An Interdisciplinary Approach to Designing an Adaptive Lighting Environment

Remco Magielse, Sunder Rao, Paola Jaramillo, Philip Ross, Tanir Ozcelebi, Oliver Amft

***Abstract*—Due to advancements in lighting technologies new opportunities for application emerge. In this paper an interdisciplinary study towards the development of adaptive lighting environments is presented. An implementation of an adaptive lighting environment is made in the domain of office work. For evaluation, experts from the domains of human-system interaction, activity and context recognition, and system architecture design are interviewed. Contributions are made with regard to the implementation of the adaptive lighting in office environments and an evaluation method that is in line with the interdisciplinary approach. From the evaluation method insights in the fields of human-computer interaction, activity and context recognition and system architecture and (wireless) networking and in topics that span across these fields are gained.**

***Index Terms*—Ambient intelligence, Context Awareness, Human-Computer Interaction, Ubiquitous/Pervasive Computing.**

I. Introduction

The domain of lighting is shifting. Thanks to the rapid developments, opportunities arise to rethink our current lighting paradigms. Light sources can be embedded into objects and environments and can be controlled through low power digital technologies. Hence, light in our environments can now be programmed to behave intelligently. Lighting enters the domain of ubiquitous computing, put forward by Weiser [1] in the early nineties. In his vision on „Ubiquitous Computing' Weiser presents a future where technology is seamlessly interwoven into the daily lives of people. In 2003 Aarts et al. presented their views on Ambient Intelligence (AmI) [2], where two important claims are made regarding AmI. They argue that 1) the technology has advanced up to a level that it is actually possible to create highly interactive environments and 2) that people are ready for it. With the recent advances in lighting technology, a similar trend can be observed; technology has reached a state where it can be interwoven dynamically into daily objects and rituals of people. For example, lighting has already become intertwined with our experience of watching television [3] and transformed our ritual of waking up [4]. The adoption of such technologies indicates that people are ready for it.

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This paper investigates the opportunity to implement adaptive lighting in the domain of office environments. Two contributions are made; First, regarding the implementation of a context aware adaptive lighting for the office environment, where light adapts to activities performed, second regarding the evaluation of the system. A qualitative evaluation method that is in line with the interdisciplinary nature of our research (described in Section 1-B) is employed and has provided insights in the involved fields, as well as knowledge in the interdisciplinary research area. In addition, insights are derived regarding the specific application.

A. Design Challenges

As new light sources can be controlled by microprocessors new opportunities to interact with the light in the environment arise. Control and interaction is an important topic in the design of intelligent environments [5], which is why different options in this application are explored. As Eggen et al. state in [5] „people should always stay in control of Intelligent Systems', where they propose that systems can behave autonomously, but people should have the ability to take control back. Markopoulos et al. provide an overview of the design considerations involved in the development of awareness systems in [6]. Two of the considerations presented are implemented in our current design; *level of user control* and *explicit vs. implicit interaction*. A hybrid approach is explored, where scenarios are triggered automatically, but flexible (manual) controls are also offered.

B. Interdisciplinary Nature of the Research

Due to the complexity of designing systems, we believe an interdisciplinary team is required. Each team member is a specialist in his own field but the team operates at the intersection of the joint field.

To investigate how such an interdisciplinary team operates and where the fields collaborate, a joint project is performed, connecting the fields of human-computer interaction, activity and context recognition and system architecture and (wireless) networking (see Fig. 1). The choice to join exactly these fields in a project is not an arbitrary one. Aarts [2] describes five characteristics of ambient intelligent environments; embedded, context-aware, personalized, adaptive, and anticipatory. We believe the combined knowledge of the three fields covers these topics. The field of human-computer interaction provides knowledge regarding interaction design and design processes. Activity and context recognition makes it possible to incorporate sensor data and inference human behaviour to actuate light accordingly. System architecture and (wireless) networking possess the knowledge and the skills to construct wireless sensors networks that provide the infrastructure for gathering and processing the sensor data to deploy adaptive (lighting) environments.

