, based on too little information (Frens & Hengeveld, 2013). To deal with this, I adopt an approach that combines design thinking with design making (Hummels & Lévy, 2013): the Reflective Transformative Design Process (RTDP) (Hummels & Frens, 2008). Creating design solutions via ideating, integrating, and realizing is at the core of this process. Design thinking is done by activities as *envisioning* and *validating* design solutions, whereas design making is supported by *cognitive* (analyzing/abstracting) and *experiential* (sensing/perceiving/doing) activities. These different activities are not prescribed in consecutive order, but designers can move from one activity to another in a non-linear order. Between the different activities, designers reflect on their actions to learn and to advance the design challenge.

7.2. Growth Plan

Where research-through-design is a broadly defined method, the specific approach used in this project is the Growth Plan (Ross & Tomico, 2009). The Growth Plan is designed to provide designers with handles to deal with complexity when designing highly interactive products and systems. It is pioneered by Ross & Tomico (2009) as an approach that deals with complex design challenges holistically. This means that the design-research challenge is not viewed from solely a technological, or experiential point of view, but considers the integration of all relevant aspects. For the design of ALEs this is valuable, as designers are faced with interwoven challenges: New technologies have to be developed (i.e., the technological point of view) in order to enable new user experiences (i.e., the experiential point of view) and to investigate how these technologies may transform society (Verbeek, 2005). Especially as the history of lighting technologies showed how innovations can result in large societal changes, it is important to consider the design of novel lighting technologies from diverse perspectives and in their full complexity. The Growth Plan is a suitable approach, as it advocates the evaluation of research prototypes in realistic contexts to gain insights into the implications of such products and systems on human experience and behavior. For this reason, the Growth Plan was selected at the start of this project.

The Growth Plan consists of three phases, *Incubation*, *Nursery*, and *Adoption*, respectively. In the following paragraphs each of these is described individually. The iterative and exploratory nature of the early phases help the designer-researcher to develop an understanding of the challenges he faces. In the later stages of the Growth Plan, the designer-researcher details and nuances his designs and evaluates them in context.

The Incubation phase is marked by keywords such as *exploration*, *creativity,* and *innovation*. During this phase the designer explores the design space through quick iterations of prototypes. Iterations in this phase typically last between several days to several weeks and help the designer to develop an understanding of the problem that he is dealing with. Results of this phase are prototypes that can be evaluated with users, for example using Wizard-of-Oz techniques (Hummels, 2000), or by consultation of experts. Results of this phase can be design guidelines or preliminary interaction models.

The most promising ideas, concepts, and insights are carried into a Nursery phase. Keywords of the Nursery phase are *converging*, *detailing* and *elaborating*. During this phase the preliminary ideas and prototypes become more nuanced and more detailed. The designer should assess whether concepts are technically feasible. Prototypes are developed up to a level that they are fully operational and act as proofs of concept to showcase technical feasibility. Iterations in this phase are longer than those in the Incubation phase and typically last several months. Evaluations in this phase are performed in increasingly realistic environments and can involve physiological, psychological, and behavioral analyses. Results of the Nursery phase are reliable prototypes, and richer insights in the implications of the technology on behavior of people.

In the Adoption phase, the high-end prototypes and design guidelines that have been developed during the Nursery phase are evaluated in real life. Keywords of this phase are *evaluation*, *real-life contexts* and, if the designer aims for this, *valorization* by industry. The Adoption phase is not focused on the generation of new ideas; existing concepts are implemented and evaluated longitudinally in real, lived context. As the evaluations in this phase are typically longitudinal, the (research) prototypes need to be operational without the continuous intervention of the researcher. This poses demands for the reliability of the prototypes. Evaluations lead to knowledge regarding the transformational value of the proposed concepts: It shows how the new technology changes the experience and behavior of people. The adoption phase may also include valorization of scientific knowledge in bringing products to market.

As was mentioned, the Growth Plan was selected as the approach to follow. As it is a new approach, this project should be considered a first case study where this approach is applied from the beginning. At the start of the project, the Growth Plan has been used to setup a rough outline of the project planning. Concretely, the Incubation and Nursery phase are targeted to last approximately 1 year each, whereas the Adoption phase is planned to last about 1,5 years. The transition moments between phases are points where the three involved disciplines outline their interests and contributions to the project. It should be mentioned that the Growth Plan is not used to structure day-to-day activities, nor does it provide designers with tools or methods to advance their design-research challenge. The Growth Plan does not prescribe designers what to do, but it provides a framework by which a designer can structure his activities.

8. Summary & conclusions

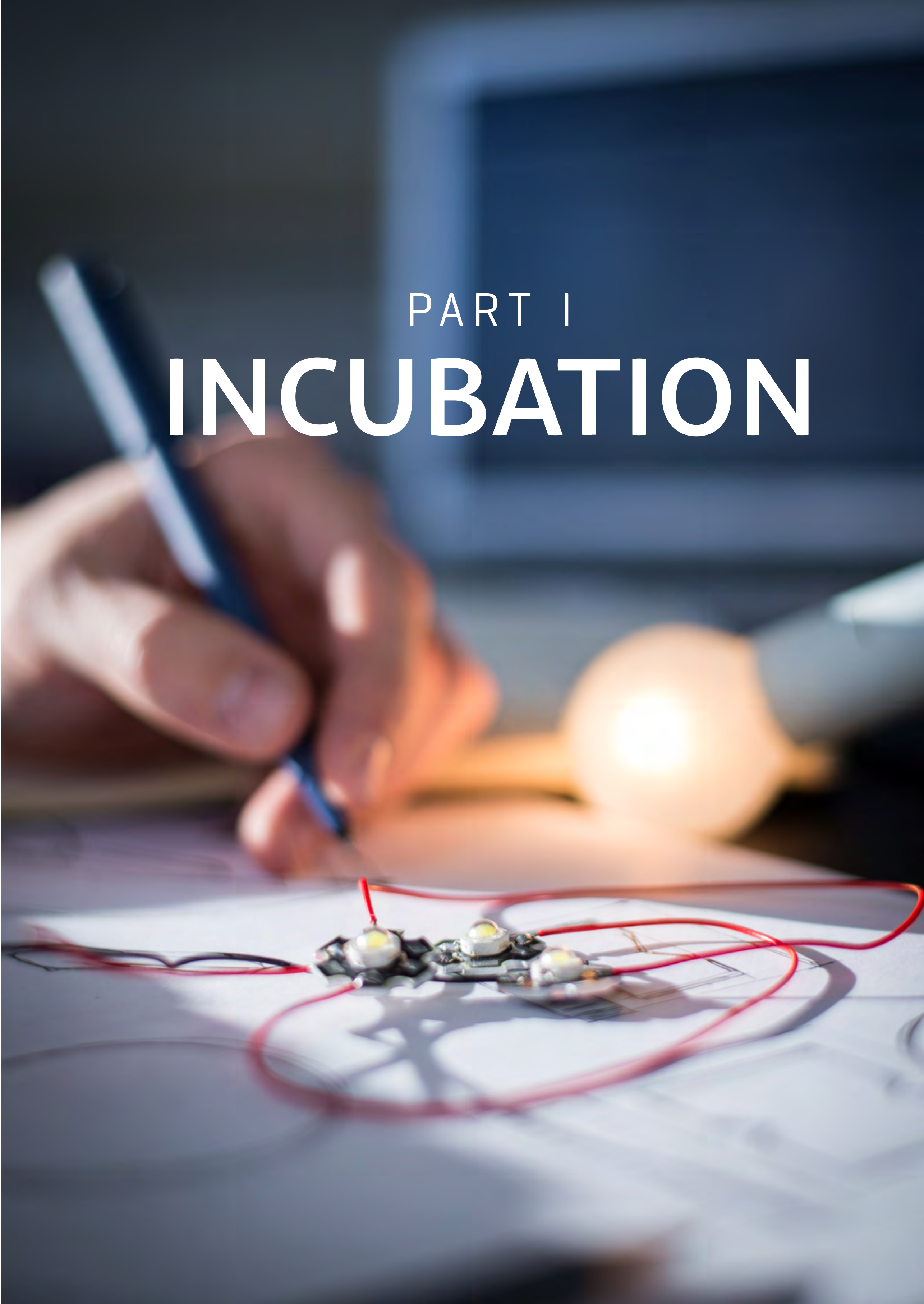
Solid-state lighting technologies have significantly advanced in recent years, such that they can now provide sufficient light to illuminate our environments. Furthermore, their nature as semi-conductors makes that they can easily be controlled through microprocessors. As a result, lighting systems can now be investigated and designed as socio-technical systems. The complex, interdependent relationship between technological opportunities, social implications, and their interactions, requires that the design of adaptive lighting environments is investigated holistically, leading to the central question in this dissertation: "*How to design for adaptive lighting environments?*"

When designing for adaptive lighting environments, contextual factors play an important role. Investigation of related work in the lighting domain showed that lighting has visual, physiological, psychological, and behavioral effects on people. Given the new technological capabilities of lighting technologies, the psychological and behavioral effects of light can be opened up to people. Comparison of the different studies regarding these two effects, revealed that contextual factors influence how people experience and behave in specific lighting conditions.

As ALEs are a socio-technical systems, designers are faced with challenges that need to be dealt with in an experiential way. This offers designers a rich perspective on the system, and makes it possible to experience possible uses of a system. Furthermore, as the influence of lighting on people is contextually dependent, it is important to create experiential prototypes that can be evaluated in-context. Embodied interaction also values the importance of context: It is in context that meaning emerges in interaction between people and technology. The Growth Plan that was selected as approach for this project, supports this view by advocating the design and evaluation of experiential prototypes in-context. This allows me to advance the design challenge in iterations of design thinking, design making, and reflection-on-action.

8.1. Structure of this dissertation

To communicate the results of my project, this dissertation follows the three phases of the Growth Plan. The following part, titled Incubation, explores the design challenge through the design of five lighting environments. The second part, titled Nursery, contains the design of Lithne, Hyvve, and Bolb, which are based on the insights of the Incubation phase. They play an important role in the final part, titled Adoption, where they are used for the implementation of three ALEs as part of a lighting system. Additionally, the Adoption phase describes the longitudinal evaluation of these lighting environments in order to gain insights into the implications of adaptive lighting environments in daily life. This dissertation concludes with a final chapter in which I reflect on the project in order to provide insights in the three sub-challenges and main design challenge of this project.



PART I
INCUBATION

Introduction to the Incubation phase

The Incubation phase is characterized by *exploration*, *innovation*, and *creativity*. In the Incubation phase the designer explores the design domain and conceptualizes initial design opportunities. The research-through-design cycles are typically short and range from one to several weeks. Via creative design techniques user concerns and desires are identified. Results of this phase are early interactive prototypes and/or installations that demonstrate initial concepts and can be used in evaluation sessions with users or experts.

In the previous chapter the starting points for this project were presented. This part contains one chapter that presents five research-through-design iterations, in which different design challenges are explored. The five sections in Chapter 2 represent the five iterations. The sub-challenges that were introduced in the previous chapter, serve as the basis for the explorations. Each section starts with formulating the challenge that is addressed in that specific iteration. This is indicated in by the italic paragraphs. These paragraphs should not be read as traditional research questions, but rather as part of my design thinking ('envisioning' in the reflective transformative design process). They are reflections on my design actions and show advancing insights regarding the design challenges of this project. The questions that are asked in these section are not to be answered with true or false, but they have a more open-ended character and oftentimes they combine a question with a possible design direction.

The first iteration is an interactive sketch, which explores the relation between contextual factors and meaningful lighting behaviors. In specific, it presents an installation where the body posture of people is taken as measure for psychological closeness and the lighting conditions are adjusted accordingly. The second iteration builds upon the first iteration, but presents an installation for a larger group of people. Via this installation I explore whether lighting behaviors can be used to influence the social dynamics of a group. In the third iteration I explore more rigorously how social dynamics are influenced by dynamic lighting behaviors: In specific the influence of spotlighting behavior on speaking behavior. Reflection on the earlier installations raised the question how control can be distributed over a group of people. This question is central in the fourth iteration, where a lighting system with three unique light controllers is evaluated in user confrontation sessions. The final iteration presents the design of an adaptive office environment. Where the earlier iterations explored different aspects of adaptive lighting environments separately, this iteration integrates the earlier insights in a single installation.

2.
Exploring adaptive lighting environments

Parts of this chapter have been published in:

Magielse, R., & Ross, P. R. (2011). A design approach to socially adaptive lighting environments. *Proceedings of the 9th ACM SIGCHI Italian Chapter International Conference on Computer-Human Interaction: Facing Complexity*, 171–176. doi: 10.1145/2037296.2037337

Magielse, R., Ross, P., Rao, S., Ozcelebi, T., Jaramillo, P., & Amft, O. (2011). An interdisciplinary approach to designing adaptive lighting environments. *Proceedings of 7th International Conference on Intelligent Environments*, 17 –24. doi:10.1109/IE.2011.28

Magielse, R., Hengeveld, B., & Frens, J. (2013). *Designing a light controller for a multi-user lighting environment*. Paper presented at the 5th IASDR 2013, Tokyo, Japan. Retrieved from http://design-cu.jp/iasdr2013/papers/1594-1b.pdf

1. Interactive sketch: a light on closeness

Light influences human behavior. Literature shows that lighting conditions have visual, psychological, physiological, and behavioral effects on people. These lessons from literature can be used to design adaptive lighting environments that provide people with lighting conditions that suit their needs and desires. However, the literature review revealed that contextual factors need to be considered to properly consider the implications of light on people. For the design of lighting behaviors, this means that it needs to be explored why, when, and how lighting environments should adapt to provide meaningful lighting behaviors.

The open-ended design-thinking above was the starting point for an initial design exploration. To this end I asked myself the following question:

- How should we design a lighting environment that adapts its behavior to support the current social setting?

This question directly relates to the first design challenge: *what are meaningful lighting behaviors* and how should we design these? To explore this challenge I created an interactive sketch. I specifically use the term sketch here to indicate that the installation created is not intended as a finished concept. Sketching is an activity to wrap your mind around the matter in an open, quick, and inexpensive way and sketches allow you to explore different possibilities, rather than confirm one solution (Buxton, 2010). Sketching can be used to explore open-ended questions as outlined above. Furthermore, pen-and-paper sketches are insufficient when you want to design the interaction between people and technology. This means that sketches should be experiential and interactive

To start, I selected a context in which (I find) light is an important part of the context: dining. Proper lighting can change a dinner from a very intimate experience, to a formal experience. Via this sketch I explore how physical and psychological closeness can be supported by specific lighting conditions. In related work, it is found that lighting conditions affect how we perceive environments (Veitch, 2001) and that dimmer lighting conditions enhance positive feelings towards others (Baron, Rea, & Daniels, 1992; Miwa & Hanyu, 2006; Werth, Steidle, & Hanke, 2012). In this sketch I use these insights to create a lighting environment that adapts to behavior of users, to support the social setting.

1.1. The scenario

For this interactive sketch the body posture of people is taken as a measure of physical closeness. Based on this *physical* closeness of people, the lighting conditions adapt to create an environment that enhances *psychological* feelings of closeness. Concretely: When people are physically close together, the lighting conditions create a 'private' light setting. When the physical distance between people is large, the lighting conditions are more 'public'. When people lean forward

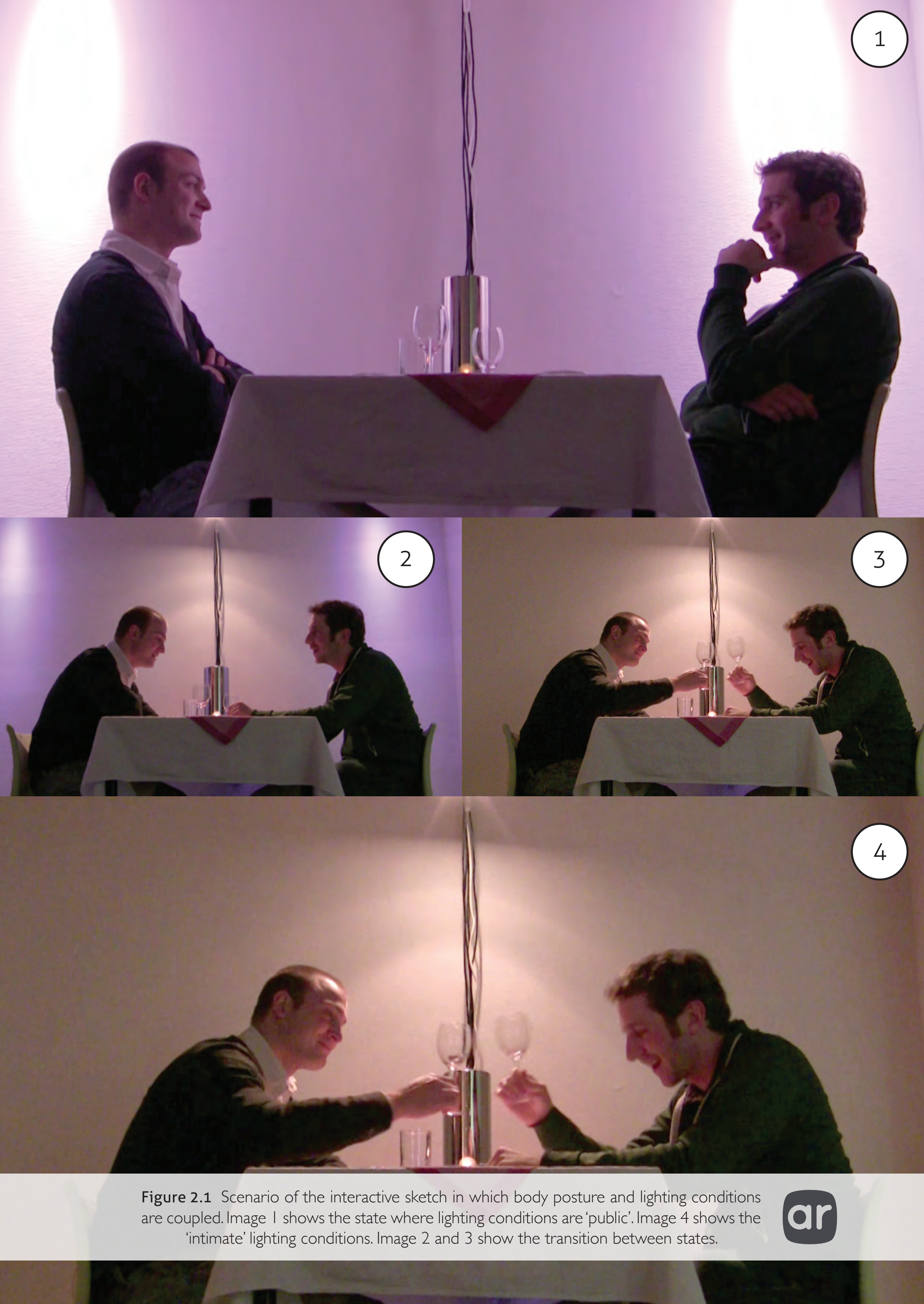


Figure 2.1 Scenario of the interactive sketch in which body posture and lighting conditions are coupled. Image 1 shows the state where lighting conditions are 'public'. Image 4 shows the 'intimate' lighting conditions. Image 2 and 3 show the transition between states.

their physical closeness is high (they are close together) and when people lean against the backrest of the seat, their physical closeness is low. The lighting conditions are adjusted on two parameters: The *overall brightness* of light in the environment, and the *light distribution* in the environment. Both of these parameters are found consistingly across different studies as parameters that influence the appraisal of a lighting environment (Flynn, Hendrick, Spencer, & Martyniuk, 1979; Hawkes, Loe, & Rowlands, 1979; Veitch & Newsham, 1998; Veitch, 2001). Specifically, in this scenario 'intimate' lighting settings are slightly dimmed and lights are aimed at the people. These lighting conditions are found to enhance positive feelings towards others (Baron, Rea, & Daniels, 1992; Miwa & Hanyu, 2006; Werth, Steidle, & Hanke, 2012). The 'public' lighting conditions are brighter and the light sources are directed at the walls. Figure 2.1 depicts the scenario of the interactive sketch. A video of the scenario can be found in online Appendix 2-A or can be accessed via Layar on Figure 2.1.

1.2. The implementation

Figure 2.2 shows the installation that comprises the sketch. The lighting setup consists of four RGB wall washers, a decorative lamp with incandescent lighting on the table and a halogen spotlight directed towards the table. Two force sensitive resistors (FSR) are attached to each chair: one to the backrest and one to the seat. These are used to determine whether a person is seated and whether he is leaning forward or not. The lighting behavior is programmed with MAX/MSP[1].

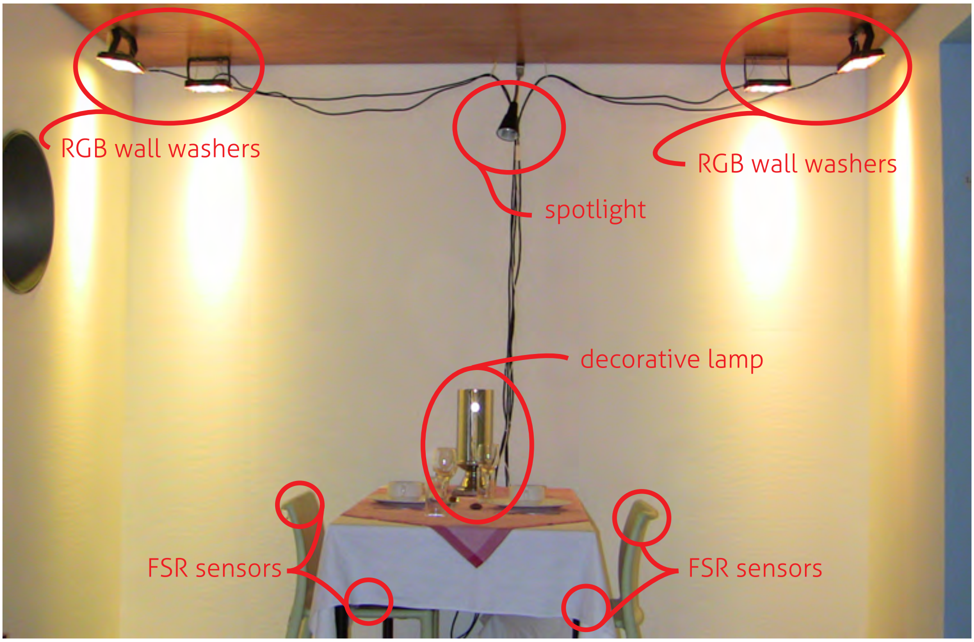


Figure 2.2 Annotated image showing the implementation of the interactive sketch on closeness.

[1] http://cycling74.com/products/max/

1.3. Insights of the interactive sketch

The interactive sketch was used in discussion with supervisors and colleagues (approximately 5-10); this formed the evaluation of the sketch. As the sketch is interactive, it is possible to experience the lighting installation from a 1st and 3rd person perspective. When having a discussion at the table, you experience the scenario from a 1st person perspective. Videos and images of others interacting with the sketch provide a 3rd person perspective. These discussions and experiences raised questions and help to set directions for new design challenges. In the following paragraphs I summarize topics that were addressed in these discussions.

The interactive sketch showed that it is possible to design dynamic lighting conditions to change the experience of the environment. More specifically, in this example the lighting conditions were designed to shift attention either to the surroundings or to the other person. When the wall-lighting was dimmed and the face of the other person was illuminated (i.e., 'private' lighting), discussions revealed that it felt as if the person was brought forward from the background; It was easier to focus your attention to the other person. Figure 2.1 shows from a 3rd person perspective that faces are more illuminated. In the cases where the background is illuminated (i.e., 'public' lighting), people were less illuminated and they seem less important.

As this example shows, lighting environments can adjust their behavior based on behavior that is predefined as meaningful. However, the interaction between people and the system raised additional questions. There is what I would like to call the 'chicken-and-egg' problem: If the lighting conditions alter our experience of the environment, do we want them to *follow* our behavior or *guide* our behavior? Is it possible that, through altering the lighting conditions, we can also alter the behavior of people: E.g., can *physical* closeness be induced by setting lighting conditions that advocate *psychological* closeness? And in case we are able to do so, who controls this? In the current installation the 'private' lighting conditions were triggered when two people leaned forward, and the 'public' lighting conditions were triggered when two people leaned backward. In the other cases the lighting conditions did not change. However, if the lighting system can also guide our behavior, who is in control of the system? Would this mean that that person indirectly controls the behavior of people? This does not provide an answer to the question, but rather provides a direction for further investigation.

Another topic of discussion regarded the *scalability* of this installation, both in terms of hardware and in terms of user experience: With two people it is simple to calculate when they are closer to each other, but how about adding a third, fourth, or even more people to the system. How does the system then determine 'closeness', and is it in this case expressed through physical proximity between people, or should there be other determinants of closeness? This also raises questions whether lighting conditions should be adjusted locally, or for the environment as a whole.

2. Lunch environments: broadening the scope

As lighting environments become contextually aware, they can provide people with lighting conditions that are beneficial or desired in that situation. The interactive sketch in the previous section revealed that lighting conditions can dynamically be adjusted based on the social setting in an environment. To determine these lighting behaviors, we might use insights from scientific studies can be combined with learning algorithms. But what if we want lighting technologies to anticipate and change behavior of people? For example, do intimate light settings also lead to more intimate conversations? Overall, this raises the question whether dynamic lighting conditions can be used to guide the behavior of people?

In this section I present the second iteration to investigate the social implications of interactive lighting systems and to further explore the design domain. Based on the insights of the interactive sketch the following questions were defined:

- How can human behavior be influenced by dynamic lighting conditions?
- What are the implications of scaling up the installation with regard to (1) behavior of the system and (2) user interaction?

Furthermore, I wanted to move from a scenario that is acted out, to more realistic human environments where people behave naturally. This can already provide early insights into the actual implications of adaptive lighting environments in daily life.

2.1. The implementation

A second lighting environment was created with a table that could fit up to six people. For each seat at the table a spotlight was installed directed at that seat to be able to highlight individual people. Above the table an incandescent lamp was placed to provide general illumination on the table surface. Colored wall washers were placed on the ground next to the walls. In the corners of the room custom designed light sources were placed that can produce upward and/or downward lighting. Figure 2.3 provides a schematic overview of the lighting setup. All light sources could individually be controlled via a DMX controller. The DMX controller in turn was connected to a computer so lighting behaviors could be programmed. An impression of the complete environment is presented in Figure 2.4.

One of the difficulties at this point was that I was not sure what the lighting behavior of the environment should be. This made it difficult to 'program behavior', as programming is typically an activity that defines and constrains. Instead I want to explore different behaviors and be able to deal with unforeseen situations. Therefore, three control boards for the lighting infrastructure were created (shown in Figure 2.5), each with a different purpose. One board controlled the colored *wall lighting*, another the *accent lighting* in the corners and the last the *spot lighting* directed at the individual seats via linear sliders and rotational dials.

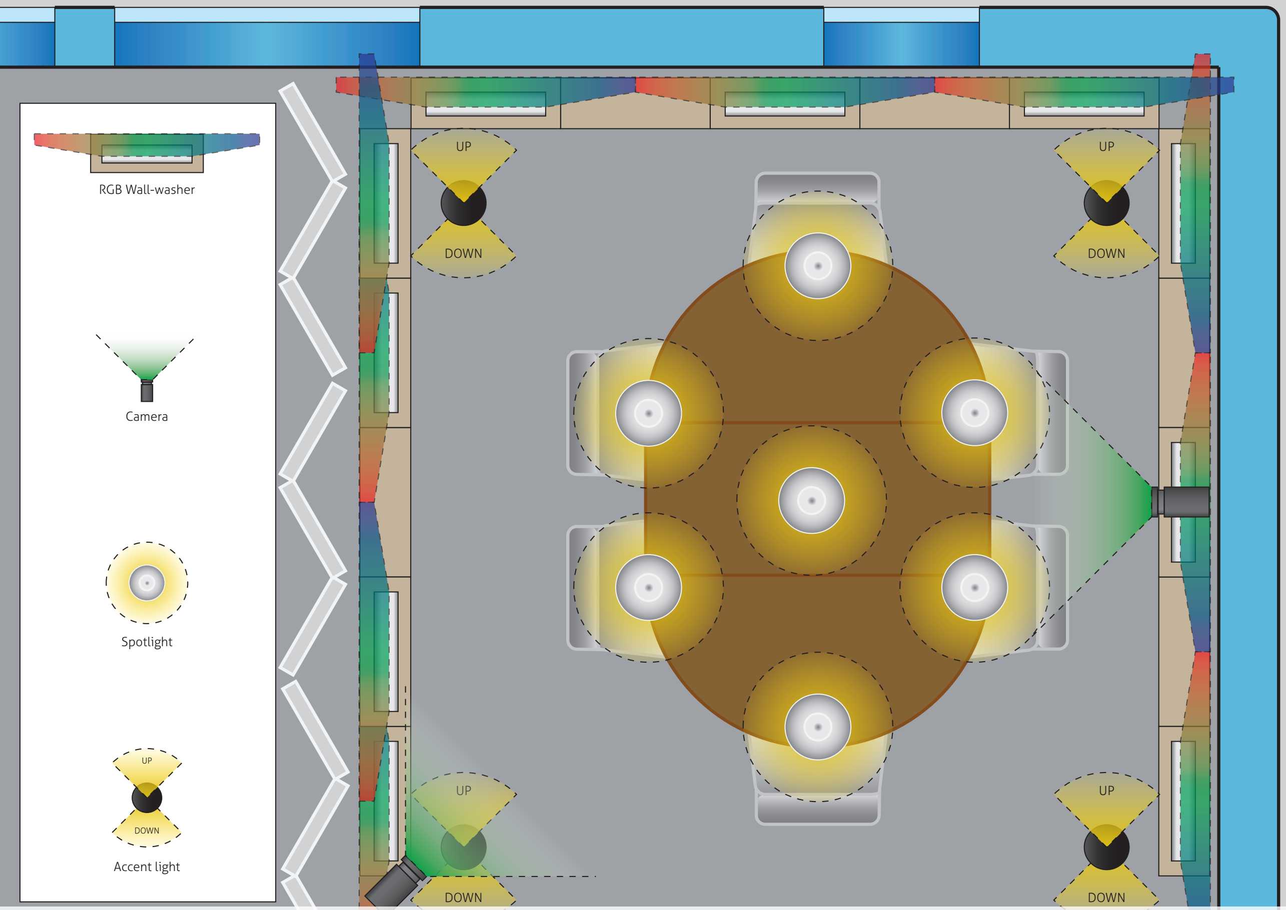


Figure 2.3 Schematic overview of the lighting setup in the lunch environment.

Figure 2.4 Impression of the lunch environment with the presented lighting setup. Photo by Bart van Overbeeke.

2.2. User evaluation session

Explorative user evaluation sessions were set up to investigate how different lighting conditions could be used to guide social behaviors. These evaluation sessions had a loosely defined structure in order to deal with unforeseen situations, and to explore different aspects during a session. The sessions had the character of user confrontations (Tomico, Frens, & Overbeeke, 2009) and essentially confront the users in a 'reality-that-could-be' with the purpose to identify strengths and weaknesses in the proposed concepts. User confrontations have a dynamic, open, and dialectical character and are constructive for the design process.

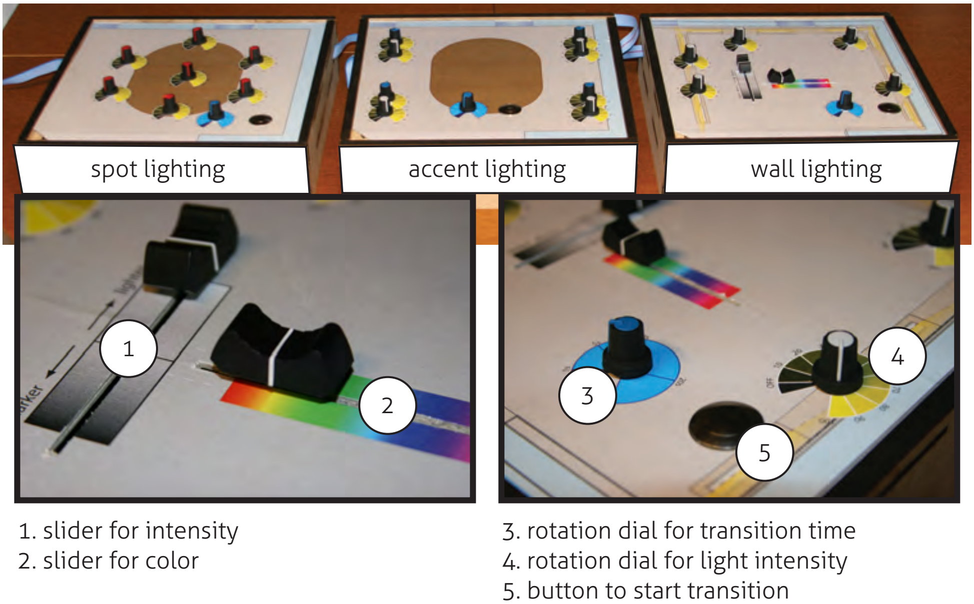


Figure 2.5 Overview of the control boards that were created to control the different light sources in the lunch environment.

Figure 2.6 Controllers adjusting the lighting conditions while participants are having lunch.

In total three evaluation sessions were conducted. Groups of participants were invited for a (free) lunch in this environment and they were told that an intelligent audio-visual algorithm was developed that would adjust the lighting conditions to their behavior. No information was provided as to what the output would look like. In reality there was no intelligent algorithm, but the cameras that were installed in the environment facilitated a group of colleagues with a direct audio-video feed of the lunch environment. These colleagues (with background as designer of interactive products and systems) received one of the control boards and acted out the intelligence of the system (see Figure 2.6), hence I refer to them as '*controllers*'. They were trained with the system prior to the sessions (i.e., they could experiment with the control boards) and they had the chance to experience the lighting conditions in the environment.

The three sessions had a slightly different character. Table 2–1 summarizes the setup of these sessions. The first session was performed with a group of six participants. During this session the controllers received instructions to induce specific behaviors. Examples of such assignments are: '*Make all people lean forward*', or '*get a specific person to talk*'. In the second and third session the controllers were given the task to create a specific light atmosphere to explore if this would indirectly influence behavior of participants. For this I selected a set of contrasting environmental descriptors (Kasmar, 1970), as shown in Table 2–2. Controllers were asked to make the environment appear, for instance, 'serene' or 'repelling'. They were allowed to discuss, collaborate, and coordinate their actions.

TABLE 2–1 Comparison of the setups of the lunch sessions

<table>
<tr><th></th><th>SESSION 1</th><th>SESSION 2</th><th>SESSION 3</th></tr>
<tr><td rowspan="2">CONTROLLERS</td><td>4</td><td>3</td><td>3</td></tr>
<tr><td>Behavior-oriented instructions
Respond to participants</td><td colspan="2">Used environmental descriptors (Appendix 2-B)</td></tr>
<tr><td>PARTICIPANTS</td><td>6 male</td><td>4 male, 1 female</td><td>1 male, 1 female</td></tr>
<tr><td rowspan="2">MEASURES</td><td colspan="3">Video observations
Reflections from participants</td></tr>
<tr><td>Informal discussion with controllers</td><td colspan="2">5x environmental descriptors poll by participants
Reflections from controllers</td></tr>
<tr><td>DURATION</td><td>30 m.</td><td>33 m.</td><td>30 m.</td></tr>
</table>

Different data were gathered during the sessions. For all three sessions video footage of the lunch environment, and reflections of the participants were collected. Additionally, I made observations of the light controllers and participants in the lunch environment. In sessions 2 and 3, participants were also asked to describe the environments using the environmental descriptors of Table 2–2 at five moments during the session. This was a brief intervention in which the participants had to tick two boxes that best fitted how they experienced current lighting conditions, which was used to see whether the environmental descriptors as created by the controllers were indeed experienced as intended by the participants. An example of these questionnaires can be found in Appendix 2-B. Furthermore, after each session participants were asked to reflect on the session and provide comments. After sessions 2 and 3, the controllers were asked to fill out a questionnaire regarding their experiences as ‘system intelligence’.

TABLE 2–2 Overview of the environmental descriptors used

Complex	Simple
Inviting	Repelling
Pleasant	Unpleasant
Feminine	Masculine
Lazy	Energetic

Elegant	Unadorned
Orderly	Chaotic
Private	Public
Serene	Disturbed
Happy	Sad

The exploratory nature of this study means that the data is used for further development of the concepts and to explore possible design directions. To review the video footage I used open coding, which means that I observed the videos to evaluate similarities and commonalities in the responses of people to the lighting conditions. This proved to be difficult though as there was no baseline measurement. The video observations were combined with the comments from the participants, to provide a combination of observations with subjective descriptions of experiences. The insights from these explorations need to be regarded as indicative results.

2.3. Results & discussion

One commonality I observed in the first session is that people ‘act’ towards brighter areas: participants reached for or requested food that was in a bright location, but they also oriented their bodies and attention to brighter areas. Figure 2.7 presents an impression of these behaviors. It seemed that people that were in the spotlight, were also in the ‘center of attention’ of the group: People rotate their bodies or gaze towards these people and address them in their conversations. Figure 2.7; 1-4 is an example of such behavior, where first the brightest area is on the – for the viewer – right hand side of the table. As can be seen, multiple people reach for items on this side of the table. The person in the white shirt is speaking. As the light moves towards the other end of the table, so do the actions of the participants. Participants now reach for objects on the other side of the table and the participant in the grey blouse, who is then in the spotlight, continues the conversation. Figure 2.7-A also shows that the person in the yellow shirt reaches for food on the bright side of the table. Comparing figure 2.7-A and figure 2.7-B shows how the orientation of the person in the dark shirt changes (indicated by the arrow) towards the brightest area. Appendix 2-B includes a fragment of the lunch that showcases these behaviors.

In session 2 and 3 (where the environmental descriptors were used) it was even more difficult to relate changes in lighting conditions to changes in behavior. What I found most interesting from these results were the ratings participants gave to the lighting conditions (A complete overview is included in Appendix 2-B). Participants were asked five times during the session to use environmental descriptors to judge the environment and to rate whether the lighting conditions were appropriate or not. In between these polls, the participants experienced the lighting conditions for approximately 5 minutes. In the lunch with 6 participants 14 out of 22 ratings were appropriate, and 8 were rated inappropriate to that context. The largest contributions to the inappropriately rated settings (7 out of 8) were made for 'dark' light settings.

Figure 2.7 Images from one of the lunch sessions. Sequence 1-4 show how the attention of the group shift with the brightest location at the table. Image 3 and A show how people reach for food in the brightest area of the table. Image A and B show for one participant how his attention moves with the brightest location.

These results are in line with literature findings, which show that darkness is not appreciated by people and that people are less 'social' in darkness (e.g., Schaller, Park, & Mueller, 2003; Adams & Zuckerman, 1991). In the lunch with two participants, only 1 rating out of 10 was considered appropriate. Even though it is difficult to draw conclusions based on only a comparison of these two groups, this suggests that a group of two people should be treated differently than a group of five or six people, strengthening the argument that when designing lighting behaviors, the context and social setting needs to be considered.

After each session, a brief plenary discussion was held with the participants. Abbreviated transcripts of these discussions can be found in Appendix 2-B. Participants were asked whether their behavior changed due to different light settings. They indicated that it is difficult to articulate whether the light was changing them or that it was just their normal behavior during lunches. However, suggestions were made as to what effects of the lighting conditions might have been. It was suggested that some settings were 'calming', and that maybe the group became more silent. Furthermore, participants suggested that transitions/changes in the lighting conditions should be slow, and some of them appreciated that the lighting conditions changed. Faster changes of the lighting conditions drew attention and were reported to communicate a message: e.g., the lunch is over. Finally, participants indicated that they lacked control; especially in the extreme (unpleasant) conditions they would like to overrule the automated behavior.

The light controllers informally discussed their experiences after session 1 and they were asked to fill out a questionnaire to reflect on their experiences after sessions 2 and 3. This revealed that the controllers found it extremely difficult – if not impossible – to adequately respond to the behavior of participants. This was partly due to the quality of the video and audio connection, which made it difficult to understand what was going on. It was difficult to follow who was talking and to identify non-verbal behavior. They indicated that you are always 'too late' when you want to respond to something happening in the environment. Also, actuating the lights was difficult for the controllers, as they couldn't experience the lighting conditions. Even though the controllers had been trained prior to the session with the system, and they had experienced the lighting conditions themselves, it was difficult to judge from the camera footage what the actual lighting conditions felt like. Even though they expressed these difficulties, they succesfully controlled the environment, as shows from two results: (1) None of the participants expressed doubts that it was not a computerized system that controlled the lighting conditions and actually suggested that the system responded to sound and/or motion and (2) many of the lighting conditions based on the environmental descriptors, were rated with the same environmental descriptors by participants.

2.4. Conclusions and insights

The explorations presented in this section were set up to provide insights to the questions: (1) How can human behavior be guided by means of dynamic lighting conditions? and (2) What are the implications of scaling up the installation with regard to (1) behavior of the system and (2) user interaction? Via the lunch explorations I acquired deeper insights in these questions, which are discussed in the following paragraphs.

Guiding human behavior

In the interactive sketch, a question that was raised was whether lighting conditions are capable of guiding human behavior. The interactive sketch was a responsive system, where the lighting conditions would follow the behavior of the people. However, in this exploration the system took an active role, and attempted to induce changes in the behavior of the participants.

Especially in the first session, the controllers were able to guide human behavior by using dynamic lighting patterns. People oriented their bodies towards brighter areas, reached for food in brighter areas, and addressed people that were more brightly lit then others. In literature similar results are found (Hopkinson & Longmore, 1959; Taylor & Socov, 1974; Veitch, 2001): These studies found that people turn their attention to brightly lit objects/locations, and that they choose paths that are brighter illuminated. From the explorations presented in this section I found indications that when such bright areas are changed dynamically, the attention of people follows these bright areas. Additional research is required though to confirm this.

