Effective Visualization and Control of the Indoor Environmental Quality in Smart Buildings

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Abstract:

Smart environments collect huge amounts of low-level data, but tend to fail to provide this data in an accessible, user-friendly, and meaningful way. Given the amount of time we spend inside buildings, the indoor environmental quality has a strong influence on our productivity and health. We developed the system *SmartSpaces* that aggregates and visualizes environmental data in a smartphone application. The goal is to provide access to this data such that users can understand and improve the factors that influence their well-being. User interface guidelines for visualizing the environmental quality are proposed. We describe a case study of occupants in a smart building that allows them to access the data. The findings show that usability and transparency increase the users' awareness of the environmental quality. This can lead to a behavioral change and therefore improve the users' health and productivity, and optimize the energy consumption of buildings.

Keywords: smart environments, smart buildings, internet of things, visualization, indoor environmental quality, mobile application, cyber-physical systems

1 Introduction and Motivation

Cyber-physical systems and the Internet of Things offer new opportunities by interconnecting everyday objects to interoperable information and communication technologies [VF13]. For instance the use of a smartphone to control lights. These smart objects are being embedded in our environment and contribute to a more convenient, healthier, and safer surrounding. Environments, such as smart cities and in particular smart buildings, equipped with smart objects collect huge amounts of data, but tend to fail to provide information in an accessible, user-friendly, and meaningful way. Especially the polluted conditions in mega-cities have raised the need for meaningful information on the environmental quality. For example air pollution can have a threatening impact on our health. However the indoor air quality is usually not considered adequately [MK00]. Given the amount of time we spend inside buildings [Bu14], the indoor environmental quality (IEQ) has a strong influence on our productivity and health [Lo09, Fi02]. The IEQ encompasses thermal quality, air quality, visual quality, acoustic quality, and energy efficiency. Data that

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provides metrics for the IEQ is often not accessible, and understandable by an end-user. Our hypothesis is that the visualization of IEQ data increases the awareness of users of the environmental quality, and as a result changes their behavior.[3]

We developed *SmartSpaces* which aggregates and visualizes IEQ data of buildings and makes it easily accessible for the end-user on a smartphone. The goal is that users can perform actions based on IEQ data to improve their well-being and energy consumption. We performed a case study with 25 building occupants. Our findings show that providing users with the access to IEQ data increases their awareness of the environmental quality, and is leading to participants being more active in controlling their environment.

This paper is organized as follows: Section 2 shows related research and focuses on the problem. Section 3 introduces the system and categorizes the IEQ. Section 4 targets the findings of the case study. Section 5 details the user interface design and introduces guidelines for the visualization of the IEQ. We conclude with an outline of future work.

2 Related Work

Eco-feedback technologies have been an important research topic for several years [FFL10]. The main objective is to provide "feedback on individual or group behaviors with a goal of reducing environmental impact" [FFL10]. Several HCI eco-feedback studies have attempted to help people understand their behavioral impact in household environments [Ga12, RB10], but do not focus on a user's workplace. However, there is the need to allow the traditional user to interact with commercial smart environments - in local and remote usage situations -, given that occupant satisfaction, health, and efficiency are a leading factor in work productivity, and the resulting generation of costs [Mi09]. With the progress in wireless technology it is now possible for users to access these elements remotely. We analyzed smartphone applications that enable users to monitor the environmental quality based on their functionality and user interface design. These applications include Foobot, Netatmo, Insteon Home Control, openHAB, Samsung Smart Home, Elgato Eve and a former version of SmartSpaces.[4] However, none of these combines qualitative semantic information with meaningful suggestions and opportunities to control.

3 Analysis and System Design

The design goal was to achieve an easily maintainable application logic for processing environmental data. As a result, we aggregate this data logically before showing it to the user. This data is enriched with the following semantic model to provide qualitative feedback beyond raw numbers: a sensor's *type*, *unit*, *value ranges*, the current *state* and *value*,

[3] Environmental awareness in this research's context is defined as the extend to which users understand, and what actions they take based on the provided environmental information.

[4] http://foobot.io/, https://www.netatmo.com/, http://insteon.com/, http://www.openhab.org/features/ui.html/, http://www.samsung.com/uk/smartthings/, https://www.elgato.com/en/eve/eve-app/, https://www1.in.tum.de/lehrstuhl_1/projects/555-ios-praktikum-2014-results#cmu/

and *suggestions* on how to improve particular situations. The designated value ranges represent environmental states – ”good”, ”ok”, ”poor” – and are assigned to the associated sensor type. These ranges vary depending on the sensor’s location, the global position of the facility, and the season of the year.

To allow for an easy comprehension of the IEQ, we suggest the following grouping in categories: *Thermal and Air Quality*, *Lighting Quality*, *Energy Consumption*. Since semantic information on the acoustic quality provides limited additional value, we focused on the remaining four IEQ indices. Thermal and air quality are considered together because sensors often measure data of both aspects, and both are often influenced by the same actuators. For instance, a window influences the temperature (thermal) and the air quality, by changing its position, and the resulting change of airflow. We added energy consumption to the IEQ categorization. The demand of saving energy as part of a ”strategy to alleviate environmental stresses is widely accepted” [Ho09], and a visualization of energy consumption can raise the awareness of personal energy use [Je03].