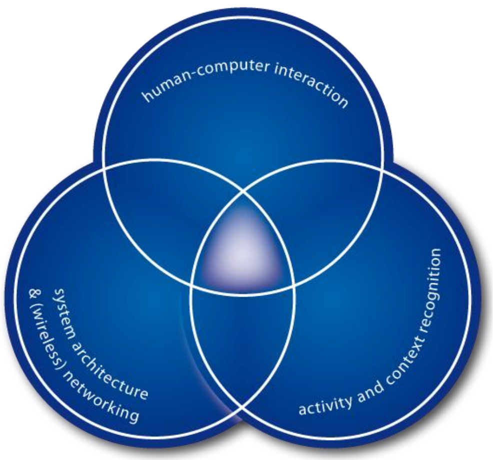

Fig. 1. Visualization of the interdisciplinary approach. The highlighted area indicates the interdisciplinary area of the project.

In the case of an interdisciplinary research team, where research is conducted at the intersection of the disciplines, it is important to get acquainted with each other's disciplines. To achieve this we believe it is of importance to develop projects in iterative cycles. An approach as described in [7] is adopted, where iterative developmental cycles are used to detail and refine concepts. This study is an early iteration and the knowledge gained here will be used for future design cycles.

The remainder of this paper describes the concept, design and evaluation of such an integrated interdisciplinary project in the area of Adaptive Lighting Environments (ALE). In Section II the design and implementation of an adaptive office environment is described. In Section III the evaluation methodology is illustrated and in IV the results from this analysis are provided. In Section V conclusions are presented regarding our work.

C. *Related Work*

Recent work in this domain focuses on e.g. using natural light to enhance office illumination [8]. Others have addressed dynamic lighting with regard to the biological influence of colour temperature [9]. Regarding static lighting conditions and lighting effects, [10] provides a structured overview of existing literature of light during office work. Considering activity recognition in the domain of office environments, several studies are done to classify human behavior, e.g. a multimodal system for recognizing office activities [11], or hand posture sensing to determine the type of interactions a user has with objects in a desk/office environment [12].

II. Design and Implementation: Adaptive Office Environment

The context of a room in an office environment was chosen. In this study we adapt lighting conditions to activities performed by user(s) in this context, since different activities can require different types of illumination. This section describes the design and implementation of this adaptive lighting environment.

A. *Scenario Description*

The adaptive office environment provides lighting conditions that support three scenarios, with interaction possibilities tailored to each scenario. The scenarios are high-level descriptions of activities typically performed in an office environment. These scenarios are examples intended to explore the possibilities of adaptive lighting in office environments and should be regarded as such. To study the effect of adaptive lighting on a social level, multi-user scenarios are included. Table I describes the selected scenarios.

Table I

Scenario Classification

Scenario	*Description*
Individual Scenario	An individual scenario includes a single person at a specific area of the table. Examples of activities in this scenario are: reading, writing, drafting. The focus of the participant is directed at the work plane. 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. E.g. Group discussion.
Group Focused Scenario	Multiple people are in the office environment; their attention is focused on one area. E.g. Presentation for a group of people or a question-answer session.

B. *Environment Description*

This subsection is divided in three parts: light infrastructure, user interaction possibilities and adaptive lighting conditions.

1) *Light setup*

A rectangular office (320 x 600 cm, height 270 cm) is used as environment for the system. A rectangular table of size 160 x 160 cm is placed in the center of the room and 8 chairs are placed around the table.

By making use of ceiling tiles an additional ceiling layer is created in which our light sources are mounted (Fig. 2). Nine Medium-Density Fiberboard (MDF) tiles of 53 x 53 cm, 3 mm thick, are designed and hung directly above the meeting table, approximately 10 cm below the original ceiling tiles.

Each tile is equipped with a spotlight in the center, aimed downward, providing light on the task area, hence their name: Task lights. Four tiles in the corners of the ceiling are additionally equipped with diffuse lights, directed at the 8 seats surrounding the table. These are used to illuminate people, and are referred to as Face lights. On top of the tiles, thus in between the original ceiling and our lowered ceiling, 6 lights are placed, directed at the walls of the room, providing general indirect illumination and are referred to as Environment Lights. All sources are 50-watt halogen lights and are connected on a separate channel to a Showtec MultiDim MKII Dimmer box [13]. This allows the sources to be controlled through a Digitally Multiplexed (DMX) signal.

