# Illuminating Adaptive Comfort: Dynamic Lighting for the Active Occupant

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Abstract

This paper makes the assertion that established concepts from thermal comfort research might be used to develop an adaptive comfort model for lighting. By gathering data from a live office environment, we demonstrate the necessity of dynamically-adapted lighting levels in order to achieve both comfort and energy savings. We detail the background and the experimental setup that is used to extract the light levels at which the occupant switches his lights on. We show how individual occupancy information can be estimated from passive infrared (PIR) motion sensors, making fixed, global set points unnecessary. Finally, we demonstrate the successful implementation of the control system.

## 1. Introduction

There exists a great body of research related to occupant *thermal* comfort; this research has debated various definitions for comfort, and understanding how they vary across people, buildings, and throughout history. Specifically, it has been shown that thermal comfort is highly localized in space and time, and that humans are capable of both acclimatising and adapting in response to changing environmental conditions (Nicol et al, 2012), (Clear et al, 2013). In this research, we hypothesize that similar conclusions can be drawn for lighting comfort. Some implications are that lighting levels might be variably adjusted or drifted automatically over the day and with the seasons; and that local supplementary lighting might be carefully applied to reduce the prevalence of lighting entire rooms or buildings throughout their operating hours.

In numerous field studies, it has been observed that illuminance thresholds vary greatly from person to person and depending on the performed task. This results in general guidelines for workplace light levels, e.g., 500-1000lux for offices. However, such static yet vague guidelines cannot be used to create a lighting strategy, which supports adaptive comfort. Not only is the range of the switch-on threshold too large (Gunay et al, 2013),(Reinhart and Karsten, 2003), but it glosses over the fact that appropriate lighting levels change over time, even for the same person in the same place.

In this work we identify analogies between thermal and lighting comfort, and interrogate if and how knowledge gained from thermal comfort research can be translated to lighting comfort. In working through these issues, we present empirical light threshold and occupancy data gathered in several offices in the research group of the authors at high temporal and spatial resolution. Based on this data, and as an initial exploration into adaptive comfort through lighting, we formulate a distributed

lighting control system that is capable to adjust the switch-on and switch-off thresholds individually for each office.

We postulate that the increased widespread use of inexpensive LED lighting in buildings will create new opportunities for automatically controlled dimmable lighting (Aldrich et al, 2010), which in turn requires a deeper understanding of lighting comfort and its variability. Our research contributes to this through a theoretical analysis and a field study, informed and inspired by important lessons from adaptive thermal comfort.

## 2. Applying the Adaptive Model to Lighting

*"If a change occurs such as to produce discomfort, people react in ways which tend to restore their comfort."*

Nicol, Humphreys and Roaf (2012), p. 29

We start with the familiar acknowledgement that comfort is dynamic, depending on the person, their activity, their previous experience, and the indoor and outdoor environment. The adaptive model for *thermal* comfort aims to create indoor environments and situations where the occupant is able to make themselves comfortable through a variety of adjustments: windows and ventilation, clothing, hot and cold drinks, moving between rooms, and minimal-energy mechanical heating and cooling. We posit that constructive analogies exist for rethinking indoor lighting, within an adaptive comfort model.

- **Person-centric and temporally dynamic**, rather than static across space and time: instead of providing constant levels of light across offices, hallways and kitchens (a global, fixed set point), we should rather embrace variation by supplying a minimal base or background level of lighting during occupied times, with capacity for further adjustments to be made quickly and easily. Such adjustments would be through adaptive measures applied by the occupant, sensitively supported and enhanced by automated systems. In other words, the fundamental approach to lighting should become person-centric (*comfort-as-goal*) rather than environment-centric (*comfort-as-product*).

- **Highly localized**: To support such person-centric comfort, those working on heating have highlighted that small, radiant heat sources (such as an electric fire or personal foot warmer) can be applied just for the time warmth is required. For lighting, the analogy might be a narrow-beam desk lamp, which can be switched on temporarily for close work, rather than raising the level of artificial light for the entire room. Previous adaptive comfort research tells us that occupants with more perceived control tend to be more satisfied with the adjustments they can make depending on their activity, task or mood. Clearly, lighting levels should be appropriate to the activities occupants are engaged in; but even for comparable activities, what is seen as appropriate or even

"normal" lighting varies between people, and can vary even for the same person at different times.

- **Slow changes** made by an automatic system allow the occupant time to gradually adjust, and are less likely to provoke discomfort. Fast changes (such as the lights suddenly switching off) may be noticeable, distracting and create an unsettled feeling. Thermal comfort research has indicated limits on changes by no more than a degree Celsius or so in the short term (a day), with no more than a few degrees in the running mean over longer terms (a week). We have very little information about how much change in the long and short term might be acceptable for lighting. But supporting such slow changes (over a day or season) might require the availability of dimmable lighting; or otherwise large numbers of smaller lights, carefully coordinated.

