A smart luminaire in an office environment: impact on light distribution, user interactions and comfort

J Nembrini[1], **J H Kämpf**[2], **M Pappinutto**[1,3] **and D Lalanne**[1]
[1] Human-IST Institute, Université de Fribourg, Bd Pérolles 90, CH-1700 Fribourg, Switzerland
[2] Idiap Research Institute, Centre du Parc, Rue Marconi 19, CH-1920 Martigny, Switzerland
[3] Eye and Brain Mapping Lab (iBMLab), Université de Fribourg, Rue P.-A.-de-Faucigny, CH-1700 Fribourg, Switzerland

E-mail: `julien.nembrini@unifr.ch`

Abstract. A smart luminaire able to change the direction of its light beam is installed in an office environment and compared to the available LEDs fixtures. Standard lighting measures are performed and a controlled user experiment is conducted, involving 22 subjects. Qualitative results suggest that very low illuminance levels can be characterized as comfortable. Quantitative results supported by statistical significance reveal (1) wider use range of illuminance levels for the smart luminaires, (2) an interaction decrease during the experiment and (3) different usage of the luminaire depending on the subject's side. Advantages and drawbacks of digitally actuated luminaires are briefly discussed.

1. Introduction

The advent of the Internet of Things (IoT) has greatly facilitated the ability to digitally control everyday objects. Numerous mundane artifacts are today digitally enhanced to offer additional capabilities such as allowing natural voice control or retrieving Internet data. Among these objects, and prior historically to IoT, the concept of SmartHome encompasses the ones such objects that address the home context [1]. If much research has been done on the usage of SmartHome devices, such as appropriation through DIY [2] or smart home data display [3], how these objects are actually used in their intended environment and whether they truly bring added value in terms of comfort or energy savings often remains unclear.

Additionally, enhancing the capabilities of everyday objects requires appropriate interfaces for exploiting their capabilities. Providing a dedicated mobile application — the current prevailing model — forces users to switch between numerous differing interfaces. On top of this, interface design shortcomings may lead users to disregard the added functionality or even induce their rejection: in the context of lighting, presence sensors in conjunction with simplistic control algorithms have a record of being overridden [4].

Lighting is an interesting context for its energy saving potential in low energy buildings [5]. However, research focuses more on developing adaptive systems to reach the standards [6, 7], for instance by increasing the daylighting share [8], rather than fostering a user-centric approach to discuss the normative framework [9]. The presented research aimed at addressing this knowledge gap by measuring and assessing the technical benefits and the actual usage of a "smart" luminaire in which the intensity and direction of the beam can be controlled over the air.

Figure 1. Prototype smart luminaire: an array of white LEDs mounted on actuators, behind an array of lenses. The actuators allow to direct the lights through the lenses for directional control.

2. Research aim

After comparing the lighting properties of "smart" luminaires with the available standard LED fixtures in terms of several key light quality indicators, the project presented here aims at exploring how the control of its non-standard capabilities translates into specific usage patterns. To study the luminaire's usage involved the development of a dedicated interface and its testing through a controlled user study setup in a room similar to an office environment.

Compared to conventional switching or dimming, directional control requires providing non-standard interaction modalities to average building occupants, which have to fit within their daily routine. However, defining an interaction system prior to study its usage bears the danger of studying more the adequacy of the interaction system itself, instead of capturing its potential usage by the occupants. Through the presented study, the research ultimately aims at developing and validating a methodology to investigate "smart" devices — e.g. requiring enhanced interfaces — in their intended environment.

3. Methods

3.1. Setup

The ceiling luminaire under scrutiny is a dynamic lighting fixture, consisting of a fixed 6x6 lenses array, above which a movable 6x6 LEDs array allows to dynamically change the light beam output (direction) by changing each LED position relative to the lenses (Figure 1). The light beam can move freely on a horizontal plane, reaching further than 45° angle from the vertical. This luminaire has been developed by a start-up company.

Two smart luminaires have been installed in a free-standing office room of 42 m^2 functioning as an experimental laboratory of the Smart Living lab in Fribourg. These luminaires were linked through a KNX/DALI bridge to the local building management system, while another interface allowed their control with simple HTTP requests, in the IoT fashion. Such interfacing enabled the use of web technologies for rapid prototyping of user interfaces, needed to control the luminaires' direction. These luminaires were installed next to the existing standard ceiling-mounted LEDs (LED beams) in order to compare their performance (Figure 2).