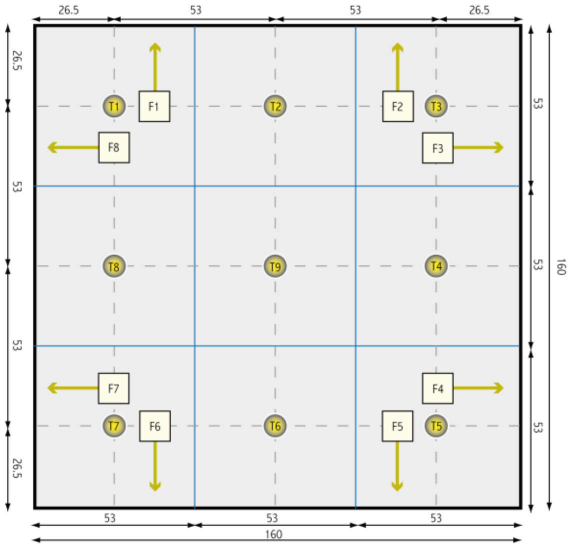

Fig. 2. Bottom view of custom ceiling design. The blue lines show the size of the tiles. The circles at the center of each tile represent the Task lights (T), directed downward. The square forms show the position of the Face lights (F) directed at people. The arrow indicates the direction in which the Face light is aimed. All lights are counted from the top-left clockwise inwards. Environment lights are not visible in this image.

2) User interaction

The user can interact *explicitly* or *implicitly* with the environment. We consider interaction as explicit when the user has to perform a specific behaviour to manipulate his environment. We consider interaction *implicit*, when the user behaves regularly, but this behaviour is sensed and triggers changes in lighting conditions. The specific user behavior and the implications on the light conditions are described in the following paragraphs.

3) Adaptive lighting conditions

Based on the scenario description lighting conditions were designed. The focal point of the activity was taken as the leading parameter to adapt the lighting to. An overview of the selected lighting conditions and behaviors in relation to the selected categories of activities is described in Table II.

TABLE II

OVERVIEW OF LIGHTING CONDITIONS

Scenario	*Lighting Conditions*
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.

When activities of an *individual scenario* (Fig. 3) are detected the system automatically dims the environment light and provides the user with a light on his work area. The user can *explicitly* manipulate these conditions using a rotation gesture to either zoom in or zoom out the illuminated work area. The device in Fig. 5 captures the rotation gesture.

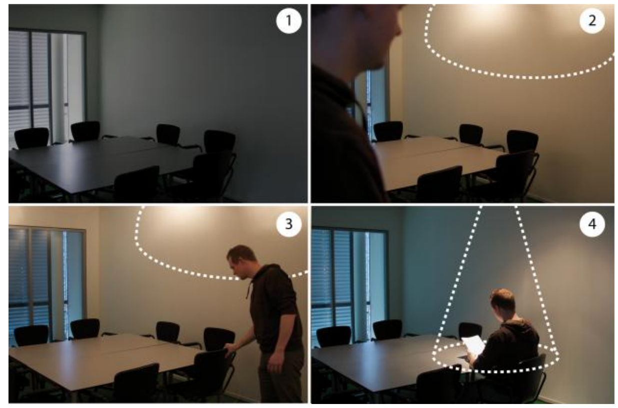

Fig. 3. Individual Scenario. When the user enters the room (1), general illumination is provided (2). When the user sits down, a spotlight on his task area is provided. The dotted lines illustrates the location of the lighting.

Expanding the illumination over the table is considered zooming out; lights in an expanding radius of the user are gradually increased in intensity, lights nearer to the user gradually dim, until an even illumination is achieved over the complete table surface. Zooming in is the reverse action of zooming out; light sources near the user increase their intensity and sources further away gradually dim done. Fig. 4 provides a scenario of this light behavior.

