Accounting for the uncertainty related to building occupants with regards to visual comfort: A literature survey on drivers and models

Fabi, Valentina; Andersen, Rune Korsholm; Corgnati, Stefano

Published in:
Buildings

Link to article, DOI:
10.3390/buildings6010005

Publication date:
2016

Document Version
Publisher's PDF, also known as Version of record

Citation (APA):
Fabi, V., Andersen, R. K., & Corgnati, S. (2016). Accounting for the uncertainty related to building occupants with regards to visual comfort: A literature survey on drivers and models. *Buildings*, *6*(1). https://doi.org/10.3390/buildings6010005

---

buildings

MDPI

Review

Accounting for the Uncertainty Related to Building Occupants with Regards to Visual Comfort: A Literature Survey on Drivers and Models

Valentina Fabi [1],*, Rune Korsholm Andersen [2] and Stefano Corgnati [1]

[1] Department of Energy, Polytechnic of Turin, 10129 Torino, Italy; stefano.corgnati@polito.it
[2] International Center for Indoor Environment and Energy, Technical University of Denmark, DK-2800 Lyngby, Denmark; rva@byg.dtu.dk
* Correspondence: valentina.fabi@polito.it

Academic Editor: Adrian Pitts
Received: 15 October 2015; Accepted: 29 January 2016; Published: 6 February 2016

Abstract: The interactions between building occupants and control systems have a high influence on energy consumption and on indoor environmental quality. In the perspective of a future of "nearly-zero" energy buildings, it is crucial to analyse the energy-related interactions deeply to predict realistic energy use during the design stage. Since the reaction to thermal, acoustic, or visual stimuli is not the same for every human being, monitoring the behaviour inside buildings is an essential step to assert differences in energy consumption related to different interactions. Reliable information concerning occupants' behaviours in a building could contribute to a better evaluation of building energy performances and design robustness, as well as supporting the development of occupants' education to energy awareness. The present literature survey enlarges our understanding of which environmental conditions influence occupants' manual controlling of the system in offices and by consequence the energy consumption. The purpose of this study was to investigate the possible drivers for light-switching to model occupant behaviour in office buildings. The probability of switching lighting systems on or off was related to the occupancy and differentiated for arrival, intermediate, and departure periods. The switching probability has been reported to be higher during the entering or the leaving time in relation to contextual variables. In the analysis of switch-on actions, users were often clustered between those who take daylight level into account and switch on lights only if necessary and people who totally disregard the natural lighting. This underlines the importance of how individuality is at the base of the definition of the different types of users.

Keywords: occupant behaviour; window opening; statistical modeling; behavioural verification; light switching

1. Introduction

In 2010, buildings still consumed nearly half of the total amount of energy used in Europe, despite international measures and building experts' challenges [1]. Indeed, as Bordass stated in 2001 [2], "real-life building performance still often undermines design expectations." Energy is consumed in buildings for various purposes: space heating, water heating, ventilation, lighting, cooling, cooking, and other appliances. This means that energy is spent in order to maintain comfortable indoor environments for occupants. Different research studies of post-occupancy evaluation of buildings' energy performance [3–9] have shown how occupants' behaviours have a huge influence over energy consumption in both domestic and non-residential buildings. In particular, Haas [3] and Filippin [4] stated that occupant behaviour affects energy use to the same extent as mechanical parameters. New automated controls and energy management systems could have great potential to improve individual comfort and reduce energy consumption. Nevertheless, their spread, along with the design strategy of controlling the most important features centrally in order to prevent users' actions, do not reduce energy consumption since the default setting could lead to considerable energy waste [10]. Furthermore, different studies [10–14] have stressed the importance of giving the occupants the opportunity to control directly the indoor environmental condition in order to set their own comfort level, in order to achieve high occupants' satisfaction. Because of this, occupants' interactions with building controls need to be taken into account when designing buildings. Behavioural patterns, based on measurements of real occupant behaviours, started to be implemented in building simulation programs in order to improve the outcome of simulation of building energy consumption [15–17]. In many papers [18–22], occupants' behaviour is analysed using stochastic models since they well reflect its intrinsic uncertainty. These papers have mainly investigated occupants' interactions with five control systems both in residential and office buildings: control of the thermal environment (heating and cooling), use of artificial lighting, habits of regulating shading devices, and operations over windows opening and closing. Models of the occupants' presence itself and the use of appliances have also been stochastically modelled based on observations. Artificial lighting is a matter of energy consumption and comfort in buildings. The annual global electricity consumption for lighting in buildings varies between 20 and 50 kWh/m^2 and, in particular, commercial buildings represent one of the main energy-consuming sectors: lighting accounts for 25% of the total energy consumed in the U.S. and 14% in EU [23]. The use of lighting has an impact on thermal energy loads (heating and cooling) and users' visual comfort. Many studies have been carried out regarding preferences and use of lighting systems in office buildings [15,24,25] but few behavioural models were developed and, subsequently, implemented in energy simulation software. The first study of manual switching actions of lighting systems, which resulted in a stochastic model, was carried out in English offices and schools by Hunt in 1979 [24]. He studied the occupants' interaction with lighting through the use of probit regression function and concluded that the probability of turning on the light at occupants' arrival is related to the daylight illuminance at the work plane. He underlined how peoples' behaviour was strictly related to their daily pattern. People switched on the lights when entering the office in the morning and switched them off during lunch break. After lunch, they turned on the lamp if the daylight levels fell below the ones in the morning but in any case occupants hardly switched the light on or off if they were in the office. On the other hand, the propensity to turn off the lights was strongly related with the length of absence from offices [25] and the tendency to rely on sensors to control lights was estimated to reduce the savings from the occupancy sensors by about 30%. Based on these previous studies, Reinhart developed in 2001 the most well-known and utilized model for predicting occupants' behaviour in relation to artificial lighting [15]. He evaluated a preliminary classification in users' types upon their attitudes towards the lighting system. In particular, he categorized users who paid more attention to the indoor lighting conditions and users who did not care about daylight and continually used artificial lighting. For the first group, he distinguished between the probability to turn on the light upon arrival in the office and during the occupants' stay in offices through the use of probit analysis. He depicted the probability to turn off the light in relation to the length of absence from the offices, as did Pigg [25].