- **Indoor lighting should be varied as natural light levels change**: Finally, a key observation from adaptive thermal comfort is that indoor conditions perceived comfortable demonstrably vary with the mean outdoor conditions. (See for example Humphreys' 1978 graph plotting outdoor monthly temperatures against indoor comfort temperatures (Nicol et al, fig. 3.2.) In daily experience, outdoor lighting levels clearly have an influence: late in the day as it gets dark, the occupant switches on the lights. But we wonder if (as was found with thermal comfort) there are not more subtle connections. In deep winter when the days are short, have occupants acclimatised, and actually require less light for reading a book, and other close-work tasks? We should consider these possible diurnal variations in light comfort levels. In combination with strategies to regulate passive (natural) light and shading (e.g. motorized louvers), we might investigate how base levels of lighting might be varied with the time of day or season; and how localized light sources such as work lamps and reading lights might also be changed.

Our field research described below represents an initial foray into applying the adaptive model to lighting. Thus, we will focus on the first point above ("person-centric and temporally dynamic"), and limit our scope of enquiry to observing at what lighting levels people apply room-level adaptations (i.e. switching on the overhead lights); and then use that information to aid in coarse control of those lights (i.e. simply switching them on or off).

## 3. Occupant Centered Lighting Control

As a live case study of adaptive lighting for active occupants, we consider an office environment for computer-based work, with offices being occupied by one or two persons, each office being equipped with a passive infrared (PIR) motion sensor and non-dimmable lighting (i.e. the lights can be turned on and off, but not regulated to a certain level).

The general objective is to develop an automated system capable of switching the lights on and off without wasting energy and/or causing discomfort to the occupant. Energy is wasted if the lights are switched on when the occupant is not present or if there is sufficient daylight. On the other hand, discomfort may be caused to the occupant if the lights are suddenly switched off while they are present, and natural light levels are too low. In addition, comfort of the occupant might be better

accommodated if the light is switched on automatically as the office becomes gradually darker, e.g. late in the afternoon.

These ideas might translate into two primary rules for the simple controller in our case study:

1. *switch on lights if someone is present and it is too dark*, and
2. *switch off lights if nobody is present or it is bright enough without lights*

In order to implement these rules, thresholds for presence and light levels must be determined. As has been shown with indoor thermal comfort, a global threshold, i.e. the same for all occupants across a building, tends to provide little support for occupants (whose lighting needs surely vary), and/or tends to be energy-intensive. As a first step towards an adaptive lighting model, thresholds might be estimated for each occupant individually. We describe our approach for this in the following.

### 3.1 Estimating Light Level Thresholds

Two metrics are possible to characterize the light level in an office environment. On one hand, the *illuminance* (in cd  sr/m$^2$ or lux) refers to the light coming from a light fixture and reaching the workspace, i.e., the desk. On the other hand, the *luminance* (in cd/m$^2$) is the light leaving the desk. Because the luminance requires an additional characterization of the reflection properties of the workspace, it introduces more variables and hence complexity. In addition, most lighting guidelines are formulated in terms of illuminance rather then luminance. Hence, we choose to consider illuminance as the target variable for determining lighting thresholds. Further, since "workspace illuminance" is our target goal, we propose to measure the vertically incident light at 15cm above desk level (see Section III-A). This is similar to the reference height of 76 cm above the floor, used in defining the recommended office task light levels quoted above (500-1000 lux) (IESNA, 2000).

While PIR-based activation is becoming more common in new buildings, switching lights on automatically based on ambient light is not prevalent. Our goal is to dynamically determine the light level at which the room becomes too dark for the occupant (for either task-based purposes, or for comfort otherwise). To help track this level, we might observe the lighting level at which the occupant actively switches the light on. In this way, we can better understand the temporal, spatial, and personal variations—the end goal being to support the occupant with minimal lighting energy.

In our case study, we monitor the light levels in each office with one-minute temporal resolution, and log the switch on/off events of the user. In a post-processing step, the most recent light level prior to each switch on event is identified. Then, the threshold value is determined as the median of the registered values over a certain period of time. Choosing the averaging window as the past few weeks (for example) allows the threshold to adapt to the occupant's changing context (e.g. performed tasks, time of year, or use of other sources of light such as a table lamp). Arguably, office-ceiling lights should be switched off if natural illuminance is very high; as a simple approach, we set 1500 lux as the mandatory switch-off threshold.

### 3.2 Estimating Time Delays

Many office environments have a functionality that switches off the lights after a certain time delay (TD) after the PIR sensor has registered the last motion event. The value ranges usually between 12 and 15 minutes. Lower values might conserve energy, whereas higher values avoid "surprising" occupants by prematurely switching off the lights.

The drawback of a constant TD stems from the fact that the PIR sensors do not register presence but rather motion. Thus, since every person has a different mobility characteristic when working at his/her desk, a sensor might be triggered differently, and small TD values may cause the system to turn off the lights too quickly. In addition, some PIR sensors have high directionality (narrowing their field of observation), and, as a consequence if a person sits in a different location relative to the PIR, it might be triggered differently.

From this, we can conclude that it is necessary to observe the mobility characteristic of the occupant individually. We employ an approach similar to (Garg and Bansal, 2000) by logging the trigger times of the motion sensor. The workings of each PIR sensor may be different, but typically there is an OFF trigger if no more motion has been detected during a certain period of time (set to 1min in our case), and an ON trigger if subsequently motion is detected. The time differences between the OFF and the subsequent ON trigger are used to derive the mobility characteristic of the occupant. After sufficient data has been gathered, the empirical distribution can be determined and the time delay TD can be set such that it covers a large percentage (or probability) of the observed data.