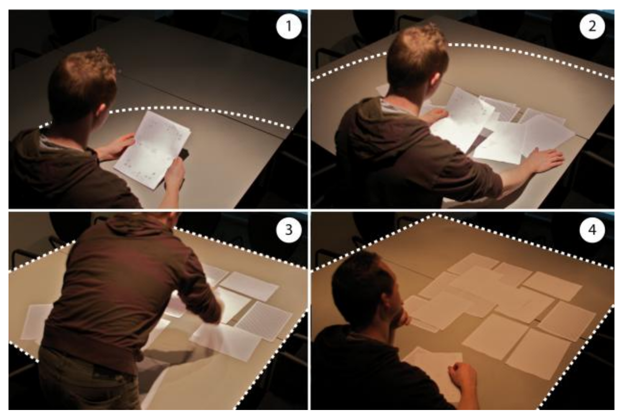

Fig. 4. The individual zoom scenario. From 1 to 3 the area being illuminated is increasing. In 4 the user has dimmed the entire surface. The dotted lines illustrate the area being illuminated.

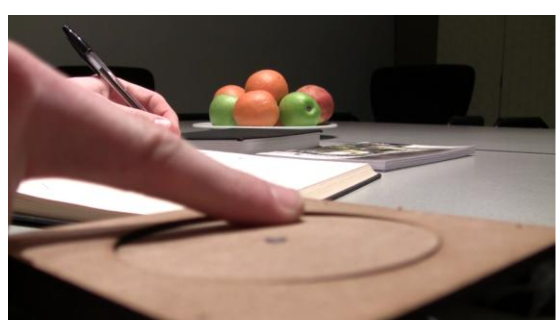

Fig. 5. The device used to capture the rotation gesture (used to zoom the light in or out) in action.

The interaction with the system in the *group distributed scenario* (Fig. 6) is significantly different from the individual interaction. When activities of this scenario are detected, light on the work plane is dimmed. Light is provided on people participating in the discussion. In this case, the system provides *implicit* interaction; interacting with the system is deduced from signals captured from the behavior of the user. The user can implicitly interact with the system through speech. Whenever a user is speaking in the discussion the light directed at him is turned on. This will highlight the participant who is speaking and involved in the discussion. Speech is detected through microphone sensors attached to the table surface.

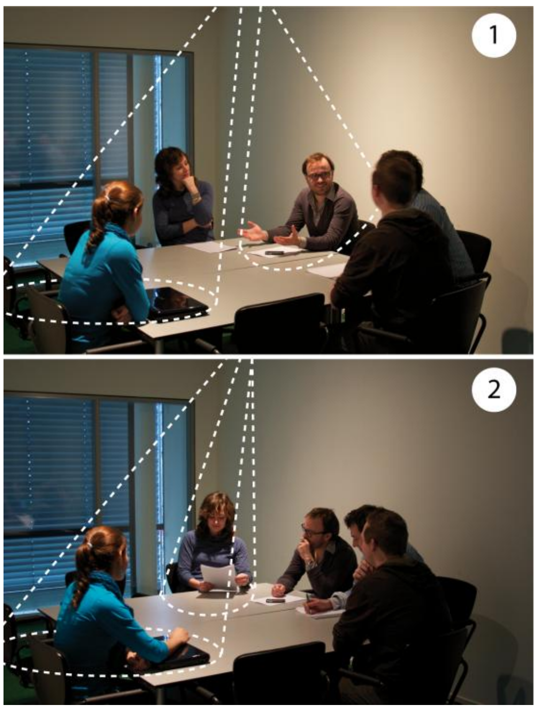

Fig. 6 Group distributed scenario. In (1) there is a discussion between the participant on the left and the male participant on the right. In (2) the female participant in the center continues the discussion and is highlighted, while the light on the male participant is dimmed. The dotted lines illustrates the participants being highlighted.

In a *group focused scenario* (Fig. 7) the user explicitly interacts with the system by manually triggering a switch to indicate a presentation activity. The environment light is dimmed and a low level of illumination is provided to the presenter. It is also possible to have a question-answer session, where the system implicitly highlights the questioner's face whenever speech in the table area is detected.