Furthermore, by guiding the 'attention' of the group, it also seemed possible to influence the conversation: i.e., people in the spotlight seemed to be addressed in the conversation. It is not clear whether higher illumination makes participants more talkative by 'pushing' themselves into the conversation, or whether the attention of others 'pulls' them into the conversation. The participants themselves reported that some lighting conditions had calming effects, and at points it felt as if the group became more silent because of the lighting atmosphere.

Implications of scale

In these lunch explorations I also scaled up the implementation to fit larger groups. Discussions on the interactive sketch questioned how ALEs could be implemented with different group sizes, and what the implications of this would be regarding system architecture and user experience.

Results of this study provide indications that in the different sessions the social dynamics of a pair (2 people) and of a group (5 or 6 people) seem to be different. Consequently, the lighting conditions that are found to be acceptable are also different. By comparing session 2 (5 participants) with session 3 (2 participants), it was found that the larger group found more lighting conditions appropriate. The two-person group rated most lighting conditions as inappropriate. For the design of lighting technologies, this would mean that its behavior should (at least) adapt to the size of the group. Furthermore, in all the groups it was found that darkness was not appreciated. This contributes to findings in literature that conclude that people in very dark lighting conditions are more ego-centric, have negative dispositions against others, and require more personal space (Adams & Zuckerman, 1991; Schaller, Park, & Mueller, 2003; Zhong, Bohns, & Gino, 2010). When designing the lighting behavior of lighting systems, complete darkness should be avoided in automated behaviors when people are present.

A final aspect regarded the interaction between the lighting conditions and the participants. In this case the controllers acted as the intelligence of the system and they constituted the interaction between the participants and the lighting behavior. They reported that it was impossible to respond fast enough to the dynamics within the group. Furthermore, they also indicated that it was hard to assess the social situation. One way to deal with this is by allowing explicit control from people using the system. That would consequently mean that the system has to infer less information autonomously and can also change its behavior based on direct information from people. Participants themselves also reported that they would like some form of control, at least to override undesirable lighting conditions. Furthermore, for the automated behaviors it seems that people prefer slow transitions, as they were less noticeable.

2.5. Further explorations

Based on the insights of the lunch studies two directions for further exploration were identified: (1) The interaction between people and lighting behaviors and (2) the potential of light to guide behavior of people.

The first topic of exploration regards the interaction between people and the system. This study revealed that controllers, representing an intelligent system, found it difficult to read the social situation appropriately. Additionally, participants indicated that they should have some form of explicit control, as this allows them to tell the system what lighting conditions they find (un)pleasant. By providing participants with opportunities to control the lighting conditions, the system requires less 'social intelligence' to act autonomously. This introduces new design challenges, as it raises the question how to distribute control over (common) lighting conditions to a group of people? This is further investigated in section 4.

Furthermore, this exploration provided additional indications that lighting conditions influence the behavior of people. It appears that via dynamic lighting conditions it is possible to elicit these changes in behavior. The 'spotlight' behavior seemed most powerful in influencing the behavior of participants. This raised a new question: If it is possible to direct the attention of people using light, can we also use light to guide the conversation?

3. Out of the darkness, into the light

Up to this point, I have been investigating what meaningful lighting behaviors for ALEs are, and how we should design these behaviors. In the previous iteration, indications were found that spotlighting behavior can be used to guide the behavior of people. Interestingly, we also use 'being in the spotlight' to indicate that people are in the center of attention. Yet, what are the implications of literally being in the spotlight? How much does a spotlight affect people in a real-life context?

In the earlier research-through-design iterations presented in this chapter there have been various indications that a spotlight influences social behavior. The study with the lunch environments suggested that through changing the 'spotlight' on the table, the conversation at the table could be influenced. Related work revealed that highlighting people is likely to attract attention of others to that person. To investigate the implications of this 'spotlight' behavior, another study was setup to further investigate this as a possible lighting behavior. In this study a group of participants perform a discussion exercise and they are exposed to a range of dynamic lighting conditions. From the earlier explorations the assumption is made that if people are more brightly illuminated, they play a more influential role in the conversation. Via pre-defined lighting scenarios it was further explored whether being in the spotlight influenced the speaking behavior of people. If this assumption is confirmed, spotlighting behavior might become an essential characteristic of future lighting environments. In this section, the contextual setup and the lighting equipment used for this study are presented first. After that an overview of the method that was used for this study is presented. This section concludes with the results and a disucssion. This study was setup and executed by Axelle Mirigay, as part of her internship at TU/e. The design and implementation of the lighting environment, as well as the analysis of the data is my own work.

3.1. Context & lighting environment

This lighting installation was created in the same environment as the third iteration, using custom designed *Hyvve* tiles (see Figure 2.8). The design of these tiles is presented in the Nursery phase. In brief: The Hyvve tiles are hexagonally shaped tiles of which the light intensity and color temperature can be controlled individually for each tile via a wireless connection. One Hyvve tile is located above each seat and provides downward illumination in order to highlight people. The original fluorescent tubes were covered on one side, so they provided indirect general illumination via the walls.

3.2. Method

Each session of six participants started with a brief introduction, where the participants of that session were welcomed by the experimenter. After this introduction participants performed two exercises during a (free) lunch that was offered to them: a *secret-guessing* game and a *crisis*

Figure 2.8 Impression of the context and lighting setup. (top) Custom designed lighting environment consisting of Hyvve tiles. (bottom) Lunch table with seats for six people. Lights are placed directly above the seats.

situation. Both exercises were used to stimulate conversation and discussion. The details of the discussion exercises are explained in the following paragraph. While the participants performed these exercises, the lighting conditions changed slowly. These changes are described in lighting scenarios, of which there were three during the session: *one-by-one* scenario, *two-by-two* scenario, and *equal illumination* scenario. Each of the lighting scenarios is discussed in detail below. An overview of the study and the order of the scenarios is presented in Table 2–3.

TABLE 2–3 Global overview of the order of the different lighting scenarios

Scenario	Description	Duration
Introduction	Researcher explains activities. Participants fill out personality questionnaire.	~ 10 m.
One-by-one	Individuals highlighted, adjacent seats medium illumination. Participants perform the 'guessing-secrets' exercise.	12 m. 30 s.
Equal Illumination	All equally illuminated, lights from high illumination to low illumination. Participants perform the 'crisis-situation' exercise.	9 m.
Two-by-Two	Two people highlighted, adjacent seats medium illumination. Participants perform the 'crisis-situation' exercise.	14 m. 30 s.
Closure	Researcher closes session. Participants fill out personality questionnaire about others.	~ 10 m.

Discussion Exercises

In the *guessing-secrets* game each participant wrote down a small 'secret' about himself: Something that the others cannot know about him. These secrets were randomly distributed over the participants, which means that each participant received one secret that was not his own. The goal was to find out which secret belonged to which participant, without explicitly asking.

The *crisis situation* posed that the participants were a team that have to deal with an emergency situation. A situation that was recent at that time was selected: a train crash near Amsterdam ("Treinongeval bij Amsterdam Westerpark," 2013). Participants had to distribute roles and assign tasks to each member of the group. Both exercises were selected, as they require conversation and participation of each participant.

Lighting Scenarios

There were three dynamic lighting scenarios in this study. Figure 2.9 presents a schematic overview of the lighting setup. Contrary to the previous explorations, the scenarios in this study did not respond to the behavior of people. Dynamic in this study indicates that the lighting conditions *changed* during the discussion, but the sequence was predetermined. Two of these scenarios were based on 'spotlighting' behavior: one-by-one scenario and two-by-two scenario. In the other scenario, all light sources provide equal illumination, but this illumination slowly decreased. In the following paragraphs each of the scenarios is discussed individually.

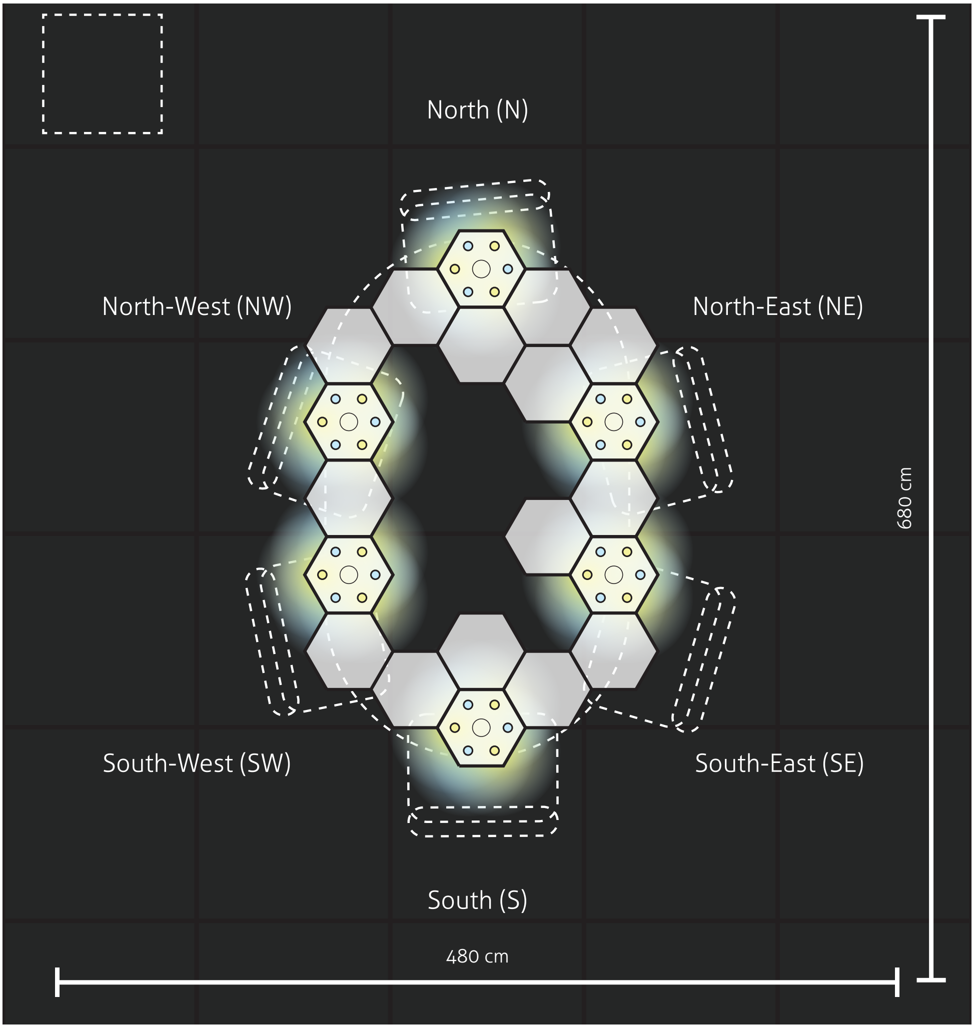


Figure 2.9 Lighting environment for this study containing six active Hyvve tiles.

In the *one-by-one* scenario one participant was illuminated more brightly than the others. This means that participant was 'in the spotlight' so to speak. The two seats next to this person were illuminated with a medium level illumination to reduce high contrasts and create a more gradual transition to lower illumination levels. Each person was illuminated equally in a predefined, non-linear order. The order of illumination is presented in Table 2–4. A visual sequence is included in Appendix 2-C. The scenario started with medium illumination for all participants. After this each participant received the high illumination level once, the medium illumination level twice and the low illumination level three times. Each condition was maintained for 120 seconds and the transition between the conditions lasted 10 seconds, which is a rather slow transition, only noticeable when you pay close attention to the light sources.

TABLE 2–4 Illumination sequence for the one-by-one scenario

	30 s.	120 s.	120 s.	120 s.	120 s.	120 s.	120 s.
N	M	L	H	L	M	M	L
NE	M	L	M	M	L	H	L
SE	M	L	L	H	L	M	M
S	M	M	L	M	L	L	H
SW	M	H	L	L	M	L	M
NW	M	M	M	L	H	L	L
L	Low illumination (10%)						
M	Medium Illumination (40%)						
H	High Illumination (100%)						

The *equal illumination* scenario was a scenario in which all participants received an equal level of illumination. The sequence dimmed the lighting conditions from high, to medium, to the low level of illumination, as is presented in Table 2–5. Each step was maintained for 180 seconds, the total scenario lasted for 9 minutes. A visual overview of this scenario is provided in Appendix 2-C. The transition between each condition in the sequence took 10 seconds.

TABLE 2–5 Illumination sequence for the equal illumination scenario

	180 s.	180 s.	180 s.
N	H	M	L
NE	H	M	L
SE	H	M	L
S	H	M	L
SW	H	M	L
NW	H	M	L
L	Low Illumination (10%)		
M	Medium Illumination (40%)		
H	High Illumination (100%)		

The final scenario was the *two-by-two* scenario. In this scenario the illumination between participants was divided unequally. This is to test whether unequal distribution of illumination affected the discussion. The exact illumination sequence is described in Table 2–6. Please note that this sequence consists of six main conditions, and five transitory conditions. The transitory conditions were included to make the changes less noticeable and more gradual. The amount of time each participant was exposed to each illumination level is described in Table 2–7. A visual overview of the two-by-two scenario is provided in Appendix 2-C. The transition between each condition in this sequence was 10 seconds. The total duration of this scenario was 870 seconds, or 14.5 minutes.

TABLE 2–6 **Illumination sequence for the two-by-two scenario**

	120 s.	30 s.	120 s.	30 s.	120 s.	30 s.	120 s.	30 s.	120 s.	30 s.	120 s.
N	L	M	H	H	H	M	L	L	L	M	H
NE	L	L	L	L	L	L	L	L	L	L	L
SE	L	L	L	M	H	M	L	M	H	M	L
S	H	H	H	M	M	L	L	M	H	M	L
SW	L	L	L	M	M	M	H	M	L	L	L
NW	H	M	L	L	M	M	H	M	L	M	H
L	Low illumination (10%)										
M	Medium Illumination (40%)										
H	High Illumination (100%)										

TABLE 2–7 **Cumulative exposure time per seat to each illumination level for the two-by-two scenario**

	L	M	H
N	390 s.	90 s.	390 s.
NE	870 s.	0 s.	0 s.
SE	510 s.	120 s.	240 s.
S	270 s.	210 s.	390 s.
SW	540 s.	210 s.	120 s.
NW	270 s.	240 s.	360 s.
L	Low Illumination (10%)		
M	Medium Illumination (40%)		
H	High Illumination (100%)		

Figure 2.10 Impression of the lunch study. The uneven light distribution is slightly visible. The far end of the table is most brightly lit.

3.3. Results

Seven sessions were held in total, with six participants per session (for an impression see Figure 2.10). Two of these sessions were 'control sessions' (CS) (n=12, age: 21-55 μ=29.3, SD=9.5) in which there were no lighting scenarios, but the lights were set to medium level continuously throughout the session. Five sessions with dynamic lighting (DL) were held (n=30, age: 19-50 μ=27.3, SD=6.8). In each session there was an equal division of males and females (3 male, 3 female per session). For all sessions video footage was captured, which was coded by one observer with the items summarized below. As the process is labor-intensive, and no interpretation is required for the coding, one coder was found sufficient.

- The time (in seconds) a participant spent under the three lighting conditions: low, medium and high, illumination.
- The duration (in seconds) a participant speaks: the speaking duration.

The results of the coding can be found in Appendix 2-C. The high light condition from the equal illumination scenario was excluded from the analysis. Prior to the equal illumination scenario the experimenter explained the second exercise (crisis situation) and handed out the required materials to the participants. It was observed that for some sessions during the first sequence of the equal illumination scenario (high illumination) participants were mostly reading the materials. Therefore this data is not representative of 'discussion behavior' and was omitted from analysis. A pilot experiment did not reveal this flaw.

As participants did not spent equal amounts of time in the different lighting conditions a 'speaking ratio' is calculated for all conditions. The speaking ratio is calculated as the total speech duration in a certain light conditions, divided by the total time spent in that light condition. I first examined the difference between the lunches in which static lighting was used and the lunches with dynamic lighting. This means that I calculated the average speaking ratio for the complete CS and for DL. These speaking ratios were compared using an independent samples t-test using SPSS; a software package for statistical analyses. A boxplot of the speaking ratios per session is provided in Figure 2.11. The T-test revealed a significant difference in speaking ratio, indicating a higher speaking ratio in the dynamic lighting sessions (M=18.5, SD=6.1) than in the static lighting sessions (M=13.3, SD=7.3); $t(40)=2.4$, $p=.02$ (two-tailed). Eta squared was calculated at .126. This expresses that approximately 12% of the variance in the speaking ratio is explained by the different lighting conditions. Overall, these results suggest that the sessions in which dynamic lighting was used were different than the control sessions.

The differences between the three dynamic scenarios were further investigated. First, the data were inspected visually using a box-plot (presented in Figure 2.12). This shows that the differences between the different conditions are small. The results reveal that with a higher light intensity the duration of speech decreases as is summarized in Table 2–8. This is observed for

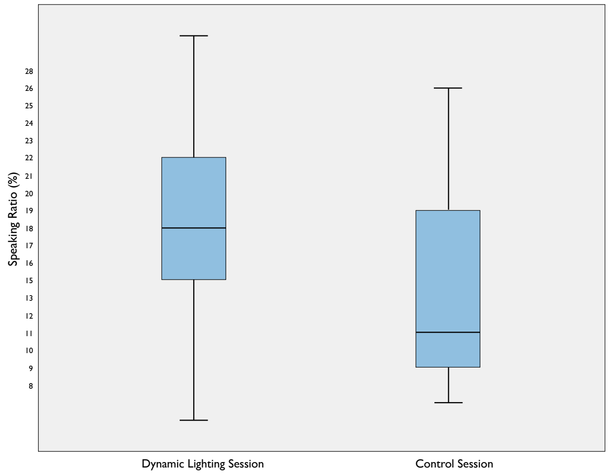


Figure 2.11 Boxplot of the speaking ratios for the dynamic lighting (left) versus the control (right).

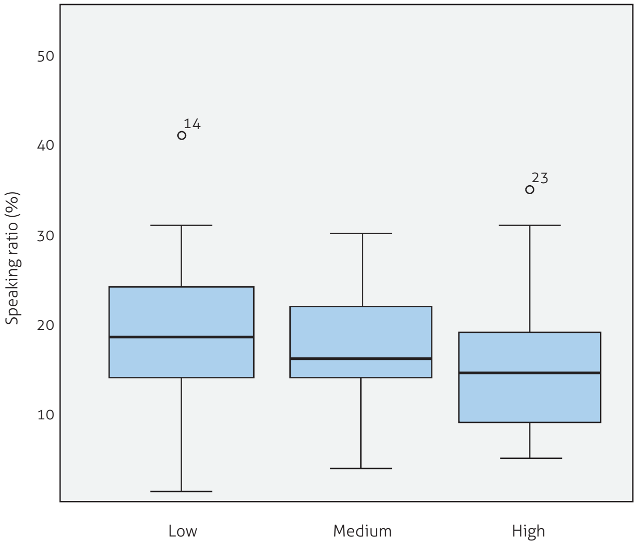


Figure 2.12 Boxplot of the speaking ratios for the dynamic lighting sessions from low (left), medium (middle), high (right).

all the lighting scenarios. A repeated measures (within-subjects) ANOVA over the cumulative ratios reveals a significant main effect of light intensity on duration of speech (Wilks' Lambda = .80, F(2,28)=4.598, p=.046, multivariate partial eta squared = .197). Pairwise comparisons with Bonferroni correction demonstrated a significant difference of roughly 4% (p=.038) between the speaking ratio in the high and low light condition. This means that people on average spoke approximately 4% less under the high light condition compared to the low light condition. The average speaking duration for this sample of participants was 388 seconds, which means that the difference between the speaking duration is between 15-16 seconds. This result is only found if we look at the cumulative data: For the individual scenarios the respective main effects are not significant. Further analysis of the data might yield more results, yet I acquired enough insights for further design iterations: The effect of the intervention is small and the effect size is small, which informs me that this should not be the core value of my design.

TABLE 2–8 Summary of the cumulative speech ratio per lighting condition

Lighting level	*N*	Mean	Standard Deviation
Low	30	19.63	7.85
Medium	30	17.33	6.28
High	30	15.60	7.68

After each session participants were briefly asked to respond to the session. Abbreviated transcripts of these discussions can be found in Appendix 2-C. What is interesting in these results is that some participants in the dynamic lighting sessions indicated that they had not noticed changes in the lighting conditions, whereas others did.

3.4. Discussion & conclusions

A comparison of the control session with the dynamic lighting session showed a small significant difference in the speaking ratio; people spoke more in the sessions with dynamic lighting. These results should be interpreted with great care, because the overlap in the populations is large, but they suggest that either the dynamic lighting scenarios, or the lighting conditions used in these scenarios have an effect on the speech ratio of people: i.e., people speak more when lighting conditions dynamically adapt.

When examined the data from the dynamic lighting scenarios was further examined – to investigate whether the spotlighting behavior influenced the behavior of participants – statistical analysis revealed a small effect of spotlighting behavior on the speaking duration of people. This suggests that under high light levels people tend to speak shorter than under low light levels. These results suggest that a 'spotlight-effect' does not stimulate discussion, instead it seems to be the other way around: Being in a darker area of an environment makes one more talkative. However, the effect is small (only 4%) and the effect size is rather small, indicating that a small percentage of the variance can be explained by the changes in the light levels.

Furthermore it can be questioned whether 'speaking duration' is sufficiently rich to capture 'contribution' to the discussion. It may be that some people speak only little, yet provide valuable input to the discussion, and there may be people that speak often, but do not help the discussion forward. Future research might assess the contribution of individual participants, for example through subjective ratings of others, or through measuring the quality of decisions that were made. Also, non-verbal behaviors should be examined in future investigations.

All the sessions were conducted in English, which was not the native tongue for most participants. This might have influenced the outcomes, even though most participants speak English on a regular basis. Additionally, it was attempted to mix participants as much as possible, but there were groups in which participants knew each other. This includes groups where participants had different hierarchical relationships, as staff and students were mixed. Given the realistic setting for this experiment, it is difficult to control for confounding variables. The small differences that were found, showcase the difficulty when designing in realistic contexts with all of their nuances and complexities.

Interestingly, there were reports of participants who did not notice changes in the lighting behavior. This may indicate that the dynamic lighting scenarios were well-balanced and were not disruptive to the social context, but this might also explain why only a small percentage of the variance can be attributed to the lighting conditions: Some people didn't notice changes in the lighting conditions.

Where earlier iterations showed that 'spotlighting' behavior might have practical feasibility, this study does not support this. This leads me to conclude that this should not be the core focus. Spotlight behavior might still be implemented, but should be part of a larger palette of lighting behaviors, where users control the spotlighting behavior. The most important conclusion for me is that the value of a dynamic lighting conditions should not solely be in the behavioral changes it induces in people.

4. Multi-user interactive lighting

From the previous iterations I learned that the behavior of a lighting environment should not only be targeted to influence/change the behavior of people. Particularly, the previous iteration revealed that changes in behavior were only small, and this spotlighting behavior might not be meaningful to people. However, what the previous lighting environment lacked, was the means for people to exercise control over their lighting conditions. In this iteration, I explore how to provide people with control over their lighting conditions. Additionally, lighting environments are oftentimes used by multiple people. When someone decides to adjust the lighting conditions, this inherently means that the lighting conditions for everyone are adjusted. Current lighting systems rely solely on the social context for issues to be resolved. Wouldn't it be possible to provide all users with control and allow them to decide upon lighting conditions together?

Lighting environments typically offer single-person interaction possibilities: E.g., switches, dimmers, and/or remotes provide a single user with control over the entire environment. Lighting conditions – in contrast – are typically shared. Why is the control over the global lighting conditions not shared between individual users? Literature shows that people prefer to have control over their lighting conditions, if possible down to single luminaires (Moore, Carter, & Slater, 2002b). Motivations to provide users with individual control are diverse. It is reported that more energy can be saved if users are offered control (Escuyer & Fontoynont, 2001; Jennings, Rubinstein, DiBartolomeo, & Blanc, 2000; Moore, Carter, & Slater, 2002a; Moore et al., 2002b), but (individual) control over lighting conditions also seems to elicit positive psychological changes, such as improved mood and satisfaction with lighting, environment, and performance (Escuyer & Fontoynont, 2001; Newsham, Veitch, Arsenault & Duval, 2004).

These results strongly advocate individual control opportunities for each user. From an individual user perspective this is a great idea, but from a social perspective it is difficult to predict what the implications might be. As Moore et al. (2002a) identify, not all users will actually control the lighting conditions when they are given the chance to do so. Some may fear a conflict with other users more outspoken and stronger personalities might make the decisions for an entire group. To resolve such issues they propose to make the 'control groups' as small as possible. A control group refers to the number of luminaires that are controlled together. The smallest control group would for example be to have a switch for each luminaire in an environment. Essentially, they argue that each light source should be adjustable individually. Moore and colleagues found that the size of the control group significantly correlated with the levels of conflict.

For individual workspaces small control groups can be a solution. This means that each user controls the lighting at his desk. However, there are situations where even small control groups do not resolve these issues: In open-plan offices with adjacent desks the distance between people might be too small to offer control to both users. Also in collaborative group workspaces or meeting environments, it may be difficult to provide each user with individual control over his own light source, without affecting the lighting conditions of others.

In this exploration another approach is taken. Rather than providing each user with individual control over a small light control group, I investigate how a lighting system can support mechanisms for shared control. The lighting system is aimed to acquire a role in the social context in order to balance control between different personalities. It provides each user that wishes to take part in the control of the lighting conditions with the opportunity to do so. Consequently, each user can be offered individual control and potentially benefit from the advantages this brings.

This section has the following structure. First I outline the context, the lighting setup and the outline of this exploration. After this I present three different light control interfaces. At the end of this section I present the results of a user evaluation with the three light control interfaces and the conclusions of this exploration. The design of the lighting interfaces, and the setup and execution of the evaluation was performed by three master students of the department of Industrial Design of Eindhoven University of Technology. The project was proposed and setup by me, and I performed the analysis that is presented here.

4.1. Context & lighting environment

This exploration is situated in an office meeting environment. This environment is selected as it represents a situation where it is difficult to provide each user with individual light control. In an existing meeting room the lighting setup was replaced with a custom lighting installation, containing individually controllable halogen light sources. An elliptical meeting table was placed in the center of the room with four seats on four sides of the table. Pilot investigations with discussion scenarios suggested that four people was a suitable number for this study. Four halogen light sources were aimed at the walls, to act as wall-washers and to provide general illumination. Four spotlights were aimed at the seats, making it possible to illuminate all the seats individually. Figure 2.13 presents an overview of the lighting setup.

Three master students designed lighting controllers for this lighting environment. Each student designed the controller from a different perspective. These different perspectives are used to investigate how control can be shared over different users, and investigate the implications of different control structures on social behavior. The three selected perspectives are (1) an *individual* perspective, (2) a *shared* perspective, and (3) a *hierarchical* perspective. These pose different, but feasible scenarios for future light controllers. In the following subsection the three control interfaces are presented.

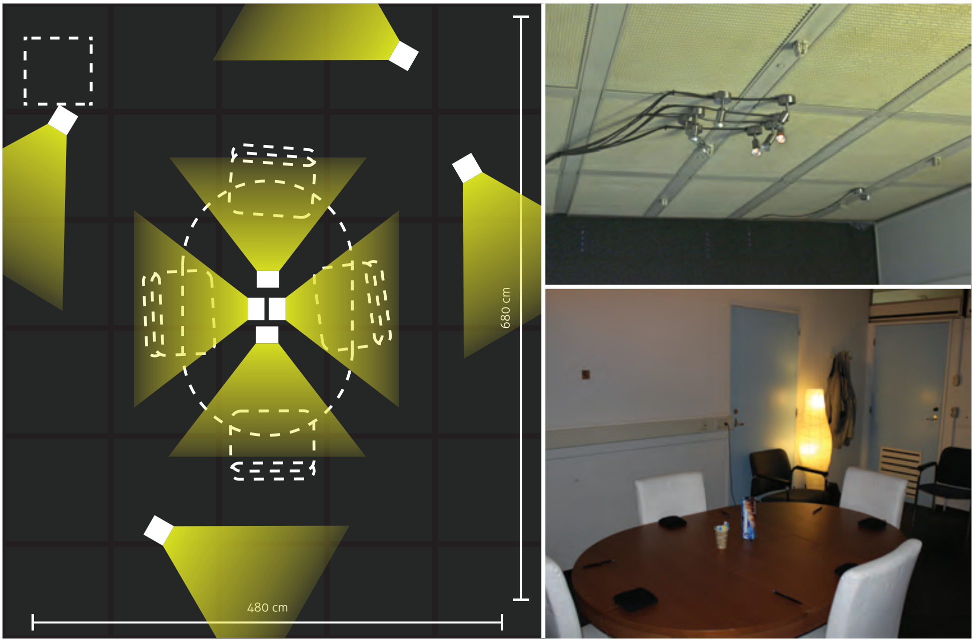


Figure 2.13 (left) Schematic overview of the lighting setup in the meeting office environment. (top right) Impression of the lighting setup. (bottom right) Impression of the meeting table..

4.2. Individual, shared, and hierarchical control

The controllers presented in this scenario offer users different structures of control. The implementation of the three light controllers and the lighting installation was fully operational. Via this exploration I want to find out whether these different structures cause behavioral changes.

Individual controller

The individual controller (shown in Figure 2.14) provided each user with control over the spotlight directed at his seat. This essentially is the individual control with small control groups that is advocated by Moore et al. (2002b). The controller itself was a touch-sensitive pad that was placed in front of the user. By touching this pad light intensity was added to the spotlight of the user. The force with which one touches the pad was related to the amount of intensity that

Figure 2.14 (left) The four individual controllers. (center) Hitting the controller to make a firm statement. (right) Gently touching the pad to slowly increase the light intensity..

Figure 2.15 (left) The four shared controllers. (center) Pressing the knob to cast a vote. (right) Rotating the knob to select who to vote for (including oneself)..

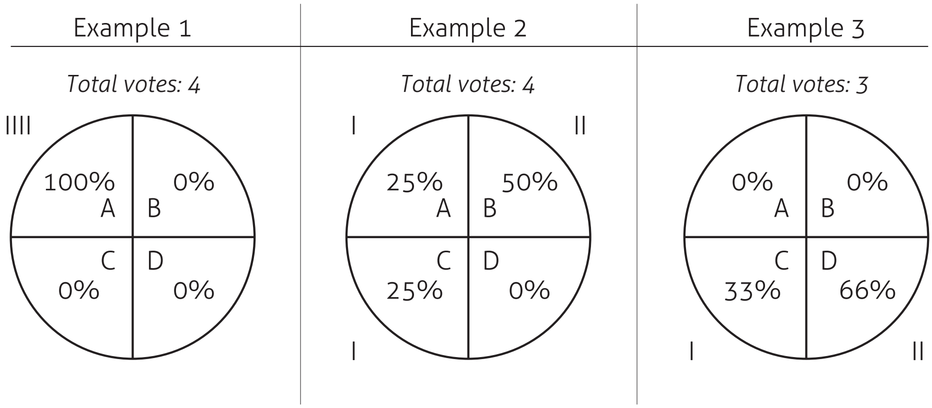


Figure 2.16 Three examples of vote distribution with the shared controller.

Figure 2.17 (left) The hierarchical controller and four receivers. (center) Pointing towards a receiver to adjust the lighting conditions. (right) Scrolling forward or backward to respectively increase or decrease the lighting conditions.

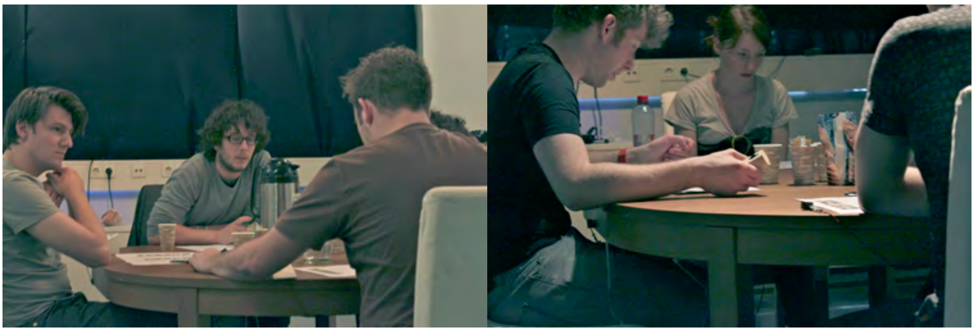


Figure 2.18 Impression of the user confrontation sessions. (left) People using the shared controller. (right) People using the hierarchical controller..

was added. In this case, this meant that if you placed your hand on the pad, the light intensity slowly increased, but if you hit the pad hard, the light intensity was directly set to its maximum. The design was such that it could be used in expressive ways during the discussion.

Shared controller

The shared controller (shown in Figure 2.15) provided each user with an equal share in the general lighting conditions. The difference with the individual controller is that in this system each user contributed to shared lighting conditions. The controller contained four marks, representing the four seats at the table. The user could set the controller to one of the four locations and press the button to 'cast his vote'. Voting was not required. The lighting conditions follow the distribution of the votes, which meant that the light at each seat is the number of votes for that location divided by the total number of votes. Thus, the total light intensity is 100%, and in case all four participant voted, each vote counted for 25% (=100/4) of the light intensity. If all four users voted for one location, the spotlight at that location was set to 100%. However, when one vote was given to person A, two to person B and one to person C, the light distribution was respectively 25% for person A, 50% for person B, and 25% for person C. If only three people voted, the votes represent a larger part of the light intensity. If person C and D received respectively 1 and 2 votes out of 3, the lighting distribution was respectively 33% and 66% for person C and D (see Figure 2.16). Users could also vote for their own location, and they could override their previous vote at any time. To trigger participants to reconsider their votes, the designer added a timing interval to the validity of their votes. Whenever a user did not cast a vote for a long period of time, his vote would be lost, and the light would be distributed according to the remaining votes.

Hierarchical controller

The hierarchical controller (depicted in Figure 2.17) provided the participants with a hierarchical control structure: The control was unequally distributed. One participant received all control over the entire lighting system and the others remain (literally) empty-handed. The controller was a pointing device with a scroll wheel. By pointing the device towards the receiver that is in front of someone, and thus pointing towards that person, light could be added or removed. The receiver was directly coupled to the spotlight aimed at that seat. By scrolling forward (towards that person) light was added, by scrolling backward (away from that person), light was removed.

4.3. User evaluations

Via user evaluations (see Figure 2.18) the implications of the three controllers were evaluated. Similar to the lunch studies in the previous section, a constructive evaluation method was used. This means that no formal hypotheses were formulated. Rather, the sessions were given an open character, in which users were confronted with one of the three designs, and were asked to reflect on their experiences afterwards in order to provide insights for the following question:

- What are the implications of different forms of control over an interactive lighting environment on the social setting?

In total three sessions, each with four participants (*N*=12, age: 20-26) were performed. All participants were students of the department of Industrial Design of TU/e. Each evaluation consisted of two parts, with two similar assignments for the participants. One part of the evaluation was performed under static lighting conditions, the other part was performed while using one of the three light controllers. Participants were asked to perform the exercise of a survival case ("Survival! Exploration: Then and Now", n.d.). In this survival case the participants had to imagine they were stranded either on a deserted island (case: Jamestown), or on the moon (case: Moon), and they could only carry a small amount of equipment. They had to rank a list of items in order of importance, first individually and then collectively. This exercise was used to stimulate discussion between participants. Table 2–9 summarizes the three sessions that were performed and presents the order in which the cases were performed.

TABLE 2–9 Overview of the user evaluations

	SESSION 1	SESSION 2	SESSION 3
CONTROLLER	Individual	Shared	Hierarchical
PARTICIPANTS	2M, 2F	4M	2M, 2F
SURVIVAL CASE WITH CONTROLLER (ORDER)	Jamestown (1)	Moon (2)	Moon (1)
SURVIVAL CASE WITH STATIC LIGHTING (ORDER)	Moon (2)	Jamestown (1)	Jamestown (2)

Each group thus performed two different survival cases. In one case they used one of the three controllers, the other discussion was held under static lighting conditions that users could not adjust. Responses to the three controllers were compared between the subjects. After each session the participants were asked to reflect on their experiences.

4.4. Results

A complete overview of the user evaluation results (i.e., transcripts) can be found in Appendix 2-D. It must be noted that all participants were Industrial Design students that are trained to think at conceptual and abstract levels about these novel systems. This may have biased their behavior and attitude.

The individual controller was designed to stimulate *individuality*. People had full control over their individual light sources. Interestingly, participants indicated that, in this context, they would also like to have control over the lights directed at others: "*When I'm talking I would like to be able to put light on the others so I can see them.*" There were also indications that people wanted to use light in a more expressive way, for example to "*show that I agree with someone, or* *that I want to engage in a discussion with someone.*" Being limited to only control your individual light source implied that you could only draw attention to yourself. Participants indicated that this felt unnatural and unpleasant to put yourself in the spotlight and say: "*Guys, I want attention!*"

With the shared controller the light is considered a resource that had to be shared. This limitation is artificial – it is not physically impossible to provide more light – but it impacted the way people perceived this resource. One participant remarked that the light "*is a social thing (…) I would like to have more control to give light to others (…) Sometimes I wanted to tell others they had to vote for a specific location if you see that someone needs light.*" This participant seemed to be considerate of what others might need, and how he could support them. Other participants also reported forms of involvement and reciprocal behavior, for example one participant stated: "*You want to put people that are talking or writing into the light.*" Another said that he put people in the light, because he "*wanted others to listen to the person speaking.*" All these comments give the impression that people using this controller seemed to be more consciously considering the needs and possible wishes of others. Of course, it is not said that participants in the other sessions did not do this, but such comments were not provided in those discussions.

The hierarchical controller was designed to distribute control unequally and as such advocate a role of power for one participant. The person in control (there was only one) has no restrictions to adjust the light settings as he pleases: The others have to submit to him. Initially, the person in control reported that he tried to provide all 'speakers' with light. Meaning that when a person was saying something, he provided that person with light. Soon he noticed that it was not possible to keep up with the pace of the discussion and he switched to a different strategy. People "*that represented my opinion*" were put into the spotlight. This strategy seemed to have the intended effect on the discussion, as one participant reported: "*It is frustrating if you are in the dark that people can't look you in the eyes and you notice they listen less to you.*" One person expressed his frustration, and reported that it felt as though he was never put in the light. However, when the video footage was reviewed this person was in the spotlight most of all participants. It might be that whenever he wanted to express his opinion that he was not put in the spotlight and therefore felt 'left out'. At the end of the session the person in control admitted that he felt uncomfortable with the power that he had as "*all people entered as equals.*"

4.5. Conclusions

In this iteration I explored whether different forms of control could be implemented in an interactive lighting system and what the implications of these different forms of control are.

First, the user confrontation sessions revealed that the three different controllers elicited three different user experiences. The participants clearly describe ways of using the lighting system that are in line with the control structures. Furthermore, the evaluation showed that –

irrespective of the form of control that was offered – if people are offered richer forms of light control they incorporate it in their behavior.

It seems that the structure of control that was offered to people also influenced their perspective on the group. For example, both in the individual and in the shared scenario participants gave comments about providing light to others. However, in the individual scenario these comments had a more self-centered tone: They describe what that person would like to achieve by putting others in the spotlight. For example, it puts the other in the spotlight, so *I* can see them. In the shared controller scenario participants seemed more engaged with the situation of the others and the comments have a more social tone: For instance, provide light to people to facilitate *them*, or to notify others to listen to that person.

These combined results provide indications that the way in which control over a lighting system is offered to people influences their behavior. The results of this study strengthen my argument that it is important to design controls that fit thee social context. The current investigation was a first confrontation of users with the system. Long-term implications need to be investigated in longitudinal studies.

Furthermore, this exploration again provided indications that being in the spotlight has social connotations. People don't like to be in the dark, because they felt excluded if they were placed in the dark. This supports the findings of the lunch studies that highlighting individuals in a group can impact the social dynamics. In comparison to the previous section, where spotlighting was found to have limited effect, in this session users had control over the lighting behavior. This means that they could use the lighting behavior, whenever it was applicable to the situation. This strengthens my argument that an ALE should offer users with diverse lighting behaviors, but that users make these behaviors meaningful in-context.

5. The adaptive office environment

Lighting environments influence the way people feel and behave in them. To this end, lighting behaviors have to be designed that are meaningful for specific settings. The first three iterations revealed that this should not be a single lighting behavior, but that there should be diverse ways in which the lighting environment can behave. Also, there are diverse motivations to provide people with ways to interact with the lighting behavior. The previous iteration showed that the way control is offered to people potentially influences the way people behave in these environments. Additionally, individual control offered to users may lead to situations of conflict. In these cases, a lighting system can structure the way control is balanced between users or between users and the system. The question that is central in this iteration is: How can meaningful lighting behaviors and user interaction be implemented into a single integrated design solution?

In this section I present the design of an adaptive office environment. This research-through-design iteration is slightly different when compared to the the previous iterations. The previous iterations had an explorative nature and were used to investigate the design space of adaptive lighting environments. The aim of this installation is to create an integrated lighting environment with all the aspects that were explored separately in the previous installations (e.g., interaction with, and social implications of the lighting system) to create a coherent adaptive lighting environment. Furthermore, this project was executed in collaboration with two other Ph.D.-students which provides the project with an interdisciplinary character. In this project I collaborated with Sunder Aditya Rao and Paola Jaramillo Garcia. The work presented here was performed by me, unless stated otherwise.

In this section I first present the concept for the adaptive office. This is followed by a description of the lighting installation that was implemented, a description of the light-body as interaction concept, and the three scenarios of user interaction and lighting behavior. This installation was evaluated by experts. The results of this evaluation are presented at the end of this iteration, along with a discussion and conclusions.