This paper mainly focuses on factors influencing light-switching behaviour. The main goal of the paper was to investigate the possible drivers for users to switch lights on and off in office environments.

Visual performance and comfort were defined along with the parameters and characteristics that influence them. The main findings in literature on light-switching patterns are illustrated and behavioural models presented with particular attention to Reinhart's study [15].

2. Lighting Behaviour and Visual Comfort

Since the main purpose of the study was to investigate possible drivers for light switching, in the following the main influencing factors for people to adjust artificial light in indoor spaces with regard to visual comfort are described.

In general, lighting conditions in indoor environments are related to three separate aspects:

- sky light: refers to the diffuse light coming from the sky.
- sunlight: direct and reflected light from the sun.
- artificial light: electrical light to be used in order to reach a comfort level if natural light does not/cannot achieve it.

An adequate luminous environment should guarantee visual performance to users in terms of correct view, visual comfort, and safety. Generally, it is possible to cluster the variables that influence visual performances in relation to three main categories: occupant physiology, visual tasks, and indoor environment (physical quantities describing the amount of light and its distribution in space). In particular, visual comfort may be defined as "a subjective condition of visual well-being induced by the visual environment" [26]. Visual comfort has been commonly studied through the assessment of some factors characterizing the relationship between the human needs and the light environment, such as the amount of light, the uniformity of light, the quality of light in rendering colours, and the prediction of the risk of glare for occupants.

Visual comfort is also highly dependent on the task to be performed. Different lighting settings are required for working spaces, entertainment spaces, *etc.* [27]. Finally, indoor surfaces are also relevant: light is absorbed and reflected by room surfaces and this alteration of light will affect users' perceptions. Consequently, as stressed by Veitch [28] and Boyce [27], lighting quality cannot be expressed simply in terms of photometric measures, and it is not possible to determine a single, universally applicable recipe for good-quality lighting.

The main parameters that influence visual comfort and lighting quality are illustrated in the following paragraphs. The authors took into consideration both the physical environmental variables (translated primarily in photometric indicators) and then the psychological and physiological attributes derived from literature. To comprehend the dissertation and to contribute towards the final aim (identification of the drivers), the parameters were clustered considering the distinction between external and internal factors made by Schweiker [29], together with the five categories defined by Fabi *et al.* [30]. As defined in Schweiker *et al.* [29], external factors are those factors related to the building's science, like physics. In particular, indoor or outdoor physical variables (temperature, relative humidity, *etc.*) or factors related to the time of day or the building's characteristics are studied in this category. Internal factors are related to the field of social sciences, for example preference, attitudes, cultural background, and so on. Later, Fabi *et al.* [30] identified five main categories of drivers for occupants' interaction with the building and systems: environmental, contextual, psychological, physiological, and social. The main indicators both for design and for field measurements were also included. The authors chose to use the aforementioned indication to classify the variables that in literature appeared to be influencing the light-switching behaviour.

2.1. External Factors

2.1.1. Physical Environmental Factors

Sun and its position: direct sunlight contributes towards the indoor lighting environment and is often the main source of glare for occupants [31]. It also represents the day's progression and can be easily determined through the calculation of azimuth and sun elevation for any world location using geographic coordinates (latitude and longitude).

Daylight: the daylight level has a big influence over indoor luminous conditions; allowing the user agreeable and high-quality vision, the exploitation of natural light provides energy savings and provides the user with a visual relationship to the outside. In Frontczak *et al.* [32], daylight condition was rated as the most influential indoor environmental factor taken into consideration when arranging the comfort conditions at home, and "light" and "sun" were the most frequently used words used by the respondents to describe factors contributing to comfort. Daylight is generally evaluated as illuminance on the façade or illuminance on the window. It is measured in lux, which indicates the ratio between the luminous flow that affects the surface (window or façade) and the surface itself.

Lighting level: the lighting level inside a space is indicated mainly by illuminance. The amount of light over inner surfaces substantially affects visual performance: visibility could be denied for a lack as well as for an excess of illuminance. Different lux levels inside the space should be taken into account: the lux range suggested by standards and regulations has a minimum value of 20 lux, which allows the identification of surrounding people and objects, up to 5000 lux for specific tasks. In particular, the minimum illuminance level required in an office over the working plane is 500 lux for task such as writing, typing, and reading [33].

Daylight penetration: in design processes and for certification system requirements, this is measured through the evaluation of the average daylight factor, which represents the relationship between the indoor daylight illuminance and the corresponding outdoor illuminance without considering sunlight. It can be evaluated both statically and dynamically. Recently, several dynamic daylight performance metrics have been developed, such as daylight autonomy and useful daylight illuminances. In post-occupancy evaluations, the daylight level results are measured when no lighting system are operating. Illuminance should be measured in different points of the room: task plane, at the back of the room, or where the illuminance is thought to be lowest and/or highest. Field and research studies have shown that the illuminance range under which occupants are accustomed to working is very wide and still needs further investigation. A semi-directed interview conducted by Escuyer [34] showed that people working with computers preferred illumination levels between 100 and 300 lux. On the contrary, people working without them prefer illuminance levels between 300 and 600 lux. Moore [35] stated that occupants need a low illuminance level, while Begemann *et al.* [36] underlined that people added between 300 and1200 artificial lux to daylight in four offices oriented northwards in the Netherlands.