Thus, instead of choosing static time delays, we define target probabilities. This approach has two advantages. First, by regularly updating TD using only recent data, (again, perhaps the past few weeks), the TD can adapt to changes in the activity of the occupant or parts of the office used. Second, even if the same probability value is chosen for all rooms in the building, it will translate into different values for each office based on the mobility characteristic for that particular office. Thus, it adapts to different sensor positioning, rooms, and occupants.


## 4. Experimental Results

### 4.1 Measurement and Control Setup
As location for the experimental setup, the authors used their own office building ("HPZ") on the Hönggerberg campus of ETH Zurich, Switzerland. It was built in the 1970s and completely refurbished in 2011 (see Fig 1a). In particular, it has been equipped with "digitalStrom", a power line communication (PLC) network especially interesting for retrofit applications, as no new hardware lines have to be installed.

Each device on the network has a unique ID to communicate its status with the main digitalStrom server, the "dSS". Using a web-API, the dSS allows easy access to the state of the motion sensors, the lighting, and logging the events of the light switches. In addition, lights can be switched on or off. (Dickmann, 2011)

The digitalStrom setup does not measure the lighting levels in the offices, and only offers a limited logging system. Therefore, it has been extended with a customized solution as follows. Each office is equipped with an AMS TSL 2561 digital

illuminance sensor[1], installed about 15 cm above desk level, and measuring the vertically incident light onto the workplace. The sensor is connected to a Raspberry Pi[2], which communicates the with a central control server over LAN. This central server maintains logs of all the events in a MySQL database for data analysis. In addition, the central server acts as gateway to the dSS, which is on a different network due to security reasons. Figure 2 summarizes the networking layers.

The setup has been installed in eight rooms in the building (see Fig. 1b). Out of these, three offices are occupied by two people (G23, G25.2, G26.2), and one is a single-occupant office (G25.1). The others are unique purpose rooms, such as the the kitchen (G22), a large meeting room (G27), a large office with varying number of occupants (G24), as well as one workshop (G25.2). With the exception of G22 and G23, which are oriented east, all investigated rooms have a south orientation.
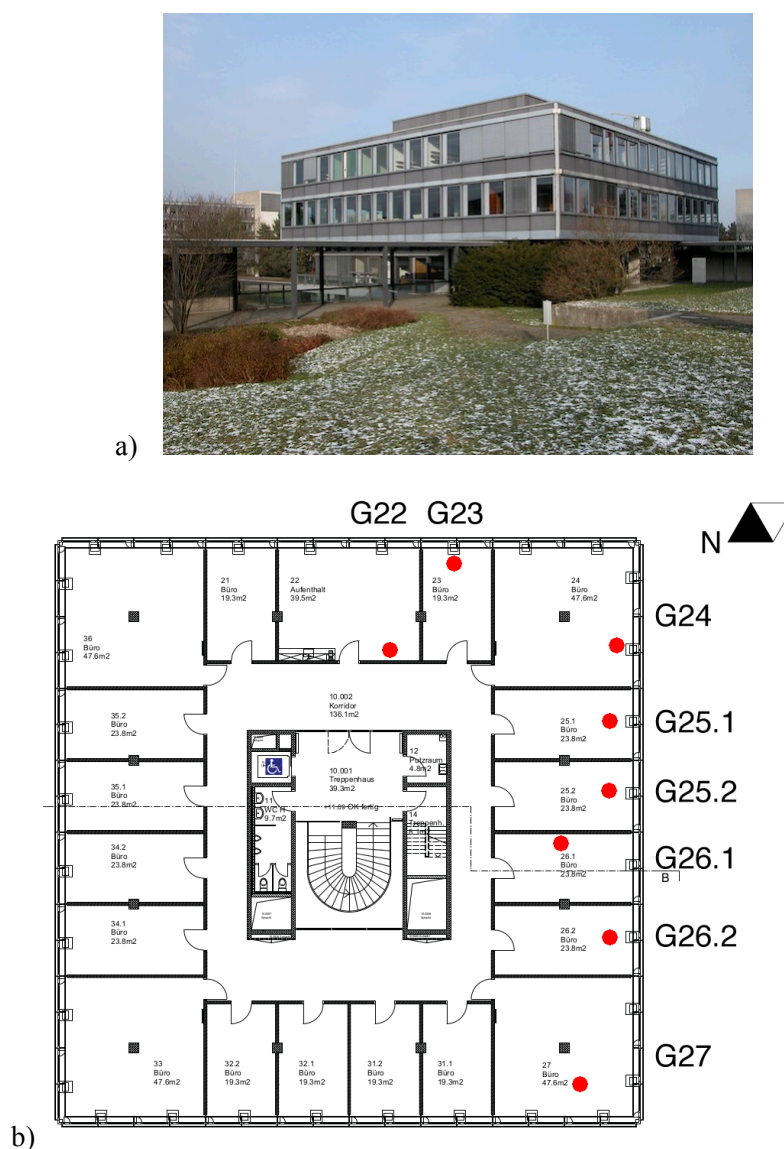


a)



b)

**Figure 1.** The HPZ building used in this study. a) photo, b) floorplan. Red dots indicate sensor

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[1] http://www.ams.com/eng/AmbientLightSensor, retrieved January 2014