3.2. Lighting characterization

The luminaires' lighting performances were measured using two different setups: a desktop positioned longitudinally (setup 1) and perpendicularly (setup 2) to the axes of the two luminaires (Figure 3). With these settings, illuminance, Color Rendering Index (CRI), color temperature and uniformity, were measured at 100% intensity for the "smart" luminaires, in order to evaluate to what extent the quality of the lighting was impacted by the lenses. For comparison purposes, the same measurement procedure was made using the standard LED beams with a measured lighting power density of 3.89 W/m^2.

3.3. Controlled user study

In order to study user acceptance, a user study has been designed, consisting of a controlled environment without natural light, with two different test conditions: standard ceiling-mounted LEDs (LEDS) and smart luminaires (SMART). The working planes were placed exactly between two light sources (on the left and right side for the subject) to maximize illumination uniformity

Figure 2. Smart luminaires (blue) and “standard” LEDs (orange) fittings on the ceiling of the LIER lab/meeting room.

Figure 3. Meeting set-up table (160x80 cm) - longitudinal (Setup 1) and perpendicular (Setup 2)

Figure 4. User study setup: users are invited to work on their own computer in a controlled light environment without daylight. They can set the lighting conditions through the prototype interface. In the SMART condition (depicted), each smart luminaire can be controlled individually. Note the double shadow cast by the two luminaires.

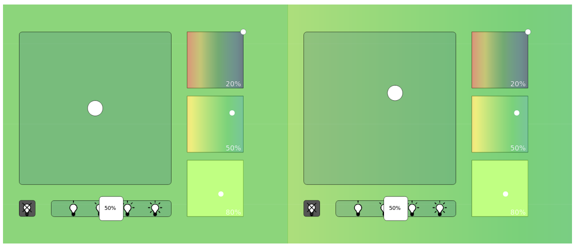


Figure 5. Prototype smart luminaire control interface: position and intensity controls, simple memory “pads”, doubled for each lamp.

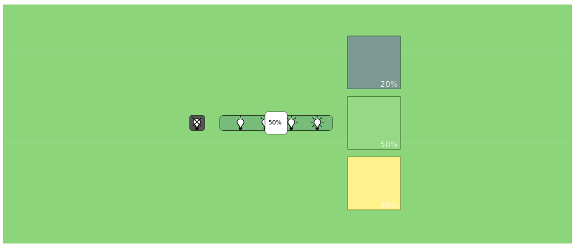
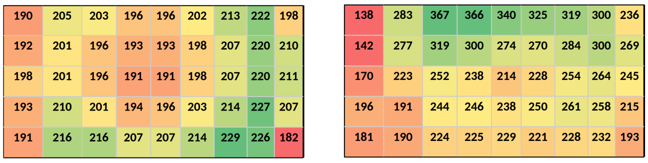


Figure 6. Prototype “standard LED’ control interface, designed to match the smart luminaire interface: intensity control and memory “pads”.

for both conditions. After an initial testing phase to get familiar with the control application, subjects worked on their own laptop for 45 minutes, freely choosing their comfortable light levels thanks to a mobile application (Figure 4), but subjected to light intensity resets to 55 lux every 15 minutes (thereby dividing the experiment time into three *trials*).

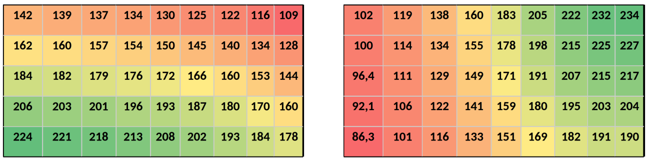
Two versions of the mobile application were developed, both with very similar interface to eliminate interface bias (Figures 5 and 6), allowing subjects to control both lights individually in the SMART condition (direction & intensity), and only the overall intensity in the LED condition. Subjective and qualitative assessment was recorded through an online questionnaire after the experiment (demographics, appreciation of luminaire and user interface), whereas quantitative measures consisted in interface usage log records and illuminance measurements. The user study was completed by 22 subjects (55% male, 45% female, 70% students, 30% administrative staff or research, 5 participants rejected).