Illuminance uniformity: the overall illuminance in a space should not display high diversity, in particular between the illuminance at the task plane and the rest of the room. The lux level ratio is an indicator for illuminance uniformity: the international standard on lighting [33] stated that the minimum value divided by the mean should not be lower than 0.7 for the task area and 0.5 for the immediate surrounding zone, which is considered to be at least 50 cm around the task area. Illuminance uniformity is also needed for daylight: the illuminance on a window surface should not be much higher than that in the back section of the room. In the design phase, this criterion is measured using the daylight factor, considering the ratios between the minimum and maximum values in indoor space. In the operational phase, measurements could approximately evaluate illuminance uniformity through the ratio of various recorded illuminance values. Halonen and Lehtovaara [37] observed that some of the 20 people working in an office facing east in Finland increased the artificial light level at their desk even if the daylight level was increasing. They attributed this behaviour to the high ratio between the vertical illuminance available at the back of the room and the vertical illuminance near the windows.

Luminance contrasts and distributions: luminance is the ratio between luminous brightness emitted directly or indirectly by a surface and the surface itself related to a viewer's position and light direction. For this reason, luminance contrast represents an important parameter for visual perception. Every indoor surface illuminated by artificial appliances or by the sun will partly reflect the light. Luminance distribution influences the necessity of eye adaptation. However, the difficulty of evaluating it, both in design and in the operational phase, precludes its usage as driving factor. Since luminance contrast is strictly related to subject position, it is evaluated by a specific direction. Moreover, it is important to note that it is related to a more detailed project level (interior design).

Glare: this implies a reduction of visual ability when the environment fails in luminance parameters (too high a luminance contrast or not adequate distribution) due to a too-luminous object (surface reflecting or direct source). Glare due to the sun should be considered during the building's design phase. However, it is difficult to evaluate and shading factors should also be taken into account.

Indeed, Bülow-Hübe [38] concluded that glare or luminance contrast can possibly be adjusted through shading device adjustments.

Climate and sky conditions: weather conditions have a direct influence on the amount of daylight coming into a space. For this reason, dynamic simulation software is better at evaluating daylight amounts than static software packages since they at least partially take climate variations (reference year) into consideration. The level of illuminance outside is directly affected by the sky conditions and so is directly reported in this contextual variation. In a case study, Begemann [35] found that under a cloudy sky an average of 1000 lux of artificial light was added to daylight.

Other important factors that influence a person's visual comfort as well as their behaviour over lighting systems are the *light appearance* and *rendering capability*. These aspects need to be taken into account by designers in order to provide users with an adequate indoor lighting environment as established by the standards indicators, e.g., color rendering index and colour temperature. However, as with luminance contrast and distribution, they are related to a more detailed level of building design and it could be assumed that these do not have a high influence on switching actions.

2.1.2. Contextual Factors

Obstruction: The presence of other buildings or elements in front of a building can constitute shading, thereby reducing the penetration of daylight into the indoor space [31]. This context should be taken into account both when evaluating lighting conditions and analyzing measurements.

Time of day: this influences the presence or absence of daylight [31].

Building design: orientation, internal environment dimensions, and characteristics and dimensions of external openings are all parameters influencing the physical environmental indicators [31].

Shading devices: the transmission of daylight to the indoor environment depends strictly on the shading devices' position. In the design phase, shading and lighting systems should be strictly related. The design choice (fixed external elements or movable systems) affects the light performance differently during a building's operational life. Shadings actually represent a system that depends on occupant preferences and behaviour; even if many studies stressed the interaction between the two systems and the necessity of studying them together, there is still a lack of knowledge regarding users' control over daylight-linked lighting and shading in office buildings, as proposed in Galasiu and Veitch [39].

Position of the occupants' work plane and lighting control: The occupant's work plane with respect to the window influences his/her use of artificial lighting. Besides that, the position of the lighting control is also relevant. Light switches for ceiling lights are generally positioned near the entrance of a room. This factor might influence occupant actions over the lighting systems and could be one of the reasons why a high number of actions are made at the occupants' arrival, while during the intermediate period actions are mainly infrequent. Hunt [24] underlined that this seeming reluctance to switch lights on or off during occupied periods could be generated by occupants' reluctance to take action that might disturb or distract other occupants working in the same room.

2.2. Internal Factors

A study carried out by Begemann [36] on 170 subjects who had the possibility to adjust work plane illuminance, wall illuminance, and colour temperature over a wide range (illuminance range: 200–2000 lux, colour temperature: 2800–5000 K) at any time they wanted showed how the individual settings were different from person to person. Many of these parameters are typically related to the more detailed level of lighting design but some of them also affect switching actions. The internal factors are strictly related to the users. The categories under this section are: physiological, psychological, and social factors [30].

2.2.1. Physiological Factors

Visual acuity: the visual capacity is related to the modification of color and depth perception. It varies from person to person and is often related to age.

Gender: Laurentin [40] stated that generally a sex difference with regard to visual comfort exists, but actually women are more sensitive to thermal comfort while men are more sensitive to sky conditions and visual comfort.

2.2.2. Psychological Factors

Preference towards natural light: almost all respondents of a survey carried out by Cuttle [41] (99% of 471 office workers) answered affirming that offices should have windows and 86% of them prefer daylight to artificial light. People prefer daylight as it contributes towards comfort, pleasantness, and correct visual and color appearance [42].

Thermal comfort: Laurentin [40] noticed that when thermal conditions are not pleasant, lighting conditions are also considered unpleasant.

2.2.3. Social Reasons

Cultural level: regardless of individual importance, cultural level could influence people's attitude towards light.

Occupancy: Occupants cannot switch lights on/off if they are not present in the room. As a consequence, the probability of switching lights on should be 0 if the room is unoccupied. Moreover, the major social parameter investigated and found to be a driver for the blind usage behaviour is the presence of other people in the room. It is feasible to assume that this is also a driver for light-switching.