[2] http://www.raspberrypi.org, retrieved January 2014

locations

The control state/action table is summarized in Table 1. Note that the table only shows conditions, which require explicit action of the controller. In brief, communication between the software is setup as follows. The central server analyses the occupancy and light data daily, and saves current set points for the time delay and the light level threshold. The Raspberry Pi queries this set point from the server, compares them to the current values, and sends appropriate control commands to the server, which then communicates them to the dSS. If the user has switched off the lights, controller action is suspended for 2 hours. This is required to deal with situations, such as darkening the meeting room to use the projector.
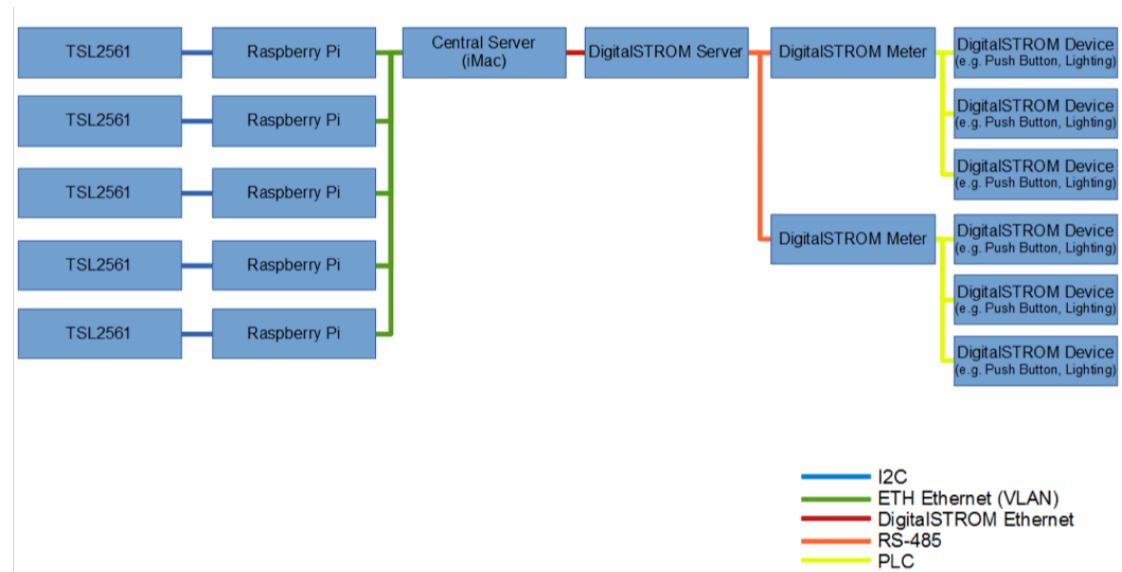


***Figure 2.*** Network architecture

| | States | | | | Controller Action |
|---|---|---|---|---|---|
| # | Occupied | Lux < threshold | Lights are ON | Lux > bright threshold (1500lux) | Switch Lights |
| 1 | No | Yes | Yes | No | OFF |
| 2 | No | No | Yes | No | OFF |
| 3 | Yes | No | Yes | Yes | OFF |
| 4 | Yes | Yes | No | No | ON |

***Table 1.*** Summary of control states and actions

## 4.2 Adaptive Set Points

Figure 3 and 4 shows the distribution of the lighting thresholds in the offices in January 2014. In Figure 3, the data is organized along the time of day, explicitly showing when the thresholds have been generated, while in Fig.4, the frequency count is shown.

We can identify first tendencies from this preliminary dataset. We observe that the largest amount of the data is generated in the kitchen (G22) and the meeting room

(G27), which is not surprising since all members of the research groups on the floor frequent these rooms. In most cases, the data is clustered in two groups, one around 0lux and much higher at 400-500lux. The first group contains the events that most probably occur when the occupant enters a dark office. The second one considers events when the room is getting darker, resulting in the occupant switching on the lights, typically occurring in the afternoon, after 12:00.

We can extract a set point for the control system as the median of the data. To take into account both groups, we show both, the median using all the data, and the median using only afternoon data. Note that the latter will typically be larger than the former since the morning data generates a bias towards lower values. In both, Fig.3 and Fig.4, we can observe that the afternoon median provides a reasonable indicator for the light threshold.