4 Usability Study

Our goal was to classify how data should be visualized for displaying meaningful building sensor information to the user, and to elaborate how the IEQ should be represented to be best understood by the user. We approached an empirical research method with quantitative data (response times and error rates) and qualitative data (interviews). A random sample of 25 participants was selected on an American university campus for a wider range of people with various areas of experience, consisting of application domain experts – such as architects, data scientists and building physicists –, and technology-oriented users, as well as traditional users.[5] Preliminary to the study, the goal of a minimum of 20 participants was defined to ensure that different user groups can be addressed. However, the study did not include old, impaired, blind or color-blind people.

All participants were shown sensor values visualized with different approaches (value-only, color-only, a categorization, and combinations of all three), as well as screenshots of a high-fidelity prototype. Questions of interpretation, performance, preference, and open questions were asked.[6] Each user’s first answer was recorded. This study concludes that a color-coding approach achieves the best performance, in terms of both, response time and error rate. We found that an overview can help users understand the current environmental state. Users prefer the display of more data rather than less, and find a color-coding approach confusing if used for both, action and status elements.

[5] We define a technology-oriented user as a building occupant that uses a smartphone application to monitor the environmental quality. A traditional user is a building occupant that interacts with a building using physical controls.

[6] As an example, for each visualization, users were asked to interpret a value, e.g. ”81°F”, and if this given level was suitable for office work.

5 User Interface Design

The design of the SmartSpaces' user interface was based on user centered design ideas using an iterative and incremental approach. Potential users and application domain experts were continuously engaged in the design process from the beginning on.

We reviewed several smartphone applications that visualize environmental data in terms of usability and user interface design concepts. On this basis, we propose the following seven user interface design guidelines for the visualization of environmental data:

1. **Groups**: Environmental data should be grouped in *Thermal and Air Quality*, *Lighting Quality*, and *Energy Consumption*. Within these three categories, devices of the same kind should also be grouped to create a logical structure. Groups and devices should be presented by meaningful icons and keywords to get a fast overview of the environmental state.
2. **Overview**: Overviews and aggregations of each IEQ category should be used to help the user to understand information faster.
3. **Color-coding**: Environmental states should be color-coded to help users to a faster and better understanding.
4. **Data Interpretation**: Quantitative data should be combined with qualitative interpretations in order to be meaningful for the user.
5. **Outdoor Values**: If available, outdoor values should be provided for comparison.
6. **Suggestions**: Given certain situations, appropriate advice to improve the environmental quality should be provided.
7. **Control**: If available, the user should be provided with the ability to instantly control actuators to improve the situation, e.g. to reduce the relative humidity.

There is a trade-off between the amount of information that can be displayed (expressiveness) and the degree to which the specified goals can be achieved (effectiveness). The combination of expressiveness and effectiveness [Ma86] was a major design goal of SmartSpaces.

Our design model conceptualizes a view divided into three cells representing the three IEQ categories. Figure 1 shows the main status screen and two out of three category detail views, which can be invoked by tapping on one of the categories. The detail views provide additional information, such as further sensor values, the ability to control actuators, suggestions, and comparative outdoor values. Color-coded status indicators help the user to understand if there is a need for improvement.

6 Summative Evaluation

The prototype was evaluated through user testing and a structured interview with five participants [NL93]. The goal was to evaluate the prototype's usability, effectiveness, and the

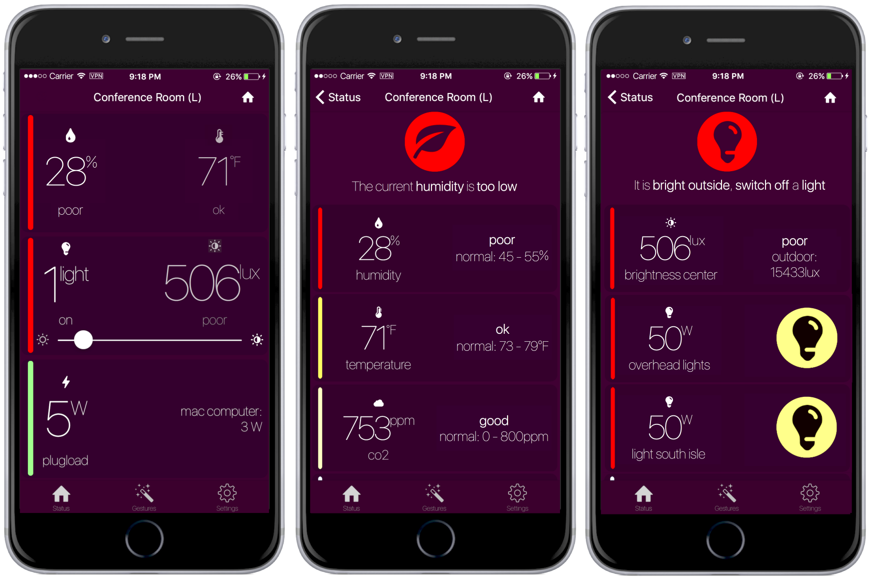

Fig. 1: We used a color-coding approach to visualize the current environmental state.

users' satisfaction. All users were asked to use the SmartSpaces application for one week. After this week, we observed an overall improvement in the correctness of the interpretation of environmental values.