3. Understanding Switching Behaviour: Observing and Modeling

Electric lighting provides suitable indoor conditions for visibility and other occupant needs. The required illuminance levels vary with the user's activities, age, degree of fatigue, and cultural background. Looking at the variety of variables influencing visual comfort, natural questions arise: "which variables influence users' switching action over a lighting system?" "Which are the representative indicators already depicted in the literature by surveys and field measurements?" Several studies that observed occupants' manual switching actions over lighting systems have been carried out over the past decades.

They showed that in private or two-person offices occupants' behaviour related to lights is individual but not arbitrary. In this sense, even if light-switching thresholds vary within a group of subjects, individuals use their controls consciously and consistently. This observed consistency forms the theoretical basis for the formulation of user behavioural models. Field data further suggest that individual control is partly governed by a number of basic behavioural switching patterns, *i.e.*, quantitative correlations that relate user manipulations to external stimuli like temperature and lighting levels or arrival/departure at work.

Apart from this principal task of electric lighting, the act of switching on the lights can also be interpreted as a signal that the occupant is "at work and has not left for the day". This range of perceived roles of electric lighting can cause individuals to follow drastically different lighting control strategies. In the following, the major findings as well as stochastic models of occupants' switching actions over the lighting operational system are illustrated.

The first study of manual switching actions on lighting systems resulting in a stochastic model was carried out by Hunt in 1979 [24]. He collected data in English offices and schools through a system of time-lapse photography (with eight mini-intervals). Daylight levels were obtained from average hourly values of total and diffused horizontal illuminance measured at local meteorological stations. He depicted lighting status and user occupancy from pictures while the ambient sky conditions were synchronously recorded in the form of hourly means of diffuse and global irradiances. Analysing the occupancy patterns, he distinguished data from the intermittently and continuously occupied spaces. Hunt [24] firstly investigated the correlations between switching-on probability on arrival and the external luminance levels using a probit regression function, concluding that different room populations reacted in a similar way. For this reason, he inferred the daylight levels at the workplace from the horizontal external illuminance and gained a quantitative relation, concluding that occupants' interaction with lighting can be forecasted using the daylight illuminance at the workplace.

People's interaction with automated lighting control devices was investigated in 63 private offices in a Wisconsin university building by Pigg [25]. User occupancy and lighting status were registered for 11 months along with two surveys. The length of absence from offices was strongly related to the propensity to turn off the lights and people in offices with occupancy sensors were only about half as likely to turn off the lights when they left the room as they relied on the occupancy sensors to control the lights for them.

Boyce [43] collected for two weeks occupancy, lighting status, and desktop illuminance data from two open-plan offices in England. He investigated the statistical relation between desktop illuminance and switching actions. Data agreed with Hunt's prediction [24] since the numbers of switch-on actions increased with the reduction of illuminance. He concluded that the factors determining switch action were the availability of daylight, the level of occupancy (open space), the presence of direct sunlight, and the contextual aspect of workstation positions.

Begemann [36] monitored two offices in Eindhoven (the Netherlands) during a period extending over winter and summer. They found that one subject chose an average of 800 lux of artificial lighting independently of the daylight level. Furthermore, when blinds were retracted under clear sky conditions, the chosen artificial lighting level even increased to 2000 lux when daylight reached 2500 lux. The average at the workplace was 1900 lux. For Love [44], these discrepancies between his study and Hunt's [24] were often due to the absence of blinds: high artificial levels were chosen to reduce the large spatial brightness gradient within the room. In any case, this represents another driver of human actions: uniformity between illuminance coming from the outside and inner illuminance.

Love [44] investigated light-switching in two private offices with south- and north-facing orientations in Calgary (Canada) (1998). He measured occupancy, light status, and desktop luminance every 4 min for four months while the blinds were retracted during the whole measured period. Switching probability functions for the two offices were consistent with Hunt's outcomes for multi-occupant spaces [24]. He attributed the difference in the minimum illuminance threshold to interior factors.

The occupancy, dimming, and switching status of artificial lights together with venetian blinds' status were collected for eight weeks (December–March) in 58 private offices in Boulder (CO, USA) by Maniccia *et al.* (1999) [45]. The results highlighted that 74% of the subjects used the dimmer and a lower percentage turned off the lights entirely, suggesting that the majority of workers preferred to exploit daylight. Most blinds adjustments appeared in southern- and western-facing offices and the number of actions decreased with time of day, indicating that their main aim was to occlude direct sunlight.

Jennings [46] evaluated the potential energy savings of various lighting control strategies in a private office in San Francisco over a seven-month period. Diffuse and global irradiances were collected every 5 min, as well as the occupancy status, artificial light use, and the power used. The data revealed that for just eight of the 35 offices the total lighting period was shorter than the total occupied period, meaning that the majority of subjects left their lights on independently of the prevailing daylight situation.

Reinhart [15] studied the lighting behaviour in 10 southwest-facing offices in Weilheim, Germany. Users could only switch the system on or off, while the dimming system was automated. The internal and external variables, along with the status of electric lights and blinds, were collected from March to December 2000. They are listed as follows:

Indoor variables:

- Work place occupancy
- Work plane illuminances
- Indoor temperature

Behavioural variables:

- Status of artificial lighting
- Status of external blinds

Outdoor variables:

- Outdoor temperature
- Global horizontal irradiance
- Vertical illuminance in façade

He firstly observed that all users worked at least sometimes without lights being switched on (in contrast to Jennings [6]) and even if they had similar occupancy profiles, control strategies over artificial lighting were classified into two behavioural categories: people who constantly keep their light on and people who operate their lighting with respect to the indoor daylight levels. In order to verify that artificial lighting is mainly switched on at the beginning of a period of occupation [24], he grouped switch-on events into three classes:

- Switch-on at arrival: lighting switched on at the beginning of an occupation period;
- Intermediate switch-on: the artificial light was activated after 15 min of office occupation;
- No occupancy: switch-on was detected but the occupancy sensor did not detect user occupancy.