190	205	203	196	196	202	213	222	198
192	201	196	193	193	198	207	220	210
198	201	196	191	191	198	207	220	211
193	210	201	194	196	203	214	227	207
191	216	216	207	207	214	229	226	182

138	283	367	366	340	325	319	300	236
142	277	319	300	274	270	284	300	269
170	223	252	238	214	228	254	264	245
196	191	244	246	238	250	261	258	215
181	190	224	225	229	221	228	232	193

Figure 7. Distribution of maximal potential illuminance values (lux) for the smart luminaire: (left) setup 1, (right) setup 2. Orienting light on the working plane leads to little difference between setups.



142	139	137	134	130	125	122	116	109
162	160	157	154	150	145	140	134	128
184	182	179	176	172	166	160	153	144
206	203	201	196	193	187	180	170	160
224	221	218	213	208	202	193	184	178

102	119	138	160	183	205	222	232	234
100	114	134	155	178	198	215	225	227
96,4	111	129	149	171	191	207	215	217
92,1	106	122	141	159	180	195	203	204
86,3	101	116	133	151	169	182	191	190

Figure 8. Distribution of maximal potential illuminance values (lux) for the of "standard" LEDs: (left) setup 1, (right) setup 2. The fixed LEDs produce different distributions of illuminance values.

Table 1. Light characterization for Setup 1 & 2 with maximal potential illuminance

	Setup 1		Setup 2	
	Smart	LEDs	Smart	LEDs
Power consumption	13.8 W	163.3 W	13.8 W	163.3 W
CRI	83.6	70.4	83.5	70.3
Color temperature	3918 K	3937 K	3988 K	3946 K
Average illuminance E_m	204 lx	167 lx	249 lx	163 lx
Minimum illuminance E_{min}	182 lx	109 lx	138 lx	86 lx
Uniformity $g_1 = E_{min}/E_m$	0.89	0.65	0.55	0.53

4. Results

4.1. Smart luminaire characterization

The distribution of measured lux values are presented in Figure 7 for the smart luminaire, and Figure 8 for the standard LEDs. Energy consumption and light characterization are presented in Table 1. The ability of the smart luminaire to direct lighting on the surface of interest (working plane) allows to reach better lighting conditions at less than a tenth of the energy cost of standard ceiling mounted LEDs fixtures, while color indices are overall comparable. The advantage in terms of uniformity depends on the setup: setup 1 displays better uniformity thanks to the user's positioning between the two smart luminaires. Setup 1 was used for condition SMART in the user study. Setup 2 was slightly adapted for condition LED to improve uniformity.

4.2. Controlled user study

4.2.1. Qualitative results Qualitative results showed that the very low reset illuminance levels were nevertheless evaluated as comfortable by a small majority of users, supporting other studies involving work on rear-lit screens [10]. Subjects also self-reported low interaction frequency with the interface (Figure 10). The interface itself was positively rated and allowed a majority of users to set comfortable lighting conditions (Figure 9). This last result provides good confidence that the low light levels recorded and assessed as comfortable are not biased by interface shortcomings.

4.2.2. Quantitative results Quantitative results revealed that users spent more time in mid-range illuminance for the LEDS condition whereas users using the smart luminaire (condition SMART) favoured the lowest illuminance range (Figure 11). Considering the number of

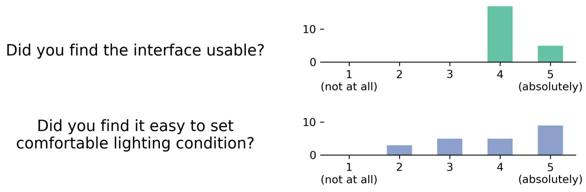


Figure 9. The control interface was well rated by the subjects (above), the setting of comfortable conditions received less clear agreement, but positive in majority (below)

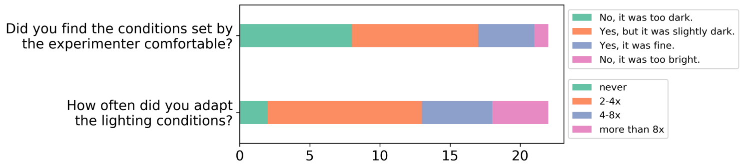


Figure 10. Subjects rated reset light levels heterogeneously (above), and self-reported low interaction frequency (below). Only chosen options are shown.