SmartSpaces' usability was evaluated by using the System Usability Scale (SUS) [Br96] which is composed of a ten item questionnaire using a five-point Likert-Scale. The SUS score achieved the rating "above average". It should be aimed to achieve a rating of 80.3 or higher [SK05], however, the reached score of 71.5 is sufficient, given that a minimum score of 68.0 considers a system to be usable. Further questions based on a five-point Likert-Scale resulted in a high user satisfaction.

7 Conclusion

The results of this research show, that by effectively visualizing IEQ-relevant information of a smart building, users can understand their environmental state better, and take appropriate actions. The general difference of SmartSpaces compared to similar applications is the combination of qualitative semantic information with meaningful suggestions, and opportunities to control devices to react on the presented information.

Future work consists of automated notifications for users about environmental information and context-aware feedback. Besides, gathering outdoor sensor data will contribute to our understanding of indoor environments, and our ability to track environmental changes in the outdoor climate and air quality conditions. The relevance of outdoor conditions, such as fine and coarse particulates, rising humidity conditions, increasing windspeeds, and changes in solar intensity, all have significance to the effective management of our indoor environmental quality for health and energy efficiency.

References

[Br96] Brooke, John: SUS-A quick and dirty usability scale. Usability evaluation in industry, 189(194):4–7, 1996.

[Bu14] Bureau of Labor Statistics (BLS): American Time Use Survey (ATUS). Technical Report USDL-15-1236, U.S. Department of Labor, 2014.

[FFL10] Froehlich, Jon; Findlater, Leah; Landay, James: The design of eco-feedback technology. pp. 1999–2008, 2010.

[Fi02] Fisk, William J: How IEQ affects health, productivity. ASHRAE journal, 44(5):56–56, 2002.

[Ga12] Gamberini, Luciano; Spagnolli, Anna; Corradi, Nicola; Jacucci, Giulio; Tusa, Giovanni; Mikkola, Topi; Zamboni, Luca; Hoggan, Eve: Tailoring feedback to users' actions in a persuasive game for household electricity conservation. In: Persuasive Technology. Design for Health and Safety, pp. 100–111. Springer, 2012.

[Ho09] Hoyt, Tyler; Lee, Kwang Ho; Zhang, Hui; Arens, Edward; Webster, Tom: Energy savings from extended air temperature setpoints and reductions in room air mixing. In: International Conference on Environmental Ergonomics 2009. 2009.

[Je03] Jensen, Ole Michael: Visualisation turns down energy demand. In: ECEEE Summer Study. 2003.

[Lo09] Loftness, Vivian; Aziz, Azizan; Choi, JoonHo; Kampschroer, Kevin; Powell, Kevin; Atkinson, Mike; Heerwagen, Judith: The value of post-occupancy evaluation for building occupants and facility managers. Intelligent Buildings International, 1(4):249–268, 2009.

[Ma86] Mackinlay, Jock: Automating the design of graphical presentations of relational information. Acm Transactions On Graphics (Tog), 5(2):110–141, 1986.

[Mi09] Miller, Norm; Pogue, Dave; Gough, Quiana; Davis, Susan: Green buildings and productivity. Journal of Sustainable Real Estate, 1(1):65–89, 2009.

[MK00] MØLHAVE, LARS; Krzyzanowski, Michal: The right to healthy indoor air. Indoor air, 10(4):211–211, 2000.

[NL93] Nielsen, Jakob; Landauer, Thomas K.: A Mathematical Model of the Finding of Usability Problems. In: Proceedings of the INTERCHI '93 Conference on Human Factors in Computing Systems. INTERCHI '93, IOS Press, Amsterdam, The Netherlands, The Netherlands, pp. 206–213, 1993.

[RB10] Rodgers, Johnny; Bartram, Lyn: ALIS: an interactive ecosystem for sustainable living. In: Proceedings of the 12th ACM international conference adjunct papers on Ubiquitous computing-Adjunct. ACM, pp. 421–422, 2010.

[SK05] Sauro, Jeff; Kindlund, Erika: A method to standardize usability metrics into a single score. In: Proceedings of the SIGCHI conference on Human factors in computing systems. ACM, pp. 401–409, 2005.

[VF13] Vermesan, Ovidiu; Friess, Peter: Internet of things: converging technologies for smart environments and integrated ecosystems. River Publishers, 2013.