The probability of switch-on actions upon arrival in the 10 offices qualitatively fitted Hunt's correlation function [24]. The same procedure was used to infer intermediate switching-on actions. It displayed a step-like behaviour: 2% of actions occurred below 240 lux, while 0.5% occurred for higher illuminance levels. Concerning switch-off actions, only 60% took place on departure, while the remainder were made on arrival after a period of absence. He suggested that this behaviour was related to the artificial lighting typology: since it was an indirect light with a dimming function, occupants become unaware that the lights are activated and discover it when they come back from places with different lighting conditions.

Open-plan offices in four buildings were surveyed by Moore [35] and in 12 workstations the following variables were monitored every 15–20 min: the working plane's illuminance, luminary output, external illuminance, and switching actions. Lights were switched on by occupants upon arrival for work. Lighting levels remained unchanged during the day and lights were turned off when programmed to do so in the evening.

Lindelof and Morel [47] investigated intermediate light switching in 20 single or two-person offices of the Solar Energy and Building Physics laboratory at EPFL Lausanne, Switzerland. The following data were collected (mid-November 2002 to mid-January 2005):

Indoor variables:

- Air Temperature (°C);
- Interior illuminance (lux).

Outdoor variables:

- Air temperature (°C);
- Wind speed and direction (m/s);
- Diffuse irradiance (W/m^2);
- Global irradiance (W/m^2);
- Solar illuminance (lux).

Behavioural variables:

- Blind status;
- Occupancy;
- Window opening;
- Electric lighting (continuous dimming);
- Heating set point (°C).

The probability of actions (excluding simultaneous actions over both light and blinds) was inferred upon the illuminance considering a database with 5 min time-steps. The illuminance threshold (varying from user to user between 100 and 200 lux) identified probabilities of switching-on actions between 1% and 10%. Regarding the switch-off actions, no significant correlations were depicted due to a lack of action. User behavioural patterns suggested that the amount of time users tolerate visual discomfort before using manual controls should be correlated to the level of their discomfort. A user in a very dark or very bright room will act on the controls earlier than a user in a room whose visual environment is just at the discomfort threshold [45].

However, the relationship between this delay and the level of discomfort was not confirmed in this study.

Mahdavi [48] collected data in three office buildings in Austria: 13 scientific staff offices at a university, 29 single-occupancy offices in a high-rise office building for international organizations, and six offices in a government building. They observed users' control actions during working days in relation to both lighting and shading systems, considering and collecting the following parameters every 5 min:

Indoor variables:

- Air Temperature (°C);
- Relative Humidity (%);
- Illuminance level at workstation (lux).

Behavioural variables:

- Lighting status (on/off);
- Blinds status (0% = open, 100% = closed);
- Occupancy (present/absent).

Outdoor variables:

- Air temperature (°C);
- Relative humidity (%);
- Wind speed (m/s);
- Horizontal global irradiance (W/m^2);
- Vertical global irradiance (W/m^2).

The data were analysed with a linear regression analysis. Switch-on action was only upon arrival and it was found that only illuminance levels below 200 lux were likely to trigger actions at a non-random rate. Switch-off actions had a clear relationship with the subsequent duration of absence; occupants switch off lights more frequently if they are going to be away from the office for longer periods. Moreover, data collected in two buildings suggest an increase in the rate of intermediate switch-off actions due to higher levels of prevailing task illuminance levels.

The set-up and main results of the analyzed papers are summarized in following table (Table 1):

Table 1. Total number of actions over the ceiling lighting system.

Paper	Building Types	Measured Variables	Target Behaviour	Variables Found to Be Drivers for the Target Behaviour
Hunt D.R.G. (1979) [24]	3 medium-sized, multi-person offices; 2 school classrooms 2 open-plan teaching spaces (UK)	Lighting status User occupancy Desktop illuminance Daylight illuminance Diffused irradiance Global irradiance	Manual light switching	Desktop illuminance User arrival
Pigg *et al.* (2002) [25]	63 private offices Wisconsin (USA)	User occupancy Lighting status	Automated light system interactions	Absence duration
Boyce *et al.* (2006) [27]	2 open-plan offices (UK)	User occupancy Occupancy level (number of people) Lighting status Desktop illuminance Daylight illuminance Direct sunlight Room interior design	Manual light switching	Daylight illuminance Occupancy level (number of people) Avoidance of direct sunlight Room interior design
Begemann *et al.* (1997) [36]	2 offices (The Netherlands)	Daylight illuminance Desktop illuminance Sky condition Blind position	Preferred lux level	Daylight availability
Love J.A. (1998) [44]	2 private offices (Canada)	Office orientation User occupancy Lighting status Desktop illuminance	Manual light switching	Desktop illuminance
Maniccia *et al.* (1999) [45]	58 private offices Colorado (USA)	Dimming control usage Artificial light status Blinds adjustments Daylight illuminance	Dimming actions; Artificial light status Blinds status	Office orientation Avoidance of direct sunlight
Jennings *et al.* (1999) [46]	35 private offices California (USA)	Diffuse irradiance Global irradiance User occupancy Lighting switching Used power	Potential energy savings related to lights	User occupancy

Table 1. *Cont.*

Paper	Building Types	Measured Variables	Target Behaviour	Variables Found to Be Drivers for the Target Behaviour
Reinhart (2001) [15]	10 offices (Germany)	Office orientation Desktop illuminance Indoor temperature User occupancy Outdoor temperature Global irradiance Vertical illuminance in façade Lighting status Blinds position	Manual light switching	User arrival Desktop illuminance
Moore *et al.* (2003) [35]	12 offices	Desktop illuminance External illuminance Luminary output Lighting switching User occupancy	Manual light switching	User arrival User departure
Lindelof and Morel (2006) [47]	20 offices (single/two-person) (Switzerland)	Indoor temperature Outdoor temperature Diffuse irradiance Global irradiance Wind speed and direction Room illuminance User occupancy Window opening Blind position Electric lighting (continuous dimming) Heating set-point	Manual light switching	Room illuminance
Mahdavi *et al.* (2008) [48]	48 offices (Austria)	Indoor Temperature Indoor relative humidity Desktop illuminance Outdoor temperature Outdoor relative humidity Wind speed Horizontal and vertical global Irradiance Lighting status Blind status User occupancy	Manual light switching Manual blinds adjustments	Desktop illuminance Absence duration