When comparing the determined thresholds, we can clearly observe differences in the individual offices, ranging from as low as 91lux (in G24) to 530lux (G22). This confirms the potential for energy savings and the motivation to use user adapted set points in the control system.
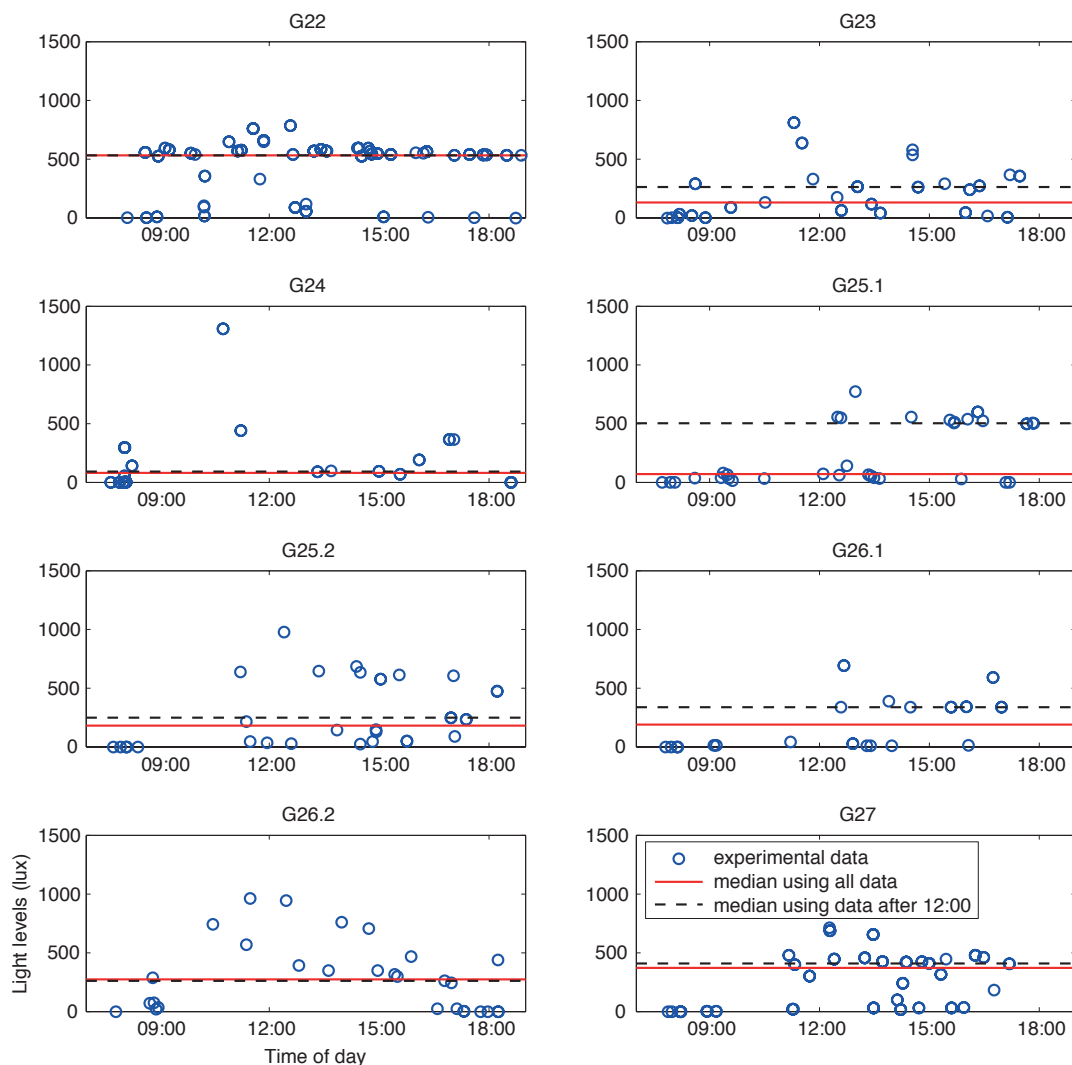
***Figure 3.*** Distribution of registered light level thresholds during the time of day (data for January 2014)
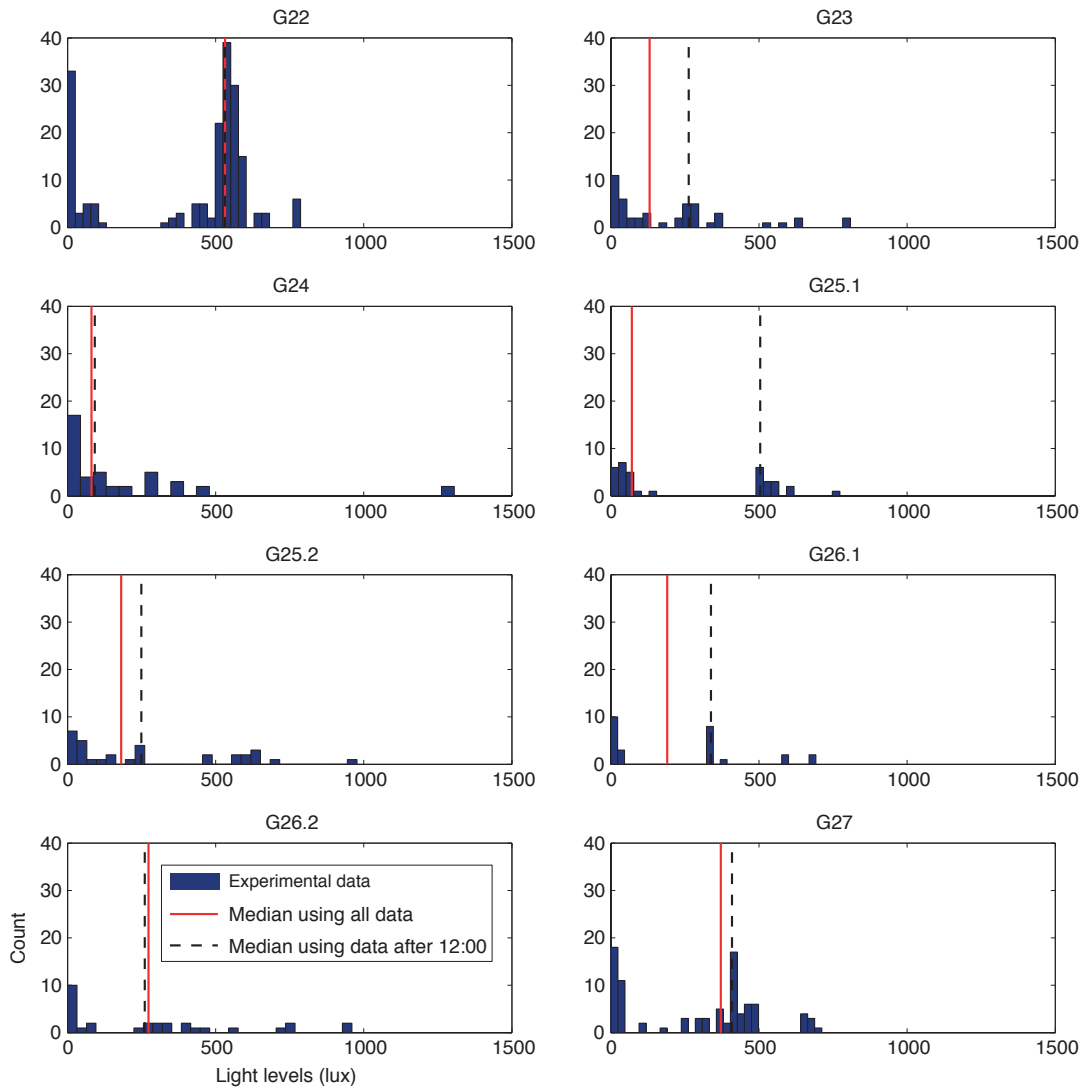