5.1. The adaptive office

For this project we decided to create an adaptive office environment inside the university building. The goal of this environment was that it should adapt to typical office behaviors and should change its lighting conditions to activities performed by user(s). For the current installation three scenarios of use were selected: (1) *individual scenario*, (2) *group distributed scenario,* and (3) *group focused scenario*. A brief description of each scenario and typical activities is provided in Table 2–10. These scenarios are inspired by office behaviors that were observed in the daily routines of direct colleagues. Furthermore, the activities in each scenario might require different forms of lighting, which makes it relevant to adjust the lighting conditions to these activities.

Once these activities were selected and defined, lighting behaviors that support these specific activities were conceptualized. The 'focus of attention' of the activity was taken as the leading parameter to adapt the lighting conditions. In Table 2–11 the lighting behaviors are described. Each lighting scenario is described in more detail in the next section.

TABLE 2–10 Description of the activities in the office context

Scenario	Description
Individual Scenario	A single person is working on an individual task at a table. The focus of the participant is directed at the work plane. Examples are: reading, writing, drafting. (Note that two people in the office space can both be involved in separate individual activities. Multiple people do not necessarily imply a group scenario)
Group Distributed Scenario	Multiple people are in the office environment and the participants interact with each other. Their attention is not directed towards a single point of focus, such as a presentation or demonstration. For example, a group discussion.
Group Focused Scenario	Multiple people are in the office environment; their attention is focused on one area. For example, presentation for a group of people, a demonstration, or a question-answer session.

TABLE 2–11 Description of the lighting behavior for the adaptive office environment

Lighting Scenario	Description
Default	No activity scenario is activated yet. Environment light is provided. Task and spotlights are turned off.
Individual Scenario	Task light is provided on the work plane of the user. Environment light is dimmed. The user can 'zoom' the light over the work area.
Group Distributed Scenario	Medium level illumination is provided on the work plane. Environment light is dimmed. When a person speaks this person is highlighted.
Group Focused Scenario	Low level illumination is provided on the work plane and in the environment. Light is provided on the main speaker. Participants asking questions are highlighted.

Users interact explicitly or implicitly with the lighting conditions. Interaction is considered *explicit* when the user has to perform a specific behavior to manipulate the environment. Examples of explicit interaction with a lighting system might be: pushing light switches, rotating dimmers, or triggering light scenes. Interaction is considered *implicit*, when the user behaves regularly, but this behavior is sensed and triggers changes in lighting conditions. For example, when light is turned on because a user enters the room. In the following sections the lighting setup and the interaction possibilities for each of the lighting scenarios are described.

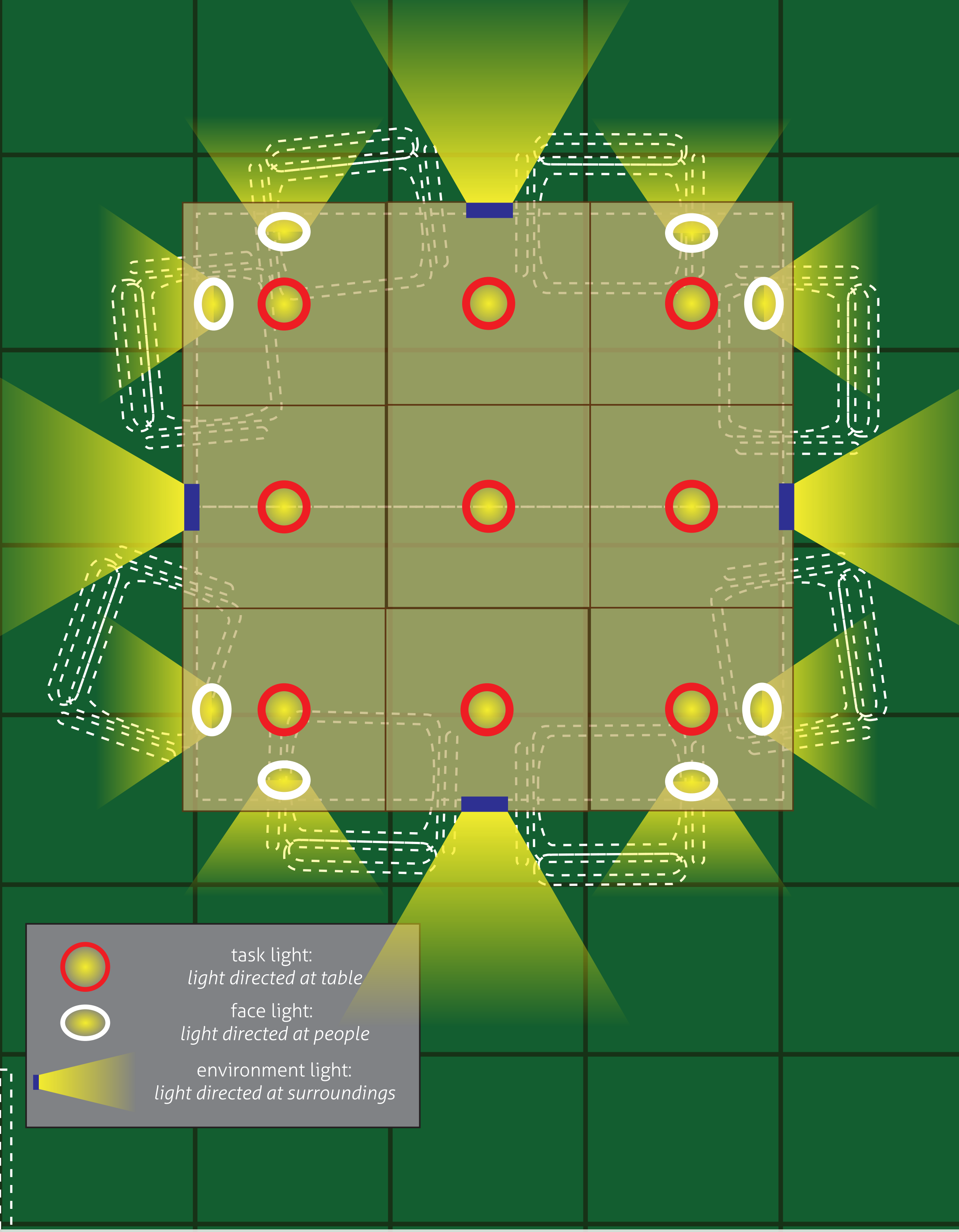


Figure 2.19 Schematic overview of the lighting environment for the adaptive office. Three types of light are displayed: task light, face light, and environment light.

Figure 2.20 Implementation of the lighting environment for the adaptive office

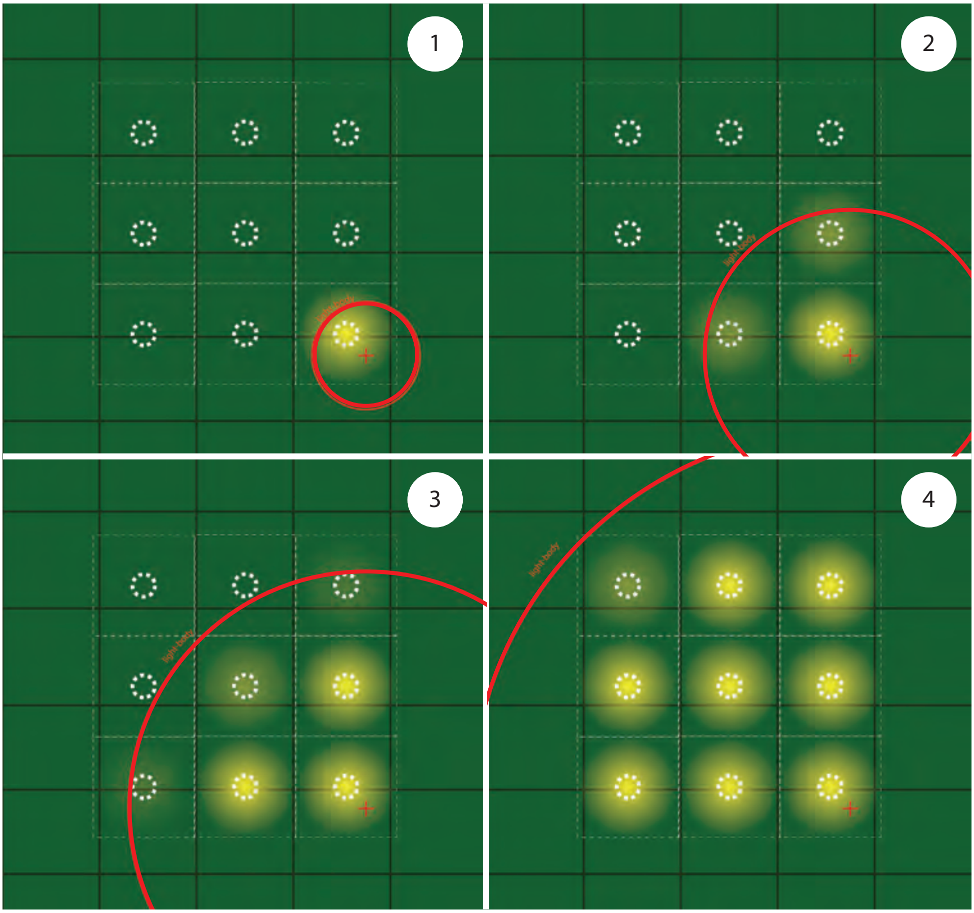


Figure 2.21 Schematic overview of the light-body concept. The circle indicates the shape of the light-body. The cross marks the center point of the light-body. In this example, the light-body is increased in size, as shown through the increasing radius of the light-body, resulting in more light sources switched on.

5.2. Lighting environment

The installation was implemented in a rectangular office environment (600 x 320 cm). A square table of size 160 x 160 cm is placed in the center of the room and 8 chairs are placed around the table. Figure 2.19 presents a schematic overview of the environment and lighting installation.

Based on the lighting scenarios that were defined, a lighting infrastructure was conceptualized and developed (see Figure 2.20). The lighting system consists of three types of lighting: *environment lighting*, *task lighting,* and *face lighting*. The lighting installation was mounted directly below the existing ceiling infrastructure. The lighting installation consisted of nine custom created ceiling tiles. Each tile was equipped with a spotlight in the center, aimed downward, to provide light on the task area. These lights are named 'task lights'. Four tiles in the corners of the ceiling were additionally equipped with diffuse lights, directed at the 8 seats surrounding the table. These were used to illuminate people and are referred to as 'face lights'. On top of the tiles, in between the original ceiling and our lowered ceiling, 4 lights were placed to provide general indirect illumination. There are referred to as 'environment lights'. All sources were 50-watt halogen lights, connected on separate channels of a DMX controller, making it possible to control all light sources individually.

The remainder of this section describes the implementation of the lighting behaviors for the adaptive office environment. I first introduce the 'light-body' as a control concept for the Individual Scenario. This provides users with a single control to change light distribution and light intensity. Afterwards I present and discuss the three lighting scenarios (Individual, Group distributed and Group focused). For the different lighting scenarios, variations of the spotlight behavior, that was investigated in earlier iterations, are used. For these scenarios, the lighting behavior supports people to focus their attention.

Light-body

The light-body is – what I call – a 'mediating interaction concept', which is used to control a set of independently controllable light sources distributed over a space. A light-body defines the relationships between a collection of light sources, such that they can be controlled as a unity: i.e., These light sources together form one *body* of light, hence the name. The advantage of controlling distributed light sources via a light-body is that users can manipulate a number of light sources at once in an understandable way. The shape and behavior of the light sources can be defined in the specific implementation of the light-body. Users thus interact with the light-body, rather than with each light source individually. Fonckel (2013), for example, uses a light-body in its interaction to provide people with the feeling they hold a beam of light in their hand that they manipulate. Deckers (2013) used the light-body in her research to provide people with the feeling of an acting entity with perceptive qualities.

The specific implementation of the light-body concept for this installation is as follows. A circle is mapped onto a digital map of the light sources in the environment. Light sources within this circle are included in the light-body: they listen to the behavior of the light-body. Light sources outside this circle are excluded from the light-body, and are turned off in this case. A schematic overview that explains the working of the light-body concept is provided in Figure 2.21. The light-body is used in the Individual scenario to control the lights on the workplane.

Individual scenario

When activities of an Individual scenario are detected (how these are detected is discussed later) the system automatically dims the environment light and provides the user with a light on his work area. This means that the task lights are enabled, the face lights are turned off and the environment lights are dimmed. This scenario is shown in Figure 2.23. When the user is seated at the table he can explicitly manipulate these task lights via a light-body. In this case, the spotlight helps people to focus their attention to their work: Their work in front of them is illuminated, the surroundings are dimmed. Additionally, people can explicitly manipulate the lighting conditions, as they wish to focus on other aspects.

In our implementation, the distance between the center of the light-body and the edge of the light-body describes a linear decreasing intensity. As a result the light-body has 'soft edges': i.e., The light intensity of individual light sources is lower at the edge than in the center of the light-body. In the Individual scenario the user can change the size of the light-body, through actions that we named 'zooming in' and 'zooming out'. Users manipulate the size of the light-body using the device depicted in Figure 2.22. Expanding the illumination over the

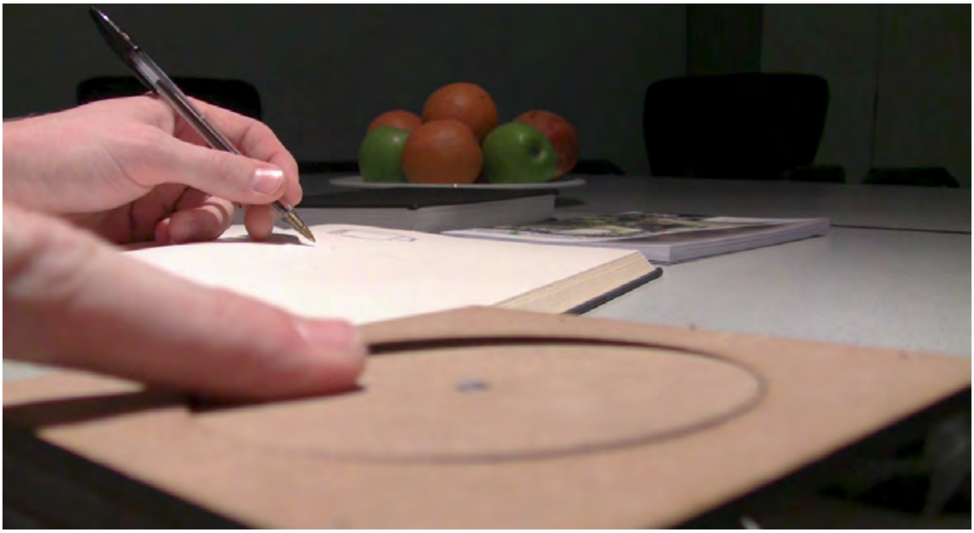


Figure 2.22 The device used to capture rotating gestures that are used to change the size of the light-body and as such manipulate the lighting conditions.

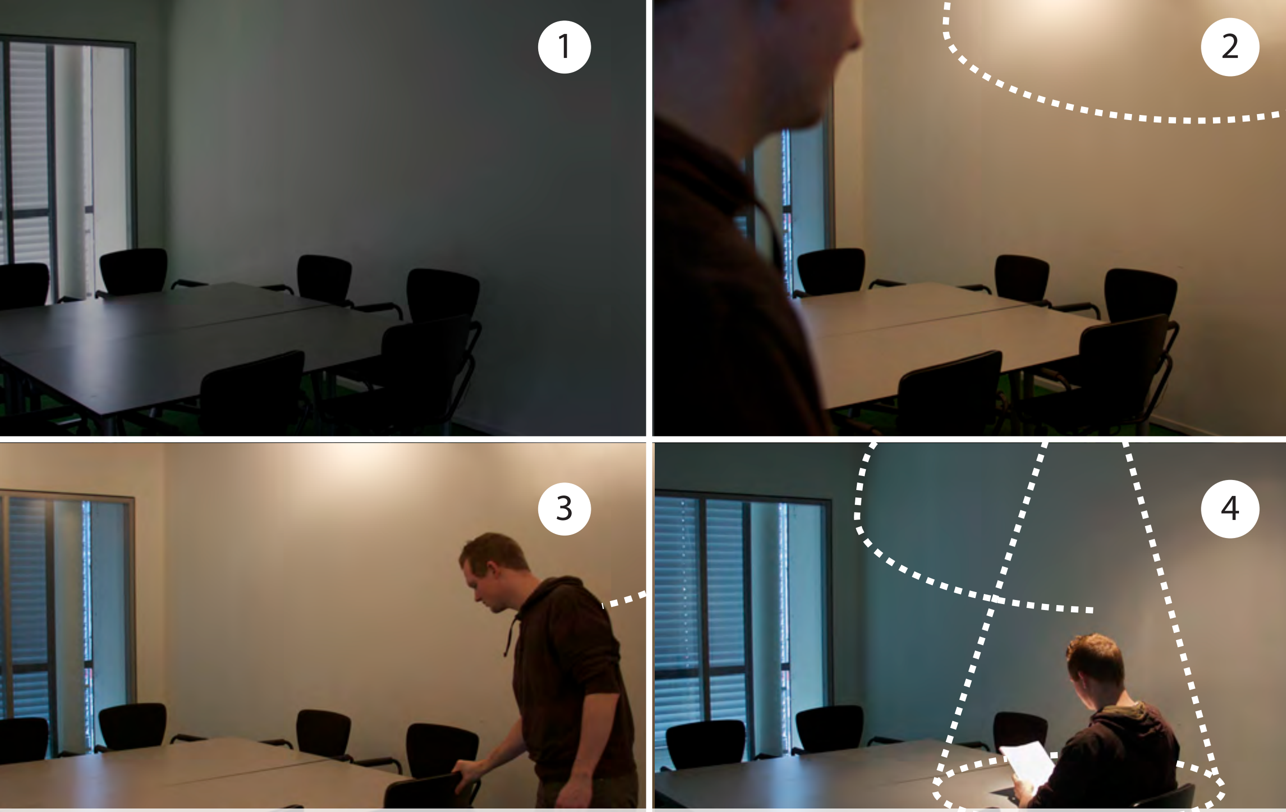


Figure 2.23 Individual scenario. The user enters the room (1) general illumination is provided (2). The user sits down, a spotlight on his task is provided. The dotted lines illustrate the location of the lighting.

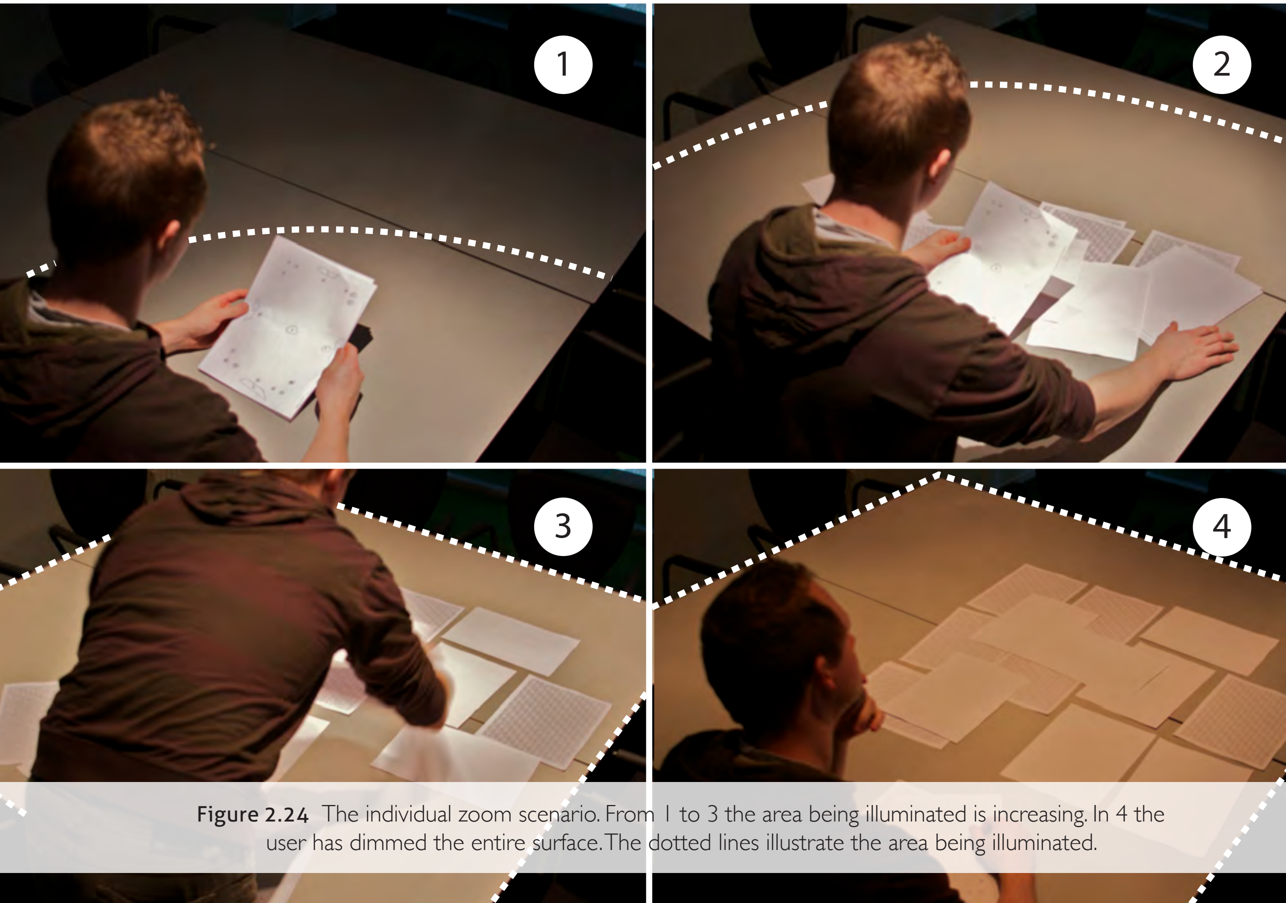


Figure 2.24 The individual zoom scenario. From 1 to 3 the area being illuminated is increasing. In 4 the user has dimmed the entire surface. The dotted lines illustrate the area being illuminated.

table is considered zooming out; the size of the light-body is increased, meaning that lights in an expanding radius of the user are gradually increased in intensity until an even illumination is reached over the complete table surface. Zooming in is the reverse action of zooming out; the size of the light-body is decreased. Additionally, the size of the light-body determined the maximum intensity: A small size relates to a high maximum intensity and a large size relates to a low maximum intensity. As a resulting behavior the user can create a bright spotlight on his location, or zoom out to cover the entire table with light. Figure 2.24 provides a scenario of this light behavior.

Group distributed scenario

Whenever multiple people are in the environment and they perform an activity as a group, the group distributed scenario is activated. When activities of this scenario are detected, light on the work plane (produced by the task lights) is dimmed but not turned off. This allows people to write and make notes. The focus in this scenario is on the people participating in the discussion. To support this, the faces of people engaged in the discussion are illuminated using the 'face lights'. The interaction with the system in the group distributed scenario is different from the individual interaction. In this case the system provides implicit interaction: Whenever a person is speaking in a discussion the light directed at him is turned on. This is depicted in Figure 2.25. The spotlight stays on for half-a-minute after the participant has stopped speaking. When multiple people are involved in the discussion, they are all illuminated. This lighting behavior is informed by the insights from earlier iterations, where people in discussion scenarios were illuminated. However, in this case the behavior is made contextually relevant, by linking it directly to a person's participation in the discussion. In this implementation, each participant has individual control over his lighting conditions.

Group focused scenario

A group focused scenario needs to be explicitly triggered by the user, for example when someone wants to give a presentation. The environment light is dimmed on three sides, and only on the side where the presentation is held, a low level of illumination is provided to highlight the presenter. When people at the table ask questions, the microphone sensors detect which person is speaking, and the system provides a spotlight to this person. This allows the presenter to identify who is asking the question. The lighting behavior thus supports the audience, by highlighting the speaker, and it supports the speaker, by highlighting participants that ask questions. In this was it helps participants by guiding their attention. Figure 2.26 presents an example of the group focused scenario.

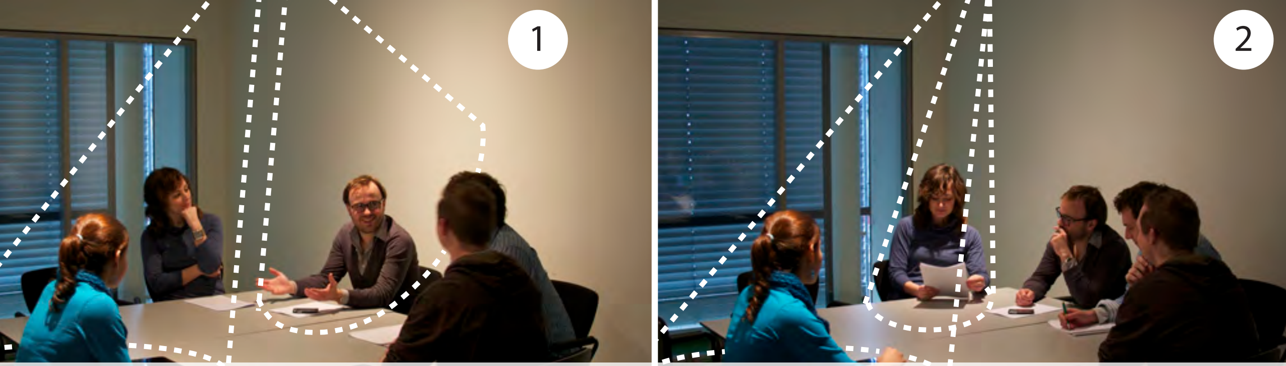


Figure 2.25 Group distributed scenario. (1) Discussion between the participant on the left and right. (2) Female participant in the center continues the discussion and is highlighted, light on the male participant dims. The lines illustrate the lighting behavior.

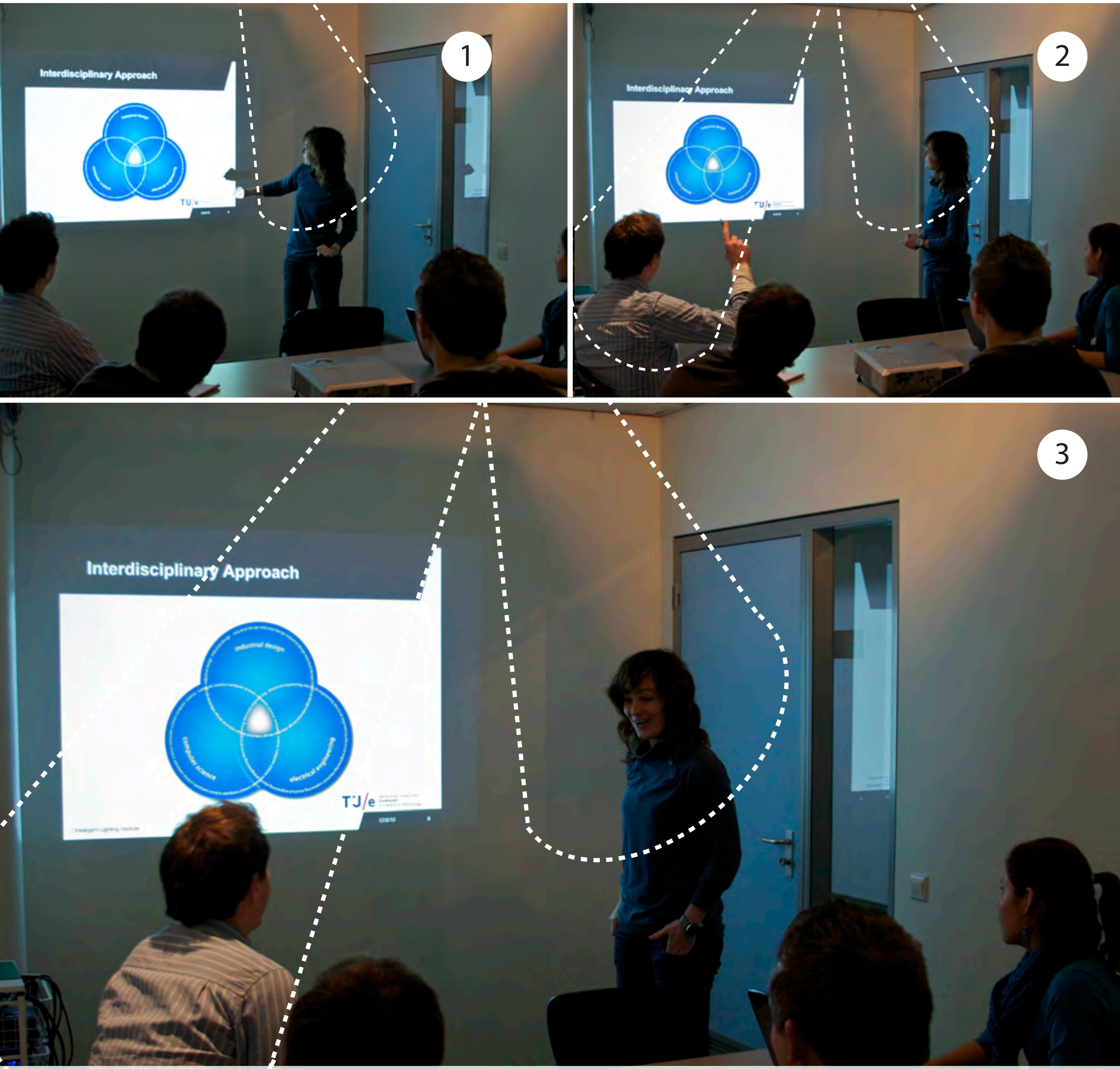


Figure 2.26 A presentation is being held. The male participant on the left indicates he has a question to ask (2) and is provided with a spotlight (3). The dotted lines illustrate the participants being highlighted.

System architecture

To distinguish the different activity scenarios a multimodal sensing approach was used for the recognition of various activities. Table 2–12 presents the sensors that were used and the behaviors that are considered characteristic for the classification of that scenario.

TABLE 2–12 Overview of the sensors used for activity recognition and characteristic behaviors that are detected

Classification	Characteristic Behavior	Sensor
Occupancy (default)	Person(s) enter(s) the room	Motion Sensor
Individual Scenario	Person(s) sit(s) on a chair	Force Sensor
Group Distributed Scenario	> 1 Person seated and at least 1 person speaking	Force Sensor Microphone
Group Focused Scenario	*User triggered*	Button

A motion sensor was installed directly above the door. This sensor detected people entering the room and as such classified occupancy in the room. When occupancy was detected, the default lighting scenario was triggered. Force sensors were placed in the seats and were used to detect when and where people were seated. This information was also used to determine whether there was an individual or a group in the environment. Finally, microphone sensors attached to the table surface were used to determine whether participants were speaking. The activity classification scheme for the different activities was developed by Paola Jaramillo Garcia and can be found in Appendix 2-E.

The system was implemented using a centralized setup. The behavior of the system was implemented with the OSAS framework (Bosman, Lukkien, & Verhoeven, 2009). A central PC was connected to a DMX controller in order to manipulate the light sources. The sensors were attached to a BSN node[1] and distributed across the room in the locations that were described in the previous paragraph. Sunder Aditya Rao, who was responsible for the system architecture and wireless networking, implemented the activity classification algorithm. An overview of the system deployment can be found in Appendix 2-E.

Due to limited availability of sensors and nodes, and due to time constraints, the system was not fully implemented. However, the demonstrator that we created included all the lighting behaviors and scenarios as explained before up to a level that they could be experienced. Practically, this means that not all seats were equipped with force sensors, and not all the microphone sensors were installed.

[1] http://vip.doc.ic.ac.uk/bsn/index.php?article=167

5.3. Evaluation

Since the system was not fully implemented it was not possible to perform evaluations of users actually using the system. Instead, we decided to evaluate the system via expert reviews. In this case experts with different backgrounds provided their views to the system. From this evaluation we gathered rich information, as the experts possess in-depth knowledge in their respective fields, which they can use to benchmark this system. Another benefit is that these experts are able to reflect on the concept rather than the implementation, and they are capable to envision future scenarios for the system.

TABLE 2–13 **Structure of the expert evaluation sessions**

Phase	Duration	Description
Welcome	5 m.	Experts are welcomed and introduced to the three Ph.D. students. Background of the project is explained.
Experience	10 m.	Expert experiences the Individual, Group distributed and Group focused scenario with Ph.D. students acting out in the group scenarios.
Discussion	40 m.	One Ph.D. student interviews the expert in a semi-structured interview.
Closure	5 m.	Experts are thanked for their participation.

Nine expert evaluation sessions were held. From each field of the Ph.D. students three experts participated in the evaluation, which lead to a broad range of knowledge in the expert pool. The experts represented the following fields: user interaction, environmental psychology, lighting design, coding and modulation of information, signal processing systems, communication, multimodal sensor networks, machine learning systems, wireless sensors networks, real-time systems, and distributed systems architecture. The range of expertise varied from professors to higher year Ph.D.-candidates. Each expert had individually experienced the adaptive office and discussed the implementation in a one-hour session. The structure of the expert evaluation sessions is summarized in Table 2–13.

For each expert evaluation session, the concept was first explained and the implementation was demonstrated. The expert experienced the system by going through the three scenarios. This meant that he first entered the room individually, sat down and interacted with the lighting system via the controller. After this, the three confederates entered and acted out other participants in a group distributed scenario. Finally, the Group focused scenario was activated and one of the confederates pretended to give a presentation without slides. Once the expert indicated he understood the system, a semi-structured interview with the expert started. For this interview, a question-route was developed, which was tailored to the field of expertise of the expert. Each question route (examples included in Appendix 2-E) typically started with introductory questions regarding the experience of the demonstration, continued onto the main field of expertise and concluded by addressing topics of the related fields. The session was led by the Ph.D.-student who invited the expert, such that the field of expertise aligned with the expert. The other Ph.D.-students could ask additional questions when necessary, but typically made notes. Each session was recorded on video for analysis afterwards.

5.4. Results

The three researchers reviewed the video footage independently and made an abridged transcript. The researchers transcribed quotes from the discussion, removing irrelevant conversation (such as pauses, stuttering, or fillers). The result is a list of quotes (included in Appendix 2-E). The final selection of quotes was clustered using a Long Table Approach (Krueger & Casey, 2000) in which all captured quotes were printed on individual cards and laid out on a large table. The three Ph.D.-students collaboratively grouped similar and/or related quotes to form clusters. This was done in a two-step process: (1) clustering, and (2) reflecting and discussing clusters. The clustering was performed with open-coding, which means that no predefined groups were made. However, the following questions guided the clustering process:

- Does the quote relate to the field of research of the three Ph.D. students?
- Does the quote address interdisciplinary aspects of the project?
- Is the quote specific to this application?

The clusters that were formed are placed under these three topics and are presented in Table 2–14. In the second step we discussed and reflected upon the clusters to draw insights for further development. These insights are derived from commonalities between quotes in different clusters, or from quotes that specifically drew our attention. This means that the insights do not necessarily follow the structure of the clusters.

TABLE 2–14 **List of clusters that emerged from the grouping exercise**

Individual Interests	Interdisciplinary aspects	Application specific
1. User Interaction	4. System evaluation criteria	7. Lighting aspects
2. System Architecture	5. Future scenarios	8. Personal experiences
3. Activity Recognition	6. Considerations for adaptive lighting environments	

User interaction

User interaction was one of the topics that covered my domain of expertise. Aspects that were raised by the experts are (1) motivations for people to interact and differences between explicit (user control) and implicit interaction (automated behavior), (2) the feeling of being in control and other feelings associated with interaction, and (3) possibilities for multi-user interaction.

In general experts considered *natural*, *easy,* and *rich* interaction opportunities as important principles when designing interaction possibilities. Experts agreed that there should always be a way for the user to interact with the system and to override automated behavior: "*You always want to be able to overrule the system*". As indicated by some experts interaction should be a mixture of explicit and implicit control. However, one expert indicated that implicit interaction should be approached differently as "*you become more critical about what is happening*", because "*if (...) all of a sudden things are happening, it may be more intrusive*."

Giving people with control possibilities was found important and it is valued as it provides people with a feeling of security. Moreover, we found preferences for systems that are not fully automated, but where the control is given to the system mainly when the system can outsmart the user. For instance, by providing awareness of energy consumption, by providing alertness when the user needs it, or by simplifying repetitive tasks and/or in situations that are (too) complex for the user to deal with. It was suggested that systems should not be designed to fit all users, nor should they be intended to always provide optimal lighting conditions for each user. After all, a user himself knows his wishes and intentions best: "*It will be hard to outsmart me on my preferences.*" The user control that was offered in the Individual Scenario was found interesting and innovative. One expert suggested that a user should be able to also control where the light goes, for example through linking the location of the controller to the location of the light. Interestingly, comments were captured that describe a role of light and control over the lighting system that is not directly related to functional aspects. Things that lighting impacts are: feelings of *ownership*, *territoriality,* and *intentionality*. One expert remarked that the ritual of changing the lighting conditions is important: "*it gives people some time to get accustomed to the settings and to the meeting we are having.*"

Finally, opportunities for the design of multi-user interactions were expressed. Few, but diverse comments were captured in this category. One expert stated: "*There are social structures that have to be accommodated by the technology.*" On the other hand there were questions about providing individual control to each user. Responding or predicting group behavior was suggested as one of the areas in which a system can outsmart the user and thus could be a motivation for the system to automate behavior. As I have expressed in earlier chapters, I personally believe that designing for multi-user interaction with adaptive lighting environments can provide more natural, social ways of interaction and is required for future systems to succeed.

System architecture and Activity recognition

The second topic is related to the fields of my fellow Ph.D.-students in this project. In this subsection I discuss aspects of system architecture and activity recognition. From the analysis four categories emerged that are discussed here. These categories are (1) centralized architecture versus (2) decentralized architecture, (3) communication between system components, and (4) modular or emerging structure.

A centralized approach was found convenient in terms of precise decision-making, because all information is available in a central location. From this location one can easily verify (and control) the status of the system. As opposed to the centralized architecture a distributed architecture was suggested. Some experts preferred this, because it is more scalable and potentially more fault-tolerant. From the perspective of communication, in the distributed approach the data traffic remains local and the payload gets smaller, because the interpretation is done as close to the source as possible. There were also suggestions that combine both centralized and distributed, depending on the application. An expert mentioned it could also be dependent on what companies that produce these systems "*are driving for.*" Overall there was no strong preference for one or the other; both solutions have their strengths and weaknesses that one has to consider when setting up a new system. The experts mentioned that the future smart systems should be modular or should adapt to the emerging behavior "*You want that to become pluggable components into the software system of the user's home.*" Experts who chose distributed also argued that this approach would fit emergent behavior well.

With adaptive lighting we aim to adjust the lighting conditions to human behavior and activities. In order to do this the system should be able to acquire meaningful information from its context. Experts indicated that such an approach requires the utilization, in most of the cases, of multiple sensing modalities. Most experts believed that coordinating all these sources of information is likely to be easier in a centralized approach. However, this limits the scalability of the system. Data should be processed locally: "*Don't send data (…) only send information.*"

Lighting aspects

Many of the experts provided comments regarding the aesthetics of the lighting conditions. This regarded two aspects: (1) basic lighting considerations and (2) behavior of the lighting environment. These aspects are discussed respectively in the next paragraphs.

All experts agreed the direct top-down face lighting was unacceptable. The quality of the light settings seemed to be important to all experts. It was suggested there should be a basic level of illumination at all times, and accents are placed in different locations for different scenarios. It should further be considered that shadows, contrast and light levels are defining aspects of the experience of lighting conditions, which were not optimal in this installation.

Different experts raised questions with the spotlighting behavior. They deemed it unnecessary for this context and this group size and the behavior is not adequate as "*You're always too late.*" Only in the presentation scenario they found it helpful, but in the discussion scenario it was considered less relevant. Instead the light could illuminate different speakers, and does not need to change continuously. Considering the dynamics of lighting in general, several comments were received that indicate that transitions between states should be hardly or not at all noticeable.

Future scenarios and Other considerations

After the experts discussed the implementation, they were asked to express their vision on ALEs. This raised three aspects: (1) general opinion regarding ALEs, (2) envisioned future of ALEs, and (3) aspects that we should consider when designing these environments.

Firstly, most of the experts related well to the overall idea of adaptive lighting environments. There was only one expert who said: "*I don't believe in automatic adaptation.*" The other experts were more positive *"We are animals that are used to changing light conditions, (…) replacing that by completely static light conditions is, for me, not the most natural way.*"

Experts were also asked to envision how they see the future of adaptive lighting environments. Most experts argued for an easy to install and (user-)programmable structure. They envisioned a system that is built from modules that users put together in their own way. Importantly, users should be able to extend the system with their own services and preferences. An important reason to provide an open-ended system is that there will always be an uncertainty of how the system will be used: "*The reason to be service oriented is, because you don't know your environment.*" The system could come with initial functionality, but users should be able to adapt and expand it. One expert mentioned other application areas, such as museums, supermarkets, concerts, or restaurants. However, as another expert remarked, "*With a lot of these applications, we need knowledge that is not out there yet.*"

One of the considerations that experts mentioned is that 'subtlety' will be a key issue in the design of adaptive lighting systems. The system has to fade into the background, "*I would like the system to be transparent and almost unnoticeable to me.*" Increasing subtlety is likely to reduce annoyance when the system makes erroneous decisions. This corresponds with the finding that lighting transitions should be smooth. One expert envisioned that when changes in the environment become subtler, other aspects become more important. This also corresponds with the remarks that the lighting transitions should be subtle.

5.5. Conclusions

The adaptive office presented in this chapter is a concept for future lighting environments, where lighting conditions dynamically adapt to the activities performed by users in order to support this activity.