4. Discussion

Researchers concluded that maintaining good comfort conditions relating to lighting for people is challenging, since the perception of glare and adequate light levels varies between individuals [35,39]. Previous studies highlighted a number of parameters, including low/high luminance level and glare presence, which are in compliance with user satisfaction assessment. Poor lighting conditions can produce discomfort. Glare in the room and an inadequate light level on task surfaces can create visual discomfort that may result in dissatisfaction, reduce accuracy in task performance, and increase the time required to complete tasks.

Field studies with automated lighting systems suggested that occupants frequently override these systems, either indicating discomfort or implying their desire for a tailored indoor climate [2,49]. It is clear from analysing previous studies that differences in building design (e.g., window size, orientation, thermal mass, *etc.*) and indoor environmental control characteristics should be considered when comparing results.

To investigate the drivers of interactions with the lighting system, a wide range of indoor variables have been monitored in various campaigns around the world. The previously displayed papers highlight the drivers included in Table 2.

Table 2. Driving forces for energy-related behaviour with respect to lighting.

		Switch ON		
Physiological	**Psychological**	**Social**	**Physical Environmental**	**Contextual**
	Individual attitudes	Occupancy level	Work plane illuminance	Room interior design
		User occupancy	Daylight illuminance	Office orientation
		User arrival	Direct sunlight	
		Switch OFF		
Physiological	**Psychological**	**Social**	**Physical Environmental**	**Contextual**
		Absence duration		Room interior design
		User departure		Office orientation

From the analysed studies it is clear that there is not a shared approach to the identification of driving forces for occupants' light-switching behaviour. In particular, it emerges that there is still a disagreement as to whether workplace illuminance is the best predictor when simulating the actions on artificial lights. Moreover, some parameters are not considered in any of the surveyed studies, like the relationship between physiological factors like occupants' age or gender and switching-on actions. Generally, physiological (gender or age) or psychological aspects are not investigated to the same degree as the physical drivers. Moreover, there are not yet studies on light-switching in residential buildings.

Most studies focus on determining the most important drivers and put little emphasis on the variables that do not show up as drivers. However, highlighting variables found to have little or no impact on occupants' lighting behaviour may help direct future research. Behind the parameters that are found to have an impact on occupant behaviour, Table 3 shows the variables that were included in the surveys but found not to be drivers. Unfortunately, the table is far from exhaustive because many papers only report the variables that have an impact on occupant behaviour.

Table 3. List of variables that have been found not to drive lighting behaviour.

Parameter	Driver Type	Source
Gender	Physiological	Begemann *et al.* (1997) [36]
Age	Physiological	Begemann *et al.* (1997) [36]
Season	Contextual	Begemann *et al.* (1997) [36]
Light sensor control	Contextual	Pigg *et al.* (2002) [25]
time spent in offices with the lights off	Contextual	Pigg *et al.* (2002) [25]

For switch-on actions, many studies have clustered occupants' behaviour. Love [44], Boyce [42], Jennings [46], and Reinhart [15] distinguished between users that take daylight level into account and switch on lights only if necessary and people who totally disregard natural light. This result is a fundamental driver for all switching actions. Office occupancy was often divided into arrival, intermediate, and departure stages, with a higher switching probability during the entrance or leaving of spaces, probably in relation to contextual variables: light switches were near to the door, people did not want to interrupt work, or others did not perceive lighting differences (Figure 1). From the analysed papers, absence time has emerged as the main driver for switch-off actions, while task-plane illuminance was the only environmental factor found to influence switching-on actions. Some considerations can be made in relation to the different switching actions.

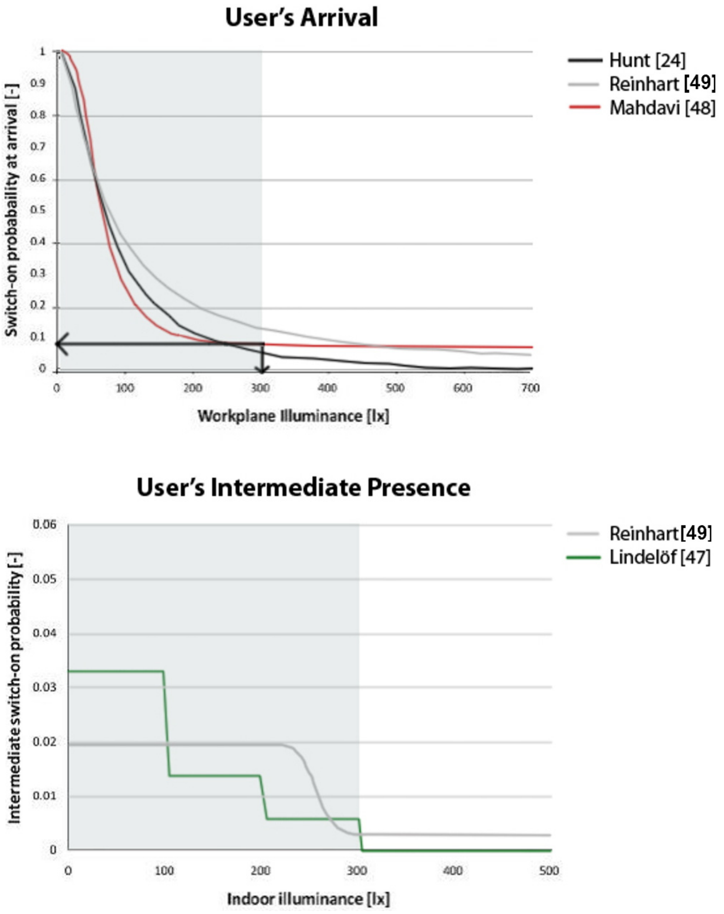

Figure 1. Comparison of probability functions of switching the lights on at users' arrival and intermediate presence, adapted from [49].