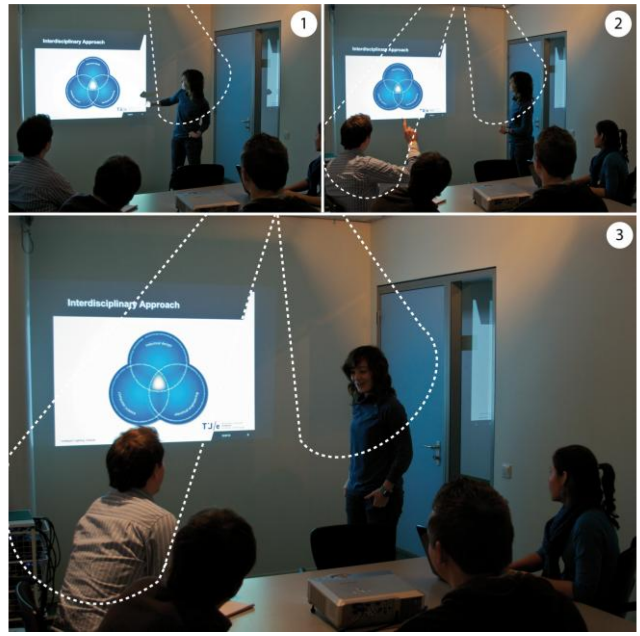

Fig. 7. A presentation is being held. The male participant on the left indicates he has a question to ask (2) and is provided with a spotlight (3). The dotted lines illustrate the participants being highlighted.

C. Activity Recognition Modeling

In order to distinguish the different scenarios, we used a multimodal sensing approach for the recognition of the activities. The sensors used are described in Table III.

TABLE III

SENSORS USED FOR ACTIVITY RECOGNITION

Classification	Characteristic Behaviour	Sensor
Occupancy	Person(s) enter(s) the room	Motion Sensor [14]
Individual Scenario	Person(s) sit(s) on a chair	Force Sensor [15]
Group Distributed Scenario	> 1 Person seated and at least 1 person speaking	Force Sensor [15] Microphone [16]

We used the following procedure to develop our classification scheme: sensors were mounted on wireless sensor nodes and distributed in various locations in the room. Raw data is collected by a central computer at sample rate of f=100Hz, and digitized with a 10-bit Analog to Digital Converter provided by the wireless sensor node. The behavior of the sensors was derived from the signals gathered as follows.

The motion sensor presents an output that decreases when motion is detected in range of the sensor. A motion sensor is placed above the doorframe to detect a person entering the room.

The force sensor presents an output that increases when weight is applied. A force sensor is placed in a chair to detect when someone sits on the chair.

The sound sensor is passed through a signal-processing unit that comprises two stages: DC offset elimination [17] and a zero cross detection [17]. Both techniques are common in speech detection algorithms and since we consider ideal scenarios for running the tests, while not being specifically optimized to compensate for environmental noise, this implementation allowed us to detect human speech. Standard techniques exist and could be integrated to compensate for environmental noise in the speech detection step. A microphone was placed on the surface of the table to detect human speech.

An activity classification scheme based on explicit decisions was developed as shown in Fig. 8 is used for the classification of the scenarios. . By using this scheme, the office scenarios have been classified according to detected activities using the sensors described above.

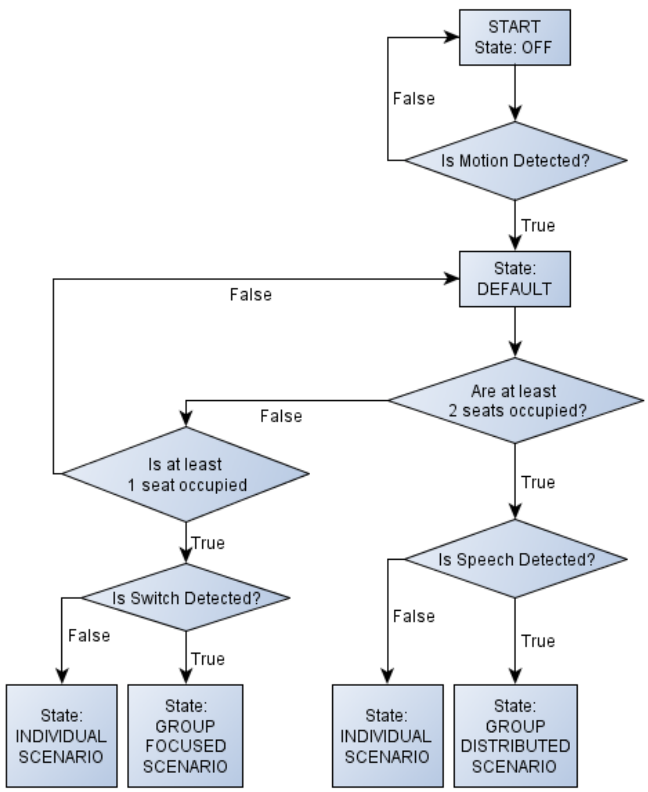

Fig. 8. Office environment activity classification scheme using an explicit decision graph.