The opinions of the experts regarding the system architecture were mixed and did not favor centralized over decentralized or vice versa. Both architectures have their own benefits and disadvantages, and those should be considered individually for each implementation. Experts argued in favor of a modular structure for lighting systems, both in terms of setup and lighting behavior. They argued that if users are provided with plug-and-play modules, they can build their own lighting system that fits their needs. Furthermore, a system could come with initial lighting behaviors, but users should be able to adjust these to their own preferences. For modular setups, the light-body could be used as a light control concept as it provides users with a mechanism that is consistent across different lighting setups.

One of the central design challenges in this dissertation is to explore novel ways of interacting with ALEs. In this implementation, two forms of interaction were explored: implicit and explicit. Evaluations by experts revealed that implicit interaction (automated behaviors of the system in response to user behavior) should be treated cautiously and should only be done when a system can outperform a user. Explicit interaction (i.e., user control) should be rich, easy, and natural, for example in the form of the controller that was designed. This controller was appreciated as it offered simple, but rich control in a single device. Furthermore, experts also identified designing interaction in multi-user settings is an important challenge for ALEs. They questioned whether it is possible to provide individual users with control. Instead, it was suggested that systems could learn group behaviors and respond to those. This could imply that intelligent systems could provide a mechanism to balance control over a group of users.

Regarding the design of meaningful lighting behaviors, this implementation showed how lighting behaviors can be coupled to behaviors of people. For example, different variations of spotlighting behavior were implemented. By connecting this lighting behavior to specific parameters of human behavior, its relevance changes per scenario. The spotlight behavior that was implemented in the group scenarios again was appreciated in the presentation context, but not in the discussion context. In general, the experts argued for subtle lighting behaviors. Rapid changes to keep up with the dynamics of a discusison were not appreciated. Also, experts argued that people want to understand what is happening, so lighting behaviors should be understandable and predictable. This again stresses the importance of the influence of contextual factors on the appreciation of lighting behaviors.

Concluding the Incubation phase

In the Incubation phase I explored the design domain of ALEs in various lighting installations. These explorations focused on two aspects: First, I explored how to design meaningful lighting behaviors for ALEs. Second, I investigated the implications of ALEs on social settings. Third, I explored novel interaction mechanism to interact with ALEs. In the following paragraphs I summarize the findings of Incubation phase regarding these topics.

The explorations with users suggest that lighting influences our behavior, but that the effects are small. This showed me that the core value of my design should not only be in its ability to change the speaking behavior of people. Instead, a diversity of lighting behaviors should be implemented. Furthermore, the quantitative measures I used might not fully express the implications of the lighting system. In future evaluations I combine this with qualitative evaluations to get broader and richer insights. When multiple people were offered control over a shared lighting environment, indications were found that the way this control is offered influence the way we perceive others and influence behavior towards them. This insight, combined with expert evaluations of the adaptive office installation who indicated that social aspects are important for future lighting system, I argue that a lighting system should provide mechanisms to balance control among a group of users. This could be one of the key aspects for the acceptance of adaptive lighting environments, and I aim to investigate this further in the Nursery phase. Specifically, I present the design of a light controller that facilitates multiple users to interact with a lighting environment, whereby the system provides mechanisms to balance control between users.

Most of the installations in the Incubation phase were implemented using off-the-shelf technologies. My experiences with implementing ALEs confronted me with the difficulties of using such technologies. While it is possible to create interactive installations, the technology is not tailored for such purposes. The products are typically large, cumbersome, and tailored for industrial purposes. These are not limitations of the LED technology itself, but of the way it is implemented. Additionally, experts advocated modular and scalable lighting technologies, where applications can be tailored towards specific people and contexts. Based on these insights I designed the Hyvve system, which is presented in the Nursery phase as well as a custom-designed wireless node, named Lithne, to control the system.

PART II
NURSERY

Introducing the Nursery phase

The second phase of the Growth Plan is named the Nursery phase. The most promising concepts and ideas of the Incubation phase continue into the Nursery phase. The concepts are 'nurtured', which means that they are further investigated and developed. In this phase the designer pays more attention to details. Where the Incubation phase can have extreme cases, in the Nursery phase more nuance is added to the original concepts. Evaluations in this phase are less exploratory, and are typically investigations in (semi-)controlled environments. Consequently, prototypes in this phase should be robust, such that they can be deployed in longitudinal studies. Especially when considering that the prototypes also will be used in the Adoption phase, where the designer might not always be present to intervene, prototypes should be able to operate in a stand-alone fashion. Typically the length of the research-through-design cycles increases from several weeks to several months or even up to a year.

A brief story to start with

In March 2011 I spent three weeks in Siena as lecturer for the student module 'Light through Culture' (Marti & Overbeeke, 2011). In this module a group of students from our university (TU/e) *and a group of students from the University of Siena collaborated on interactive light installations. The module took place in the museum Santa Maria della Scala. The museum is built on the remains of old parts of the city and the Via Francigena: an ancient pilgrimage road that literally runs through the museum. Recent excavations had uncovered spaces that shed a new light on the history of Siena. The goal of the module for the students was to communicate these historical narratives via an interactive light installation. In three weeks the students created four interactive installations to engage the visitors of the installation in an interactive story through four spaces*[1].

Later that year I participated as a lecturer in another module. This time the goal of the module was to build an interactive light installation for the annual light festival GLOW. In this festival various artists and lighting designers present exhibitions and installations throughout the city centre. The university was celebrating its 55th anniversary and to celebrate this, they participated in the festival with multiple installations. The students developed an interactive lighting installation (BRAINpulse) that used the main building of the university as a lighting façade. Visitors could use the flash of their photo cameras to spark the building with imagination[1].

The students successfully created both installations and the responses of the visitors were positive. However, as I witnessed the design process of the students there were things that struck me. In both cases there was a gap between conceptualization and implementation. Concepts were generated in creative sessions: Drawings, videos, and oral explanations were provided, but rarely were there early experiential sketches. This made it difficult to provide feedback to the students, as we could not judge the experience of the installations.

[1] Videos of the installations are included in Appendix-II: Nursery

Once a concept was selected and the implementation started, too much time was spent on 'getting the stuff to work'. Where I believe design students should focus on fine-tuning the behavioral qualities of the installation, most time was spent on getting the correct wire to the correct socket. At the end of the day there was too little time left to create the optimal experience for the visitors. For example: In Siena, the first visitors were literally in the first space of the exhibition, while in the last space the students were removing the last bugs from the software and cleaning up.

Other things that I noticed is that for the GLOW installation several hundreds meters of cables were installed throughout the main building of the university. Students spent over a week to get all the equipment in place and connected. In Siena there were difficulties with 'synchronizing' the spaces with each other. One of the reasons for this is that many wired solutions exist, but there are few reliable and understandable wireless solutions available.

These experiences, combined with the insights from the Incubation phase, revealed that for designers of interactive lighting installations (environments) there should be tools that support designerly ways of working. Designers require a platform that is easy to program, but does not limit them to a set of predefined actions. Practically, this means that they need to be able to use different sensors and actuators and a programming language that is sufficiently understandable and 'open'. Furthermore, the technology should not induce a 'technical' perspective towards implementations, but designers should be able to transcend to a level where they can explore and prototype behavior of a product or system. Additionally a prototyping tool should offer a workflow that fits an iterative design approach and allows for explorations in context.

This part of the dissertation contains three chapters that present the design of respectively Lithne, Hyvve, and Bolb. Lithne is a prototyping platform that facilitates designers in the development of prototypes of networked products and systems. The platform bridges the gap between an explorative design approach and implementation. Furthermore, the Hyvve system is presented. Hyvve is a flexible and modular lighting system that aims to support research and development of adaptive lighting environments. The last chapter of this part presents the design of Bolb. This is a personal and portable light controller. Bolb also embeds mechanisms to facilitate interaction between multiple users, based on the explorations of the Incubation phase. These three technologies are used in the Adoption phase where I present the implementation and longitudinal evaluation of an adaptive lighting environment.

3. Designing tools: Lithne & Hyvve

Parts of this chapter have been published in:

Magielse, R., & Offermans, S. (2013). Lithne – a platform for interaction designers to develop interactive networked environments. *Proceedings of the 9th International Conference on Intelligent Environments 2013*, 137–144. doi: 10.1109/IE.2013.14

Magielse, R., & Frens, J.W. (2013). Hyvve – A modular and flexible light system. *Proceedings of the 9th International Conference on Intelligent Environments 2013*, 116–123. doi:10.1109/IE.2013.15

1. Introduction

When designing interactive products and systems, creating experiential prototypes is essential (Frens & Hengeveld, 2013). Making experiential prototypes synthesizes design thinking and design making: The information that a designer has acquired throughout a process integrates into a physical hypothesis. Additionally, a working prototype allows for experiential evaluation of the product or system in context. The results of such an evaluation can be used to fine-tune the system, which contributes to achieve a desired user-experience.

In order to develop experiential prototypes of ALEs, tools are required to design, develop and implement intelligent such environments. While there are many different tools available to develop interactive prototypes or networks, not many of these tools are tailored for use in an iterative design process in context. The workflow of the designer and the workflow that many of these tools support are not aligned. The explorations in the Incubation phase and experience in educational activities revealed six requirements for a prototyping platform that are important for a tools for design of ALEs. Designers need (1) a platform that allows sensors, actuators and processors to be embedded in the environment. Many of the installations incorporated (2) different sensors and actuators, which should easily be connected to the platform in a comprehensible way. Furthermore, lighting behaviors need to be designed (3) in-context in an (4) iterative way. As intelligent environments typically consist of a plurality of nodes that are distributed throughout the environment, a prototyping platform should (5) facilitate simple-to-understand networking capabilities. Finally, (6) designers should be prepared to think in behavioral terms, rather than in technical terms. This helps them to overcome the complexity of the existing technology and address the complexity of the context they design for.

In this chapter I present two tools – Lithne and Hyvve – that have been developed, and I provide an insight into the motivations for development. In the following section I review existing tools for design. Then I present the different components of the Lithne platform and describe how the different components relate to the earlier mentioned requirements. After that I present Hyvve as a modular and flexible lighting system. In the conclusion of this chapter I reflect on, and discuss both platforms.

1.1. Tools for designing interactive prototypes

There are many tools that support the development of interactive products or wireless networks. For example, Wikipedia alone already lists over fifty wireless sensor nodes that can be used to create wireless (sensor) networks ("List of wireless sensor nodes," 2013) and this list even excludes platforms without wireless capabilities. Why should yet another platform be added to this extensive list? One of the most practical reasons is that not all of these platforms are actually available. For example, many platforms that are developed by research institutes are not commercially available. Another important motivation is that not all these platforms are well documented. When one wishes to adopt such a platform this requires a significant investment in terms of time, often with a steep learning curve. Furthermore, most of these platforms are designed for dedicated wireless applications that excel in one core quality (e.g., energy-efficiency, low power consumption, or computational strength), and they cannot be applied to any project. While they are superior in this regard, it is often difficult for designers who do not have a background in (embedded) programming to understand how to use these platforms.

On the other hand there are tools that are specifically created to support interaction designers. Greenberg and Fitchett (2001) presented 'Phidgets' as one of the first platforms to create interactive prototypes. Phidgets consists of microcontrollers connected via USB to a computer and a wide assortment of sensors that can be connected in a 'plug-and-play' fashion. Sensors are connected to the main Phidget board, and the sensor data can be accessed by software written on the computer. In addition several actuators (e.g., motors, or light sources) can be attached to the main board and controlled via the computer. Phidgets facilitate a designer with a workflow to rapidly prototype interactive concepts. The disadvantage is that Phidgets always require a computer to be attached to the main processor board. It is not possible to program software onto the microcontroller and run it stand-alone. Furthermore, the Phidget sensor boards impose a specific form-factor to the design, which limits the freedom of the designer.

Currently, the most popular tool amongst interaction designers is the open-source platform Arduino[1]. Arduino provides hardware components, a programming environment with its own programming language, a website with tutorials and quick start guides and they support a large community that answers questions and provides examples. Arduino leverages two core qualities that make it a popular platform: The developers of Arduino provide a simplified programming language and a rich set of instructions and tutorials on how to work with the platform. This means that anyone can get started easily as it is simple to learn to use the platform. Second, there is a large creative community that contributes to the platform with new hard- and software development (Mellis & Buechley, 2012). This results in a platform that is easy to learn, provides freedom to develop diverse applications and a community that provides continuous support and advice to realize diverse implementations. Yet, the Arduino platform is rather limited in terms of computational and wireless capabilities. For more advanced interactive prototypes one soon is constrained by the limited capabilities of the platform.

As of 2012, the Raspberry Pi[2] (RPi) has entered the field. The Raspberry Pi is an ARM-based computer, running on Linux, which offers far superior computational qualities when compared to Arduino. The RPi is pitched as 'a computer the size of a credit-card', but the actual dimensions are slightly bigger than that. It contains various in- and output connections, such as USB, Ethernet, or HDMI, that make it simple to attach the RPi to external equipment. The popularity of the RPi is rapidly increasing, as it is a cheap, yet powerful device that supports a high variety of uses. The RPi is also developing a large community that provides help and

[1] http://arduino.cc/
[2] http://www.raspberrypi.org/

explanation to those new to the platform. Many examples and tutorials that are offered for the RPi are however single-purpose: They for example explain how to make the RPi into a media-player or web-server. While the RPi offers superior hardware, it lacks the integrated and simplified workflow of the Arduino and it is not trivial to create a simple piece of software using your own sensors and actuators.

Microsoft has released their .NET Gadgeteer framework (Villar, Scott, Hodges, Hammil, & Miller, 2012). This platform to create interactive prototypes, also consists of hardware, sensors, actuators, and software development tools. The Gadgeteer framework uses a modular approach, where users build their own prototypes. It advocates a workflow where a designer can visually assemble, connect and program his prototype and this can be uploaded to the physical hardware. Additionally, all the hardware components are available as 3D-models, facilitating an easy transition to developing physical models using rapid prototyping techniques.

What Phidgets, Arduino, and Raspberry Pi all lack is the ability to easily develop wireless network applications. Although the Arduino provides libraries for Bluetooth, Wi-Fi, or ZigBee networks, one still has to assemble the hardware correctly and develop an understanding of network architectures and messaging protocols to be able to work with it. There are some Arduino-based alternatives, such as JeeNode[1], or Arduino Fio that facilitate an integrated wireless module and an Arduino IDE-programmable microchip. For the RPi the same applies: it is possible to connect wireless adapters to the board, but using them for dedicated purposes is more complex. Overall, these alternatives still require a fair amount of knowledge before you are able to set up a small wireless network beyond point-to-point communication, which is crucial for the development of intelligent lighting environments. These platforms are targeted at technicians rather than at designers.

1.2. Tools for lighting design

The installations in the Incubation phase were created using off-the-shelf equipment. This equipment is typically used in architectural lighting or stage and theatre lighting. When implementing the installations I was soon confronted with the limitations and complexity of commercially available lighting equipment both in terms of hard- and software. Lighting standards such as DMX or DALI[2] facilitate interoperability between equipment of different manufacturers, yet the different types of cables and connectors can be puzzling. For example, some light sources can be directly connected to a DMX controller, whereas others need additional intermediate equipment. Although the lighting quality of this equipment is generally good, this equipment is intended for long-term installation and for static lighting conditions. Therefore, the use of such equipment for designing interactive lighting environments is often complex, and adding 'interactivity' and intelligence is difficult. The software to control this type of equipment is not tailored towards interactivity. Software packages allow for the creation

[1] http://jeelabs.net/projects/hardware/wiki/JeeNode
[2] see Glossary at the end of this dissertation

of different lighting behaviors (e.g., scene setting, color animations, video display), but creating context-aware behaviour and connecting to sensors in the environment requires skills that are not available to most designers. This makes it difficult to investigate interactive or intelligent lighting environments. Currently, some wirelessly controlled light sources are entering the market such as the Philips Hue (Bui, Lukkien, Frimout & Broeksteeg, 2011; “hue”, 2013). Although these systems are still rather costly, installation is easy and a Software Development Kit (SDK) is available that allows for control of these lights. However – for the time being – connecting this to a complete environment remains challenging.

The following requirements were set for the design of a future lighting system: A lighting system should be (1) flexible and modular to make it possible for lighting designers to tailor lighting setups to the context they design for and to easily make changes. It should be possible to (2) ‘program’ custom lighting behaviors into the system and it should be possible to (3) integrate data from external sources in order to create context-aware and intelligent light behaviors. Furthermore, the system should prepare designers to (4) design for lighting behaviors, rather than be concerned with technical implementation. Following these requirements, Hyvve is designed.

In the following section, first the Lithne platform is presented: It consists of hardware components, software to program the hardware and software libraries. The platform is targeted at interaction designers, who generally have some experience in programming and electronics, but it is not their main expertise. Lithne is developed in collaboration with colleagues of the ILI. Together with Serge Offermans the development was initiated, and early prototypes were created. In later stages, other colleagues, student assistents and interns worked on the project. The hardware, as presented in the next section, is designed by a professional electrical engineer, and a first batch of 200 nodes has been professionally assembled. The Lithne platform serves as the basis for the Hyvve platform. This is a modular system that can flexibly be setup by designers of lighting environments. It consists of Hyvve tiles – which are independently controllable, decentralized, and distributed light sources – a grid structure to attach these tiles to, and software to program custom lighting behavior. is presented, as a solution for designers to ideate, conceptualize and implement ALEs.

2. Lithne

Based on the requirements outlined at the start of this chapter, two are applicable for to the Lithne hardware: (1) The form factor of the board should be small enough that it can be embedded in portable prototypes and (2) it should be easy to connect additional components (sensors/actuators) to the board.

The first requirement mainly addresses the size and weight of the board: The board should is small (73.0 x 39.5mm), and light-weight. Yet, we also aim to support portable prototypes, which indirectly implies that the board should be able to operate from a portable power source (i.e., a battery). The second requirement states that it should be simple to connect external electronics to the board. This is an explicit choice as we believe that the when designing a prototype of an interactive product or system, the interaction should be leading the implementation. In certain cases this might mean that new sensing solutions have to be created. This allows designers to explore novel interaction styles, which is one of the core design challenges of this project. With readily available sensors there is the danger that one designs from what is available rather than from what is required. Also, a pre-defined form factor for sensors reduces the flexibility of the platform.

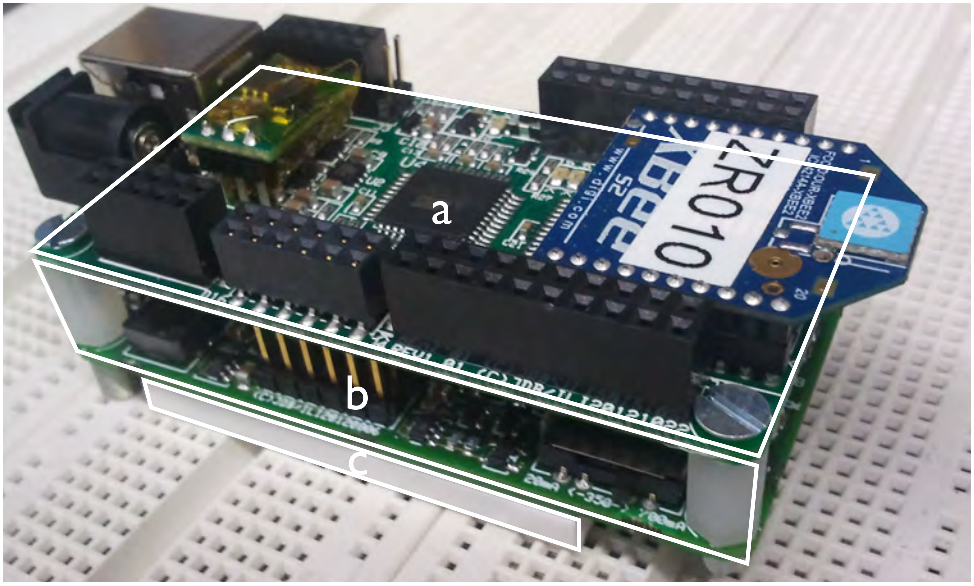


Figure 3.1 A fully assembled Lithne node containing (a) a main board, (b) a battery power supply board, and (c) a battery.

The Lithne hardware (Figure 3.1) consists of four components: (a) main board, (b) a battery power supply board, (c) a battery, and possibly dedicated sensor/actuator board(s). We decided to use a basic 'building blocks' approach (Dutta, Taneja, Jeong, Jiang, & Culler, 2008) for Lithne, which means that the users select the functionalities they need for their application and assemble the hardware accordingly. They 'build' their node out of pre-assembled 'blocks'. For Lithne this means that hardware components can be stacked onto one another. In the following sections more detailed descriptions of the individual components are provided.

2.1. Lithne main board

The Lithne main board (Figure 3.2) comprises of two Atmel microcontrollers, named respectively (a) co-processor and (b) main-processor. Details regarding the specifications of these processors can be found in Appendix 3-A. We selected these microprocessors as they are compatible with the Arduino programming environment, but they have more computational capabilities. To facilitate wireless networking the node contains connectors for a (e) Digi XBee module. The node can be powered via (c) USB or via an external power cord connected to the (d) 2.1mm power plug or via a battery.

The user can program the main processor. This can be done either via a USB-port or 'over-the-air'. How this is achieved is explained later. The co-processor is pre-programmed with firmware to support wireless programming and wireless communication, and cannot be programmed by the user. The co-processor acts as a bridge between the XBee module and the main processor. For the wireless communication we decided to use XBee modules (which use the ZigBee protocol) as this is currently one of the standard wireless protocols. These modules provide reliable mesh networking, which is a form of networking where each individual node in the network topology can communicate to every other node, and they can easily be interfaced from the selected microcontroller. The Digi XBee Module is connected to the co-processor via an UART-line. The manufacturer of these boards also produces Wi-Fi modules with the same physical and pin layout. This means that in the future, the Lithne boards could also communicate via Wi-Fi. The hardware thus is prepared for wireless networking, which means that a user does not have to attach any additional components.

The XBee modules are configured such that they handle most of the technical wireless transmissions by themselves. For example, the node checks whether messages arrive and retransmits any failed messages. The benefit for a user is that he does not need to be concerned with writing message verifications, but can focus on what information to transmit between devices. The disadvantage is that as a user you have less control over the actual message transmission and network architecture.

2.2. Lithne Battery Power Supply Board

Since prototypes may require nodes to be embedded in mobile devices, it should be possible to operate them via battery power. This makes it possible to create portable prototypes without power supply wires. For this reason a battery supply board was developed (Figure 3.3) with the

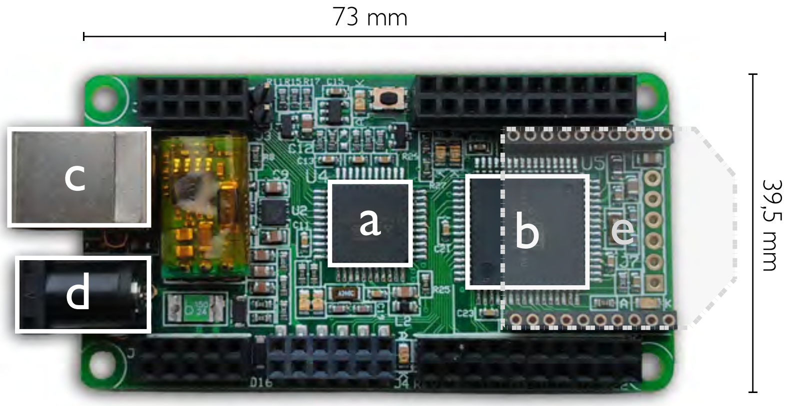


Figure 3.2 The Lithne main board with (a) co-processor, (b) main processor, (c) USB-port, (d) 2.1mm power supply, and (e) XBee module.

Figure 3.3 The Lithne battery board.

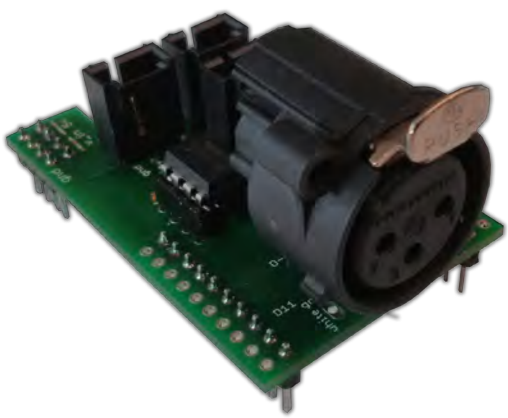


Figure 3.4 Example of an actuator (DMX) shield for the Lithne node developed by Serge Offermans.

same dimensions as the main board. This battery board makes it possible to operate the node from a Lithium-ion-polymer (LiPo) battery. Furthermore, this board can charge the battery when an external power source is connected to the main board. Since we use the board mainly for lighting applications, four LED drivers are embedded on the board. These drivers can be used to control regular and powerLEDs, to facilitate quick and simple explorations. The benefit of using a modular approach is that not each component has to be developed in the same quantity and users can select whether a battery operated node is required for their purpose.

2.3. Sensor and actuator boards

Lithne nodes can optionally be equipped with dedicated sensor and/or actuator shields. These shields can be tailored towards specific applications or can simplify specific tasks (e.g., connecting sensors, or connecting LEDs). Ideally, any shield is accompanied by a software library. This facilitates a smooth integration with the current platform and allows users to quickly apply the shields in their applications. Figure 3.4 provides an example of a DMX shield to control DMX lighting equipment. This is in line with good practice: For example, Arduino and Gadgeteer offer similar packages of hardware shields and accompanying software libraries.

2.4. Software

To provide designers with a smooth workflow, it should be easy to program the main board. Lithne supports this with software to program the main board and libraries that can be used to create software. Code for the Lithne main board can be written directly in C++, but we advocate the use of the Arduino framework. We provide a library for wireless networking and an application that allows users to wirelessly reprogram nodes in the network. An overview of all the software can be found in Appendix 3-B.

Lithne programming IDE

Programming the Lithne main board is done with a slightly adapted variant of the Arduino IDE. There are advantages of integrating Lithne with the existing software of Arduino: First, professionals with experience and knowledge on the matter have developed the software. The software has been used for several years and is in stable condition. Second, many people are already familiar with the software. Rather than introducing a new software package, we build on existing knowledge. Third, most of the previously developed software extensions are, or can be made, compatible with Lithne hardware. Important for interaction designers is that they can program in the Arduino language, in C++, or a mixture of both. This allows them to start with very simple applications and as their experience grows they can move to more advanced concepts and implementations. Software can be uploaded via USB, or wirelessly, as is discussed in the next section

Wireless programming tool

With the Lithne platform we want to facilitate design of prototypes in context, which allows prototypes to be adjusted to the specifics of that context. This implies that it should to be possible to easily adjust software even when devices are embedded. Ordinarily, new software has to be uploaded to a microcontroller via a wired interface. This means that the boards should always remain accessible to the user. However, when we think of embedded prototypes this practically means that the lid cannot be closed until the software is finished. This disrupts the design process and does not allow designers to experience the full implementation before the software is actually finished. What we want to advocate is a design process where the software is developed iteratively and in context, such that designers can focus on designing for experiences.

For this reason the Lithne platform provides support to reprogram nodes wirelessly. This is achieved by incorporating two processors on the main board where one programs the other. Practically, this means that an application is written on the computer, composed into a series of wireless packets that are transmitted to the co-processor, which then overwrites the software of the main-processor. This complete procedure of wireless programming is facilitated by a separate application that we developed. As Lithne is targeted at the development of networked prototypes, there will typically be a multitude of Lithne nodes in an environment. To allow users to deal with this, the Lithne upload tool also facilitates simple node management functionalities. Each Lithne node can wirelessly be (re)-named by the user, to give it a recognizable, meaningful name. The name of the last uploaded file is also stored, so the user can review which node has which application running.

The combination of the Lithne programming IDE and the wireless upload tool provide a smooth workflow to support the iterative design approach that is desirable for the development of networked products or systems. Changes in code can be quickly made in the Lithne IDE and directly uploaded to specific nodes in the network. This allows for short cycles of rapid prototyping, and evaluation of both system performance and user experience in context. Together with the simple network management facilities of the wireless uploader, users can easily maintain and program their networks, even when the nodes are embedded in products and environments.

Software libraries

Next to facilitating wireless programming of the Lithne node, we also want to facilitate designers in creating wirelessly networked applications. To this end, we developed software libraries that can be used with the Lithne hardware. Via these libraries we offer users a network structure and functionalities to communicate between nodes. With these libraries we stay close to programming concepts, such as object-oriented programming (OOP), that most interaction designers are familiar with. The two libraries that we made have similar structures, yet their implementations are specific to the programming language. In the libraries we ask the user to specify the same information when transmitting a message. Essentially this means that a user needs to specify (1) who to send the message to (this can also be a Node-object), (2) what functionality should be addressed, and (3) any arguments that might be required for that function. Generally, this means that a user composes a message that contains this information and transmits it. The library takes care of the correct network addressing and the actual transmission. For a user this means that he does not need to be concerned with the transmission of the data, but can focus on the content of the data. This again advocates to the user to think about *what* the system should *do*, rather than *how* it does this. A more extensive description, and the most recent versions of the library can be attained via Appendix 3-B.

In the following section Hyvve is presented, which is a modular and flexible prototyping platform for the design and development of intelligent lighting environments. Hyvve is created with the Lithne platform.

3. Hyvve

Hyvve (see Figure 3.5) is a system that consists of hexagonal ceiling tiles with and without LEDs, a grid structure, and software libraries. The 'active' tiles are tiles that provide light and they comprise of six 3-watt LEDs, a Lithne node, and connectors for sensor equipment. Hyvve uses the Lithne platform, which is used to control the light sources and can be used to program behaviors into the tile. In addition to these active tiles, there are passive tiles that do not contain any electronics. These are used to create a uniform, aesthetically pleasing ceiling and reduce redundancy of light sources in the environment.

3.1. Hyvve tiles

The Hyvve tile (Figure 3.6) has an hexagonal shape and is attached to a grid via magnets. This shape is suitable to create uniform grid-like structures. Furthermore, as most light sources and lenses provide rounded light projections, hexagonal tiles in a grid create a more uniform lighting pattern than rectangular or square tiles would create. Consequently, a hexagonal shape does not require complex optics to provide uniform lighting patterns. A simplified rendition of the light distribution is shown in Figure 3.7.

In the center of the tile a mount for a Lithne node and a sensor box (introduced later) is installed. The Hyvve tile operates at 12V and requires approximately 1.5A when all LEDs are fully on. It comprises six 3-watt LEDs: three warm white LEDs (150 lm. per LED, CCT[1]: 3300 K), and three cool white LEDs (150 lm. per LED, CCT: 7000 K). Two LED drivers control the LEDs. These drivers are used to dim the warm and cool white LEDs individually using PWM. Each LED is fitted with a 30° lens to bundle the emitted light and provide a uniformly illuminated area. The LEDs are mounted in the tile in a circular pattern, where the two types

[1] see Glossary at the end of this dissertation

Figure 3.5 Impression of Hyvve system showing a mixture of active and passive Hyvve tiles.

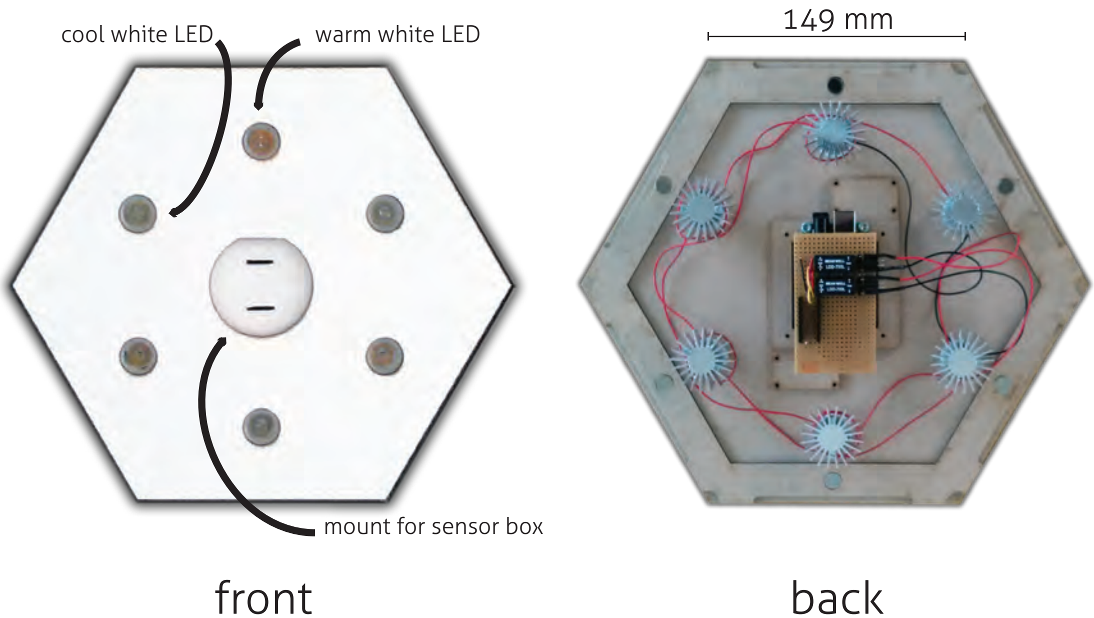


Figure 3.6 (front) Visible side of the Hyvve tile. (back) Non-visible side of the tile showing the wireless node, LED drivers and LEDs with heat sinks.

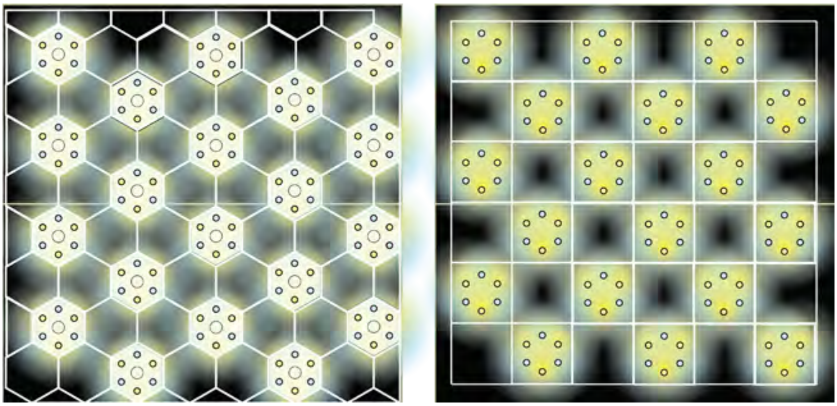


Figure 3.7 (left) Hexagonal pattern showing a uniform light distribution on the table. (right) Orthogonal patterns showing uneven light distribution. Both sketches have a similar circular light distribution.

Figure 3.8 Render of a passive sensor box containing a motion sensor, infrared receiver and a light sensor for the Hyvve system.

Figure 3.9 The Hyvve grid is shown when no Hyvve tiles are attached to it.

of LEDs are alternated in order to mix the two light colors. The light output is sufficient to provide a lighted area in which it is pleasant to read. Furthermore, the Lithne node can control the light output of the warm and cool white LEDs via the LED drivers individually. This makes it possible to control the color temperature of the light output.

3.2. Sensor box

Many intelligent lighting applications require sensing capabilities: For example to detect presence of users or measure the external lighting conditions. To allow designers of intelligent lighting applications to explore sensing solutions it is possible to attach sensors directly to each active tile. This is facilitated in the form of sensor boxes (see Figure 3.8). In the center of each active tile a sensor box can be connected via a 12-pin connector. The 12-pin connector directly connects to the Lithne node. The connector provides power to the sensor box and facilitates digital and analog communication channels. A magnet is used to keep the sensor box in place and to make it simple to attach sensors to the tile. Another reason to include a sensor box is the interdisciplinary nature of the project. As one colleague is researching distributed sensing solutions to develop context-aware lighting applications, the sensor boxes make Hyvve a suitable carrier for sensors equipment and at the same time provide an integrated platform for different disciplines.

Providing each Hyvve tile with a sensor makes it possible to locally process the sensor information and program the tile to act meaningfully with this information. This results in the traffic on the network being low. The makes the reliability of the complete network high, as failures with the sensors are restricted to a single node. Furthermore, as information is acquired and processed locally, and actuation can also be provided locally, the behavior of the Hyvve tiles can be made highly context and location specific. A benefit is that the sensor boxes are directly powered by the Hyvve tile and do not rely on battery power. Also, users are not burdened with sensor nodes attached to their desks, workplaces, or bodies. To date, no sensor box implementations have been developed yet, but two types are conceptualized:

Active sensor box – This type of sensor box has an internal microprocessor and sensors. The microprocessor deals with all data manipulation and sensor algorithms and communicates directly to the Lithne node on the tile (e.g., via a serial connection). An example of an active sensor box could be a camera processor. By using a dedicated microcontroller for the video analysis, only the relevant data is communicated to the Hyvve tile.

Passive sensor box – The passive sensor box contains sensors that are directly attached to the pins of the Lithne node, which polls and processes this information. An example of a passive sensor box is shown in Figure 3.8, containing a passive infrared (PIR) sensor, a light sensor, and an infrared decoder.

As both the Hyvve tiles and sensors boxes can be combined in a modular way, a lighting designer has many degrees of freedom to explore different setups of the system. For example, it is possible to explore the implications of multiple sensors, sensors of different types, or simply to find the best sensor location. A modular approach was also advocated by experts in the evaluation of the adaptive office installation.

3.3. Hyvve grid

The Hyvve grid (shown in Figure 3.9) is the backbone of the Hyvve tiles. The grid consists out of hexagonal outlines with sides of 150mm each. This is 1mm larger than the sides of each tile and the small distance between two tiles is sufficient to easily attach and detach a single tile in the grid. The main purpose of the Hyvve grid is to provide the system with its *flexibility*. It does this in two ways: First, the position of the Hyvve tiles can easily be changed because of magnet connections. This makes is easy for a designer to experiment with different arrangements of the tiles. Second, power is distributed throughout the grid, which means that a designer is not limited to existing power sockets. The magnets in the Hyvve grid are aligned with the magnets in the tiles so there is a sturdy connection between the two. Power is supplied to the tiles via individual wires. Future implementations of this grid should investigate whether power can be supplied to the tiles via the Hyvve grid as this would increase the flexibility of the system. The most important reason not to include this in the prototype is that bad contacts could cause the entire system to fail due to power shortages. Although the Hyvve grid has an irregular structure, it is possible to integrate the grid in existing (orthogonal) ceiling infrastructures. To deal with orthogonal structures three types of end-caps are created that fill up the edges of a grid.

The grid is a vital part of the Hyvve system as it reduces the installation of a Hyvve tile to selecting a desired location, connecting the power and 'snapping' it to the grid. The tiles can easily be (re-)placed to create custom ceiling layouts. This makes it easy to explore and experiment with varying configurations of ceiling layouts. Light sources are no longer constrained to a single location, as is the case with current lighting infrastructures, but can be placed in every location in the grid.

3.4. Hyvve software

The Hyvve hardware provides a modular and flexible structure as it allows designers to explore different physical lighting arrangements. Additionally, a lighting technology should facilitate designers and researcher to shape or 'program' the lighting behavior as this allows for exploration of novel lighting behaviors.

To provide freedom of exploration to people using the Hyvve system, two software aspects were developed: (1) firmware running on the Lithne nodes to control the Hyvve tiles and (2) an additional (JAVA) software library to simulate the Hyvve tiles and control them from a central server. The firmware running on the Hyvve tiles can be used to control the functionalities of the tile: switch on/off, change the intensity and change the colour temperature with transitions. For example, a command could be to 'set the intensity to 80 with a transition of 1500ms' or 'set the CCT[1] to 20 with a transition of 500ms'. This should prepare designers to think about light behavior, rather than the technical implementation. As this is directly implemented in the firmware, commands can be directly given to the tile, for example through custom designed interfaces. No intermediate server or gateway is required for this. Practically, this means that anyone who uses a Lithne node in the network can create an interface for the tiles. In special cases, the firmware on the nodes can be adjusted, for example to process data from sensor boxes. The latest firmware can be found in Appendix 3-C.

Additionally, software is developed to control the tiles from a PC. This software contains two classes to control the Hyvve system; one class representing the Hyvve tiles and one class representing the Hyvve grid. The HyvveGrid class establishes a connection to the wireless network via XBee. Tiles can be digitally attached and detached and moved around the grid. Hyvve-objects attached to the HyvveGrid automatically connect to the network, which means that manipulations of the light settings in simulation can be rendered in the actual environment. Consequently, this means that behavior that is programmed in the simulation environment is mimicked in the real implementation. This allows for quick simulations and explorations of light behavior. Furthermore, it is possible to monitor or manually control the installation.

The combination of the simulation environment and the actual control environment makes the installation versatile. It allows for experimentation with lighting behaviors 'offline' and/or experiencing them in an actual environment. With the simulation environment, it is possible to explore how a system scales to larger areas and to other ceiling layouts. Computationally intensive algorithms can be offloaded to a central processor that can actuate a complete environment. The central processor can also act as a gateway for other devices. However, it should be noted that currently, messages from central server to individual tiles typically takes 15-25 ms. Especially for large installations – where each tile is addressed individually – this results in latency in the system. Future development has to improve this. Appendix 3-D includes a scenario video that shows the Hyvve system and how external devices are used to control the lighting infrastructure (also accessible via Layar on Figure 3.5).