***Figure 4.*** Frequency count of the registered light level thresholds

Next, Figure 5 shows the time delay based on the data from the motion sensor in each office as a histogram, and the resulting empirical cumulative distribution function (ECDF). In addition, we show fits for the generalized Pareto (GP), and the exponential distributions, which are suitable for modeling long-tailed frequency data. The GP fit generally provides the best fit to the data, but comes at the cost of a numerical optimization process. On the other hand, the exponential fit only requires the mean of the data to be computed to estimate its single parameter. Hence, it is more appropriate if computational power is not available.

Even though in our case this is not an issue as data analysis is performed on a desktop computer, we show the implications of using the Exponential fit instead of the ECDF. Notice how small changes in the probability setting can easily lead to over- or underestimation of the ECDF. We find from our data that the best approximation is

provided for p=0.85. Further investigation is required in order to heuristically adjust the set points, e.g. if appropriate comfort is not achieved.

For our experiments, we use p=0.85 (shown as horizontal line in Fig 5), which, as was the case for the light thresholds, results in a large range of individual set points for each office (vertical lines in Fig. 5). Figure 6 summarizes the light level and the time delay thresholds for each office. Clearly, for both parameters, each office exhibits different thresholds, confirming our premise and motivation for adaptive set points.

As for a first interpretation of the results, concerning the illuminance levels, our data suggests that light levels below the guidelines of 500-1000lux provide sufficient lighting comfort. In addition, the TD set points are mostly under the industry standard of 12-15min. Thus, we can conclude that in both cases further energy savings are possible without compromising human comfort. Of course these claims are limited by the amount of available data. A long-term experimental investigation with proper post-occupancy evaluation will provide more insight.
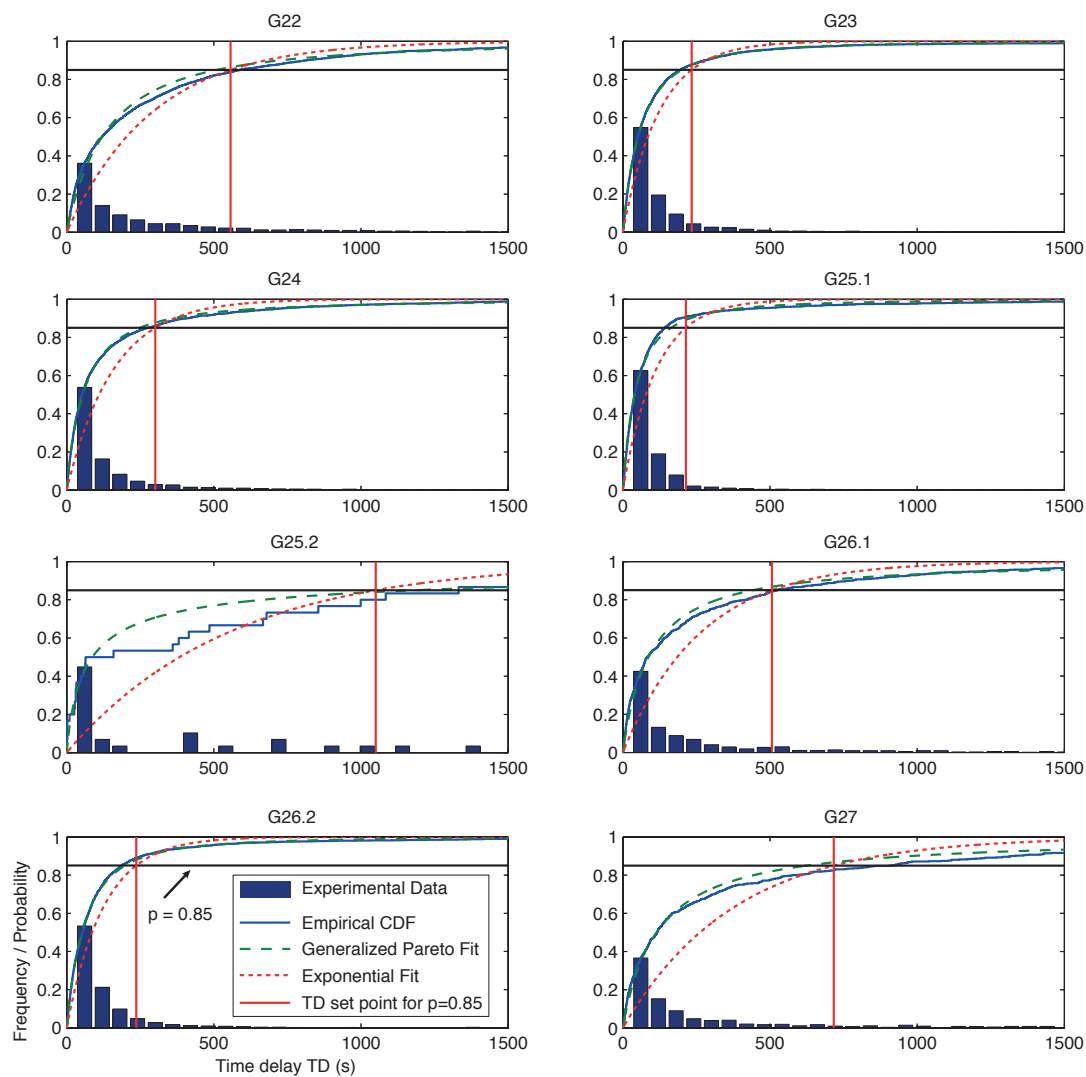