An initial state (OFF) is defined as the state in which no presence is detected inside the room. From this state there is only one possible transition; to the DEFAULT state. This state is triggered when presence is detected inside the room but no activity is yet classified.

From this state four transitions are possible:

1. OFF state; if for a period of time no activity is classified and no motion is detected the system returns to the OFF state. This typically occurs when there is no one inside the office.

2. Individual scenario: when the force sensor detects people sitting on a chair and when no speech is detected, the system shifts to the Individual scenario.

3. Group Distributed scenario: when at least two force sensors are activated (two people seated) and the sound sensor detects human speech, the system shifts to the Group Distributed scenario.

4. Group Focused scenario: when at least one force sensor is triggered and speech is detected and the manual switch for presentation is triggered, the system moves into Group Focused scenario.

D. System Architecture

Fig. 9 shows the deployment view realized for the office environment. The system mainly consists of 1) Wireless Sensor Nodes, 2) OSAS (Open Service Architecture for Sensors) framework [18] 3) Loader Node 4) DMX controller to manipulate 230v light sources (specifically LANBox [19]).

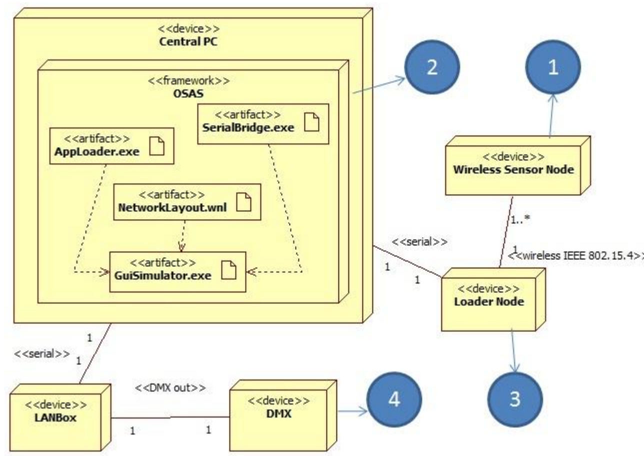

Fig. 9. Deployment view of the system architecture.

Each wireless sensor node comprises of a Body Sensor Node (BSN) [20] and a Phidget sensor. A BSN node has a Radio Frequency (RF) module, a microcontroller, a flash memory, an antenna and a 3-pin port to connect external sensors (e.g. Phidget sensors). For this implementation three different sensors (Table III) are used. Each BSN node is attached with only one sensor and provides a wireless range of up to 5 meters without an antenna and up to 25 meters by connecting an antenna.

Our implementation is programmed in the OSAS framework. This network consists of low capacity hardware nodes such as BSN nodes, a Loader node and a simulated LANBox node. OSAS allows installation of services to each BSN nodes via wireless link through a Loader node. There is one to one mapping between a BSN node and a light source. We have realized a centralized architecture where all the BSN nodes send raw data (publisher) to a simulated LANBox node (subscriber). With respect to the dimensions of the office environment and the wireless range of a BSN node, we assume that there is no multi-hop communication involved and hence the overhead of routing is eliminated. All the BSN nodes send data at the same time interval. In our situation each node sends data at a time interval of 200ms. The subscriber (LANBox node) defines the time interval. The simulated LANBox node is responsible for performing computation over received raw data and sends appropriate messages to the LANBox hardware device. The algorithm for performing activity recognition is represented in the scheme shown in Fig. 8. The LANBox device in turn sends control signals to specific channels of the digital dimming device.