3.5. Designing Hyvve

Though chronologically presented in this dissertation, the actual design of Hyvve was intertwined with other design-research activities. The design of Hyvve is informed by insights acquired in the evaluation of the adaptive office: It has a modular structure, and different behaviors can be programmed into the system. Yet, prototypes of the Hyvve system were used in various installations. One of these installations was already presented in Chapter 2.3, others

[1] see Glossary at the end of this dissertation

are presented in the Adoption phase. These installations have served a dual nature: They are used to showcase the capabilities of the system, but they have also been instruments in the design of the Hyvve system. Consider the following examples: The study presented in Chapter 2.3 required a central server to control the lighting behavior, because the lighting behavior had to be consistent between conditions. This led to the development of the JAVA software to control the installation from a central location. The JAVA software in turn allowed others to develop for the control of this system. A colleague (Serge Offermans) developed a tablet application and implemented two physical interfaces with the Hyvve system (Magielse & Offermans, 2013). Furthermore, having a central server also makes it easily possible to integrate a light-body as a mechanism to control several light sources.

4. Discussion & conclusions

In this chapter I presented Lithne and Hyvve as tools to facilitate designers of interactive (lighting) environments. The design of these technologies is based on experiences with creating interactive lighting environments and insights acquired in the Incubation phase of the project.

4.1. Lithne

Lithne is a platform that facilitates interaction designers to explore and implement networked products and environments. Experiences with designing interactive installations showed that there is a discrepancy between the way designers would like to work, and the tools they have available to work with. Many tools advocate a way of working that constrains an iterative design process in context with explorations targeted at behavioral qualities of the system, rather than at technical qualities of the system. At the start of this chapter I outlined six qualities that a tool for interaction designers should contain. The Lithne platform is based on these requirements. The hardware is (1) small enough to be embedded in prototypes and (2) external hardware can easily be connected to the Lithne boards. Furthermore, since we added support for battery-powered operation it is possible to create portable prototypes. The simple programming language and easy procedure to upload new applications to the Lithne boards supports (4) an iterative design process. Additionally, users can develop their prototypes (3) in context, since new applications can be uploaded wirelessly. This means that devices can be embedded in products and environments and users can direct their attention to shaping the experience for users. Finally, with the (5) simple-to-understand network library, users are guided to think in terms of (6) how they want their system to behave, instead of being concerned with the technical infrastructure.

The individual components of the Lithne platform cannot outperform similar platforms in terms of hardware specifications (e.g., faster processing, or more flexible network architectures) or software specifications (e.g., programming environment, and programming language). The core value of the platform is in the simple and integrated solution that specifically supports an iterative design process in context. It opens up new opportunities for designers of interactive systems that are in line with their design process. Workshops with students show that the platform enables them to create an initial network within several hours. However, one of the difficulties, as we experience now, is to provide complete and up-to-date documentation and support for the platform. Although we initially aimed to distribute the platform, first at our own university and later also outside the university, we now realize that it is difficult to achieve this as this is a time-consuming and labor-intensive process that is difficult to perform well in addition to other duties.

An important issue when working with prototyping tools is the reliability of the individual components. Even though it is difficult to quantify the 'reliability' of the Lithne platform, our own experiences and those of students were promising. Students are able to adopt the platform in their projects and have presented working prototypes of networked systems. Furthermore, our own installations and prototypes (some of which are discussed in this dissertation) have been running for multiple months without critical failures. Especially when considering the Nursery phase as a preparation for the Adoption phase, it is important to take these factors into account. We believe that the choice for mature technologies such as the XBee hardware and Arduino platform, provide a solid basis for the Lithne platform. Even though the individual parts of the Lithne platform can be improved, the current state of the platform is stable.

4.2. Hyvve

The current system is a prototype of the Hyvve concept. This means that in the implementation and realization, concessions to the original concept are done. For the Hyvve grid solutions should be explored to supply electric power to the individual tiles in a simpler – yet robust – way. In the current implementation magnets are used to connect the tiles to the grid, but other types of connections might be explored. Also, in the current system there are only light sources that provide downward illumination for horizontal surfaces. In actual environments, light sources are required that also illuminate vertical surfaces, otherwise the complete environment will be perceived as dark. That is to say that different light sources need to be explored for future installations.

In my experience, the flexible configuration of the system has its core value in the design phase. It can be argued that end-users can rearrange the lighting installation, but the implementation of lighting behavior will remain the task of a professional designer. This will involve selection of appropriate sensor modalities and presumably some software development. Perhaps that in future installations concepts for end-user programming of lighting environments are developed that make it possible for end-users to (re-)configure their lighting environments.

Until that time a flexible infrastructure is mostly interesting during (re-)design of a lighting environment. However, this flexible nature of the Hyvve system allows for designing in context. The hardware as well as the software facilitate fast and dynamic configuration of the tiles. This means that a designer can focus his attention on the light behavior of the system and this can be explored iteratively in the actual environment. Furthermore, the sensing capabilities of the system can be coupled to the actuation capabilities of the system, which means that contextualized and localized behaviors can be provided. Also, the system supports both a centralized and decentralized architecture, which means that the choice for a specific architecture can be derived from the implementation and is not dictated by the technology. Via gateways it is possible to connect to external systems (e.g., tablets or smartphones), which means that technologies that are brought in by the user can be used in the system. Since the tiles form a unity of sensing and actuation, it can also serve as a platform for interdisciplinary work: Research on distributed sensor solutions, wireless network architectures, and interaction design can be combined in a single platform. The adaptive office (in Chapter 2) is an example of such an interdisciplinary approach to the design of adaptive lighting environments. In that installation the three involved disciplines contributed their own technologies to a joint installation. With the Hyvve system it is possible for different disciplines to collaborate on a single platform to provide a unified and integrated solution.

Hyvve is an example of a lighting system that integrates sensing, actuation, and intelligent behaviors. Contrary to the commercially available lighting equipment, Hyvve provides a lighting tile that has all relevant components integrated and remains aesthetically pleasing, without compromising flexibility and control. Where traditional lighting equipment is constrained to specific locations, Hyvve as a system is not. Tiles can be placed anywhere in the grid and are automatically configured in the network, making them directly available for use. This means that a designer does not have to decide about the location of light sources a priori, but can explore and experience possibilities iteratively in context.

4.
On the design of Bolb

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1. Introduction

In this chapter I present the design of Bolb: a personal and portable light controller. It is based on insights of the Incubation phase and of exploratory observations. Bolb is designed with three goals in mind: (1) Provide each user with individual control over local lighting conditions, (2) provide a mechanism to balance control between users that share a lighting environment, and (3) allow users to program their environment with relevant lighting conditions. To control the lighting conditions at their location, Bolb provides users with an individual light-body of which they can manipulate the size, light intensity and light color. The light-body is a mediating interaction mechanism that provides a consistent interaction experience across different lighting environments. Furthermore, when multiple users share a lighting environment, the system provides a mechanism that balances control between users. Finally, users can associate lighting preferences to locations in their environment, providing them with a mechanism to teach their system how it should behave. In the following section, I first present the motivations for the design of Bolb, and the concept for Bolb. The implementation is explained separately as this differs slightly from the original concept.

1.1. Motivation

There are various motivations for providing people with individual control over lighting conditions. One of the main reasons is that different people have different lighting preferences (Moore, Carter, & Slater, 2002a). By providing individual people with means to adjust the lighting conditions, they can set it to their own preferences. Additionally, it is reported that people who have control over their lighting conditions, have a better mood and are more satisfied with the lighting conditions than people who do not have control (Newsham, Veitch, Arsenault, & Duval, 2004). Additionally, it is found that manual control of light has the potential to save energy without compromising the perceived quality of the lighting conditions (Maniccia, Rutledge, Rea, & Morrow, 1999; Moore, Carter, & Slater, 2002b). Combinations of manual control and intelligent dimming schemes (e.g., occupancy sensing and/or daylight sensing) are able to yield even larger energy savings. This shows that providing individual control to users can result in satisfied users and lower energy bills. Yet, when control is distributed to individual users, this changes the (current) control structures for lighting environments and might lead to undesirable situations: For instance the most outspoken personalities might claim all control (Moore et al., 2002b). A possible way to resolve this is through creating lighting system architectures that allow each individual light source to be controlled. The Hyvve system facilitates this as each light source can be manipulated individually. Even then, there may be situations where individual control can lead to conflicting situations: e.g., when people are seated closely together. Furthermore, the way control is offered to people can be a way to influence the social context. Chapter 2.4 showed how control over a lighting system could be distributed among a group of people. The results provided indications that the way control is distributed between people, also affects their behavior: Individual control alone made people behave more self-centered, whereas shared control made people more considerate towards others. I therefore argue that a lighting controller should also provide mechanisms to balance control among users.

2. Sensitizing

Prior to the design of Bolb I performed exploratory observations. In these observations I followed two colleagues for one full week to gain insights in the structure of their working day and the way they use their office environments. These observations focused on the way light could support their activities. Furthermore, these observations provided inspiration for the design of a light controller. One colleague was observed for three working days, the other for two working days. During these days I made notes and took pictures of their activities and behaviors (e.g., Figure 4.1). Additionally, two desk lights were installed on their desk and via these lights I tried to provide them with lighting for the different activities they performed. I provided lighting conditions either as a suggestion to them (my initiative), or they explicitly requested specific lighting conditions. However, this meant that the lighting conditions were always created in dialogue with the people under observation. Afterwards I mapped out all the pictures and notes chronologically on large sheets. I studied these individually for commonalities and patterns, which were then discussed with the participants. Furthermore, I reflected on my role as intelligent system. This exercise provided the following insights:

- To act intelligently, a system needs sufficient degrees of freedom. In this exploration I tried to influence the behavior of participants by providing them with different lighting conditions, but I was unable to do so, as the degrees of freedom were limited.
- People structure their activities to locations that are meaningful to them and allow them to work pleasantly and optimally. One participant explained that with the simple addition of having a desk light he now had a ‘reading zone’.
- The initiative to change the lighting conditions may shift between the user and the system. A system can suggest lighting conditions if the user requested them earlier.

Figure 4.1 Impression of the observation study. (left) Two desk lights installed at the desk of a participant. (middle) The 'reading zone' that emerged when the desk light was installed. (right) Desk light installed at the desk of the second participant.

I also observed that different locations in the office environment have a different meaning to people. Particular locations (e.g., the desk, or a meeting table) are used for particular activities. Also within these locations people give different meanings to particular places on these locations. For example, at the desk people have a place where they work at their computer and a different place where they read articles. These locations may require different lighting conditions. Yet, different lighting conditions might also lead to a different use of that space, as the 'reading zone' that was suggested by one participant revealed. From this I conclude that a light controller can provide people with rich control over their lighting conditions, but it can also facilitate individuals to create lighting conditions in locations that are meaningful for their activities.

3. Bolb concept

The Bolb controller provides users with individual control over their lighting conditions via a light-body. The light-body is a mediating interaction mechanism that separates control of the lighting conditions from the physical lighting setup. This is necessary because the Bolb will be used in environments of which the lighting setups are unknown, or change frequently. Under such circumstances, a direct coupling between the lighting setup and interaction possibilities is undesirable as this would mean that the control interface would have to be adjusted when the lighting setup changes. This is especially true in the case of using the Hyvve system, which has as a core quality that it is simple to create differing lighting setups. The light-body concept, as it was used in the adaptive office, was slightly adjusted. In that implementation, there was a single rotary controller that controlled both the size and the intensity of the light-body. With the Bolb controller three parameters of the light-body can be controlled separately: the size, the intensity, and the color temperature of the light-body. The color parameter is added as the Hyvve system provides control over color temperature of the lighting conditions. In the following paragraphs the effects of manipulating the individual parameters of the light-body are discussed.

The light-body has a circular shape and controls light sources that fall within its radius. Light sources that are controlled by this light-body are set to match the parameters of the light-body: the light intensity and color (temperature). All light sources within this light-body thus provide similar lighting conditions. Whenever a user increases the size of the light-body, more light sources fall within the radius of the light-body (illustrated in Figure 4.2 with a Hyvve ceiling). This allows the user to change the distribution of light over an area. This, for example, allows a user to create a spotlight for reading activities or a large illuminated surface that is spread over the entire table for group work. The second parameter of the light-body is the light *intensity*. The intensity of the light-body is coupled to the light intensity of the individual light sources. Which means that when a user decreases the intensity to 10%, each individual tile adjusts his light output to 10% (illustrated in Figure 4.3). The third parameter of the light-body is the light *color*. It should be noted that for the current example, light color is expressed as CCT and not as RGB. However, it is also possible to create a light-body with RGB colors, as the implementation later in this chapter shows. Whenever a user decreases the CCT the lighting conditions get a warmer color. As the user increases the CCT the lighting conditions get a cooler color. When the CCT is set to 50% of the range, there is a mixture of warm and cool light, resulting in white light (illustrated in Figure 4.4).

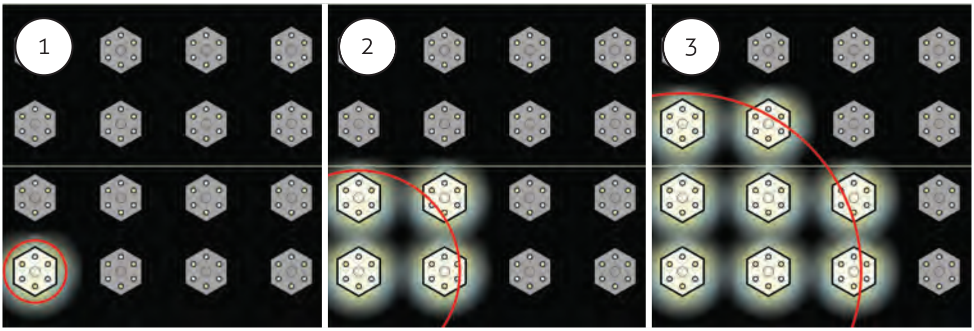


Figure 4.2 Illustration of the effect of increasing the size of the light-body.

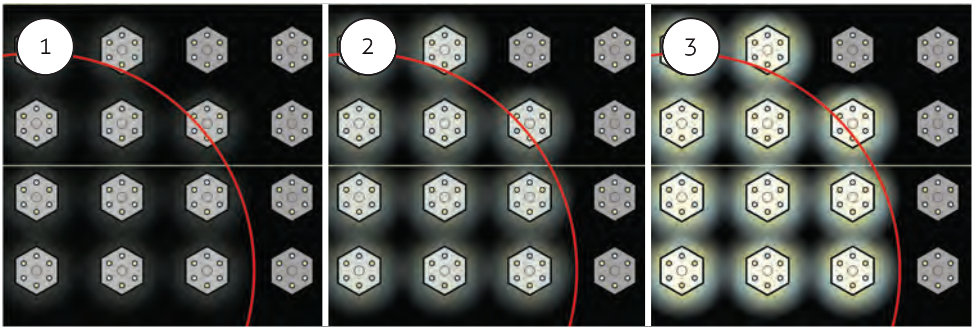


Figure 4.3 Illustration of the effect of changing the intensity. From left to right the light intensity increases from 20% to 50% to 100%.

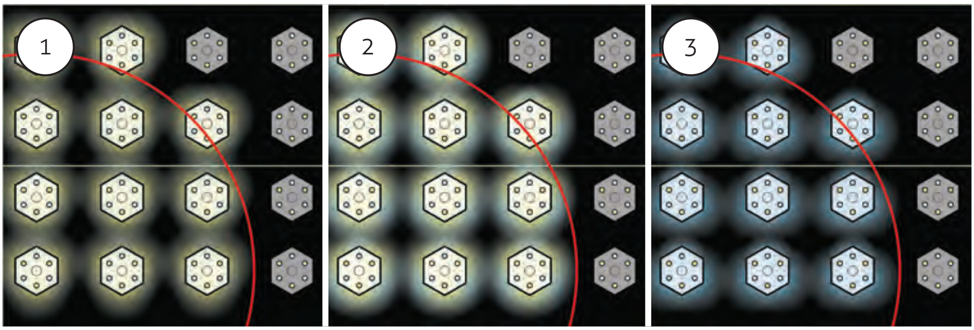


Figure 4.4 Illustration of the effect of changing the color temperature. (left) Warm white light only. (right) Cool white light only. (middle) Combination of warm and cool white light.

The center point of the light-body is linked to the location of the Bolb controller, which makes this the fourth control parameter. Research has shown that when the location of the controller and the light sources that are controlled are closer to each other, this reduces energy consumption as a user can directly experience the lighting conditions that he requires (Moore et al., 2002a). This means that with the Bolb controller, the user always manipulates the lighting conditions at his location. Furthermore, the Bolb controller is portable. Consequently, as the light-body is related to the location of the Bolb controller, it means a user can move the controller to change where he wants the light to be.

The Bolb controller thus provides each user with a personal and portable light-body and capitalizes our physical engagement with the world. Yet, users are not alone in their offices. Since each user is provided with a personal light-body, a mechanism to balance control over the lighting conditions becomes even more important.

3.1. Balancing control between users

By introducing the light-body as an interaction concept, users can individually control the lighting conditions. However, by increasing the size of their light-body users can create situations where two light-bodies overlap. In cases where the parameters of the light-body are similar, this is not an issue. But there may also be cases where two users have highly contrasting lighting conditions, for example because they are performing different activities, or because they have different preferences. This argues for a mechanism where control is distributed over different people, as was investigated in Chapter 2. In the Bolb controller, a mechanism to balance control is implemented. This mechanism has three steps: (1) Users are notified when their light-bodies interfere, after which (2) they can either decide to merge the light-bodies or not. When the light-bodies are merged (3) the users share control over this light-body. This sequence is depicted in Figure 4.5.

Users are made aware of the light-body of other participants by haptic feedback on their controller. When a user increases the size of his light-body, and this action would cause overlap with another light-body (Figure 4.5, image 2), haptic feedback is provided to the user: The rotational dial cannot be rotated further. When the user holds the rotational dial in the position to increase the size of the light-body, after several seconds the intensity of the haptic feedback decreases and the light-bodies are merged. This procedure makes the user aware of his action, and makes it a conscious decision to engage in a shared light-body.

When the user persists to increase the size of his light-body, the two light-bodies are merged (Figure 4.5, image 3). However, this means that at least one of the light-bodies needs to change its settings. In this case the light-body of the person entering the other light-body is adjusted. This is inspired by social norms in daily life: When you enter someone else's space, you adjust to the context of that person. It is common courtesy that you do not change the lighting conditions of someone else when you enter a space. Practically, this means that the settings of the light-body of the person entering, are set to the settings of the light-body of the other person. This procedure applies to any additional light-bodies that are merged: The light-body that initiates the merge, adjusts its light settings to the light-body it merges with.

From then onwards, control over the light conditions is shared. This means that both users can contribute equally to the shared lighting conditions. Practically this means that the resulting light intensity and light color are the average of the light-bodies of both users. It must be noted though that this only occurs when one user decides to make changes to the lighting conditions, as these parameters are equalized in step 2. Furthermore, the amount of change one person can make is limited. When one wants to make large changes to the lighting conditions, this is only possible when it is done in collaboration with the other. To disengage from a merged light-body a user can simply reduce the size of his light-body until both light-bodies are separated (Figure 4.5, image 4).

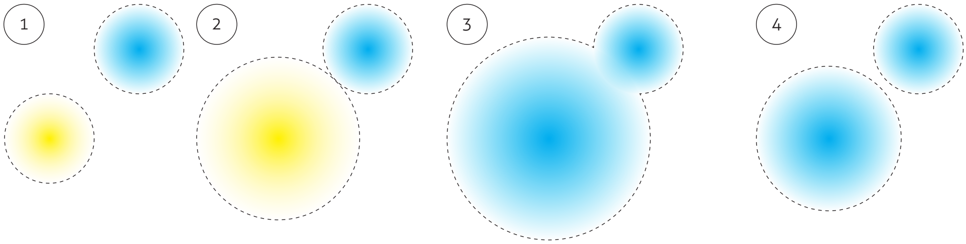


Figure 4.5 Representation of the different states of sharing a light-body. (1) Two separate light-bodies. (2) One light-body is increased and almost interferes with the other light-body. (3) Two light-bodies are merged and their parameters equalized. (4) Two light-bodies are separated again.

3.2. Creating meaningful light behavior

In the previous sections I described how the Bolb controller provides users with a light-body to individually control lighting conditions as well as shared control via a balancing mechanism. The third purpose of the controller is to allow users to program a lighting system with lighting conditions that are contextually relevant. The Bolb controller enables users to couple lighting conditions they prefer to locations in their environment that are meaningful to them. To create a relation between meaningful locations and preferred lighting conditions the Bolb is sensitive to three aspects:

- *Environment*; the physical space in which the Bolb currently is situated. In an office there is for example a working environment with individual desks or a meeting environment. Generally an environment constitutes a room or space.
- *Location*; a location is a part of an environment and is a particular place in that environment. An environment might have multiple locations that are meaningful for

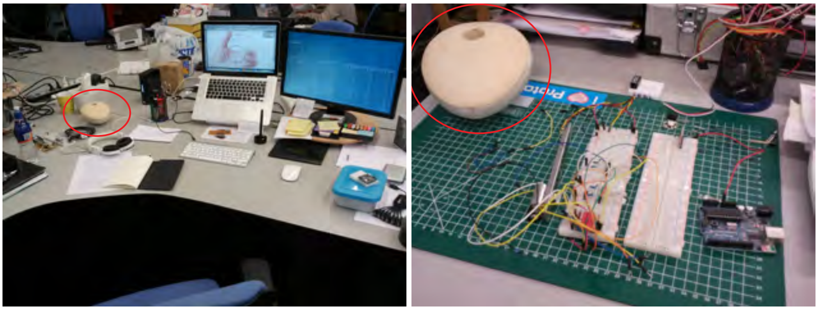


Figure 4.6 Example of the Bolb controller in one environment at different locations, where it can support different activities. (left) Desk work. (right) Detailed work with electronics.

Figure 4.7 Impression of how the orientation influences the lighting conditions. (left) Individual work in a meeting environment with spotlights on the workplaces. (right) Bolb put towards the side of the table to provide general illumination for an informal meeting.

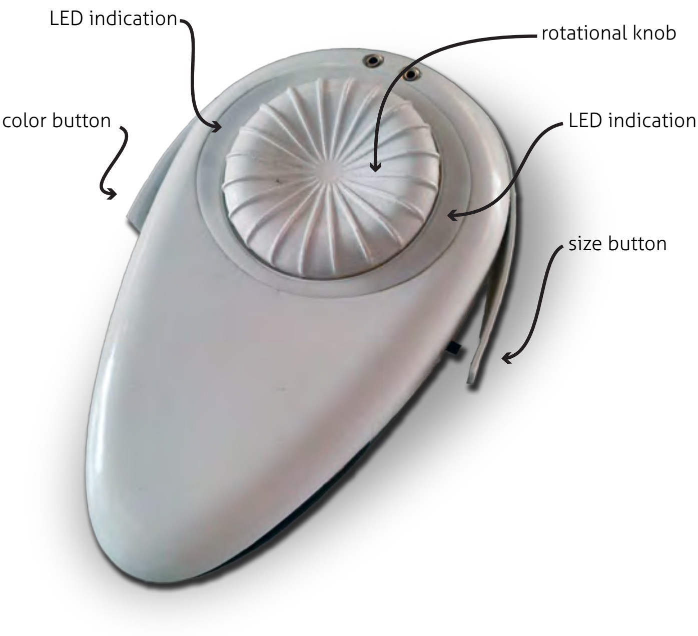


Figure 4.8 Prototype of the Bolb controller.

a user. As was seen in the observation a workplace might contain a location for reading and another for computer work. Figure 4.6 presents an example of a sketch of the Bolb controller in different locations.

- *Orientation*; each location might serve different purposes. For example, a meeting environment can facilitate formal and informal meetings and the group size might vary. This might require different lighting conditions. Therefore the orientation of the Bolb controller can be used to differentiate between lighting conditions at one location as is shown in Figure 4.7.

Whenever lighting preferences are stored, the variables of the light-body are coupled to the three parameters of the light-body (size, intensity, color). In the future whenever a user places the Bolb controller in a familiar environment at a particular location in a particular orientation, the lighting conditions that are stored for that combination are recalled.

In the design of Bolb I took an embodied perspective to interaction. In the first place, I observed that the location in which people perform activities is meaningful to them: Reading documents takes place at a different location than computer work, or discussions. Furthermore, each location may be used for different activities, for example at a meeting table informal and formal meetings are held. The Bolb controller in the first place provides people with the opportunity to adjust the lighting conditions to locations that are meaningful to them. Furthermore, by contextualizing preferences in specific locations, Bolb also capitalizes on a user's historical interactions. Over time, this means that Bolb develops personalized behaviors, based on the way that its owner uses it.

4. Bolb implementation

In this section I present the actual implementation of the controller. For practical reasons the the implementation of the controller differs slightly from the concept. Investigation towards a full implementation of the concept revealed that this would have implications for other components in the system: i.e., this would require the development of sensor boxes for the Hyvve tiles. The distinction between the design and the prototype is most apparent in the way users can program light behaviors in their environment. Figure 4.8 shows the prototype of the Bolb controller, which is created with a Lithne node with a battery board.

4.1. Manipulating the light-body

As was mentioned earlier, the Bolb controller allows users to manipulate three parameters of the light-body: the *size*, the *intensity* and the *light color*. The rotational knob controls these three parameters: In all cases the principle is that rotating clockwise increases the value, rotating counter-clockwise decreases the value. With the buttons on the side the user can select which of the parameters to manipulate. The rotational knob is attached to a motor. This motor is used to provide force feedback to the user. The software that operates the Bolb controller contains a local representation of the light-body (see Figure 4.9). The internal representation of the light-body is used to enable actuators such as LEDs and motors. The light color is divided in an RGB representation or a CCT representation. Depending on the context the user is in, one of the two is active. In an area where most light sources are RGB light sources the user controls light via an RGB controller. In other spaces the user controls the CCT, for example in environments with Hyvve tiles installed. Intensity, color, and size are constrained to a minimum and maximum value depending on the size of the environment. Additionally, there are minimum and maximum borders that indicate the light-body of other users which depend on whether the user can engage or is engaged in a shared light-body. An overview of the software of the Bolb is presented in Appendix 4-A.

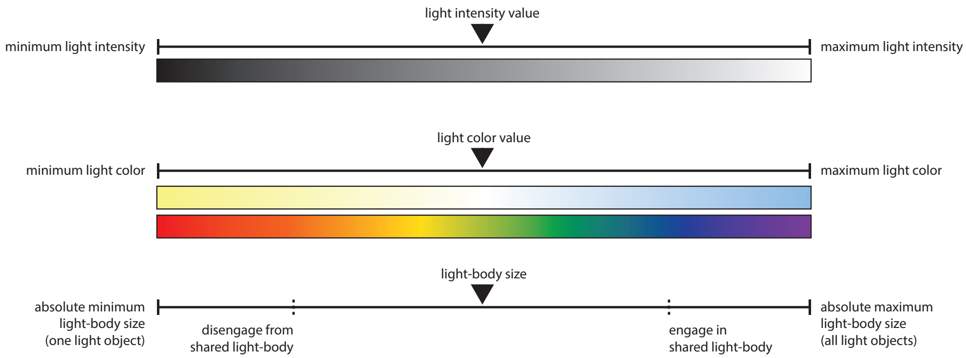


Figure 4.9 Representation of the three parameters of the light-body and their value ranges.

All variables are mapped on a linear scale. However, for the light intensity – and to a certain extent also for the light color – the light output is not linear. It would be possible to correct the logarithmic mapping of the light output to a linear scale, yet this would have cost too much (time) resources that were not available in the current project and was found of lesser importance for this implementation. In the following sections the parameters that users can manipulate are discussed individually.

Manipulating light intensity

When no button is pressed the *light intensity* parameter is active. The Bolb controller provides feedback and feed-forward to the user via the LEDs next to the rotational dial (see Figure 4.10). The LEDs on the right are brighter than the LEDs on the left to indicate what happens when the user rotates clockwise: the lighting conditions become brighter. The LEDs on the left are dimmer and show that when the user rotates counter-clockwise: the lighting conditions get dimmer. When the user reaches the minimum or maximum intensity, the motor prevents the user from rotating further. The light intensity parameter is also used to activate and deactivate the controller. When a user completely dims the light intensity (sets it to 0), the light-body of the user is deactivated. As is explained later, this also means that other users can no longer 'feel' this light-body. In this control-mode the LEDs show the current color that is selected. This provides the user with two points of reference on the intensity scale.

Manipulating light color

When the user presses and holds the left button on the Bolb controller the *light color* parameter is activated. Whether the RGB or CCT parameters are used depends on the context in which the Bolb is used. For example, in an environment with many Hyvve tiles, CCT is used, in other environments RGB might be used. When there is a mixture of CCT and RGB tiles, a translation from one parameter to the other is made.

When in CCT-mode the user can increase the color temperature by rotating clockwise: The lighting conditions become cooler. When the user decreases the color temperature, by rotating the knob counter-clockwise, the lighting conditions become warmer (Figure 4.11). When in RGB-mode the Bolb allows the user to manipulate the hue value of the lighting conditions (Figure 4.12). The hue value is chosen as a control parameter for the light color as this allows users to cycle through all possible light colors using a single scale.

Manipulating the size of the light-body

When the user presses and holds the right button on the Bolb controller the size parameter of the light-body is activated. The user increases the size of the light-body by rotating clockwise, and decreases the size of the light-body by rotating counter-clockwise. In this mode there is no visual feedback on the device (see Figure 4.13: middle): The user should observe in the space the effect of his manipulation to see whether the light-body has reached the desired size. The light-body is constrained to cover at least one light source and at most all the light sources in the environment. By constraining the size of the light-body to at least one light source, users cannot make their light-body so small that no light source responds when they manipulate other parameters. This could lead to confusion. The maximum size is constrained to cover all light sources in an environment. This informs the user that there is nothing more to control, and prevents situations where a user increased his light body to an immense size, from which it would take a lot of time to reduce it to normal proportions. Additionally, when there are other light-bodies in an environment, the maximum size is constrained to the edge of the nearest light-body. Users manipulate the size to (dis-)engage in a shared light-body, as was explained earlier. In every case when the user reaches the end of a range haptic feedback is provided.

Only when a user encounters another light-body (as he is increasing the size of his light-body), the controller also provides visual feedback. The tactile feedback prevents the user from rotating further and the LEDs on the right side light up in a yellow color, as is depicted in

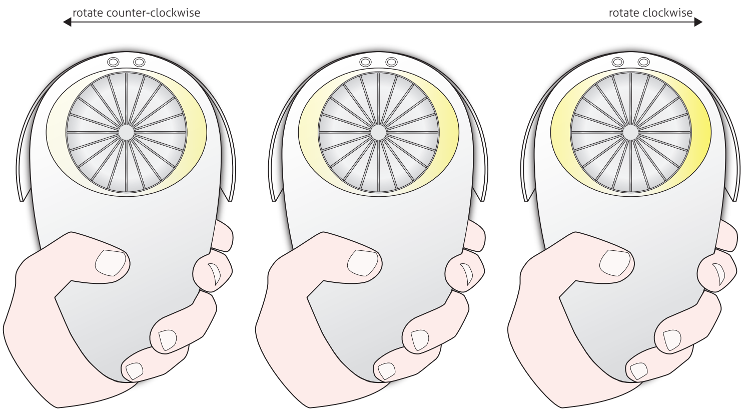


Figure 4.10 The Bolb controller in intensity mode. The left image depicts the knob as it completely rotated to the left. The center image depicts the Bolb when the intensity is set approximately halfway the range. The right image shows the Bolb when the intensity is set to its highest.

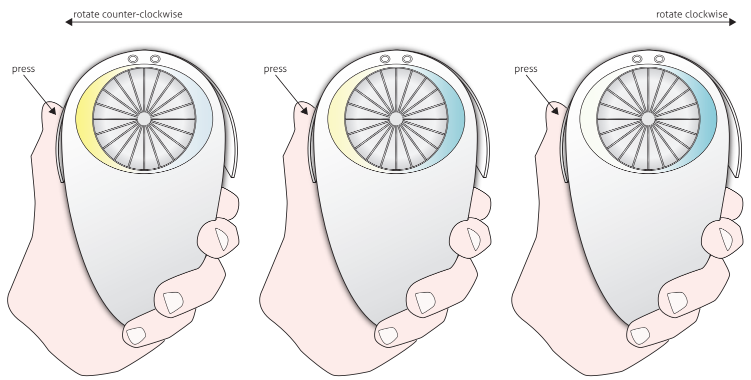


Figure 4.11 Bolb controller in CCT-Mode. The left image shows the controller as it is completely rotated towards warm lighting conditions. The center image shows the neutral white lighting conditions. The right image shows the cool white light settings.

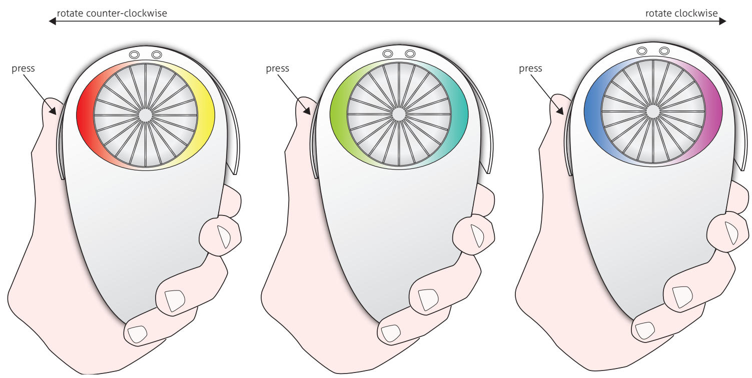


Figure 4.12 Sequence of manipulation of the light color by cycling through different hue values.

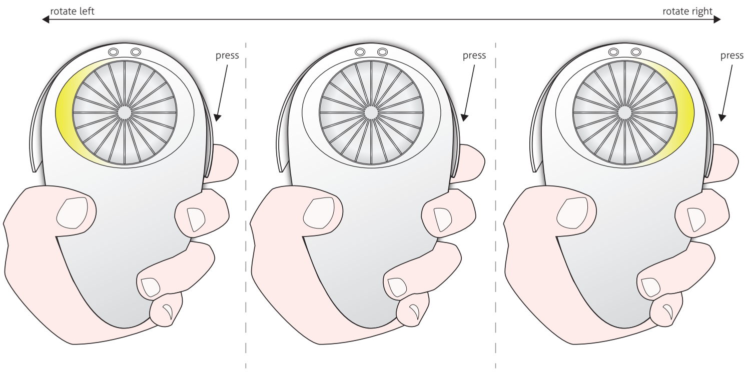


Figure 4.13 The Bolb controller in size mode. The center image shows the default behavior. (left) The visual feedback when a user disengages from shared control. (right) The visual feedback when the user engages in shared control.

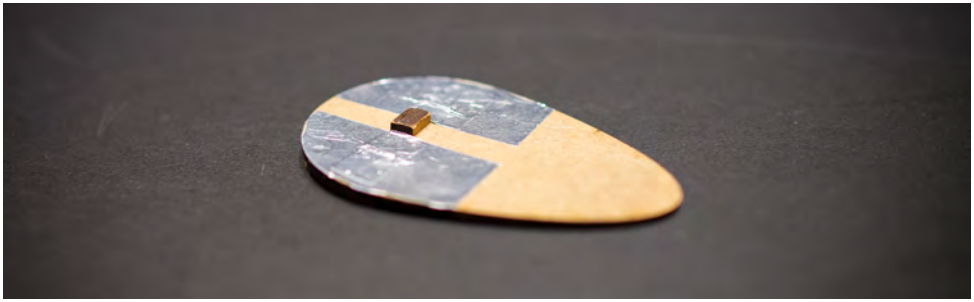


Figure 4.14 The docking station that allows users to move their light-body to different locations. Lighting conditions can be attributed to each docking station.

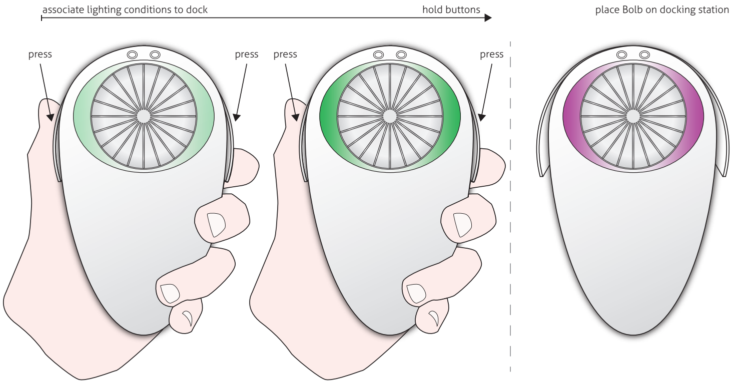


Figure 4.15 Bolb behavior of associating (left and middle) and retrieving (right) lighting preferences.

Figure 4.13 on the right. This informs the user that he encounters another light-body. The user now has a choice to either stop rotating or merge the two light-bodies. When the user chooses to increase the size of his light-body, the haptic feedback decreases over time and the two light-bodies merge, following the balancing mechanism that was explained earlier. Whenever the user wishes to disengage from the shared light-body he can decrease the size of his light-body. When he is about to reduce the size such that the two light-bodies would be separated again, the Bolb again provides haptic feedback to indicate this border. Furthermore the LEDs on the left side will light up in a yellow color, as is depicted in Figure 4.13 on the left. The haptic force diminishes over time to indicate to the user that he disengages from the shared light-body. The light-body keeps the settings of the shared light-body and does not return to the settings it had prior to sharing control. This is done to provide a calm transition from one state to the other. As users have full control again, they can set the lighting conditions to whatever they prefer.

Sensing environment and location: Moving the light-body

The location of the light-body depends on the location of the controller: The center point of the light-body is coupled to the position of the controller. To make this possible, the Bolb controller needs to sense the environment it is in and the location within this environment. One possible implementation could be via sensor-boxes attached to the Hyvve tiles that communicate via line-of-sight communication to the Bolb (Appendix 4-A elaborates on other solutions to implement the behavior described in the concept). However, this would require the design and implementation of these sensors boxes. In this case, a simpler and less costly solution was implemented via *docking stations* (see Figure 4.14). Each docking station contains a resistor with an unique value that pre-configured to correspond to a specific location. When the user places the Bolb controller on one of the docking stations, the light-body moves to the location associated with that docking station. These docking stations thus constitute a reference to the earlier mentioned 'environment' and a 'location' in one. The orientation of the Bolb controller as a parameter to determine the lighting conditions is not implemented. Instead, different docks can be coupled to one location, which has a similar result. With this implementation users can experience a light-body that can be taken to different environments and that is linked to different locations. In addition to moving the light-body via the docking stations, users can also associate preferred lighting conditions to every dock. When the user places the Bolb on the dock, not only is the light-body moved to that location, also the lighting conditions associated to this docking station are retrieved.

Associating and retrieving lighting conditions

The Bolb controller allows users to associate preferred lighting conditions to particular locations in their environment via docking stations. This makes it possible for users to teach the system what lighting conditions they would like to have at specific locations. Associating lighting conditions to a dock requires explicit action from the user. When a user has created lighting conditions that he wishes to associate to his current location, he presses and holds both buttons on the Bolb controller. Visual feedback is provided on the Bolb: The LEDs emit a green color on both sides (Figure 4.15, left). If the user keeps both buttons pressed for one second, the current lighting conditions are associated to the most recent location of the Bolb. The LEDs show a green color and remain like this until the user releases both buttons.

When a user places the Bolb on a docking station, the resistor value is read. The Bolb flashes purple to indicate to the user that the associated lighting preference will be loaded (Figure 4.15, right). Lighting preferences are stored individually per user on a central server. Practically, this means that when the user docks his Bolb, the size, intensity, and light-color of the light-body that are stored, are loaded to the current light-body and his current settings are overwritten. Appendix 4-A provides the algorithm that is used to store and retrieve preferences.

5. Summary & conclusions

This chapter presented the concept and implementation of Bolb. The concept is based on the insights acquired through literature, insights of the Incubation phase, and insights of exploratory observations. Bolb is designed with three goals in mind: (1) Each user is provided with individual control over his lighting conditions via a light-body. (2) In multi-user situations people can share control and the system balances control between users. (3) Through interaction with the system users can associate their preferences to particular locations in their environment. This allows users to create lighting preferences for places and activities that are meaningful to them.

The concept of the Bolb controller is inspired by explorations in the Incubation phase. Specifically, the concept of the light-body was used in the adaptive office environment. Experts suggested that a portable version of the controller that was created there, would provide easy and rich control for users. The Bolb controller provides this rich and easy control in a portable form. Furthermore, the mechanism with which control is distributed between people is based on the insights of Chapter 2.4. This study showed that if people have the means to 'act socially' via the lighting system, this also reflects in their regular behavior.

Offering control over lighting conditions via a light-body makes it possible to provide one interaction mechanism to users. In this form it provides a control experience that is consistent across different lighting setups. This also makes it possible to use the Bolb controller as a controller in diverse environments. Users can be offered a single interaction concept in different environments, which potentially simplifies control over lighting conditions in environments they have not been in. A disadvantage is that all light sources are considered to be equal; down lighting, wall washers, and accent lighting are controlled by the light-body, and cannot be controlled individually. This reduces the richness and freedom to create highly diverse light settings.

The light-body provides users with a mechanism to control personal lighting conditions from a 1st person perspective. Their actions are based on their current location and lighting conditions are adjusted from their point of view. This contrasts with the traditional 3rd person perspective on lighting control of light switches and dimmers that, irrespective of the position of the user, are always related to their place in the environment. Research shows that this localized interaction leads to more satisfaction with the lighting conditions and energy savings. The Bolb controller also incorporates principles of embodied interaction: Bolb capitalizes physical, social and historical engagement with the world in order to provide meaningful lighting behaviors to people. In the implementation I attempted to maintain these characteristics in simplified form.

For the balancing mechanism insights from the Incubation phase – where control was shared over different people – and inspiration from social norms – where it is common courtesy to respect someone else's settings as you enter his environment – were used. The current implementation should still be considered in a social context though: It is possible for someone to merge two light-bodies and slightly change the lighting conditions, without the other person having to accept this. I believe that in practice, this will not be acceptable and when someone does this, he will be addressed on his behavior. I consider the current implementation as a negotiation mechanism: When someone merges the light-bodies, a dialogue between the two people starts, and one person can ask the other to change the lighting conditions.