Switch-on: The analysed studies were carried on over samples of different sizes. Models of switch-on probability upon arrival were based on studies characterized by data from a small number of offices. This statement is not valid for the work carried out by Mahdavi [48], which considered 48 offices. In any case, the figure below displays how the illuminance level that constitutes the turning point for a switch-on probability is a bit lower, similar to a step function. Furthermore, it is interesting that Boyce's data are in accordance with Hunt's model [24] even though he collected measurements in open-plan offices, while the probability was inferred considering private or two-person offices. Begemann's study [36] underlined the important role that could be played by lighting uniformity in the indoor environment. Interior factors played an important role since individuals or people clusters were considered in almost all the studies. However, unfortunately, the majority of the subjects studied disregarded daylight conditions.

Switch-off: It is difficult to infer switch-off probability due to the fact that few actions were measured, proving that people are not used to turning off lights. It is noteworthy that the occupancy detector implies worse behaviours also. On the contrary, it is also significant that in Reinhart's field measurements almost half of the lights were turned off on arrival rather than when people left the office [15].

Moreover, previous studies discussed the importance of cultural and social factors in the study of human–building interactions, highlighting the need for more broadly distributed office behaviour monitoring campaigns. Statistically, a high number of field studies about occupant behaviour and the use of artificial light have been conducted in several European countries [24,27,36,38–40,43,47,48], while studies in the United States are rather limited [25,35,44–46].

Further studies are then required focusing on lighting control typologies and users' lighting behaviour. A research question could be the relationship between automated lighting control and users' interactions. For example, we might undertake an investigation of users' interaction between controlled roller shades and/or dimmable electric lights using different control typologies (including manual operation and overrides on automated operation) and what are the resulting shade positions and electric light levels. Another interesting question regards the preferred visual conditions in offices with different shading and lighting control setups.

With regards to visual comfort and satisfaction with the indoor environment, the effects of shading and lighting control setups should be investigated.

A next step would be to study the influence of various control system parameters as well as system performance indicators from a user experience perspective. These topics should be studied in future and validated with user field tests in different office lighting settings.

5. Conclusions

Interactions between occupants and lighting systems represent a field of research on occupant behaviour that needs further investigation. The main focus of this paper was to investigate the possible drivers for users to switch artificial lights on or off. Different possible drivers (influencing factors) that might induce human beings to act could be identified from an examination of previous studies, which directly observed occupants' behaviour regarding light in everyday office life. The probability of switching lighting systems on or off appears to be strictly related to what could be called the "moment of presence." Office occupancy was often divided into arrival, intermediate, and departure periods. The light-switching probability has been reported to be higher during the entering or the leaving time in relation to contextual variables. Furthermore, for the switch-on action, users were often clustered between those who take into account the daylight level and switch on the light only if necessary and people who totally disregard the natural lighting. This underlines the importance of how individuality is at the base of the definition of the different types of users. Even if daylight seems to influence to some extent the switch-off operation, absence duration was depicted as the main driver. However, it proved more difficult to infer switch-off probability due to correlations between explanatory variables. It was concluded that occupants were not as used to turning off lights as they are to turning them on.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Buildings Performance Institute Europe (BPIE). *Europe's Buildings under the Microscope: A Country-by-Country Review of the Energy Performance of Buildings*; Brussels, Belgium, 2011.
2. Bordass, W.; Cohen, R.; Standeven, M.; Leaman, A. Assessing building performance in use 3: Energy performance of the Probe buildings. *Build. Res. Inf.* **2001**, *29*, 114–128. [CrossRef]
3. Haas, R.; Auer, H.; Biermayr, P. The impact of consumer behaviour on residential energy demand for space heating. *Energy Build.* **1998**, *27*, 195–205. [CrossRef]
4. Filippin, C.; Flores Larsen, S.; Beascochea, A.; Lesino, G. Response of conventional and energy-saving buildins to design and human dependent factors. *Sol. Energy* **2005**, *78*, 455–470. [CrossRef]
5. Andersen, R.V. Occupant Behaviour with Regard to Control of the Indoor Environment. Ph.D. Thesis, Technical University of Denmark, Copenaghen, Denmark, 2009.
6. Gill, Z.M.; Tierney, M.J.; Pegg, I.M.; Allan, N. Low-energy dwellings: The contribution of behaviours to actual performance. *Build. Res. Inf.* **2010**, *38*, 491–508. [CrossRef]
7. Bahaj, A.S.; James, P.A.B. Future Energy Solutions. University of Southampton. Available online: http://www3.hants.gov.uk/fes.pdf (accessed on 4 February 2016).
8. Norford, L.K.; Socolow, R.H.; Hsieh, E.S.; Spadaro, G.V. Two-to-one discrepancy between measured and predicted performance of a "low-energy" office building: Insights from reconciliation based on the DOE-2 model. *Energy Build.* **1994**, *21*, 121–131. [CrossRef]
9. Menezes, A.C.; Cripps, A.; Bouchlaghem, D.; Buswell, R. Predicted *vs.* actual energy performance of non-domestic buildings: Using post-occupancy evaluation data to reduce the performance gap. *Appl. Energy* **2012**, *97*, 355–364.
10. Bordass, B.; Bromley, K.; Leaman, A. User and occupant controls in office buildings. In *International Conference on Building Design Technology and Occupant Well-being in Temperate Climates*; Sterling, E., Bevia, C., Collett, C., Eds.; Building Use Studies: Brussels, Belgium, 1993.
11. Paciuk, M. The Role of Personal Control of the Environment in Thermal Comfort and Satisfaction at the Workplace. Ph.D. Thesis, University of Wisconsin, Milwaukee, WI, USA, 1989.
12. Jensen, K.L.; Toftum, J.; Friis-Hansen, P. A Bayesian network approach to the evaluation of building design and its consequences for employee performance and operational costs. *Build. Environ.* **2009**, *44*, 456–462. [CrossRef]
13. Toftum, J.; Andersen, R.V.; Jensen, K.L. Occupant performance and building energy consumption with different philosophies of determining acceptable thermal conditions. *Build. Environ.* **2009**, *44*, 2009–2016. [CrossRef]
14. Wagner, A.; Gossauer, E.; Moosmann, C.; Gropp, Th.; Leonhart, R. Thermal comfort at workplace occupant satisfaction—Results of field studies in German low energy office buildings. *Energy Build.* **2007**, *39*, 758–769. [CrossRef]
15. Reinhart, C.F. Daylight Availability and Manual Lighting Control in Office Buildings—Simulation Studies and Analysis of Measurements. Ph.D. Thesis, University of Karlsruhe, Dusseldof, Germany, 2001.
16. Fabi, V.; Andersen, R.V.; Corgnati, S.P.; Olesen, B.W. A methodology for modelling energy-related human behaviour: Application to window opening behaviour in residential buildings. *Build. Simul.* **2013**, *6*, 415–427. [CrossRef]
17. Parys, W.; Dirk, S.; Hugo, H. Coupling of dynamic building simulation with stochastic modelling of occupant behaviour in offices—A review-based integrated methodology. *J. Build. Perform. Simul.* **2011**, *4*, 339–358. [CrossRef]
18. Nicol, J.F. Characterizing occupant behaviour in buildings: Towards a stochastic model of occupant use of windows, lights, blinds heaters and fans. In Proceedings of the 7th International IBPSA Conference, Rio de Janeiro, Brazil, 13–15 August 2001.
19. Nicol, J.F.; Humphreys, M.A. A stochastic approach to thermal comfort-occupant behaviour and energy use in buildings. *ASHRAE Trans.* **2004**, *110*, 554–568.
20. Rijal, H.B.; Tuohy, P.; Humphreys, M.A.; Nicol, J.F. Using results from field surveys to predict the effect of open windows on thermal comfort and energy use in buildings. *Energy Build.* **2007**, *39*, 823–836. [CrossRef]
21. Haldi, F.; Robinson, D. On the behaviour and adaption of office occupants. *Build. Environ.* **2008**, *43*, 2163–2177. [CrossRef]