III. Qualitative Evaluation Methodology

In this study a qualitative evaluation technique is employed, often referred to as *focus groups.* Since our system was implemented with a limited set of sensors nodes we could not perform an evaluation with a group of users. In our case the evaluation is performed with individual experts with a background in one of the related fields. This approach is expected to provide a rich source of information, since the experts possess in-depth knowledge in their fields to which they can benchmark this system. Additionally they are able to reflect on the concept rather than the implementation, and they are capable to envision future scenarios for the system. The following expert groups were consulted:

(1) experts in user interaction, environmental psychology and lighting design

(2) experts from the domain of coding and modulation of information, signal processing systems, communication, multimodal sensor networks, and machine learning systems

(3) experts in wireless sensor networks, real time systems and distributed systems architecture.

The range of expertise varied from professors to higher year Ph.D. candidates. Our methodology of evaluation and analysis is described in the following paragraphs.

A. Interview Session

In total nine expert evaluation sessions of one hour were held. From each field three experts participated in the evaluation, leading to a broad range of knowledge in the expert pool. Each session had the following structure:

The concept and implementation is explained and demonstrated. The expert is offered the opportunity to experience the system through acting out the three scenarios. Once the expert indicated he understands the system, a discussion starts. For this discussion a question route [21] is developed, tailored to the field of expertise of the participating expert. Each question route 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. Each session is videotaped for analysis afterwards.

B. Analysis

The three researchers reviewed the video footage independently and each made an abridged transcript. In the abridged transcript the researchers transcribe quotes from the discussion, removing irrelevant conversation. The final selection of quotes is clustered using a Long Table Approach ([21] p.132) in which all captured quotes are printed on individual cards and laid out on a large table. Similar or related quotes are grouped together to form clusters. In our case this is performed in a two-step process. In the first step the quotes were divided in eight topics. These topics are based on 1) the individual fields of interest, 2) topics joining the three disciplines and 3) application specific topics. The specific topics from our selection are provided (the number specifies to which category of topics they belong): *user interaction (1), system architecture (1), activity recognition (1), evaluation criteria (2), considerations for adaptive lighting environments (2), future scenarios (2), lighting aspects (3)* and *personal experiences (3).* All captured quotes were placed in these eight topics before continuing to the next step. In the second step the quotes were placed on a large sheet of paper in groups. From this grouping a selection of categories emerged.

The results in Section IV describe insights gained from clustering process.

IV. Results

A. User Interaction

As stated in the introduction, user control and interaction are areas we consider challenging and fundamental in the design of adaptive lighting environments. We investigated these topics with the help of a qualitative evaluation approach. Through analyzing the expert responses on the topic of user interaction, we found that control over the environment is important for people, because it provides a feeling of *security.* Experts considered *natural*, *easy* and *rich interaction opportunities* as important principles when designing interactions.

Moreover, we found preferences for systems that are not fully automated, where the control is given to the system mainly when the system can outsmart the user. This can, for example, be through being aware of energy efficiency, by providing alertness when the user needs it, by simplifying repetitive tasks or in situations that are complex for the user to deal with.

Regarding the interaction possibilities, experts generally agreed that there should always be a way for the user to interact with the system and to override automated behaviour. "*You always want to be able to overrule the system.*" As indicated by some experts this interaction is likely to be a mixture of explicit and implicit forms of control.

We see opportunities in design of multi-user interaction. Few, but diverse comments were captured in this category. One expert stated, "*there are social structures that have to be accommodated by the technology*." We believe design for multi-user interaction can provide more natural, social ways of interacting with intelligent environments.

Interestingly, comments were captured that describe an additional layer to lighting effects, such as *ownership*, *territoriality* and *intentionality*. One expert remarked that the ritual of adapting lighting conditions is important: "*it gives people some time to get accustomed to the settings and to the meeting we are having.*"

B. System Architecture

To analyze the design and implementation of our system architecture we categorized the experts' comments on this topic in four categories namely a) centralized architecture b) decentralized architecture c) communication d) modular or emerging structure.

Three out of nine experts found the centralized approach convenient in terms of precise decision-making, since all information is available in a central location. From this location one can easily verify the status of the system.

Again, three out of nine experts preferred a *distributed architecture* over *centralized*, thanks to the scalability and fault-tolerance potential. From the perspective of communication, in the distributed approach the data traffic remains local and the payload gets smaller, since the interpretation is done as close to the source as possible. However a few experts claim "*In distributed you might need to do lot more communication when different subsystems have to interact*".