Finally, the Bolb controller provides users with the ability to inform their system about preferences they have at specific locations in their environments. For the current implementation, this is achieved via docking stations. However, in the future, such additional equipment might not be required. The information that users provide to the system can also be used to feed learning algorithms. For example, patterns during the day or over seasons might be identified by learning algorithms and these can be used to enhance the lighting conditions a system suggests to its user. Furthermore, information of different users might be combined to acquire information about preferred lighting conditions for environments. This, for instance, can be used when new users enter the system; They can be offered lighting conditions that most people find pleasant.

Concluding the Nursery phase

This part of the dissertation presented the Nursery phase of the project. In retrospect, the Nursery phase has led to the development of 'enabling technologies': Lithne, Hyvve, and Bolb. All of which were ideated, conceptualized, and implemented into functional prototypes. The technologies are interoperable, meaning that they technically work together as a system.

Lithne, Hyvve, and Bolb, have their foundations in the insights acquired in the Incubation phase. The Lithne platform is based on my experiences with the installations created in the first part, and observations during educational activities. Lithne has enabled the development of Hyvve and Bolb. However, this should not be considered as a sequential process. Hyvve and Bolb have in turn also shaped the Lithne platform, both in terms of hard- and software. For example, the Hyvve system led to the integration of high power LED drivers on the Lithne battery board. Furthermore the design of Lithne and Hyvve was also informed by interdisciplinary requirements. This is reflected in the integration of the sensor boxes with the Hyvve tiles, which provides research opportunities in the domain of embedded and distributed sensing solutions. In addition, each Hyvve tile is equipped with an individual node, facilitating research towards distributed network structures.

The Bolb controller was designed to investigate personal and portable lighting controls. However, as multiple people in an environment have control over that environment, mechanisms to balance that control need to be implemented. The Bolb offers one such mechanism. Additionally, Bolb can be used to provide a system with information about personal preferences of users that have been made accessible via docking stations.

The following part of this dissertation is the Adoption phase. In the Adoption phase, three adaptive lighting environments are created in three environments, using Lithne, Hyvve, and Bolb. With these lighting environments a longitudinal evaluation is performed.

PART III

ADOPTION

Introducing the Adoption phase

The final phase of the Growth Plan is named the Adoption phase. The aim of this phase is to acquire knowledge about the true implications of novel technologies in the daily life of people. Ultimately, people should *adopt* the technology into their daily routines. The Adoption phase is marked by the keyword *realistic*. The Adoption phase has a broad scope and may vary from research evaluations up to the actual development and deployment of products and systems containing important research insights. Ideally, real people are asked to use products and systems in real contexts. Evaluations in the Adoption phase are typically longitudinal studies in which both quantitative and qualitative analyses are applied to form an idea about the way the novel technology transforms the life of its users. Longitudinal evaluation consequently means that it is not possible for the designer-researcher to always be present. This puts high demands on the quality of the research prototypes and for the evaluation methods. Research prototypes have to be rendered to a level that they can operate without continuous intervention of the researcher. Additionally, it should be taken into account that people use the products and systems in ways that are unforeseen. Similar considerations apply to the evaluation methods. Ideally, an evaluation provides rich information about the experiences of users, which is supported by quantitative data of the actual use of the prototype. The work that I present in this part of the dissertation covers the first steps in the Adoption phase.

In this part of the dissertation a longitudinal evaluation that I performed. Three lighting installations were implemented, using Lithne, Hyvve, and Bolb in a Living Lab. Four participants used these environments over a period of six weeks. In this period, their interaction with the system was logged, and their experiences were discussed in reflection sessions. The results of this study are translated to 10 insights that can be used to design ALEs.

5. Evaluating adaptive lighting environments

1. Introduction

In the Incubation phase diverse aspects of ALEs were explored. The explorations of that phase resulted in insights for the design of technologies of Lithne, Hyvve, and Bolb. In the Adoption phase, I integrated the insights from earlier phases, and technologies in the implementation of three ALEs for an office environment. These installation were used in a longitudinal evaluation.

1.1. Living Labs

The Adoption phase advocates evaluations that are conducted in a realistic context; the prototypes should be used in a 'lived' context. Evaluating novel technologies in realistic contexts is also known as a 'Living Lab' approach (Arrigoni, 2013; Kidd et al., 1999; Markopoulos & Rauterberg, 2000). A Living Lab typically is composed of novel technologies that are deployed in real environments with the aim to catalyze the creation, exploration and evaluation of these technologies. Living Labs are particularly suitable to investigate how novel technologies impact the natural behavior of people, because they confront people with technology in the richness of their daily life. The outcomes of studies performed in Living Labs are generalizable to classes of products in everyday life. Furthermore, Living Labs are a suitable method to evaluate the shortcomings of prototypes as they are confronted with a variety of behaviors.

Traditionally, the Living Lab approach aimed at bringing users into controlled environments that resemble realistic environments, for example the 'AwareHome' (Kidd et al., 1999), 'Vacation on Campus' (Markopoulos & Rauterberg, 2000), or 'HomeLab' (De Ruyter, Aarts, Markopoulos, & IJsselsteijn, 2005). These are all laboratory settings developed for people to visit for a period of time. In recent years this focus shifted (Bergvall-Kareborn, Hoist, & Stahlbrost, 2009): As powerful computational capabilities become available in ever smaller devices that are connected to the Internet, it has become possible to bring research prototypes out of the lab. Technology no longer constrains evaluations to take place in one location. Instead of bringing people to technology, the technology can be brought to people. Consequently, novel technologies are installed in real-world contexts. For example, research towards adaptive public lighting takes place with actual public lighting installations (Den Ouden, Keijzers, Szostek, & De Vries, 2012). Living Labs in its current form are also used as a mechanism for collaboration between industry and academia (Schuurman et al., 2013), as it allows companies to evaluate their technologies in a semi-controlled environment and provides research with the latest technologies and a platform for experimentation and evaluation. Recently, Experiential Design Landscapes (EDLs) emerged (Peeters, Megens, Hummels, Brombacher, & IJsselsteijn, 2013). In EDLs design making and design thinking are interwoven into society via experiential prototypes. The purpose of EDLs is to explore the implications of novel technologies in experiential, contextualized settings and to provide a designer-researcher with the means to improve his design proposition in short iterative cycles, based on contextual insights.

The original, and often most important, motivation for using this type of 'research-in-the-wild' techniques is one of ecological validity (Markopoulos & Rauterberg, 2000): I.e., how applicable are the outcomes of the study for the real-world? Especially when moving towards integrated and networked products, systems, and services the results of de-contextualized laboratory studies may not necessarily transfer to daily life. Living Labs embrace the richness and complexity of real human behavior. By confronting users with research prototypes in real environments, the researcher acquires insights in the behavioral and/or societal transformations that this new technology brings about. One of the considerations with this type of evaluations is that it is difficult to compare two cases to each other, simply because a researcher cannot guarantee that all participants were exposed to similar conditions. Results should be interpreted as conditional outcomes, rather than general truths (Hummels, 2000), and they can be generalized to a class of products/technologies (van den Hoven et al., 2007).

My motivation for using a Living Lab in the Adoption phase is to acquire insights into the way the concepts of Hyvve and Bolb – representing technologies for ALEs – are adopted by people and the experiences they elicit. This is guided by research objectives that vary from open-ended questions – about the general acceptance of ALEs – to specific questions regarding the experience of design solutions (e.g., light-body) that I propose.

2. Longitudinal evaluation

The Adoption phase aims to acquire insights in how users *adopt* new technologies in their everyday life, which is why a Living Lab iss used: This means that evaluations are performed with people that use the system in real contexts. The evaluation is set up as a hybrid approach of a *field* and *analytical* study (Sharp, Rogers, & Preece, 2007). This means that the evaluation takes place in a natural setting. Participants are specifically selected, and they are provided with training prior to the evaluation. By training the participants I aim to overcome novelty effects of the system. This increases the likelihood that participants adopt the technology into their everyday behavior. Moreover, the selected participants have knowledge regarding the topic of lighting. This should make them able to provide well-articulated reflections, based on their experiences with the system.

In the longitudinal evaluation study participants interacted with the system for a period of six weeks. Three ALE were used for this evaluation, namely Break-out Area, Meeting Room, and Open-plan Office. These are spaces that are currently already being used by the people that participate in the evaluation, which means that these environments are *lived*: People already work in these environments and the spaces are part of their daily routines. At the same time, the environment is rather controlled, which means that it is easy to intervene in case of issues or malfunctioning of the installations. In the following subsection I first describe my research objectives. After this I present an outline of the study, including a description of the ALEs that were used, the participants, and the measurements that were taken. Then the results of the study are presented and discussed. Finally, the conclusions regarding the research objectives are presented.

2.1. Research objectives

The ALEs that are presented provide people with rich, personal, and portable control over their lighting conditions. To my knowledge, this is one of the first studies in which people are confronted with such highly interactive lighting environments for an extended period of time in a real environment. This means that there is no knowledge that provides insights into the implications of such adaptive lighting environments on the daily behavior of a group of people. Specific to this evaluation I outlined the following research objectives, based on the three challenges that I presented at the start of this dissertation.

First, To acquire insights for the design of meaningful lighting behaviors this study investigates the lighting preferences people have for specific environments, activities, social contexts and/or other aspects. This contributes to the understanding of how lighting behaviors are meaningful.

Second, the evaluation is set up to provide insights regarding the social implications of adaptive lighting environments with personal lighting conditions. Additionally, it investigates the experiences and opinions of people on the mechanism to balance control as implemented in the Bolb controller.

Third, this study is expected to provide general insights that are useful for the design of novel interaction concepts. It aims to provide insights regarding the way people use personal, portable controls for ALEs, their motivations to change lighting conditions, and what degrees of freedom people would like to have over their lighting conditions. Regarding the specific concept of the light-body, this study investigates how people relate to light control that is spatially and temporally coupled to their location. Furthermore, the study investigates how people experience the contextualized preferences as a possibility to personalize the system.

2.2. Outline of the evaluation

The evaluation period (shown in Table 5–1) spans six consecutive weeks. During the evaluation period both quantitative and qualitative data are gathered. For this evaluation, four participants were selected. They were trained to work with the three ALEs and Bolb controller at two moments in the evaluation period. The first training was held at the beginning of the evaluation. In this training participants received plenary instructions about the system, they could ask questions, and could experiment with the system. In the third week another training session was held where the system was explained once more and participants could ask questions about issues they encountered.

TABLE 5–1 Overview of the evaluation setup

Week	Activity	Qualitative	Quantitative		
1	Training I		Observation camera images (interval 30s.)	Server screenshots (interval 10s.)	Server interaction log files (XML)
2		Individual reflection I			
3	Training II				
4		Individual reflection II			
5					
6					
7	End of evaluation	Plenary reflection			

Quantitative data were gathered continuously by a central server in the form of log files, screenshots, and images from observation cameras. These data provide insights into the patterns of use of the participants. Qualitative data were gathered in reflection sessions and provide insights into the experiences, motivations, and opinions of users. After the first and the third week participants had individual reflection sessions in which they discussed their experiences. After the complete evaluation period of six weeks, a plenary reflection session was held.

During the evaluation period the influence of external lighting conditions will be measured and controlled. At three points during the day (morning: 10:00, mid-day: 13:00, and afternoon 16:00) the light levels in the environments were measured and, when needed, the blinds were lowered (i.e., if they have been adjusted by others) to establish a light level of approximately 100 lux in the ALEs. As the evaluation was performed in the spring season, exterior lighting conditions may be dominant over artificial lighting conditions. By lowering the blinds, a context is created in which artificial lighting is required for pleasant light settings. How the lighting conditions were exactly controlled is described in Appendix 5-A. In the following sections I elaborate on the ALEs, the selected participant, and the (qualitative and quantitative) measures that were taken.

2.3. Adaptive lighting environments

Tthe Living Lab consisted of three spaces containing three ALEs: the Break-out Area, the Meeting Room, and Open-plan Office. These environments are continuously in use by students and employees of the university. They are selected as they represent different types of office behaviors: e.g., individual deskwork, one-to-one meetings, group meetings with internal and external members and presentations. Observations on the use of these spaces revealed typical behaviors for each environment, these are included in the description of each space. One of the benefits of using these spaces is that they are allocated next to each other, yet they offer users three completely different contexts. By using these environments it is possible to assess how the proposed interaction concepts are applicable in different situations. Each of the environments is used for different types of activities and the ALEs are thus confronted with a diversity of ways in which they can be applied. This makes using these environments suitable for two reasons: From a usage perspective the three environments provide insights in a variety of activities and how people use highly interactive lighting systems in those contexts. From a technical perspective, the lighting installations are confronted with various contexts and behaviors and this provides insights into the applicability and generalizability of the proposed concepts. In the following three subsections respectively the Break-out Area, the Meeting Environment and the Open-plan Office are presented.

Break-out Area

The Break-out Area (see Figure 5.1) is a space where people can retreat for individual work/ reflection, relax, or have informal meetings. The space contains two seating areas: One consists of two comfortable chairs for individual or two-person activities, and the other has benches for small group meetings. The space advocates an open-door policy, meaning that people cannot book the space in advance, but rather go there on a first-come-first-served basis. The lighting setup and infrastructure are designed and created by Serge Offermans, a colleague, and has been operational for over a year. The space is well known among students and staff and is used on a daily basis, for example for student-coach meetings, or by groups of students for discussions and brainstorm sesssions. The space contains 16 colored (RGB[1]) LED wall washers attached to the ceiling, 8 sources on the left and 8 sources on the right side of the room (see Figure 6.1 via Layar). Additionally, there are five luminaires that provide downward lighting and can be controlled for CCT. A light object ('Solime', design by Bart Dohmen) that provides colored lighting is positioned in the center of the room. Lithne nodes can control each individual light source via DMX. The space can be darkened using a motorized blinds system.

The lighting installation in the Break-out Area also serves as a platform for students to develop interactive lighting systems. All the light sources in the environment can be controlled individually using the Lithne platform. For the setup this means that I program behaviors onto the environment, but also that students working on projects related to the Break-out Area make use of the space to develop and test their prototypes. For the evaluation, the environment is programmed to override any other settings when a person uses the Bolb controller in the Break-out Area, as to make sure others do no interfere technically with the evaluation. However, the disadvantage is that also during the evaluation period this space may be 'in use' by others who are working on their projects in this environment. This is one of the consequences of using real environments for evaluations: These spaces are in use by others. It would be too disruptive and unrealistic to claim the space for a longitudinal evaluation. I made sure that during the evaluation period the space remained operational for my evaluation.

[1] see Glossary at the end of this dissertation

Figure 5.1 Break-Out Area. (top) Meeting area with comfortable benches. (bottom) Retreat area with two comfortable chairs for individual work or one-on-one meetings.

Figure 5.2 Impression of the Meeting Room with the ceiling of Hyvve tiles.

Meeting Room

Next to the Break-out Area a meeting environment is located. A meeting table (200 x 200 cm) is placed in the center of the room, with seats for 8 people. This meeting environment is used for more formal meetings, for example with external parties, or for meetings with larger groups. Occasionally individuals who would like to work quietly come here. This space can also be darkened using motorized blinds.

Above this table a ceiling of Hyvve tiles is installed, containing twelve active Hyvve tiles. Each Hyvve tile contains one Lithne node and can be controlled for CCT and intensity individually to provide downward illumination. There are no other light sources in this space. The Lithne nodes in this room are part of the same network as the Lithne nodes in the Break-out Area, meaning that they can communicate to each other and that the controller can be used across environments. The meeting room with the Hyvve tiles is depicted in Figure 5.2.

Open-plan office

Next to the Meeting Room, the Open-plan Office space is located. An impression of the Open-plan Office with its lighting installation is provided in Figure 5.3. This 'openness' means that the desks are placed in a large open space to constitute the workspaces and that they are not separated by walls. Staff of the department of Industrial Design uses this office space. Next to the workspaces of the employees, there are workspaces of students. This locations has been in use as an office space for a long time, meaning that the technology for this evaluation was installed at existing workspaces. The Open-plan Office contains four large desks. The desks are placed in a way that people are facing each other. Each desk is typically assigned to a specific person, yet there are people that are in the office part-time. At times when they are not there,

Figure 5.3 Impression of the Open-plan Office.

it frequently occurs that others use the space for that day as a flexible workspace. There are blinds on one side of the space. These blinds are not automated and cannot completely darken the space. Above each individual desk five Hyvve tiles with LEDs are located, accumulating to twenty 'active' Hyvve tiles for this space. All the Hyvve tiles provide downward illumination and the intensity and the CCT can be controlled separately for each tile. Also, in this space each Hyvve tile is equipped with a Lithne node that is connected to the same network as in the other two spaces.

2.4. Technical implementation

To control the ALEs presented in the previous paragraphs, four Bolb controllers were made. A central server was used to control the three ALEs, which means that all information and communication passed through a central server. This allowed me to control the behavior of the system and gather data on a central location. Concretely, the server contains a map with all the environments and all the light objects in these environments, where each digital object on the server is associated (via a unique hardware and software address) to a real-world light object. Manipulations on the server were directly transmitted to the actual installation.

On the server, one light-body was associated to each Bolb controller. The most important role of the server is to determine the behaviors for the complete system. In practice, this means that the server changes the position of the light-body whenever a user docks his Bolb, the server calculates which light sources should be actuated, based on the parameters of the corresponding light-body. This means that when a user interacted with his Bolb controller, this information was transmitted to a server wirelessly. The server interpreted how to actuate the light sources and transmitted the commands to do so to the respective actuators. Furthermore, the distance between two light-bodies was used to provide haptic feedback via the Bolb controllers. When two Bolb controllers shared a light-body, the server provided the corresponding 'sharing behavior'. Finally, the preferences that users created were stored on the server.

3. Participants

Important in the evaluation is that the participants adopt the proposed concepts in their everyday routines. For this purpose a sample of four people that currently work within the Open-plan Office were asked to participate. These participants (see Table 5–2) were selected as they represent a mixed set of backgrounds, interests, and daily routines in this office context. The participants are familiar with all the environments (Break-out Area, Meeting Room, and Open-plan Office), and they use these spaces in their daily work.

Most of the participants that are selected for this evaluation can be considered well informed (some even expert) in the domain of system design, interaction design and/or lighting. A downside of using well-informed participants for the evaluation is that it potentially introduces a bias to the evaluation study. Some participants also witnessed the development of the lighting environments. Yet, I do not regard this as a major issue as the *experiences* of the participants are realistic: None of the participants have experienced an interactive lighting installation on this scale for an extensive period of time before. At the same time, most participants have experience and knowledge in one of the fields (systems design, interaction design, lighting), which makes them capable of abstracting their experiences and insights and benchmarking this to existing knowledge. This dual nature of the participants allows for high-level reflection and insights based on real experiences.

TABLE 5–2 **Background of the participants selected for this evaluation**

	Role	Background	FTE	Typical activities
1	Secretary	Organizational affairs	0.7	e.g.; desk-work at computer, uses Open-plan Office mainly and Meeting Room occasionally.
2	Researcher	Mechanical Engineering, Industrial Design	0.8	e.g.; desk-work at computer/reading, meetings, student coaching, uses all three spaces.
3	Ph.D. student	Computer Science	0.4	e.g.; desk-work at computer/reading, occasional meetings, uses all three spaces.
4	Ph.D. student	Industrial Design	1.0	e.g.; desk-work at computer/reading/sketching, meetings, student coaching, uses all three spaces.

The participants are familiar with each other and share this space as their daily working environment. During the evaluation period the participants can, and probably will, discuss the lighting system and the light controller with each other. This discussion between participants is not restricted, as this is a realistic form of behavior when people are confronted with new technologies. The context in which a new technology is adopted is inherently a social context. Using the knowledge and skills of others is a strategy that people can apply to familiarize oneself with the system.

4. Measures

The main research objectives for this study are concerned with the experiences and opinions of users regarding personal and portable control for lighting environments: The light-body as interaction concept, mechanisms to balance control, and situated preferences. Insights to these research objectives were primarily derived from the reflection sessions. To support these insights the central server gathered quantitative data on the way the system was used. These measures were used to corroborate opinions of the participants.

4.1. Reflection sessions

To acquire insights into the experiences and opinions of participants two individual reflection sessions were held in the evaluation period. At the end of the evaluation period, a plenary reflection session was held. In these sessions participants performed exercises, discussed and reflected on their experiences with the system with me. These sessions were conducted in the Meeting Room, so participants could use the lighting system to support their answers with demonstrations in the system. Each session had the form of a semi-structured interview. This meant that a question route was prepared to guide the discussion, but depending on the dynamics of the session the order in which these questions were asked may have been adjusted. Additionally, participants performed an exercise to stimulate discussion around a specific topic. All sessions were recorded on video.

From the private interviews an abridged transcript (Krueger & Casey, 2000) was made in the form of quotes. The abridged transcript is a condensed version of the interview that only contains relevant and useful portions of the discussion. To make the individual quotes readable and understandable outside the context of the complete interview additional information is added to the quote using square brackets ('[' and ']'). This additional information, for instance, describes the question the participant was answering, or references to earlier sentences. Whenever participants use a word of which the semantic meaning is important, the original choice of words is provided between parentheses. Meta-level information was added to each quote to make it simple to retrieve the original source of the quote.

The interviews formed the basis of an Interpretative Phenomenological Analysis (IPA) (Biggerstaff & Thompson, 2008). In psychology and fields of human-computer interaction, derivatives of this analysis are used, such as 'conventional content analysis' (Hsieh & Shannon, 2005). Even though the exact procedure may differ, the goal of such methods is – in most cases – similar: namely to compress a rich information set to insights for the research objectives. Typically it involves an interpretive process in which researchers attempt to develop an understanding of the experiences of its subject. It is advocated that the researcher who evaluates the data is the same person as the one who performed the interview sessions (collecting the data). Through these shared experiences the researcher can come close to the experiences of the subject.

The results of the reflection sessions were used for two purposes. First, an initial inspection of the quotes was used to prepare for future reflection sessions. If there were topics raised by participants that were not on the agenda, they could be included in future sessions. Second, the quotes were clustered and analyzed to provide insights into the research objectives. This analysis of the quotes was a two-step procedure: In collaboration with two other researchers, the quotes were grouped in *clusters*. A set of initial clusters was provided, based on the research objectives. Additional clusters were added during analysis. An example of a cluster that was provided is:

What people said about Individual Control, which relates to *individual control* as one of the research objectives. Once all quotes were assigned to a cluster, the researchers collaboratively assessed the quotes in each cluster to distinguish which *topic* is addressed. If quotes regard multiple clusters or topics, the quotes were duplicated and are placed in both clusters and topics. By means of a discussion the researchers come to agreement about what this quote says about the topic it is placed in. This leads to preliminary insights for the research objectives. For example: 'People like individual control, because it feels luxurious'. As this information is heavily condensed, it lacks the nuance and richness that is present in the original quotes; yet it provides an overview of the most important insights.

Individual reflection sessions

Both individual reflection sessions consisted of a discussion and an exercise that participants were asked to perform. The exercises were used to stimulate participants to reflect on their experiences of the past period. In the exercise of the first reflection session, participants were presented with images of up to five situations of the past week and the lighting conditions they created. They were asked to describe the situation and reflect on the relation between that situation and the lighting conditions. In the exercise of the second reflection session, participants were asked to mark and describe their lighting preferences for the different environments on a map. An overview of discussion topics and exercises of the two individual reflection sessions is provided in Appendix 5-A.

Plenary reflection session

The evaluation period was concluded with a plenary session in which the participants reflected on their experiences with the system. The session consisted of discussions and two exercises to stimulate the discussion. The first exercise was a statement-questionnaire that participants were asked to fill out one day prior to the plenary reflection session. In this questionnaire, the participants were presented with statements regarding the system that they have to 'agree' or 'disagree' with. These statements were based on an initial inspection of the transcripts and notes of the individual reflection sessions and they address topics that had been discussed during the individual reflection sessions. As the statements can only be agreed or disagreed to, participants are likely to have different opinions and they were asked to discuss their different points of view.

The second exercise was GroupSorter (Soute, Bakker, Magielse, & Markopoulos, 2013). In GroupSorter, participants individually rank seven aspects of the lighting system. These aspects (e.g., usability of the controller, accuracy and precision of the system) were derived from the research objectives, combined with initial results of the individual reflection sessions. The participants were asked to rank aspects in order of importance: Aspects they experienced as being highly important should be ranked high, aspects they experienced as being of less importance are ranked low. They first ranked items individually. Afterwards, they were asked to create a ranking all participants agreed with. The individual ranking schemes could be compared to the final ranking scheme, but the most insightful data came from the discussion the participants had while developing the shared ranking. The moderator stimulated participants to provide arguments for their opinions and examples of situations during the discussion.

4.2. Quantitative measures

The reflection sessions were largely based on the opinions and motivations provided by participants. However, participants may not always be aware of their behavior. Therefore, all interactions with the system are logged in data files. Additionally, whenever a user interacted with the system a screenshot of the central server was produced (with an interval of 10 seconds between screenshots). This allowed for visual inspection of the interaction during the evaluation period.

The three spaces were each equipped with a network camera. This camera was set to take snapshots every 30 seconds when presence was detected. The images were stored on a server and were used in reflection sessions with participants, and in the evaluation afterwards. This provided an overview of how people used the environments throughout the evaluation period.

These measures were used to evaluate the patterns of interaction of each participant. The images collected by the observation cameras were used to construct an overview of when each participant was present in which environment (between 8:00 and 18:00) during the evaluation period. These overviews provided an indication of the presence of participants, as it is impossible to determine exactly when people come in and leave. To avoid ambiguous situations I simply counted whether people were present in a specific time frame: E.g., when a participant was observed at 17:05 on the snapshots, the participant was considered present for the period 17:00 – 18:00.

The information about the presence of participants was combined with data about their interactions with the system to combine into *patterns of use*. For this purpose 'moments of interaction' during the evaluation period were counted, which were based on the screenshots generated by the server and the data log files. As a moment of interaction might involve several manipulations of the lighting conditions, a series of consecutive manipulations (e.g., a user changes the color temperature and light intensity consecutively) within a time frame was considered as one 'moment of interaction'. However, based on the data that was acquired, and observations of participants interacting with the system, this time frame was decided.

5. Results

The evaluation period spanned six weeks, from May 14th, 2013 until June 25th, 2013. Excluding weekends and leave days, participants used the system for 29 days. In the first week various issues in the software were revealed, including difficulties with the docking stations. Therefore, I decided to postpone the introduction of the docking stations to the second training session. After the first week of evaluation, the software issues that were encountered were resolved. At the second training day, the system was disabled to update the software. During the evaluation period other minor issues (such as loose buttons) were encountered. A log of the issues or malfunctions of the systems can be found in Appendix 5-B.

Influence of external lighting conditions

Throughout the evaluation period, light measures were collected at five points in the Open-plan Office, four points in the Meeting Room, and four points in Break-out Area. Whenever the space was occupied the measurements were not taken, as it would be too disruptive to the activity that was carried out. Table 5–3 presents the average results of these measures for the three environments. A complete overview of the light measures can be found in Appendix 5-B.

TABLE 5–3 **Summary of the light measures in the three environments**

	OPEN-PLAN OFFICE	MEETING ROOM	BREAK-OUT AREA
AVERAGE	157.3 lx	74.4 lx	50.7 lx
STD DEV	87.8 lx	19.2 lx	30.1 lx
MAXIMUM	581 lx	188 lx	152 lx
MINIMUM	15 lx	36 lx	7 lx

5.1. Patterns of interaction

To determine the patterns of interaction, five weeks of the evaluation period were included. The first week of evaluation was excluded, due to the previously mentioned software issues. The patterns of interaction are therefore considered over a period of 25 days, instead of the 29 days that were mentioned previously. Based on the reflection sessions and inspection of the log files, unique moments of interaction were counted if there was at least a five-minute interval between the last manipulation and the new manipulation, except when people change between environment; docking a Bolb in a different location within interval was counted as a new moment of interaction. For example: A user dims the lights at his desk and then moves to the meeting room, where he docks his Bolb. This is counted as two interaction moments. This interval may appear long, yet observations during the evaluation period showed that people tended to wait for the system to respond, before they would further manipulate the lighting conditions. With five-minute intervals, it is safe to assume that this is a new moment of interaction, as the system had sufficient time to process the request. Table 5–4 summarizes the interaction patterns of the four users. The patterns of interaction show that participants interacted with the system approximately every 80 minutes, yet there are large variations between individuals

TABLE 5–4 **Summary of the patterns of interaction**

	P1	P2	P3	P4
DAYS PRESENT	13	19	12	22
HOURS PRESENT	98	170	69	196
INTERACTIONS	70	105	82	133
AVERAGE TIME BETWEEN INTERACTIONS (IN MINUTES)	84	97	50	88

Additionally, Figure 5.4 presents an overview of the interaction pattern for each participant. The marked time frames indicate that a user was present. The number indicates the number of interactions a participant had during that time frame. This is also translated to the color coding of the cells: The darker the cell, the more interactions that participant had. For each day the three environments are presented, where the first column is the Open-plan Office, the second column the Meeting Room and the third column the Break-out area.

5.2. GroupSorter

The GroupSorter exercise was performed during the final plenary reflection session. Based on the research objectives and topics discussed in the individual reflection sessions, seven aspects of the system were selected for the ranking. Table 5–5 presents the seven topics and the descriptions provided to participants.

TABLE 5–5 **Selection of system aspects used for GroupSorter exercise**

System Aspect	Description provided to participants
Controller usability	*A controller should be easy to use/learn and functions need to be quickly available.*
Responsiveness of the system	*The system should respond immediately to my actions.*
Individual control	*The system allows me to individually control my lighting conditions.*
Location of control	*Controls should be portable and/or within reach.*
Accurate & precise	*The system should allow me to manipulate the lighting conditions precisely and should always represent the system's state correctly.*
Personalization	*The system should allow me to enter my personal preferences and should respond accordingly.*
Universal control concept	*Controlling lighting conditions should be similar in all environments and lighting setups.*

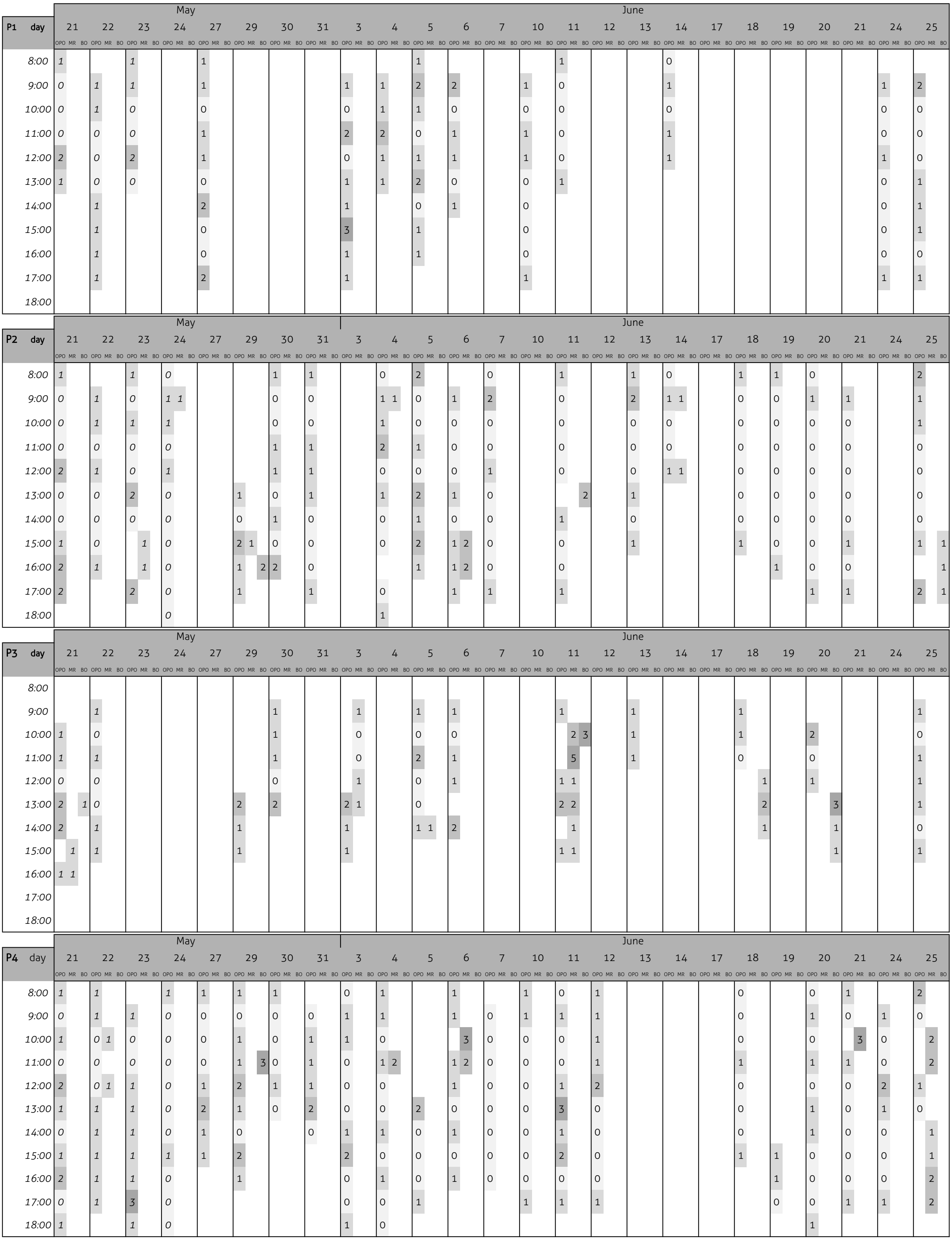


Figure 5.4 Overview of the interaction patterns of the four participants.

With the data from the individual ranking schemes (see Table 5–6) the agreement between the participants using Kendalls's coefficient of concordance (N=7, k=4) is computed at W=0.72. For the calculated s (s=322) this value is significant at the level of p<.01. This means that this sample of participants applied a similar standard for qualifying these aspects of the system.

TABLE 5–6 Results of GroupSorter (1=most important, 7=least important)

System aspect	Group	P1	P2	P3	P4	Sum of Ranks
Controller usability	1	1	1	3	1	6
Responsiveness of the system	2	2	4	1	2	9
Individual control	3	3	2	4	5	14
Location of control	4	4	3	5	4	16
Accurate & precise	5	6	5	2	6	19
Personalization	6	5	6	6	3	20
Universal control concept	7	7	7	7	7	28

5.3. Reflection sessions

Eight individual interviews – two with each participant – and one plenary interview were held. From these sessions abridged transcripts were made, which resulted in a total of 531 quotes (included in Appendix 5-B) divided over 15 topics in 8 clusters as is presented in Table 5–7. First, a clustering procedure was performed in collaboration with two other researchers from the department of Industrial Design for the quotes collected in the individual reflection sessions. The clusters and topics that resulted from this analysis were used as input for the clustering procedure of the quotes of the plenary reflection session. This was performed in collaboration with two (different) researchers from the department of Industrial Design. In the remainder of this section I present a selected overview of the different responses participants provided.

Light & Lighting conditions (A)

Cluster A summarizes the quotes that participants made regarding Light & Lighting Conditions. Interestingly, when participants were asked what factors determine their choice for lighting conditions, most of them mentioned the *activity* or *task* they are performing. However, when they were asked to specify lighting conditions they prefered for specific tasks, they were unable to articulate what these were. The influence of *contextual* (e.g., external lighting conditions, temperature) and *personal* factors (e.g., mental state/mood) seemed more influential to their decisions. Furthermore, participants seemed to be unaware of the implications of light on them. One participant indicated that it 'activated' her, another indicated that it changed how he perceived the temperature of the environment.

Based on the different responses, it appears that lighting conditions should not cover a small area of the desk, and it should not be too dark. Mostly, participants had all the five light sources above their desk on. Furthermore, extreme ends of the color spectrum (completely warm/cool) were not appreciated, and they preferred a mixture of warm/cool white light or slightly towards the warmer end (approx. 3500-4500 K). Furthermore, participants indicated that since they had control over their lighting conditions, they could explore possibilities which increased their awareness about what lighting conditions are pleasant.

Light-body (B)

In the Open-plan Office and Meeting Room, people appreciated the light-body as it provided them with personal, individual control from a 1st person perspective. In the Break-out Area they found the light-body difficult, as the lighting setup not only had down-lighting but also wall-lighting, which in their opinion serves a different purpose. Furthermore, they proposed improvements, for example by having multiple light-bodies or a gradient fall-off. For simple actions (turn on/off) the light-body was found too difficult.

Bolb controller (C)

Overall, the Bolb controller was appreciated as it offered people personal and portable control that was richer than their original lighting system. However, there were also many issues reported with the controller, which show that the usability of the controller should be improved. Interestingly, one of the striking aspects that was revealed is that people did not focus on the controller while they interacted with the lighting system. Instead, they looked at the ceiling to see the result of their action. This is corroborated by observations during the evaluation. This explains why people did not see the feedback on the controller and had difficulty to control the lighting conditions accurately.

Control (D)

People highly appreciated individual control, though they questioned how this would scale to a complete office. Furthermore, they felt invited to interact, because they had diverse degrees of freedom. This also shows from the motivations that people had to change the lighting conditions, which were both *functional*, and *hedonistic* (it is fun, change because they can, change for change's sake). They also indicated that simply knowing that they are in control was pleasant.

The quotes reveal that people want to have basic functionalities available at all times, but that high precision and accurate control may, in the long run, not be required. However, rich and precise control helped them though to get an understanding of what they find pleasant.

TABLE 5–7 Overview of clusters, topcis and aspects that resulted from the quote analysis

Cluster	ID	Topic	#	Aspects addressed
A. Light & Lighting conditions	A1	Factors that influenced desired lighting conditions	33	activity, changing an activity, external lighting conditions, mental state, mood, social context, temperature (indoor/outdoor), weather, time passed since last change
	A2	Which lighting conditions people preferred	48	are different, are not so different, are personal, they could be dynamic, light distribution not too small, not in the 'spotlight', not too dark, mixed color, warm-but not too warm, are stable with small changes depending on context.
	A3	How lighting conditions affected people	8	they don't know, activates them, changes perceived temperature
	A4	How people describe lighting conditions	4	they don't know, atmosphere, active
	A5	Whether people were more aware of their lighting preferences	20	they don't know, they (think they) know, they need to explore, allows self-reflection, learn what the options are, they have some awareness
B. Light-body	B1	What people thought about the concept of the light-body	36	it is pleasant, offers first-person perspective, size is less important, could expand in different ways, relation between parameters was ambiguous, it can be too complex, could have gradient fall-off, could be multiple light-bodies per person
	B2	What people thought about the light-body in specific contexts	14	is applicable to any lighting setup, is not applicable to any lighting setup, need more light-bodies for different light types
C. Bolb controller	C1	What people thought about the Bolb controller	60	like that it is portable, simple to use, is too big, interaction is not clear, has to be learned, feedback insufficient, rotational dial too much friction, add reset button, did not focus on controller when adjusting light, did not represent system state accurately, difficult to accurately control lighting conditions, unexpected behavior, disrupt flow of interaction, developed feelings of attachment

D. Control	D1	What people thought about individual control	20	feels special/luxurious, it was pleasant, liked that it is personal, do not want to intrude other's space, question scalability
	D2	What people said about the degrees of freedom of control	36	invites to interact, it should work, basic functions should be easily accessible, should be sufficient resolution, low resolution is sufficient, does not have to be precise, felt and want to feel in control
	D3	How people used the system	24	it was fun, change because they can, change for change's sake, communicate availability, forced to interact, to increase performance, to be energy conscious, see if it still works, turn on in the morning, didn't change much during day, change few times a day, forget to turn it off when leaving desk, they behaved differently, did not behave differently
E. Balancing control	E1	What people thought about balancing control	80	did not use it, it was not clear, it was unpleasant, lost too much control, didn't feel like sharing, has no added value, don't want to intrude space of others, want different or no balancing mechanism, maybe in different context, do not mind sharing light or controller
F. Preference docking stations	F1	What people thought about the preference docks	41	easy to use, worked well, matched expectations, people prepared system for future interactions, quickly start the system, adjust the lighting after loading setting (point of reference), changed their preferences over time
G. Social aspects	G1	Social implications of the lighting system	28	others are triggered to interact, leads to discussion, not disruptive when others interact, could imagine that it would be disruptive
H. Other aspects	H1	Quotes that did not fit other clusters	42	experienced frustration because of latency or incorrect behavior, latency is issue, were aware that it is prototype, indications of novelty effect, aware that it is an evaluation, became habituated to the system, there is more to gain

Balancing control (E)

The balancing mechanism was not appreciated, as it was too difficult and participants felt they lost control. However, participants could see that such mechanisms are required, especially when multiple people have individual control. They proposed simpler solutions to balance individual control. They proposed that sharing can take place in the social context, although opinions about this were mixed. One participant indicated that he did not mind sharing light or a physical controller. Another participant indicated that he highly appreciated individual control and wanted a mechanism where he could prevent others to 'intrude' his light-body.

Preference docking stations (F)

The opinions regarding the docking stations were very positive. It matched – and in some cases exceeded – expectations. Quotes revealed that this was mainly due to the simplicity that it added to the system, as it was now easy to turn on the lighting (in different areas) to personal preferences. Participants used the docking stations to turn on the lights, and – based on the settings that were loaded – they would adjust the lighting conditions, if neccesary. However, there were also indications that people actually considered that they were 'educating' their system. One participant discussed how he created pleasant lighting conditions, not to use directly, but to prepare the system for when he would work there. Another participant indicated that he kept his lighting preferences in the docks up-to-date, based on the weather conditions.