**Figure 5.** Statistical analysis of the measured time delays, with a histogram of the data (the width of one bin is 60s), the empirical cumulative distribution function, and an exponential and a generalized Pareto fit to the latter. Note how a probability setting of p=0.85 creates a
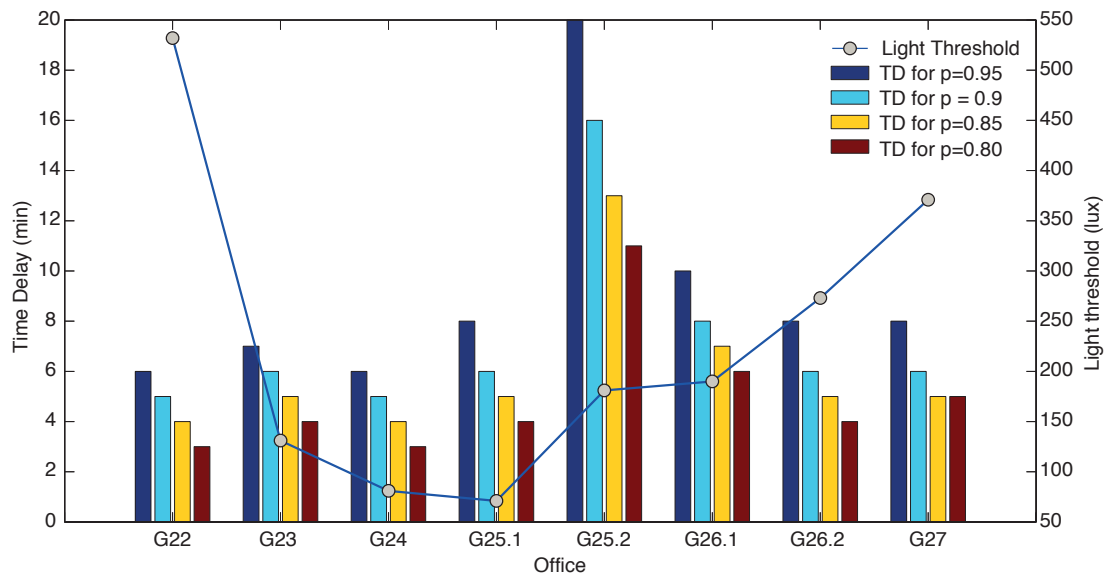
large range of set points in the individual offices.



**Figure 6.** Light level and time delay thresholds in each office. The time delays are given as a function of the probability

### 4.3 Controller Results

Figure 7 a)-e) shows a typical daily time series of the measured data, captured triggers and controller events. The occupant arrives around 8:00 in the office, which triggers a Switch ON event by the motion sensor because the office is too dark (1). The artificial lighting is turned on, and remains on until the light level in the office is rising above the bright light threshold (1500lux), at which point it is switched off by the controller to save energy (2). At around 16:00, when the light level dropped under the low threshold, the controller switches the lights back on since an occupant is present (3). At around 20:00, the occupant leaves for an extended period of time, and the system switches first the lights Off, and then back on after the returning of the occupant (4). Finally, the occupant leaves the office around 22:00 and switches the lights Off himself (5).