Some experts mention that in the near future the adaptive environments might have a combination of both centralized and distributed, depending on the application. An expert mentioned it could also be depending on what companies that produce these systems are driving for.

The experts mentioned that the future smart systems should be modular or should adapt to the emerging behavior "*I think you should be able to produce arrays of products that are highly customizable.",* "*The design should be modular*". Experts who chose distributed also argued that this approach would fit emergent behavior well "*If I want to install a new light source, if it is distributed it is easier, just plug it in*".

C. Activity Recognition

As stated in Section I, our approach is to adapt lighting conditions to human behavior and activities. The analysis of actions, expressions, emotions and other components can help to describe how humans behave, and to situate people in a particular context and location. Such an approach requires the utilization, in most of the cases, of more than one source of information. "*Multimodality typically gives you more uncorrelated and independent measurements which are likely to substantially improve the performance of the recognition.*"

Most experts believed that coordinating all these sources of information is likely to be easier in a centralized approach. This however puts a constraint on the complexity and scalability of the system.

D. Lighting Aspects

Considering the lighting conditions, all experts agreed the direct top-down face lighting in the Group Distributed scenario was unacceptable. "*The spotlight you put on people. It throws a lot of shadows in your face, which is not attractive to look at.*" 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.

E. Considerations

The experts related well to the idea of adaptive lighting environments. Only one expert commented "*I don't believe in automatic adaptation.*" The other experts were more positive "*In general, I like the idea light does something*" or "*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.*" One expert believes our perception of lighting will change "*lighting is not the light bulb anymore. It is a complete installation, like the heating installation.*"

Several experts expressed 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. One expert envisioned that when changes in the environment become more subtle, other aspects become more important. "*(...) for instance, what is the temperature in the room, and what is the smell in the room.*" Or "*the material of the walls is much more important than the quality of the light.*"

F. Future Scenarios

Experts were asked to envision how they see the future of adaptive lighting environments. Most experts argued for an easy to install and program structure. They envisioned a system that is built from modules users put together in their own way. "*The person can buy these modules and connect them.*" Importantly, users should to be able to extend the system with their own services and preferences. "*You need to (...) allow users to build upon that.*" 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. "*The designer might have some good ideas for some behaviour, but it assumes also some behaviour from the people and the people are always going to do something different.*"

One expert mentioned other application areas, such as museums, supermarkets, concerts, restaurants. However, as one expert remarked, "*With a lot of these applications, we need knowledge that is not out there yet.*"

V. CONCLUSIONS AND FUTURE WORK

This work presented and evaluated an implementation of an adaptive lighting environment in the domain of office lighting. Due to the complexity involved with the design of such systems, an interdisciplinary approach is adopted. With the combined knowledge from the field of human-computer interaction, activity and context recognition and system architecture and (wireless) networking we have been able to design and construct a working implementation of an adaptive office environment. The interdisciplinary approach is represented in the implementation and has proven a successful approach towards the design of adaptive lighting environments.

The implementation in itself presents a concept for future lighting environments, where lighting conditions dynamically adapt to the activities being performed by users. Other ways of adaptation need to be investigated.

One of the important challenges for adaptive lighting environments lays in the area of user control; how to balance system automation with user control and how to integrate the important rituals and social structures that accompany the control of lighting conditions. We have strengthened our belief that new lighting technologies can provide enhanced control over artificially lighted environments. Additionally there are strong indications that multi-user interaction provides interesting design opportunities.

There is a strong relationship between the architecture of the system and the information processing strategies for activity recognition. Both centralized and distributed approaches are suitable for adaptive lighting environments but the study of several applications can help us to determine the optimal solution.

The qualitative evaluation technique employed has proven to be a constructive method of considering the different parameters and evaluation criteria involved in an adaptive lighting environment. It has also been a suitable method for evaluating a system from an interdisciplinary perspective. The results of the study have provided insights in the individual fields, but also insights regarding topics that span across the involved fields. New challenges emerge for the researchers in defining new methodologies for evaluating parameters of adaptive lighting environments from an interdisciplinary perspective.

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