Social aspects (G) and Other aspects (H)

The lighting system led to discussion in the group. Participants discussed the system, their preferences, or expressed frustration when it did not work. They were aware that it was a prototype and that sometimes the system responded slow. Especially in the beginning quotes showed that there was a novelty effect, but towards the end participants indicated that they got used to the system. Furthermore, they did not find it disruptive that everyone could individually change his lighting conditions. Comments expressed that they noticed others had highly different lighting conditions than they had themselves, but people actually appreciated it. There seemed to be a balance of 'live and let live' within the group. Quotes revealed that when others changed the lighting conditions, this was oftentimes a trigger for people themselves to also adjust their lighting conditions.

Given the issues and difficulties with the system, participants enjoyed using the system and participating in the study. They expressed that there was still more for them to gain. One participant mentioned that he used the Meeting Room more because the lighting system was installed there. After the plenary reflection sessions finished, the participants also asked: "*what can we do to keep the system?*" This shows that – even with the critical remarks they had – the system had added value to them.

6. Discussion & insights

In this section the results of this study are discussed and insights are provided with regard to the research objectives outlined at the start of the chapter. I first discuss the study in general. After that, I discuss the outcomes and I generate insights from the results.

6.1. On the study

It must be noted that this is a first evaluation where ALEs were evaluated over an extended period of time. The lighting installations and interaction devices that were used in this evaluation, are research prototypes, which has consequences for the scale on which an evaluation can be performed. Developing these prototypes is a labor-intensive process and requires significant economic investment. For this evaluation I decided to make four prototypes of the Bolb controller. This inherently limits the number of participants that could use the system at one time. Future evaluations should be performed with more users, and also with users that have different backgrounds. A consequence of using prototypes is that issues and malfunctions can occur. However, all issues that were encountered in this study were resolved within 24 hours.

Given these limitations, the experiences of participants were sufficient for them to be able to provide insights into the implications of ALEs in their daily routines. Participants were able to provide examples of their motivations and experiences, which show that people truly used the system. Furthermore, images from the observations cameras and the data logs revealed that people used the different spaces.

In many lighting design guides or handbooks, typical illumination values are provided for specific activities: E.g., for orientation purposes 100 lux should be sufficient and regular office work requires between 250 and 500 lux at the workplane. When comparing these guidelines to the measures of the exterior lighting conditions it is clear that these levels are on average not met by external daylight conditions. Therefore, we can expect that participants require additional lighting from the lighting system.

6.2. Lighting preferences of people

> INSIGHT 1— PEOPLE ADJUST LIGHTING CONDITIONS TO CONTEXTUAL FACTORS, PERSONAL ASPECTS AND THEIR VIEW ABOUT POSSIBLE BENEFICIAL EFFECTS.

When people are provided with control over their lighting conditions, they change their lighting conditions frequently, as shows from the interaction patterns. These interaction patterns reveal that participants spent most time in the Open-plan Office. Furthermore, visual inspection shows that there are no clear trends in the interaction patterns, and that there are large differences between the participants. This personal character of the interaction patterns is corroborated by the diverse motivations that people expressed to change lighting conditions throughout the day. Their preferred lighting conditions depend on the personal context of the user: Factors such as weather, external lighting, and temperature play a role in this and – next to that – personal aspects such as mood and level of alertness are used to determine the lighting settings. Furthermore, when participants selected lighting conditions they also considered possible beneficial effects it might have on them, even though they are not certain whether the lighting conditions truly have this effect. For example, one participant indicated that she set the lighting conditions slightly cooler, as this might help her to boost her performance at the end of the day. Another participant made the lighting conditions slightly cooler, when it was warm outside, as it made him feel less hot.

> Insight 2— providing people with the opportunity to change their lighting conditions allows them to explore their lighting preferences. This helps them to understand which lighting conditions are pleasant for specific situations.

The lighting conditions that people reported to be pleasant reveals two general tendencies: The lighting conditions that were preferred were a mixture of warm white and cool white lighting, typically towards the warm end of the spectrum. Furthermore, there should be 'sufficient' light. People reported to be satisfied with a rather broad range of lighting conditions as long as they are not in the spotlight, and it is not too dark. This insight could be interesting for the automation of lighting behaviors: A system might not be able to set lighting conditions that are pleasant, but it might avoid lighting conditions that are generally unpleasant. What is more interesting is that people had the opportunity to explore different lighting conditions, which helped them to explore what they find pleasant.

6.3. Control for future lighting environments

> Insight 3— Providing people with individual, localized control from a first-person perspective enables a feeling that the space is theirs.

In this specific implementation participants were provided with personal and portable controls over lighting conditions that were richer than their original light controls. Control was offered in the form of a light-body, which was appreciated where there was only down lighting, for example in the Open-plan Office and Meeting Room. It was appreciated as it offered users a 1st person perspective from which to control their lighting: All manipulations to the lighting conditions were performed from their point of view. This gave people the feeling that the lighting was theirs: it was personal and marked their space.

INSIGHT 4— DIFFERENT LIGHTING SETUPS AND ENVIRONMENTS REQUIRE SPECIFIC CONTROL CONCEPTS AS USERS VIEW THESE CONTEXTS FROM A DIFFERENT PERSPECTIVE. USER CONTROLS SHOULD BE DESIGNED TO SUPPORT THE USER PERSPECTIVE.

The relation between the parameters of the light-body was ambiguous at some points. For example, when the size of the light-body was increased, more light sources were enabled, which meant that also the light intensity increased. Future implementations of the light-body could balance these behaviors: E.g., when a user increases the size of the light-body the intensity of the individual light sources could be reduced to maintain a constant light intensity. Users did not feel that the current implementation of the light-body was a light control concept that was applicable to any lighting configuration. The light-body specifically led to difficulties in the Break-out Area, because there were different roles for specific light sources: e.g., down-lighting, and wall-lighting. At the same time the question was raised whether it would (in any case) be desirable to have a form of control that is applicable across contexts, as different spaces and lighting setups afford different behaviors and thus require different control concepts. The results of the GroupSorter corroborate these findings, as the 'Universal Control Concept' was ranked lowest.

INSIGHT 5— USERS LIKE TO FEEL IN CONTROL OF THEIR LIGHTING CONDITIONS AND SHOULD NEVER FEEL THAT THEY LOSE CONTROL, OR THAT CONTROL IS TAKEN AWAY FROM THEM.

From a broader perspective, the light-body provided people with rich, personalized and portable control over the lighting conditions. People appreciated individual control, as it provided them with feelings of being in control. This aspect was also ranked high in the GroupSorter exercise. Participants found it difficult to argue why having (a feeling of) control is so important to them. This "control for control's sake" argument is also found by others (Bordass, Leaman, & Willis, 1994). Furthermore, this is strengthened by the result that loss of control was a negative experience and led to frustration with the system.

INSIGHT 6— BRINGING THE LOCATION OF CONTROL AND THE RESULTING ACTION CLOSE TO THE USER STRENGTHENS THE FEELING OF INDIVIDUAL CONTROL AND OWNERSHIP.

Another aspect regarding the Bolb controller is its *portability*. The reflection sessions revealed that this was appreciated and in the GroupSorter this scored average. Making the control for the system portable was found pleasant. The location of control and the resulting action formed a unity at the location of the user, which strengthened the feeling of having *personal* light. One participant even expressed that he was attached to the controller, as it knew his preferences. Furthermore, one participant indicated that he found it reassuring that when he moved to another space and enabled the light there, he knew that the light was disabled at his previous location. By establishing a relation between the location of the user and the location of light control, feelings of personal space and territoriality were strengthened. Participants expressed they did not want to *invade* the space of others, and that they do not like it when others *intrude* their light. The fact that they used this type of terminology also expresses that they considered the light to be something of them; something personal.

> INSIGHT 7— BASIC LOW RESOLUTION CONTROLS SHOULD ALWAYS BE AVAILABLE, HIGHER PRECISION CONTROL OPTIONS SHOULD BE AVAILABLE UPON REQUEST OF THE USER.

The light-body offers participants controls with a high resolution that they can precisely manipulate. However, the evaluation showed that in this implementation, participants did not experience the control to be precise: This was partially due to latency of the system, and partially due to the ambiguous relation between parameters of the light-body (as discussed earlier). Both the GroupSorter and reflection session reveal that participants felt that control over lighting conditions does not have to be highly accurate and precise. As participants explained: The most basic functionalities (e.g., on/off, retrieve default settings) should be offered to users in simple ways and should always be accessible. In most cases, participants want to 'quickly' get started. This was also corroborated in the way the preference docks were used: During the evaluation they were used to rapidly load earlier settings. This presumably is influenced by the large bandwidth of acceptable lighting conditions: As long as extreme light conditions are avoided, people are generally 'okay' with the lighting conditions. However, upon request of the user, more precise control should be offered to users.

Balancing control in a social context

> INSIGHT 8— LIGHTING SYSTEMS SHOULD ALLOW PEOPLE TO SHARE CONTROL IN AN OPEN, NON-PRESCRIPTIVE WAY OVER LIGHTING CONDITIONS, BASED ON INTERACTIONS THAT TAKE PLACE IN THE SOCIAL CONTEXT.

The responses to the implementation of the balancing mechanism were negative. Insight 5 can be used to explain the negative experiences with the current implementation of the social balancing mechanism. Participants felt that they *lost* control, not that they *shared* control. For the current implementation it was required for two users to interact simultaneously in order to control the lighting conditions. However, as the reflection sessions revealed, this is not how control is shared in a social context: One participant described that when he had a meeting with another participant, they decided up-front who would bring his controller. Furthermore, there was no added value in sharing control. A participant described that in one case he wanted to share lighting conditions to help a less skilled participant to change her lighting conditions, but the balancing mechanism actually restricted him to do so.

This argues for balancing mechanisms that have a more 'open' character and do not restrict the user in his control freedom. In retrospect, the failure of the balancing mechanism can be explained by the mismatch between the goal of the user and the behavior of the system: E.g., a user wants to expand his light-body to gain more light, but instead the system merges the two light-bodies and limits the freedom of control the user has. From this perspective, it is understandable that users feel that they lose control, instead of gaining control over more light sources. Therefore, I argue that balancing mechanism should rely on both the social context, and the technology: For example, a system could facilitate people to grant others control over their lighting conditions, so they can help them to change their lighting conditions. Participants could understand that especially in larger installations such mechanisms would be required, but they should be less prescriptive of how people must behave.

Contextualized preferences

> Insight 9— personal lighting profiles on which systems can act, should be based on historical and contextual interactions of people.

The system provided people with the opportunity to store lighting preferences in their surroundings. In the current implementation preference docks were used to facilitate this. The responses to these preference docks were positive. Participants appreciated that they could move their light-body independently through the system, and that the preference docks provided access to basic functionalities. Participants appreciated that the system provided suggestions when no historical preferences were available. They also reported that they prepared the system for future use. One participant suggested that instead of storing the actual preferences of users, the system should be able to develop an understanding of contextual factors that people are sensitive to, and provide suggestions based on that information: E.g., person A might change his lighting conditions when the weather changes, and person B might change his lighting conditions most when he changes activity, the system might make suggestions based on this meta-level information.

> Insight 10— Allowing users to explicitly provide personal information to the system helps them to understand and appreciate automated behaviors of the system

The situated preferences was a mechanisms that allowed users to provide the system with personal information. The interaction patterns, the positive appreciation of the preference docks, and the appreciation for individual lighting show that people have a desire for lighting conditions that fit their personal routine: This could be an argument for the development of personal profiles about lighting preferences. However, it is important that users can explicitly provide information for personal profiles. This is supported by two observations: (1) Participants took the time to prepare the system for future use, and (2) participants appreciated suggestions by the system, because they could relate them to their earlier actions. This, on the one hand, indicates that users are willing to invest in 'educating' their system, and on the other hand makes the automated behaviors of a system comprehensible, as users can understand why a system makes certain suggestions.

System intelligence can be used to automate system behaviors. Automated behavior may be used to provide users with suggestions, based on historical patterns. However, the evaluation also revealed possibilities to provide local automated behaviors. The user patterns show that people typically turn on the system upon arrival, and turn it off when they leave. During the day, when they leave their workplace, they often forgot to dim/turn off the lights, while in retrospect they believe they should do this. This is an opportunity to automate such actions. With the Hyvve system it is possible to attach sensors and to provide automated behaviors locally. However, this should be done carefully: The evaluation showed that if the system shows unexpected or undesirable behaviors, this leads to negative experiences such as frustration.

7. Conclusions

In this chapter I presented the setup and results of a six-week longitudinal evaluation of three ALEs in a Living Lab. This study was performed to acquire insights into the research objectives outlined at the start of this chapter. These research objectives relate to the (1) design of meaningful lighting behaviors, (2) the social implications of the lighting system, and the experience with (3) novel interaction concepts. This is one of the first studies where people are provided with individual, portable, rich control for a lighting system. To my knowledge, it is the first study that evaluated behavior of people using such a system over a longer period of time.

I conclude that lighting behaviors become meaningful to people in the context in which they take place. This shows from the diverse motivations for people to change their lighting conditions that are functional (i.e., people want to have light that 'sufficient' light), and personal (i.e., their mental state, mood). Furthermore, control over lighting conditions allows people to explore what lighting conditions are pleasant for specific settings and it seems to support them in assigning value to the lighting system. The differences in interaction patterns corroborate that meaningful lighting behaviors are not universal across users (they are not even consistent within users) but they are constituted in-context. Based on this, I conclude that offering people control allows them to make lighting behaviors meaningful.

As users are provided with individual control, people understand the need to structure and balance control across users. The results of this study show that the current implementation of the mechanism to balance control between users was not appreciated. However, people do not have a negative opinion regarding shared forms of control in general, as they actually showed forms of sharing behavior, and they indicated that on a larger scale such mechanisms would be required. Furthermore, people attempted to collaborate via the system, but the technology constrained them to do so. The introduction of the personal and portable lighting controls shaped a new social context, in which the current implementation of the balancing mechanism did not fit. This new social context advocated 'live-and-let-live' principles: People did not experience different lighting conditions as disruptive, nor did they find it unpleasant when others interacted with the lighting system, because they knew they could also do it. This shows that people have positive opinions regarding sharing control and lighting conditions, as long as it has an 'open', non-restrictive character that fits the social context. This might imply that at times people want to maintain the control they have and they do not want to share lighting conditions with others, whereas at other times they should be able to fully take over control of others, in order to help them. Paradoxically, it is the unbalance of control from a technical point of view that can provide balance from a social point of view. However, it should be every individual who decides for himself who has control over his lighting conditions.

People related well to a light control concept that allowed them to control the lighting conditions from their 1st person perspective. The study also showed that people assign different roles to specific light types. For example, in the Break-out Area there was down lighting and wall lighting, which served different purposes for people. I conclude that a light control concept should provide sufficient degrees of freedom to people to control these roles of light independently.

Based on the results and insights of this study I conclude that controls should be offered to people on different levels. Simple controls, with low precision, should be readily available. Furthermore, richer forms of control that allow people to change lighting conditions with high precision, should be accessible upon request of the user. These can gives users with the opportunity to enter preferences and preferred behaviors into the system. Such mechanisms can support people to better understand and appreciate automated behaviors of the system.

Concluding the Adoption phase

The Adoption phase is the final phase of the Growth Plan and aims to investigate the implications of ambient intelligent technologies in everyday life. In this final part of the dissertation I presented the implementation of a Living Lab environment, consisting of three ALEs in three environments. These three spaces, respectively Break-out Area, Meeting Room and Open-plan Office, were selected as different types of activities take place in them. Four participants were provided with personal and portable Bolb controllers, which allowed them to interact with the lighting system in these three environments.

The lighting system was evaluated over a period of six weeks. Throughout the evaluation period quantitative measures – in the form of images, data logs, and light measures – and qualitative measures – in the form of reflection sessions – were captured. The evaluation was setup to provide insights regarding research objectives that fit the design challenges of this project. These cover (1) the design of meaningful lighting behaviors, (2) investigating the social implications of adaptive lighting environments, and (3) the exploration and design of novel interaction concepts. The study showed that lighting behaviors become meaningful as people contextualize them for personal and hedonistic motivations. Furthermore, the study revealed that an ALE should fit a social context, by allowing people to balance how control is distributed in an open, non-prescriptive way. Finally, the study indicates that novel interaction concepts should be designed from a user point-of-view, as people assign different roles to lighting in their environment, which should be available in interaction. Furthermore, control should be offered at different levels, where low-precision controls (e.g., on/off and presets) should be available at any time, and high-precision controls need to be available upon request of the user.

Overall, this study should be regarded as a first evaluation in the Adoption phase. Given the insights and conclusions of this study, new evaluations should be conducted. Furthermore, the installations themselves show how different technologies (e.g., Lithne, Hyvve, Bolb) are interwoven in a systemic way to create different lighting setups that are tailored to different contexts. These lighting installations showcase the versatility and flexibility of Hyvve. Additionally, as the Lithne platform is also used in the Break-out Area it has been possible to integrate this environment into the lighting system, which exemplifies the systemic character of the lighting environments.

With the Adoption phase I conclude the project. In the following chapter I discuss the project, its approach, and its outcomes and I reflect on the main design challenge of *how to design for adaptive lighting environments.*

6. Reflections & conclusions

1. Introduction

This final chapter contains reflection on the entire project. I have selected three aspects on which I reflect. First, I reflect on using the Growth Plan as research-through-design approach, and present insights in the Growth Plan, based on my experiences. Secondly, I reflect on the systemic nature of the design challenge, and the lessons that can be taken from this project regarding the design of socio-technological systems. Third, this chapter concludes with reflections and conclusions on the main design challenge of *how to design for adaptive lighting environments.*

2. Research-through-design via the Growth Plan

Throughout this dissertation I used the Growth Plan to structure my design-research activities. Initially, the Growth Plan was used to determine an overall planning for the project. Furthermore, it was used to communicate about the different design activities.

2.1. Planning, communication & application

As was presented in the first chapter, the Growth Plan's primary purpose was planning and communication. The project was set up according to the Growth Plan, which provided a rough outline of the time frame in which activities had to take place. Furthermore, the project was used to communicate between disciplines: E.g., what would be goals for the individual Ph.D.-students in the Nursery phase, or where would be the overlap in terms of research interests? However, during the project I noticed that it was difficult to articulate whether the project as a whole was in the Incubation, Nursery, or Adoption phase. In retrospect, this seems to be a consequence of the focus on designing for systems.

Looking back, the Growth Plan was applied in a different way than is described in the original description. Ross & Tomico (2009) describe the Incubation phase as the stage in which sketches and simple prototypes are created, and only include contextual factors in the Nursery phase. Furthermore, their case study does not extend into the Adoption phase, which makes it difficult to relate their abstract description to a concrete implementation. What this project showed is that even in early explorations (e.g., sketches, simple prototypes) in the Incubation phase, evaluations can take place in context. For example, using off-the-shelf technologies, and by acting out system components, it is possible to implement experiential systems and to evaluate these with experts or users.

2.2. Out of sync: dual nature of the designer-researcher

The Growth Plan is intended to provide structure to the design process. However, throughout the project it was difficult to identify in which phase the project as a whole was. The dual nature of the design-research challenge, and the approach of developing a system, contributed to this.

I first elaborate on the dual nature of the main challenge: Research-through-design is an approach where design activities are used to catalyze research questions. As such, research questions and design insights advance throughout the process. In the Growth Plan this is not different. At the start of this project, one main research challenge and three sub-challenges were defined. Explorations in the beginning of the Incubation phase investigated these three sub-challenges (mostly) individually. Towards the end of the Incubation phase, more integrated explorations were performed. The insights of these explorations were used to design Lithne, Hyvve and Bolb in the Nursery phase. Finally, research questions were addressed in the Adoption phase that related back to the original challenges, but were more specific and refined based on all insights acquired. However, the individual design and research activities matured at a different pace (on which I elaborate in the next paragraph). This makes it difficult to determine for the project as a whole in which phase it was: Some research activities took place in the Incubation phase, whereas design activities already advanced to the Nursery phase.

Second, the systemic approach towards the design challenge made it difficult to frame the project in one phase. This is because the nature of the design challenge for this project differed from the challenge of the doctoral research of Ross (2008), which is taken as a case study for the Growth Plan. His lamp is a single product that was iteratively developed along the lines of the Growth Plan. The difference to the work is that this project was approached from a systemic perspective from the start on. In that respect, the development of Lithne, Hyvve, and Bolb could individually be described in a Growth Plan, as all three have undergone a process whereby initial explorative sketches, models and prototypes were refined through contextual evaluations (an impression of this process is shown in Figure 6.1). Although it could be argued that Lithne, Hyvve, and Bolb indirectly imply a consecutive order – as Lithne is required for Hyvve, and Bolb is meaningless without a lighting infrastructure – this actual design process was much more intertwined. For example, the requirements of Lithne are based on the requirements of Hyvve, whereas the capabilities of Hyvve are dependent on the capabilities of Lithne.

To exemplify this design-research duality, and the systemic perspective, I take the design of Hyvve as an example. The initial ideas for Hyvve emerged from the adaptive office implementation. Based on this, initial prototypes of the Hyvve system were created; this eventually created the demand for the Lithne platform. Whereas the development of Hyvve can reasonably be argued to fit the Nursery phase, my research activities regarding the 'spotlight' behavior were still in the Incubation phase. This a-synchronous process shows clearly in the Chapter 2.3, where the Hyvve tiles are used to investigate spotlight behavior. This shows that when using the Growth Plan to iteratively advance design-research challenges of systemic nature, the exact phases may shift and eventually the project may be in different phases at once. However, under such circumstances the Growth Plan is helpful as it sets boundaries for the different activities.

Figure 6.1 Impression of the design process of Hyvve (top) and Bolb (bottom).

2.3. Defines boundaries

In a process where specific activities take place in different phases, it is helpful if a designer can maintain an overview of the entire project. Consequently, this means that a designer needs to recognize when activities have reached 'sufficient' depth to advance to a next phase. Via this project, I contribute to reflections by Frens (2006), Hengeveld (2011), and Deckers (2013) on their doctoral work. They state that research prototypes should contain 'sufficient' product, system, and behavioral qualities, respectively. Yet, the term sufficient can mistakenly be interpreted as 'anything goes', even though the authors have not intended it as such. However, it can be helpful to have handles as to what is 'sufficient' during the design process. In this, I agree with Hengeveld, who argues that 'sufficient' is defined by the (design or research) knowledge one seeks for. From that perspective, the Growth Plan provides insights into what can be considered 'sufficient' at different phases throughout the design process. For example, the first Interactive Sketch (Chapter 2.1) was part of the Incubation phase, where I had to advance my design thinking and my research direction. In this case, this implied that I used off-the-shelf technology, asked participants to perform behaviors that I had predefined in order to explore open-ended research directions. At that point in time that was 'sufficient'. As the Incubation phase targets innovation and exploration, opening up novel concepts to an experiential level–so they can be evaluated in brief sessions, in semi-controlled environments–is sufficient. The Nursery phase extends this and as the designer has initial (experiential) insights at this phase, he needs to deepen out the experiential implications of several concepts. Sufficient – at this stage – implies that prototypes need to be able to operate without continuous intervention of the designer so they can be used in evaluations in realistic contexts, in order to provide rigorous research outcomes. Finally, the Adoption phase demarks the stage where others should be able to adopt the design solutions and insights. Sufficient then implies that a designer is ready to transfer responsibility over his contributions to others.

2.4. Adoption: transferring responsibility

A final topic of discussion regards the nature of the Adoption phase: This phase targets the evaluation of technologies that are adopted in daily life. Specifically, the adoption phase argues that innovative technologies are evaluated in realistic settings to provide rich insights into the implications of that technology.

However, I add to this that adoption implies that a technology is out of the hands of the designer-researcher: it is out of control and the designer is no longer responsible for it. What this means is that if a designer-researcher targets 'adoption', this has consequences for his design-research activities. Essentially, his outcomes should allow to be adopted by others. Steps in this direction were observed with the Hyvve implementation. For example, a colleague from the faculty of Computer Science used the Hyvve installation in the Meeting Room to explore and implement a distributed lighting behavior algorithm. Another colleague implemented a lighting controller (i.e., LightPad (Magielse, Offermans, 2013)) to control the Hyvve system above his desk, after the evaluation had ended.

Even though in this project the steps towards adoption by others are small, this topic should deserve attention of the research community. In a design-research landscape, where evaluations take place in the real world (e.g., Living Labs, Experiential Design Landscapes), it should be questioned how far the responsibility of the designer-researcher goes: When has a project matured sufficiently, such that a designer can withdraw from it?

3. Designing for systems

In the introduction of this dissertation, I argued that adaptive lighting environments represent a socio-technical system. Designing for systems entails new challenges (Frens & Overbeeke, 2009). The structure of the system, with diverse relationships between people and technology, a high number of stakeholders, and various perspectives that one can take, results in challenges that are complex. Designing interaction from this systemic perspective – where functionalities no longer reside in single products alone – potentially breaks the unity of form-interaction-function (Frens, 2006). I argue that this requires reconsideration of this triad, and that systemic design challenges should be approach from both a 1st and 3rd person perspective.

3.1. Systems perspective on rich interaction

Frens (2006) shows how rich interaction is an integration of form, function and interaction in order to provide people with information-for-use. In summary, he argues that designers should create action-possibilities that inherently communicate to a user how to act and what the consequences of his actions are. The difficulty with designing for systems (of interactive products) is that the unity of form, function, and interaction may not be static. For example, the Break-out Area is an environment that is defined by the colored atmospheric lighting, whereas the Open-plan Office is defined by functional task lighting. Additionally, the Break-out Area is an environment that is subject to change, as different projects contribute lighting solutions to the system. Both spaces would benefit from a dedicated controller where the action-possibilities are tailored towards the context and application. After all, the activities in the Break-out Area are different than the activities in the Open-plan Office. On the other hand, there are good motivations to provide people with a personalized and portable controller that can be used in a wide range of contexts: First, a personal controller can learn from its user and provide personalized behaviors that are targeted to that specific user. Second, users do not require a controller for every environment.

One solution would be to create dedicated controllers for each environment that are personalized as soon as users use them (i.e., log in to your personal account). However, due to the dynamic nature of a system (people and technologies come and go, or the topology of the system changes), situations might always arise where there is an imbalance between the action-possibilities offered to a user and the state of the system. Yet, if the aim were that the action-possibilities of an interactive device should balance form, function and interaction, it would also mean that when functionality changes, a change in the other two aspects is required. Frens and Overbeeke argue along similar lines that this is one of the challenges that fundamentally impacts interaction design in a setting of designing for interactive systems (Frens & Overbeeke, 2009). There are different ways to deal with this challenge.

A solution is to rebalance the triangle through adjusting the 'form' to match the 'function' and 'interaction' of a given context. In this case, one can think of objects that change their shape (Rasmussen, Pedersen, Petersen, & Hornbæk, 2012), or modular devices that users modify to enable different action-possibilities and maintain this balance. With the growing popularity of 3D-printing techniques, modular approaches becomes feasible: Users can print new components to fit their devices to adapt them to specific situations. Even though smartphones and tablet computers cannot change their physical form, they provide a solution to create user interfaces that are contextually relevant. As they can be connected to different devices, and they provide diverse interaction possibilities, they are currently a popular way to interact with other systems in diverse contexts.

Another possibility, which was used in this project, is to provide a 'mediating interaction concept' (MIC) between the single product parameters and the system parameters. The light-body is an example of such a MIC. In this case, the light-body describes the lighting behavior in a set of parameters (i.e., location, size, intensity, and light color), which are then mapped to the physical lighting setup. Using such a MIC it becomes possible to deal with the dynamic nature of interaction in a systemic context. The Carrousel (Ross & Keyson, 2007) and M-Beam (Westerhoff, van de Sluis, Mason, & Aliakseyeu, 2012) use similar approaches as they translate expressive product parameters to system parameters. What this means, is that a static relation can be created between the physical device and the MIC. The values of the MIC should be dynamically translated to system parameters. To use this project as an example: the Bolb device provides means to change the size of the light-body, which is a static relationship: It always provides the same behavior, irrespective of the context. The server – on which the light-body is located – translates the parameters of the light-body to commands for the individual light sources in the system.

The implications of this approach are twofold. In the first place, specific MICs can be designed to fit specific contexts: E.g., the light-body would be a suitable concept for open-plan offices, whereas the Break-out Area would require another MIC (following Insight 4). This means that a designer needs to find product parameters that are contextually relevant and map these to relevant system parameters. In the second place, the mapping of parameters of the

MIC to the specific system parameters has to be performed. This can either be done manually, for example when a lighting environment is created. However, I argue that system intelligence can be used to dynamically map product parameters to system parameters. For example, changing the size of the light-body could be scaled to the size of the environment, such that the experience of controlling a small or large environment is not different. This potentially helps users to understand and predict how specific lighting setups will behave, and as such facilitate a consistent experience in interaction across different lighting setups and contexts.

3.2. 1st and 3rd person perspectives in designing for systems

Throughout this project I have taken different perspectives that are best described as 1st and 3rd person. A 1st person perspective is adopted when a designer engages in the design challenge through his own experiences. This provides access to the richness that is in the world and typically focuses on details and nuances. A 3rd person perspective is then characterized by taking a distant, analytical, and abstract perspective to the design challenge. This is focused towards global patterns and generalizability. In this section I reflect on the perspectives that I have taken throughout this project and provide examples of how they were used in this project.

The design process of the light-body is an example of designing from a 1st person perspective. As I sat in the adaptive office installation, I explored how the system could be controlled from the perspective of the user. While sitting at the table, I first illuminated my work in front of me, but later also want to see further into the space. From my perspective it made sense that if the light intensity increases, the light also expanded away from me. This behavior was implemented from a 3rd person perspective by relating the intensity to the size of the light-body in the software. Later on, the design process was fed by taking a 3rd person perspective: In the Adoption phase, multiple light-bodies began to overlap on the server, which led to erroneous behavior of the individual light sources. At that point it made sense that overlapping light-bodies were merged. This was in turn translated to a 1st person perspective by relating it to social norms.

Closely related to the perspective on the design process, the implications on social settings can also be designed and researched from a 1st or 3rd person perspective. In this project specifically, the 1st person perspective is apparent in the second installation in the lunch environment (Chapter 2.2), where a group of people acted out the intelligence of a system, and in the sensitizing activity for designing the Bolb controller (Chapter 4.2). In these cases I acted out the intelligence of the system to see in a rich context where specific lighting behaviors might be relevant. The sensitizing activity for instance revealed that people perform activities in different locations and they want to have different lighting behaviors for those activities. However, this also confronted me with the limited degrees of freedom that I had: I wanted to support the users with specific lighting conditions, but I didn't have the means to do so. This was translated to the design of Hyvve, which consists of modular tiles that can individually be controlled on different parameters. The Hyvve system as a whole was able to provide sufficient degrees of freedom. Investigating social implications from a 3rd person perspective is most prominent in the adaptive office (Chapter 2.4) – where three scenarios of user activities were predefined and implemented – and in the study regarding spotlight behavior (Chapter 2.3), where specific profiles of lighting behavior were implemented and related to behavior of people (i.e., duration of speech). In these cases, analyzing and abstracting a range of (office) activities to specific measurable classifications of those activities defined the lighting behaviors.

The behavior of the system can also be implemented from either a 1st or 3rd person perspective, although other terminologies such as 'bottom-up and top-down' or 'decentralized and centralized' have similar connotations. As I experienced throughout this project, it is easier to implement specific behaviors into the system from a 3rd person perspective. From this point of view, the designer has an overview of the system and has control over the behavior of the system. For example, the implementation of the light-body is fairly simple using a 3rd person perspective, as the location of the individual light sources is known and the location of the personal controller is known. Implementing this behavior from a 1st person perspective is more difficult, as this requires the individual light sources to have perceptive qualities. In collaboration with Sunder Aditya Rao, I explored whether the light-body could be implemented from a 1st person perspective, since this would make the system more versatile, flexible, and scalable, as no central server would be required. Practically, this implied that we had to implement a distributed algorithm running on each Hyvve tile, and that each tile had to perceive the surrounding tiles and the Bolb controller. Similar insights are reflected in the implementation of the Bolb controller. The concept is designed with a 1st person perspective in mind, but the actual implementation offered these qualities in a simplified form (i.e., via docking stations) using a 3rd person view. An implementation from a 1st person point of view would have meant that the Bolb could perceive the environment, location, and orientation in which it is placed as well as its surrounding tiles. Different perspectives lead to different solutions.

It is by alternating perspectives, and understanding how the different perspectives influence and (potentially) invigorate each other that it is possible to develop a holistic understanding of the system (Frens, Tomico, & Zimmerman, 2012; Tomico, Winthagen, & van Heist, 2012). From this I conclude that designers of interactive systems need a repertoire of skills that allow them to access the richness of experiences from a 1st person perspective, and the analytical, abstract 3rd person perspective that soft- and hardware implementations require.

4. Designing for adaptive lighting environments

In the previous sections, I reflected on this project in terms of its approach, and the systemic nature of the design challenge. This section first discusses the three sub-challenges of the project, in order to provide insights for the main challenge at the end of this chapter.

4.1. Designing meaningful lighting behaviors

The first sub-challenge poses the question: How to design meaningful lighting behaviors for ALEs? Based on this project, two design guidelines are derived. In the first place, this project shows that a designer needs to simultaneously give shape to the lighting behaviors and make them contextually relevant. Second, designing for ALEs oftentimes leads to the development of automated lighting behaviors. I argue that automated lighting behaviors at a system level are likely to fail in the long run. Instead, lighting behaviors can be automated at the level of the individual 'nodes' in the system. I add to this that if insufficient information is available, it is best to leave control to users: They can apply specific lighting behaviors when they are meaningful to them. I elaborate on both aspects in the following paragraphs.

As a matter of context

Lighting behaviors are more meaningful to people as they relate to the context in which they are used (Hummels & Lévy, 2013; Overbeeke, 2007). Insights 1 (*people adjust lighting conditions to contextual factors, personal aspects and their view about possible beneficial effects*) and 9 (*personal lighting profiles on which systems can act, should be based on historical and contextual interactions of people*) from the final evaluation corroborate this conclusion: These advocate that the value of lighting conditions is derived from contextual factors that are difficult to predict up-front and out of context. Lighting behaviors of which the meaning is defined outside the context are likely to fail in the long run, as the complex dynamics in which these systems operate are eventually unpredictable. Consider the following thought experiment: In the current implementation of interactive sketch (Chapter 2.1) the lighting behavior was now pre-defined to enhance psychological closeness. This behavior is relevant if the relationship between the users allows for this (e.g., close friends). However, this lighting behavior would not be meaningful in a formal business meeting, where the relationship between people is completely different. The results regarding the spotlighting behavior (in Chapter 2.3) further corroborate this conclusion. In this case, the lighting behavior was completely disjoint from the context and behavior of people. The results of this study revealed that the implications of the lighting behavior on the social setting were only small.

Automate lighting behaviors at node level

Adaptive lighting behaviors are often considered to be automated lighting behaviors. I would argue that generalized automated lighting behaviors, applied at a system level, are likely to fail in the long run, because the context in which they operate is dynamic. Insight 9 (*personal lighting profiles on which systems can act, should be based on historical and contextual interactions of people*) and 10 (*Allowing users to explicitly provide personal information to the system helps them to understand and appreciate automated behaviors of the system*) support this conclusion: Automated lighting behaviors need to be tailored towards the individual, as this helps people to understand why the system acts the way it does. Results from this project can be used to strengthen this conclusion: For example, the three scenarios that were implemented in the adaptive office were derived on heuristics of 'typical' office activities. However, these are not capable of dealing with unknown or unexpected situations. For instance, if the space is used for a group lunch, or the space is changed into a storage room, the behaviors that were specified are no longer relevant. This does not imply that it is not possible to automate lighting behaviors, but I argue that automation should take place on the level of the individual 'nodes': In the final evaluation, the preference docking stations provided a simple form of automation, and they were highly appreciated. This form of automation was targeted towards the specific user and to specific contextual factors. Furthermore, they were created in the context of use. Additionally, I would advice that in case of doubt, it is better to leave control to the user. Further investigation regarding automated behaviors at a personal, localized level is required in future work.

4.2. The implications on social settings of ALEs

Lighting has social effects on people. As lighting systems become embedded and networked, these social implications will play a more prominent role. However, because the intervention of the designer (i.e., the system he designs) inherently transforms the context he designs for, it is essential that a designer investigates the implications on social settings of ALEs in the context that is established when the system is installed.

Consider the context-to-be

In the previous section, I concluded that for the design of meaningful lighting behaviors, it is important that a designer relates these behaviors to the context in which they are used. In this section, I conclude that – to properly evaluate the implications on social settings of ALEs – a designer should understand the context that he establishes. I elaborate on this with an example from my work. In the project I focused on the way systems could distribute control over lighting conditions. This aspect was explored in Chapter 2.4, where control over a multi-user lighting environment was distributed over a group of people. The insights from this exploration informed me that – as control over lighting conditions was shared between people – these people expressed more social behaviors towards others. The Bolb controller was based on these insights, and on current social norms, which say that it is polite to adjust yourself to others as you visit them. However, the implementation of the balancing mechanism in the final installation was not appreciated, as it did not fit the context that was established in the new lighting system: The lighting environment in the Open-plan Office was a context where multiple individuals shared a space, but where the lighting conditions were individual and not shared. The balancing mechanism was designed in – and thus for – an environment where individuals share lighting conditions. The context that was established was not a shared, but an individual lighting environment. Insight 3 (*providing people with individual, localized control from a first-person perspective enables a feeling that the space is theirs*) and insight 6 (*bringing the location of control and the resulting action close to the user strengthens the feeling of individual control and ownership*) strengthen this argument: People were provided with individual control at their location, which implies that their feelings of individuality and ownership were strengthened by the system. In hindsight, the results can additionally be explained by the mismatch of the behavior of the system and the intention of the user: As users extended the size of their light-body to gain more light, the system behavior did not offer this, but instead restricted the user in his freedom of control and (potentially) changed his lighting conditions to those of someone else, which violates insight 5 (*Users like to feel in control of their lighting conditions and should never feel that they lose control, or that control is taken away from them*).

Consider the system as a whole

The previous reflection also shows the difficulty with the systemic nature of the design challenge. As I mentioned before, the Growth Plan eventually went 'out-of-sync' for the individual activities. Whereas the entire project advanced towards the Adoption phase – as individual components of the system and research questions had matured – the Bolb was not yet mature enough for the Adoption phase. This provides another insight: The system as a whole may have different implications than one would expect from the composition of individual components. Therefore it is essential to implement the whole system at points in the design process.

4.3. Novel interaction concepts for lighting environments

The revolution in lighting is primarily technology-driven: Technical capabilities define the lighting solutions that designers can create. However, in order to facilitate a designerly way of thinking and to support the design of innovative interaction concepts, lighting technologies need to transcend the technological difficulties and address designers at an experiential and behavioral level. Essentially, what this project showed is that in order to design for contextually relevant lighting behaviors, it should be possible to design iteratively, and in-context with a focus on behavioral qualities. The difficulty is that many of the tools that are available to designers, are not suitable for this. Therefore, I conclude that designers should be provided with tools that allow them to take different perspectives. Additionally, I argue that lighting setups should be flexible and versatile. Finally, regarding the design of novel interaction concepts: I argue that interaction concepts need to be designed to fit different contexts where specific degrees of freedom are desirable.

Allow designers to take different perspectives

I conclude that, in order to design novel interaction concepts, designers need tools that allow them to take different perspectives while designing. Most contemporary lighting equipment advocates a technical way of thinking: Big, clunky boxes are required to control cumbersome lighting equipment, given that the correct cables and connectors are available to wire the complete system. This is in sharp contrast with the tiny point source that the LED can be. Furthermore, in order to control this equipment, exact specifications have to be provided, which are easy for the technology to process, but arbitrary for the designer to understand. These technologies essentially force the designer into a 3rd person perspective. The challenge of designing novel interaction concepts is thus more a challenge of providing designers with the tools that catalyze their design activities and that focus on making concepts experiential. This is supported by insight 4 (*Different lighting setups and environments require specific control concepts as users view these contexts from a different perspective. user controls should be designed to support the user perspective*), which argues that designers need to be able to take the perspective of the user. In order to get to the complexity of the design challenge, designers should be supported to overcome the complexity of the technology and approach it from a different perspective.

Although both Lithne and Hyvve still require technical knowledge, they are first examples of research tools that support the development of lighting environments from an experiential perspective, instead of from a technological perspective. Both technologies are in development and there are still improvements to be made, but experiences with using these technologies revealed they allow for a 1st person perspective. This means that design can take place in-context and lighting behaviors can be made experiential. This catalyzes a different way of design that leads to novel interaction concepts, such as the light-body. As was explained earlier: The idea for this interaction concept initiated as I created the lighting setup for the adaptive office and I was sitting on one end of the table and wanted to control the light based on my position (This lighting behavior follows insight 6). Essentially, insight 2 (*providing people with the opportunity to change their lighting conditions allows them to explore their lighting preferences. This helps them to understand which lighting conditions are pleasant for specific situations*) also applies for designers: If designers can approach the design challenge from different perspectives, they can develop an understanding for that perspective.

In the second place, this means that the tools a designer uses, should advocate thinking about light behaviors, rather than technical behaviors: DMX equipment forces thinking in channels that control RGB, but that is not the way light is experienced by people. Instead, a designer should be able to set for example light intensity, or light color, as this is how people perceive lighting conditions. Hyvve advocates this perspective as control over the lighting conditions addresses lighting qualities that are meaningful to people: change light intensity, color temperature, and temporal aspects.