This demonstrates the successful implementation of adaptive lighting control in a live office environment. Comfort might be increased by dynamically adjusting the set-points to the occupant, and by not requiring intermediate switching actions throughout the day. In addition, when possible, energy saving changes are effected by switching the lights off when the office is sufficiently bright.
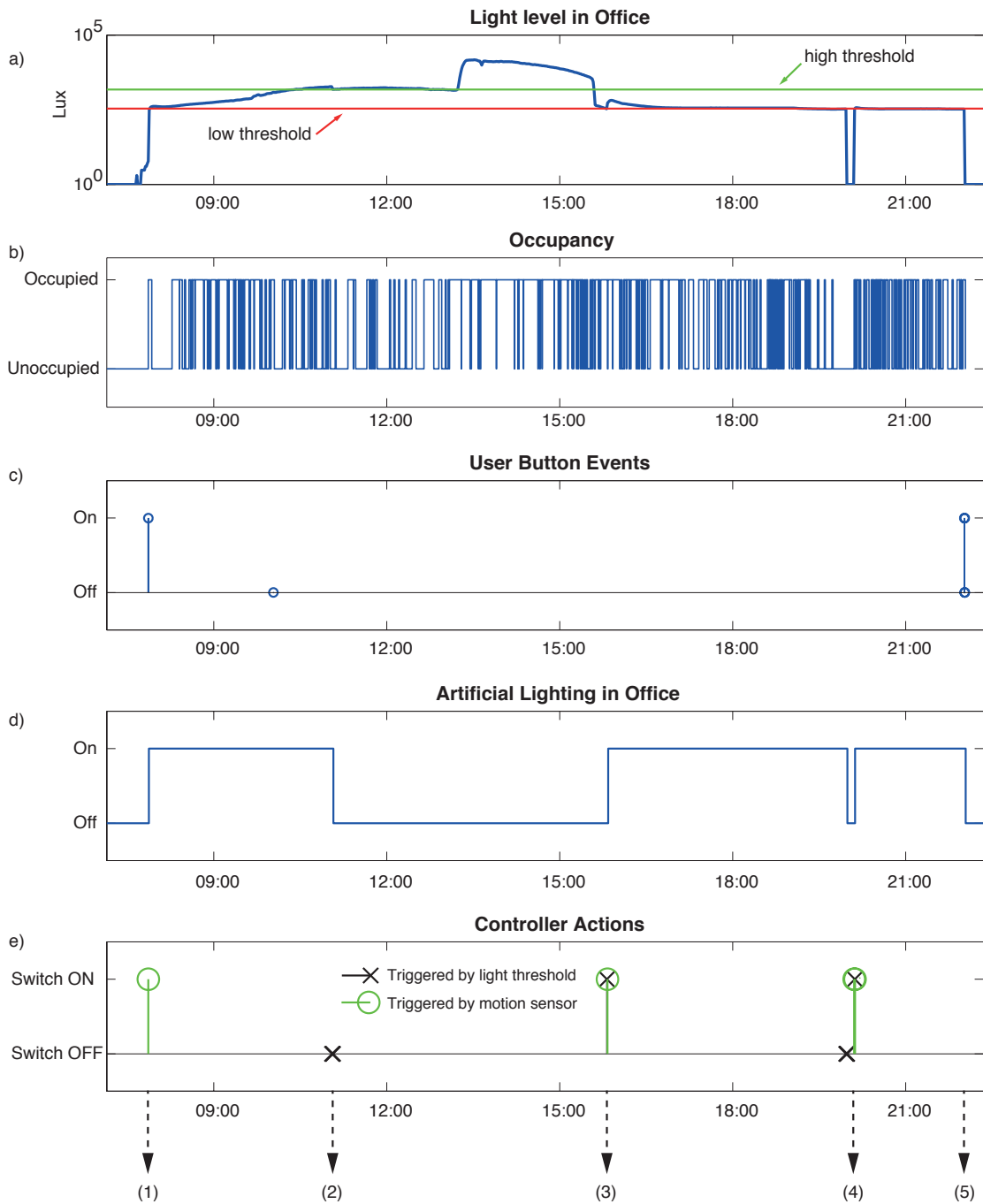
*Figure 7.* Typical daily data for the implemented adaptive control. a) Measured light levels in the office, b) motion sensor triggers, c) user button push events, d) state of the artificial lighting, e) controller actions. (1)-(5) are events occurring throughout the day, see text for explanation.

## 5. Conclusions and Outlook

In this research, we argue that in analogy to thermal comfort illuminance targets should vary according to the particular persons, activity, space and time-of-day or season. Such adaptive set points for lighting control have the potential to provide comfort to the occupant while saving energy by adjusting the light levels as necessary. We have implemented a prototype of such a control system in an office environment and determined individual set points for each office based on experimental data. The control system is running successfully in the daily operation of the building and is suitable for long-term experimentation.

Further research will include a post occupancy evaluation to investigate the effects of the automatic adaptation on the occupants. It has been noted that in control systems that interact and adapt to a human occupant, not only the system adapts, but there is also an adaptation process for the human (Mozer, 2005). This can be further explored and investigate whether its possible for example to nudge the user towards more environmental friendly behavior.

An important extension of this research will consider adding more operational flexibility to the lighting, i.e., include desk lighting control as well as dimmable lights. This will add additional possibilities for the control system to maintain a comfortable lighting level. On the other hand, the control task becomes more complex as multiple control actions are possible.

Finally, long term investigation and analysis of the experimental data will allow drawing conclusions whether seasonal or diurnal trends of the light thresholds exist, and can be exploited. Implementing a control strategy based on this knowledge will allow for increased occupant comfort and energy efficiency throughout the year.

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