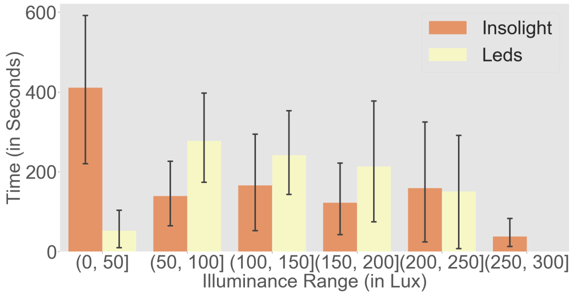


Figure 11. Cumulative time spent in illuminance range averaged across subjects and trials. No significant differences were found neither from conditions (SMART or LEDS) nor from illuminance ranges. There was no significant interaction effect.

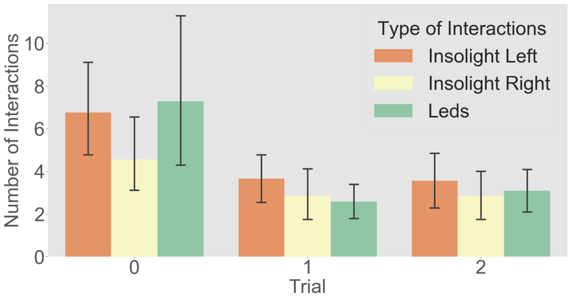


Figure 12. Number of interactions on light intensity according to LEDS, SMART left and right interface. ANOVA reveals an effect of Trials, $F(2,50)=15.59$, $p<.05$. Post-Hoc Analysis (Bonferroni-corrected) shows significant decrease in interaction between trials 0 and 1, and between trials 0 and 2 (both $p<.05$).

interactions, a higher level of interaction has been observed during the first 15 minutes (trial 0) which then decreased and plateaued in the next trials (Figure 12). We hypothesize that in this first trial, subjects experimented with the new interface in conjunction with the lighting environment, and — the novelty effect fading — got back to their work in later trials.

Since the SMART condition allowed individual luminaire control, subjects could set different light conditions in left and right sides. Interaction patterns revealed that directionality differed between the sides, suggesting an effect of right-handedness or reading direction [11](Figure 13) . Similar to Figure 12, a decrease in interaction across trials appears.

5. Discussion and conclusion

Within the limits of the investigated metrics, the smart luminaire's lighting characterization allowed to demonstrate that this type of dynamic beam control provides good lighting conditions at a reduced cost compared to a standard lighting fixture. Secondly, a controlled user study setup in an office environment allowed the testing of the luminaire's enhanced capabilities by a set of potential future users. Specific patterns of usage were unveiled, as well as the fact that lower illuminance levels seemed to be required to achieve similar visual comfort. A deeper analysis

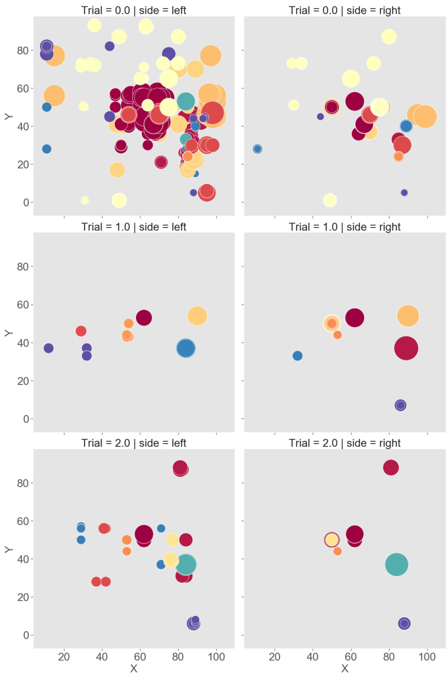


Figure 13. Interaction locations on the interface (XY) with light intensity (radius). Each color represents a subject. ANOVA reveals a principal effect of side on the X coordinates $F(2{,}34){=}15.31, p{<}.05$, but no effect on the Y coordinates. Post-hoc analysis (Bonferroni-corrected) shows that the differences in X coordinate appear between trials 0 and 1 and between trials 0 and 2 (both $p{<}.05$). The noticeable difference in interaction frequency is not confirmed by statistical analysis.

also addressing differences in perceived usage and measured interactions will be submitted in a subsequent publication.

The presented energy performance and perceived comfort results show that adding control degrees to lighting fixtures display interesting potential both in terms of energy savings and comfort increase. This potential is however counter-balanced by the need for appropriate interfaces which can seriously influence the acceptance of such devices.

More generally, the case study presented here demonstrated the potential of controlled environments for testing novel lighting devices and strategies. It also provided the opportunity to develop and validate a methodology in investigating smart devices within the environment of their intended usage.

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