Lighting setups should be flexible and versatile

In order to support designers in taking different perspectives, lighting setups need to be flexible and versatile. This allows designers to iteratively develop lighting behaviors and interaction with lighting environments: Via experiential insights the design challenge is advanced. The physical implementation of the lighting environment – to a large extent – determines the degrees of freedom a designer has. Essentially, the lighting hard- and software need to be equally flexible: It should be possible to program the behavior of the individual nodes to (so designers can take a 1st person perspective) and to program the behavior of the system at large (so designers can take a 3rd person perspective).

Provide degrees of freedom that fit the context of the user

In the previous sections I addressed two insights regarding the tools that designers need in order to develop novel interaction concepts for ALEs. In this section I focus on specific insight regarding the design of novel interaction concepts. I conclude that interaction concepts should provide degrees of freedom that fit the context in which people use them. This is primarily derived from the final evaluation (Chapter 5), which revealed that the degrees of freedom that people wish to have, varies for different contexts: At some points they felt they had too much control, at other points they felt a lack of control (following insight 5 & 7). A specific example, that well illustrates how people made the degrees of freedom fit the context are the docking stations: Participants used the docking stations as 'switches' as it allowed them to quickly turn on lights at their location. Only when the context allowed/required it, they would make further adjustments. This shows that their desire for specific degrees of freedom in control may change. Moreover, I conclude that interaction concepts should fit the perspective that people have regarding the lighting environment: E.g., the light-body fitted the perspective of people in the Open-plan Office, but not in the Break-out Area, where people considered lighting to be 'direct' or 'peripheral'. This project revealed the degrees of freedom and role of a light source as two dimensions for the design of interaction concepts. Further investigations, in different contexts and with different lighting setups are required to build more elaborate frameworks.

5. How to design for adaptive lighting environments

Now that I reviewed the design process, as well as the individual sub-challenges, I address the main challenge of how to design for adaptive lighting environments?

Designing for ALEs is characterized by explorations, design and evaluations in context, targeted at creating experiential implementations. The design process is characterized by iterative cycles of explorations, where research challenges and design solutions become increasingly more refined and detailed. Throughout the design process, the designer changes between a 1st and 3rd person perspective in order to develop a holistic overview of the design challenge, whereby he derives inspiration and insights from confrontations of design propositions with users. Such a design process embraces the richness of experiences in the real world and via analyses and abstractions the designer gets a grip on the complexity of the design challenge.

TABLE 6–1 Overview of contextual factors for design of adaptive lighting environments

Environmental factors	Physical environment	e.g., temperature, noise, purpose for which the environment is used
	Lighting setup	e.g., location, directionality of the light sources, degrees of freedom, role of the light sources
Human factors	Activity	e.g., highly focused, general
	Motivation for interaction	e.g., functional, hedonistic
	Emotion & mood	e.g., stressed, tired
Social factors	Presence of others	e.g., engaged in interaction, nearby, distant
	Relationship to others	e.g., friends, colleagues

Throughout the reflections I argued that context plays an important role in the design of adaptive lighting environments. Based on this project, I provide an operational definition of context, summarized in Table 6–1, where context refers to “the group of conditions that exist where and when something happens”[1] Contextual factors for interaction design, generally are subdivided in *human factors* and *environmental factors* (Schmidt, Beigl, & Gellersen, 1999). Following this argument, I qualify (1) the physical environment (e.g., temperature, noise, and the purpose for which the environment is used), and (2) the lighting setup (e.g., location, directionality, degrees of freedom, and purpose of the individual light source from a user’s perspective) as important parameters that define the environmental factors. The human factors then are constituted by (1) the activity, (2) motivations (both functional and hedonistic), and (3) emotion and mood of the person. Additionally, this project also contributes that the *social factors*, where the (1) presence of, and (2) relationship to other people, form a third aspect that defines the context for adaptive lighting environments. It is of importance that the understanding of these contextual factors is rooted in the adaptive lighting environment as it is envisioned, because the implementation of such an environment inherently transforms the

[1] http://www.merriam-webster.com/dictionary/context

context. Further research is required to investigate the relationship between these factors, and to determine whether other factors should be added for the design of ALEs.

Given the importance of context, a design process then should focus on establishing and investigating this envisioned context. This advocates the design and evaluation of experiential installations, and implies that the tools that designers use advocate the design of lighting behaviors from different perspectives. In order for designers to focus on experiential prototypes, I argue that lighting hardware needs to be flexible and versatile, so a designer can alternate between 1st and 3rd person design processes and implementations. This supports an iterative design process, where contextual insights can be used to further advance and specify research challenges, and at the same time explore, implement, and refine lighting behaviors and lighting environments.

Finally, I conclude that lighting behaviors acquire their meaning as people use them in context. Even though adaptive lighting behaviors that respond automatically to users are high on the agenda, I argue that fully automated environments are likely to fail. In the first place, because people *want* to be in control. In the second place because the contextual factors are highly dynamic, which means that in the long run automated behaviors will be rendered obsolete. Automated lighting may be implemented, but this should take place at the level of individual nodes, rather than at the level of the system at large. In cases of uncertainty or ambiguity it is better to leave control to the user. Additionally, if users can inform their environments *how* they would like it to behave, this can help them to understand *why* specific automated behaviors take place. Furthermore, I argue that localizing automated behaviors should be further investigated as this might be another approach to implement lighting behaviors that are adaptive and contextually meaningful.

5.1. Embracing complexity in designing for systems

The world that we live in is inherently rich and complex. Designing socio-technical systems that fit in this world entails design challenges that are equally complex. Throughout this dissertation I combined design thinking with design making in an iterative process. Furthermore, I used a designerly approach, whereby I approached the design challenge holistically through alternating between different perspectives. In this way, I was able to include the richness of the real world and to embrace the complexity of designing for adaptive lighting environments,

Acknowledgements

Completing a doctoral research trajectory is seldomly an individual effort. Much of the work that has been presented in this dissertation is work that has been performed in collaboration with other researchers and students. Where possible, I acknowledged the contributions of others to this project in the respective chapters. The following is an overview of the contributions that others have made to this project.

Chapter 2.3 - Out of the darkness, into the light describes work that Axelle Mirigay performed as part of her 6-month internship at the Eindhoven University of Technology. Axelle set up the study, performed the seven sessions and acquired all the data under my supervision.

Chapter 2.4 - Multi-user interactive lighting was a student project that I proposed and for which I was the client for three master students of the faculty of Industrial Design. Martijn Kelderman, Don Willems, and Teun Vinken (supervised by Alex Alblas, Philip Ross, and Harm van Essen respectively), created the three designs, set up and performed the evaluations and gathered all the data.

Chapter 2.5 - The adaptive office environment was a project in which I collaborated with Sunder Aditya Rao, who was responsible for the system architecture and implementation of the software on the nodes, and Paola Jaramillo Garcia, who was responsible for the activity classification algorithm.

Chapter 3 - Designing tools: Lithne & Hyvve presents the design and implementation of Lithne. This work is initiated in collaboration with Serge Offermans. The implementation was performed in collaboration with Vic Teeven, Troy Reugebrink, Jurjen de Keyzer, and Elco Jacobs. The Lithne hardware is designed by Jan-Derk Bakker.

Chapter 5 - Evaluating adaptive lighting environments describes the Break-out Area, which is part of the doctoral research of Serge Offermans. The design and installation of this environment is performed by Serge Offermans.

The photos for the cover, the table of contents, the Incubation, Nursery, Adoption part, the chapters 1, 3, 4, 5, 6, and the Curriculum Vitae page are taken by Jeroen Peerbolte.

This project is part of the Intelligent Lighting Institute of the Eindhoven University of Technology

Glossary

CCT (Correlated Color Temperature)

Correlated Color Temperature, abbreviated to CCT is “a metric for the color appearance of a the light emitted by a light source” (Boyce, 2010, p.21) and is more commonly used to describe a light source as ‘warm’ or ‘cool’. CCT is described with the unit Kelvin (K), which is a measure of temperature. “The basis of this measure is the fact that the spectral emission of a black body is defined by Planck’s radiation law and hence is a function of its temperature only. (...) When the chromaticity coordinates of a light source lie directly on the Planckian locus, the color appearance of that light source is expressed by the color temperature, i.e. the temperature of the black body that has the same chromaticity coordinates.” (Boyce, 2010, p.21) As the temperature of the black body increases, the color of the light emitted by it changes. A simple example: Fire in an hearth is typically orange/yellow, or ‘warm’ as most people would say, but the flame of a gas stove is typically white/blue, or ‘cool’. Both flames are at a different temperature and therefore emit different light colors. The same principle applies to the blackbody radiator. Contrary to what one might think, ‘warmer’ light colors have a lower CCT than ‘cooler’ light colors.

DALI (Digital Adressable Lighting Interface)

DALI is a communication protocol for lighting equipment. “It is an international standard that guarantees the exchangeability of dimmable balasts from different manufacturers” (“DALI Manual”, 2001). It is typically used in electronic ballasts to control the light sources attached to the ballast. A DALI network generally consists of one DALI controller and up to 63 DALI devices.

DMX (Digitally MultipleXed)

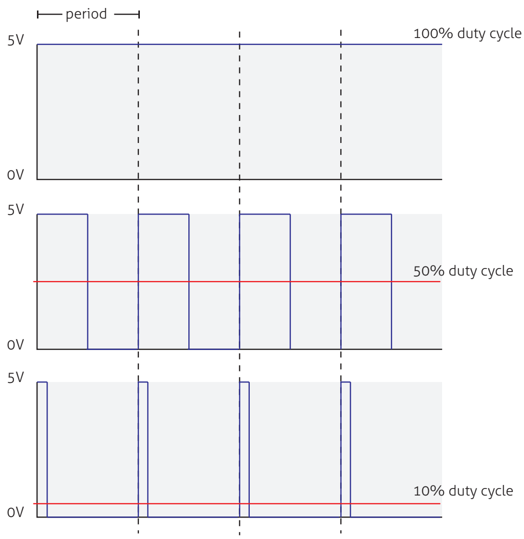
DMX, or DMX512 is a communication protocol for lighting equipment. “DMX512 is a standard that describes a method of digital data transmission between controllers and lighting equipment and accessories“ (“USITT DMX512-A”, n.d.) It is most commonly used in theatre and stage lighting. A DMX network typically consists of a DMX controller and up to 512 DMX channels. This is also known as a DMX universe.

HSB (Hue, Saturation, Brightness)

HSB stands for Hue, Saturation, Brightness. HSB is used to describe a color in a color space. It is possible to convert RGB colors to HSB colors and vice-versa. Hue is defined as: "Attribute of a visual perception according to which an area appears to be similar to one of the colours – red, yellow, green, and blue – or to a combination of adjacent pairs of these colours considered in a closed ring." (Fairchild, 2013, p.88) Saturation is defined as: "Colorfulness of an area judged in proportion to its brightness" (Fairchild, 2013, p.91) Brightness is defined as: "Attribute of a visual perception to which an area appears to emit, or reflect, more or less light" (Fairchild, 2013, p.88). My motivation to use a HSB-color space is that one can browse through different colors, by manipulating a single parameter (*hue*).

PWM (Pulse Width Modulation)

PWM stands for Pulse Width Modulation and is a common technique in digital electronics to encode an analog signal. PWM as output is generated by "a series of very rapid on-and-off pulses that can be filtered to give an average voltage. The higher the ratio of the on-time to off-time in each pulse, the higher the average voltage." (Igoe, 2007, p. 127) "The resulting average voltage is sometimes called a *pseudo-analog voltage*.... This ratio is called the *duty cycle*" (O'Sullivan & Igoe, 2004, p. 112). The *period* is the time of one on-and-off pulse. The following figure shows that if the ratio between the on-and-off pulses changes, the duty cycle changes, and so does the pseudo-analog voltage. PWM is a technique that is often used to dim LEDs.



RGB (Red, Green, Blue)

RGB stands for Red, Green, Blue. These three components are used to describe a color within an RGB color space. "Any three wavelenghts of light can be mixed in varying proportions to create many different colors.... The three primaries which can be mixed to produce the greatest number of colors are particular wavelengths of red, green and blue. For this reason, most color display systems are based on three light sources which are as close to these colors as possible" (Joblove & Greenberg, 1978, pp. 20-21).

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Summary

Recent advances in Solid-State Lighting (SSL), and specifically in Light Emitting Diodes (LEDs) bring about a revolution in the way artificial light is generated. LEDs are small, durable, operate on low-power, have a lifetime that is longer than traditional light sources, and their nature as semi-conductor makes that they can easily be controlled by microprocessors. LEDs can be embedded in environments and portable devices, and microcontrollers can control these light sources with high precision, for instance based on sensor data or via innovative interaction concepts. This opens up a complete new design space, that we name *adaptive lighting environments* (ALEs), to create context-aware lighting solutions that provide personalized, adaptive or even anticipatory behaviors. This raises the question: "*How to design for adaptive lighting environments?*"

The main challenge was divided into three sub-challenges that are explored in this dissertation. The first challenge explores what lighting behaviors are meaningful for people, and how these can be designed. The second challenge is to investigate the implications on social settings of adaptive lighting environments. Third, there is a challenge to explore novel interaction concepts with ALEs.

Adaptive lighting environments are seen as a system in this dissertation: This represents a composition of people, (interactive) technologies and the interdependent relationships between them. Designing for such systems entails design challenges that are complex: It is difficult to define the boundaries of the system and thus it is not possible to have a complete overview of the system. Furthermore, there is no single correct solution for the challenge, and there are typically multiple stakeholders, each with their own perspectives and wishes. To deal with this complex challenge a research-through-design approach is used, in which design activity is used to advance research insights. In specific, I apply the Growth Plan: This describes three phases, Incubation, Nursery, and Adoption respectively, in which design-research iterations are performed in increasingly realistic contexts. The Incubation phase targets innovation and creativity and is an exploration of the design domain. Promising concepts and insights continue into the Nursery phase, where they are further detailed, nuanced and implemented to high-fidelity prototypes. Finally, in the Adoption phase the impact of these novel, interactive lighting environments is investigated in realistic contexts where they are adopted by users. The dissertation is structured along these three phases.

Part I: Incubation contains five research-through-design iterations in which multi-user adaptive lighting environments are explored. In the first iteration, an interactive sketch was created, to explore how meaningful lighting behaviors can be designed. The second iteration continues this investigation, but additionally explores whether lighting can be used to actively steer the behavior of people. This iteration provided indications that spotlighting behavior might

affect the social dynamics of the group, as it guides the attention of people. This specific lighting behavior is more rigorously investigated in the third iteration. In this iteration, the implications of spotlighting behavior is investigated in a social setting. Participants in discussion scenarios were exposed to uneven light distributions, where either one or two people were highlighted. The influence of lighting conditions on the discussion was measured by calculating the duration that participants spoke under specific light levels (i.e., low, medium, high). The results showed that people speak more when they are not in the spotlight. However, the differences and effect size are small, from which I conclude that lighting environments should offer people with a rich palette of lighting behaviors to interact with, instead of a single, dedicated behavior. In the first three iterations, users did not have control over the lighting behaviors. In the fourth iteration, I explore control over a lighting environment can be distributed between people. Three distributions of control were selected: An individual, shared, and hierarchical system are implemented and evaluated in user confrontation sessions. Reflections of the participants revealed that the way in which control was offered, influenced their behavior: E.g., the shared controller made people consider the lighting needs of others, whereas the person using the hierarchical controller used it to provide people with light that agreed with his opinion. The final iteration is an adaptive office environment in which the design of meaningful lighting behaviors and novel interaction concepts were explored in an integrated way. The installation was evaluated with experts and resulted in design guidelines for future lighting technologies: The experts argued that user control, especially in multi-user environments, is a challenge that deserves further investigation. Furthermore, they envisioned future lighting environments to consist of flexible modules that can be tailored to specific implementations.

Part II: Nursery contains two chapters in which the design-research insights of the Incubation phase are used to develop technologies for adaptive lighting environments. My experiences with designing adaptive lighting environments, revealed that designers need new tools to support the design process of these systems. For this purpose, Lithne (a platform for designers to develop interactive networked environments) was developed. Lithne is based on the popular Arduino platform, but is tailored towards the development of interactive networked systems in general. It provides users with tools to fit an iterative workflow. Lithne allows users to program software wirelessly, making it possible to embed prototypes in products and environments. This allows for iterative, experiential design of (lighting) system behavior. Lithne serves as a basis for Hyvve, which is a modular and flexible lighting system, following the insights of the Incubation phase. The system consists of hexagonal ceiling tiles and infrastructure. The 'active' ceiling tiles contain warm white and cool white LEDs, a Lithne node, and support to easily connect sensors to it. Software on the node, and software to control the tiles from a central location, provides designers with the tools to setup their own lighting environments, and to explore and implement custom lighting behaviors. The software libraries are set up to prepare users to think in behavioral qualities, rather than in technical terms. To provide users with control over their lighting conditions, Bolb was designed. This is a personal, portable light controller that allows users to interact with the lighting system at their location. Furthermore, Bolb provides a mechanism to distribute control when multiple users share a location. Additionally, Bolb allows users to create preferences for different locations that are meaningful to them, and as such it allows users to inform the system about their preferences.

Part III: Adoption presents the design and implementation of three adaptive lighting environments in three spaces inside the Eindhoven University of Technology. These environments, Break-out Area, Meeting Room, and Open-plan Office, form a Living Lab. This is set up to investigate the implications of adaptive lighting environments in realistic contexts. For this purpose, a longitudinal evaluation is performed with four users, who each have their own Bolb controller. The research objectives of this evaluation are in line with the design challenges of this dissertation. A mixture of both quantitative (i.e., server interaction logs, camera observations) and qualitative data (i.e., user reflections) were gathered. Based on the results, 10 insights regarding the design of ALEs are formulated. In summary, these insights showed that lighting behaviors become meaningful for people in the context in which they are used. People appreciated individual control, and they understood the need to balance control among users even though the current implementation was not appreciated. Furthermore, the study revealed that people have views about the roles light sources play in their environment and interaction concepts should fit these views. Finally, simple controls should always be available, and high precision controls need to be available upon request.

The dissertation concludes with a reflection on the complete project. First, the approach that was followed is reviewed. The project shows that the systemic approach and the dual nature of design and research means that activities can take place in multiple phases of the Growth Plan simultaneously. This means that some concepts have progressed further than others: Research questions may still be in the Incubation phase, whereas design insights might already advance to the Nursery phase. The Growth Plan helps to deal with these asynchronous tracks, as it describes boundaries for individual activities. The project is also reviewed on its contribution to designing for systems: This project shows that a systemic approach easily breaks the unity of form, interaction, and function that allows for rich interaction. This can be rebalanced by mapping product parameters to system parameters via mediating interaction concepts. Additionally, I argue that alternating between a 1st person (experiential) perspective and a 3rd person (analytical) perspective in designing for systems is required in order to understand and oversee the richness and complexity of design challenges. Finally, insights for the main design challenges are provided. Regarding the design of meaningful lighting behaviors I conclude these lighting behaviors can only become meaningful as they have contextual relevance. Where adaptive lighting environments are often considered to have automated behaviors I argue that these automated behaviors should be implemented carefully, and when in doubt it is better to leave control to users. Furthermore, the implementation of an ALE inherently changes the context of use: It is therefore important that the designer who develops mechanisms for multi-user interaction, considers the social context that the lighting environment establishes, rather than the current context of use. This project also revealed that the tools that designers have to ideate and implement novel interaction concepts are of key importance. These tools should advocate a human perspective to design in making things experiential, which means that lighting setups should be flexible and versatile. Interaction concepts for lighting environments should provide sufficient degrees of freedom that fit the setting and perspective of its user.

In conclusion, designing for adaptive lighting environments is characterized by an explorative, iterative design process, focusing on the development of experiential prototypes that are to be evaluated in context. Factors to consider in the development of adaptive lighting environments are *human factors*, *contextual factors,* and *social factors*. As this dissertation shows, it is the richness of the real world that gives meaning to the social effects of, and the behaviors of systems. I argue that a designer can embrace the complexity of the design challenge by alternating between different perspective in design thinking and making.

Summary of insights

Insight 1— people adjust lighting conditions to contextual factors, personal aspects and their view about possible beneficial effects. (on page 151)

Insight 2— providing people with the opportunity to change their lighting conditions allows them to explore their lighting preferences. This helps them to understand which lighting conditions are pleasant for specific situations. (on page 152)

Insight 3— Providing people with individual, localized control from a first-person perspective enables a feeling that the space is theirs. (on page 152)

Insight 4— Different lighting setups and environments require specific control concepts as users view these contexts from a different perspective. user controls should be designed to support the user perspective. (on page 153)

Insight 5— Users like to feel in control of their lighting conditions and should never feel that they lose control, or that control is taken away from them. (on page 153)

Insight 6— Bringing the location of control and the resulting action close to the user strengthens the feeling of individual control and ownership. (on page 153)

Insight 7— Basic low resolution controls should always be available, higher precision control options should be available upon request of the user. (on page 154)

Insight 8— lighting systems should allow people to share control in an open, non-prescriptive way over lighting conditions, based on interactions that take place in the social context. (on page 154)

Insight 9— personal lighting profiles on which systems can act, should be based on historical and contextual interactions of people. (on page 155)

Insight 10— Allowing users to explicitly provide personal information to the system helps them to understand and appreciate automated behaviors of the system. (on page 155)

Samenvatting

Vernieuwingen en vooruitgang in Solid-State Lighting (SSL), en met name op het gebied van Light Emitting Diodes (LEDs), bieden nieuwe mogelijkheden voor de manier waarop kunstmatig licht wordt gegenereerd. LEDs zijn klein, duurzaam, energie-efficiënt en hebben een langere levensduur dan 'traditionele' verlichtingsbronnen. Daarnaast zijn het halfgeleiders, waardoor ze eenvoudig en precies aangestuurd kunnen worden via digitale electronica, zoals microcontrollers. Deze eigenschappen maken het mogelijk om LEDs in te bouwen in (draagbare) producten en omgevingen, en ze via computers aan te sturen. Tevens kan informatie van sensoren worden gebruikt om de verlichting aan te passen aan de op dat moment geldende omstandigheden. Een volgende mogelijkheid is om mensen op nieuwe manieren met verlichtingssystemen te laten interageren. Dit biedt ontwerpers de mogelijkheid om adaptieve verlichtingssystemen te ontwerpen, welke zich kunnen aanpassen aan bijvoorbeeld personen, activiteiten. De centrale vraag in deze dissertatie is: Hoe ontwérpen we voor adaptieve verlichtingssystemen?

De hoofdvraag is verder gespecificeerd naar drie sub-vragen, welke exploratief worden onderzocht in deze dissertatie. Ten eerste wordt er onderzocht wat zinvolle manieren zijn om een verlichtingssysteem zijn gedrag te laten aanpassen, en hoe deze gedragingen kunnen worden ontworpen. Ten tweede wordt onderzocht wat de implicaties zijn van adaptieve verlichtingssytemen op het gedrag van mensen in een sociale context. Ten derde worden nieuwe mogelijkheden betreffende interactie met verlichtingssystemen onderzocht.

In deze dissertatie worden adaptieve verlichtingssystemen beschouwd als een system: dit is een samenstelling van mensen, interactieve technologie en onderling afhankelijke relaties tussen deze componenten. Ontwerpen voor zulke systemen gaat gepaard met complexe uitdagingen. Deze uitdagingen zijn complex, omdat het niet mogelijk is om een overzicht van het systeem als geheel te hebben, omdat er verschillende – vaak tegenstrijdige – belangen een rol spelen, en omdat er niet een enkele oplossing is die juist is. Om grip te krijgen op deze complexe problematiek, wordt gebruik gemaakt van een research-through-design aanpak. Binnen een dergelijke aanpak worden onderzoeksvragen middels ontwerpactiviteiten verder uitgediept en worden mogelijke oplossingen onderzocht. Voor dit project is de specifieke methode van het Growth Plan toegepast. Deze methode bestaat uit drie fasen, respectievelijk Incubation, Nursery, en Adoption. In de Incubation fase staat innovatie en creativiteit centraal, en wordt via snelle, iteratieve cycli, het ontwerpdomein geëxploreerd. In de Nursery fase worden veelbelovende concepten uit de Incubation fase verder gedetailleerd en uitgewerkt in hoogwaardige prototypes. Tot slot wordt in de Adoption fase onderzocht wat de impact is van de innovatieve concepten, die op deze manier zijn ontwikkeld, in het dagelijks leven van mensen. De dissertatie is opgedeeld in 3 delen, welke de structuur van het Growth Plan volgen.

In Deel I: Incubation zijn vijf ontwerpiteraties beschreven die allen een ander perspectief

op de ontwerpuitdaging bieden. De eerste iteratie betreft een 'interactieve schets', waarin wordt onderzocht wat zinvol gedrag van een verlichtingssysteem kan zijn, en hoe dit ontworpen kan worden. Gebaseerd op de inzichten van deze iteratie, wordt in de tweede iteratie onderzocht of gedrag van mensen gestuurd kan worden door middel van verlichting. De resultaten van deze iteratie bevat indicaties dat de aandacht van een groep mensen gestuurd kan worden middels verlichting. De derde iteratie bouwt voort op deze inzichten en er wordt een studie gepresenteerd waarin is onderzocht of het spreekgedrag van mensen tijdens een discussie is te beïnvloeden middels dynamische verlichting. Via onevenredig verdeelde verlichtingspatronen, die varieerden gedurende een discussie, is onderzocht of mensen meer of minder spreken wanneer zij zich in de 'spotlight' bevinden. De resultaten laten zien dat mensen meer spreken, wanneer ze zich niet in de spotlight bevinden. Echter, de verschillen zijn klein. Hieruit wordt geconcludeerd dat een verlichtingssysteem een rijk palet aan gedragingen moet hebben, welke voor een gebruiker beschikbaar gemaakt dienen te worden. Waar de eerste drie iteraties participanten geen controle boden, brengt de vierde iteratie een ander perspectief op het ontwerpdomein. Hierin wordt geïnventariseerd en geëxploreerd op welke manieren controle over verlichting verdeeld kan worden over een groep mensen. Hiertoe zijn drie controlemechanismen ontworpen, vanuit drie verschillende perspectieven, namelijk: individueel, gedeeld, en hiërarchisch. Evaluaties van deze drie systemen in discussies lieten zien, dat de manier waarop controle over een groep mensen was verdeeld, invloed had op het gedrag van mensen. Bijvoorbeeld: de gedeelde controle leidde ertoe dat mensen zich uitten over de lichtbehoeften van anderen, en de hiërarchische controle werd door een participant gebruikt om mensen uit te lichten die zijn mening vertegenwoordigden. De laatste iteratie is een adaptieve kantooromgeving waarin zowel innovatieve interactieconcepten als zinvolle lichtgedragingen geïntegreerd zijn in een enkele installatie. Deze installatie is geëvalueerd met experts, waaruit richtlijnen voor het ontwerpen van verlichtingssystemen zijn gehaald. Volgens de experts wordt de manier waarop controle is verdeeld over gebruikers, voornamelijk in situaties met meerdere gebruikers, een belangrijke ontwerpuitdaging. Daarnaast bestaan toekomstige verlichtingssystemen uit flexibele modules, welke de gebruiker op zijn eigen manier samenstelt tot een verlichtingssysteem

Deel II: Nursery bevat twee hoofdstukken, welke voortbouwen op de ontwerp-onderzoeks-inzichten uit de Incubation fase. Mijn eigen ervaringen met het implementeren van verlichtingssystemen in de Incubation fase en observaties tijdens studentenprojecten hebben naar voren gebracht dat ontwerpers nieuwe gereedschappen nodig hebben om adaptieve verlichtingssystemen te kunnen ontwerpen. Hiertoe is Lithne ontworpen: Dit is een platform dat erop gericht is om ontwerpers van interactieve (verlichtings-)systemen een gereedschap te bieden waarmee ze iteratief en in-context kunnen ontwerpen. Lithne biedt de mogelijkheid om software draadloos te programmeren, waardoor het mogelijk wordt om prototypes in te bouwen, zonder dat deze bij elke update moeten worden uitgebouwd. Lithne vormt de basis voor Hyvve: een modulair en flexibel verlichtingssysteem, bestaande uit hexagonale licht-tegels en bijbehorende infrastructuur. De 'actieve' licht-tegels bevatten zes LEDs, waarvan er drie koud-wit, en drie warm-wit licht produceren. Daarnaast bieden de tegels de mogelijkheid om sensormodules te koppelen. Software bibliotheken stellen gebruikers in staat om het gedrag van de afzonderlijke licht-tegels of van het systeem als geheel te programmeren. Om gebruikers controle te bieden over hun verlichting, is Bolb ontworpen: een persoonlijke, draagbare licht-controller, die gebruikers in staat stelt om de lichtinstellingen op hun huidige locatie in te regelen. Tevens bevat Bolb een mechanisme waarmee controle over de verlichting over meerdere personen kan worden verdeeld. Daarnaast biedt Bolb zijn gebruiker de mogelijkheid om voorkeursinstellingen voor licht-condities te koppelen aan locaties die voor hem van belang zijn. De gebruiker kan op deze wijze het systeem zijn voorkeuren leren.

Deel III: Adoption beschrijft de evaluatie van een adaptief verlichtingssysteem. Er worden drie verlichtingssystemen gepresenteerd, welke zijn geïnstalleerd in de Break-out Area, de Meeting Room, en de Open-plan Office. Deze 'Living Lab' omgeving is zodanig opgezet dat, in een realistische omgeving, de implicaties van een adaptief verlichtingssysteem op het gedrag van mensen kan worden onderzocht. Hiertoe is een longitudinale evaluatie opgezet en uitgevoerd. Er zijn vier implementaties van de Bolb controller gemaakt en deze zijn gedurende zes weken zijn deze gebruikt door vier participanten. Door middel van kwantitatieve (d.w.z. data logs vanuit een centrale server, en camera observaties) en kwalitatieve (d.w.z. reflecties van gebruikers) data zijn 10 inzichten opgesteld, die gebruikt kunnen worden voor het ontwerpen van adaptieve verlichtingssystemen. Samenvattend beschrijven deze inzichten dat het gedrag van een verlichtingssysteem slechts relevant wordt voor zijn gebruikers vanwege contextuele parameters. De proefpersonen waardeerden de individuele controle die zij hadden. Zij uitten wel hun begrip dat bij grootschalige implementaties mechanismen nodig zijn om controle te verdelen over een grote groep mensen, ook al vonden zij de huidige implementatie van dit verdelings-mechanisme niet fijn. Verder toonde de studie aan dat mensen met verschillende perspectieven naar verlichting kijken en dat interactie mechanismen aan zouden moeten sluiten bij het perspectief waarop een gebruiker naar de verlichting kijkt. Tot slot, concludeer ik dat eenvoudige vormen van controle altijd beschikbaar moeten zijn voor een gebruiker en dat, wanneer een gebruiker dat wenst, rijkere controle beschikbaar moet zijn.

Deze dissertatie sluit af met reflecties op het gehele project. Ten eerste wordt de gevolgde methode van het Growth Plan beschouwd Dit project heeft laten zien dat, omdat het ontwerpen van een systeem centraal stond in dit project en omdat de uitdaging zowel ontwerpend als onderzoekend van aard was, diverse activeiten zich in diverse fasen in het Growth Plan bevonden. Dit betekent dat sommige concepten zich verder hebben ontwikkeld dan andere. Waar specifieke onderzoeksvragen nog het karakter van de Incubation fase hebben, kunnen ontwerpen zich al in de Nursery fase bevinden. Het Growth Plan kan ondersteuning bieden deze asynchrone activeiten te structureren, omdat het inzicht biedt in hoeverre activeiten uitgewerkt dienen te worden. Daarnaast kunnen inzichten worden geboden voor het ontwerpen van systemen in het algemeen. In dit project is naar voren gekomen dat de eenheid tussen vorm-interactie-functie, welke gebruikt wordt voor rijke interactie, eenvoudig verloren kan gaan bij een ontwerp met een systemisch karakter. In deze dissertatie is hiervoor een mogelijkheid gevonden, door product parameters te vertalen naar systeem parameters via een mediërend interactive mechanism. Verder laat ik zien dat een ontwerper met de complexiteit en rijkheid van een ontwerpuitdaging om kan gaan, door via een 1e-persoons (vanuit zijn eigen ervaring) en 3e-persoons perspectief (abstract en analyserend) naar de uitdaging en zijn ontwerpen te kijken. Tot slot worden er inzichten voor de sub-vragen gegeven. Wat betreft het ontwerpen van zinvol gedrag voor een verlichtingssysteem, concludeer ik dat dit alleen mogelijk is als dit gedrag relevant is in de context waarin het wordt gebruikt. Vaak wordt voor het ontwerpen van adaptieve verlichtingssystemen uitgegaan van het automatiseren van verlichting. Gegeven dit onderzoek, is het mijn advies om hier voorzichtig mee om te gaan en – wanneer er twijfel bestaat over de relevantie van geautomatiseerde gedrag – dat het beter is om controle bij de gebruiker te laten. Tevens is het van belang dat een ontwerper zich realiseert dat, door adaptieve verlichting beschikbaar te maken, hij inherent de context waarvoor hij ontwerpt verandert. Hij moet zich daarom niet zozeer richten op de huidige situatie, maar op de situatie die hij creeërt middels zijn ontwerp. Verder heeft dit project laten zien dat de gereedschappen die een ontwerper gebruikt om nieuwe (interactie-)concepten te genereren en implementeren invloed hebben op het uiteindelijke ontwerp. Ik adviseer daarom om gereedschappen te gebruiken die de mogelijkheid bieden om concepten ervaarbaar te maken (1e-persoons perspectief). Dit heeft als gevolg dat verlichtingssystemen flexibel en veelzijdig toepasbaar moeten zijn. Daarnaast concludeer ik dat concepten voor interactie met verlichtingssystemen voldoende vrijheidsgraden moeten bieden aan gebruikers, en moeten aansluiten bij de wijze waarop zij hun verlichtingssysteem beschouwen.

Samenvattend wordt het ontwerpen voor adaptieve verlichtingssystemen gekarakteriseerd door een exploratieve, iteratieve ontwerp-aanpak, waarbij de nadruk ligt op het creeëren van innovatieve, ervaarbare concepten die geëvalueerd kunnen worden in omgevingen die representatief zijn voor toekomstig gebruik. Factoren die hierin van belang zijn, zijn menselijke factoren, omgevings-afhankelijke factoren en sociale factoren. Wat deze dissertatie laat zien is dat het de rijkheid van ons dagelijks leven is, die betekenis geeft aan de sociale implicaties en het gedrag van (verlichtings-)systemen. Mijn standpunt is dat een ontwerper de complexiteit die hieruit volgt voor zijn ontwerpuitdaging dient te omarmen, door wisselende perspectieven te kiezen voor zijn ontwerp-rationale en ontwerp-activiteiten.

Samenvatting van de inzichten

Inzicht 1— mensen stellen hun verlichting in op basis van contextuele factoren, persoonlijke factoren en hun eigen idee over mogelijke positieve invloed van de verlichting.

Inzicht 2— door mensen de mogelijkheid te bieden om hun verlichting aan te passen, kunnen zij ontdekken welke voorkeuren zij hebben. Dit helpt ze om te begrijpen welke verlichting fijn is in specifieke situaties.

Inzicht 3— door mensen individuele, lokale controle te bieden, vanuit een eerste-persoons perspectief, krijgen zij het gevoel dat die ruimte van hen is.

Inzicht 4— controle over verlichtingssystemen is gebaat bij concepten waarbij de manier van controle is aangepast aan de manier waarop gebruikers deze omgeving beschouwen. Aansturing voor een lichtsysteem dient dit gebruikersperspectief in acht te nemen.

Inzicht 5— gebruikers van een verlichtingssysteem willen het gevoel hebben dat zij in controle zijn, en moeten nooit het gevoel krijgen dat hen controle ontnomen wordt.

Inzicht 6— door de locatie en het resultaat van interactie met verlichting dichter bij elkaar te brengen, wordt het van individuele gevoel van controle en 'eigendom' versterkt.

Inzicht 7— simpele vormen van controle, met een lage resolutie moeten altijd ter beschikking zijn voor gebruikers. Preciezere controlemogelijkheden moeten beschikbaar zijn als de gebruiker daar om vraagt.

Inzicht 8— verlichtingssystemen moeten gebruikers toestaan om controle te delen op een open manier, waarbij niet is voorgeschreven hoe gebruikers dienen te handelen. Dit mechanisme is bij voorkeur gebaseerd op de sociale interactie in de betreffende context.

Inzicht 9— persoonlijke profielen met lichtvoorkeuren waarop systemen kunnen acteren, dienen gebaseerd te zijn op historische en contextuele interacties van mensen.

Inzicht 10— door gebruikers in staat te stellen om expliciet hun persoonlijke voorkeuren in het systeem op te slaan kunnen zij begrip opbouwen voor automatische gedragingen van het systeem.

List of publications

From this dissertation

Magielse, R., Hengeveld, B., & Frens, J. (2013). *Designing a light controller for a multi-user lighting environment*. Paper presented at the 5th IASDR 2013, Tokyo, Japan. Retrieved from http://design-cu.jp/iasdr2013/papers/1594-1b.pdf

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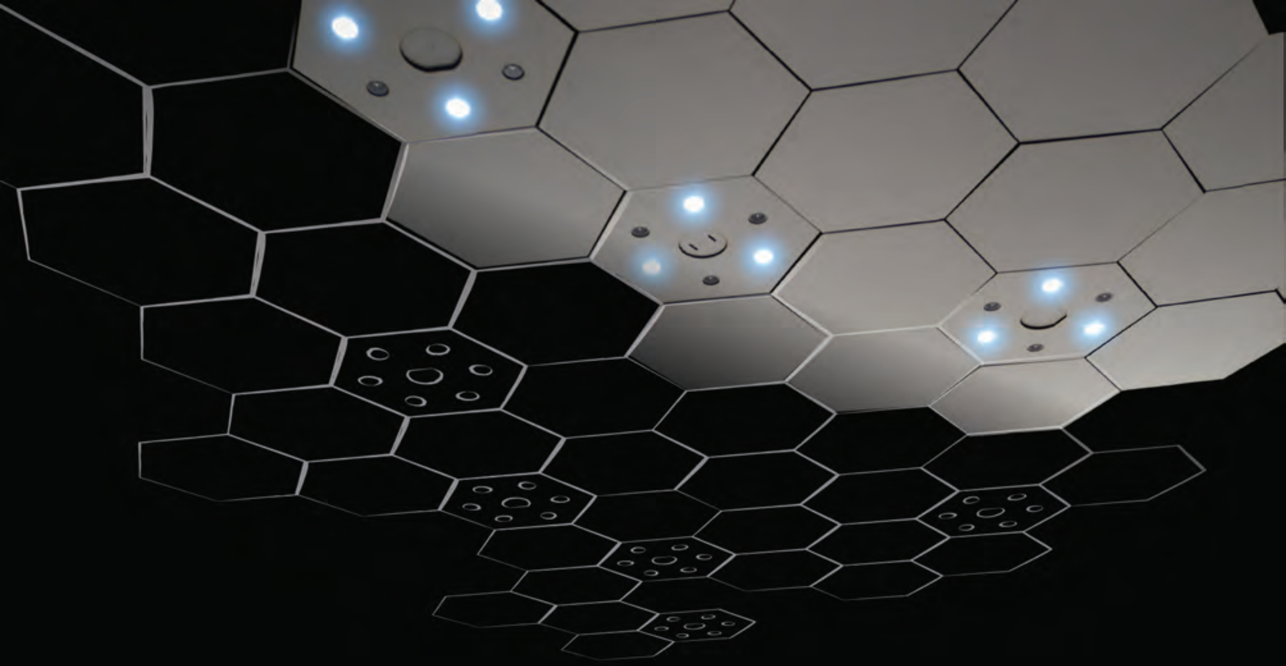
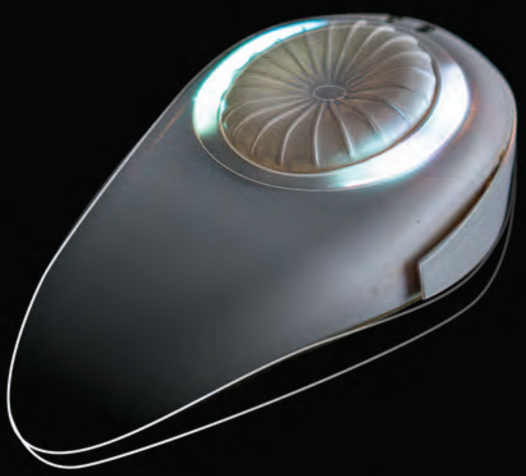
Curriculum Vitae

Remco Magielse was born on the 8th of September 1986, in Bergen op Zoom, the Netherlands. After completing his VWO in 2004 at R.K. Gymnasium Juvenaat Heilig Hart, he enrolled for his education at the department of Industrial Design at the Eindhoven University of Technology. where he completed his Bachelor (in 2007) and Master (in 2009). For his project titled 'HeartBeat' (original title: 'TreasureHunter'), Remco received the second prize in the 2008 annual international Nokia Ubimedia Mindtrek Awards. A publication on the project was presented at the renowned CHI'09 conference in Boston, MA and the project was exhibited during the Dutch Design Week. Remco graduated in 2009 on a design project with the title 'R.A.A.M. a Remote Activity and Awareness Medium' in collaboration with Philips Research.

In 2009 Remco started his doctoral work on the project with the title 'Adaptive Lighting Environments', as part of the i-Lighting the World program, which formed the start of the Intelligent Lighting Institute (ILI) at TU/e. In addition to his own work, Remco also participated in 'Light through Culture', a collaborative project of TU/e and the University of Siena, and in 'BRAINpulse', an installation for the annual light festival GLOW as lecturer and expert. Results of Remco's work have been published at several international conferences and are included in the Design United exhibition. After his doctoral research he found a position at Philips Lighting.

"Is het nog ver?" - Kees Overbeeke





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