22. Yun, J.Y.; Steemers, K. Time-dependent occupant behaviour models of window control in summer. *Build. Environ.* **2008**, *43*, 1471–1482. [CrossRef]
23. International Energy Agency. *Guidebook on Energy Efficient Electric Lighting for Buildings in Annex 45—Energy Efficient Electric Lighting for Buildings*; Aalto University School of Science and Technology: Espoo, Finland, 2010.
24. Hunt, D.R.G. The Use of Artificial Lighting in Relation to Daylight Levels and Occupancy. *Build. Environ.* **1979**, *14*, 21–33. [CrossRef]
25. Pigg, S.; Eilers, M.; Reed, J. Behavioural aspects of lighting and occupancy sensors in private offices: A case study of a university building. In Proceedings of the 1996 ACEEE Summer Study on Energy Efficiency in Buildings, Pacific Grove, CA, USA, 25–31 August 1996.
26. *EN 12665 Light and Lighting—Basic Terms and Criteria for Specifying Lighting Requirements*; European Committee for Standardization: Brussels, Belgium, 2011.
27. Boyce, P.R.; Veitch, J.A.; Newsham, G.R.; Jones, C.C.; Heerwagen, J.; Myer, M.; Hunter, C.M. Occupant use of switching and dimming controls in offices. *Light. Res. Technol.* **2006**, *38*, 358–378. [CrossRef]
28. Veitch, J.A. Psychological processes influencing lighting quality. *J. Illum. Eng. Soc.* **2001**, *30*, 124–140. [CrossRef]
29. Schweiker, M.; Shukuya, M. Comparison of theoretical and statistical models of air-conditioning-usage behaviour in a residential setting under Japanese climatic conditions. *Build. Environ.* **2009**, *44*, 2137–2149. [CrossRef]
30. Fabi, V.; Andersen, R.K.; Corgnati, S.P.; Olesen, B.W. Occupants' window opening behaviour: A literature review of factors influencing occupant behaviour and model. *Build. Environ.* **2012**, *58*, 188–198. [CrossRef]
31. Fabi, V.; Andersen, R.V.; Corgnati, S.P.; Filippi, M.; Olesen, B.W. Effect of occupant behaviour related influencing factors on final energy end uses in buildings. In Proceedings of the Climamed 11 Conference, Madrid, Spain, 2–3 June 2011.
32. Frontczak, M.; Andersen, R.V.; Wargocki, P. Questionnaire survey on factors influencing comfort with indoor environmental quality in Danish housing. *Build. Environ.* **2012**, *50*, 56–64. [CrossRef]
33. *EN 12464-1 Light and Lighting—The Lighting of Workplaces*; European Committee for Standardization: Brussels, Belgium, 2011.
34. Escuyer, S.; Fontoynont, M. Testing *in situ* of automatic ambient lighting plus manually controlled task lighting: Office occupants reactions. In Proceedings of the 9th European Lighting Conference (Lux Europa), Reykjavik, Iceland, 18–20 June 2001.
35. Moore, T.; Carter, D.J.; Slater, A.I. Long-term patterns of use of occupant controlled office lighting. *Light. Res. Technol.* **2003**, *35*, 43–59. [CrossRef]
36. Begemann, S.H.A.; Van den Beld, G.; Tenner, J.A.D. Daylight, artificial light and people in an office environment, overview of visual and biological responses. *Ind. Ergon.* **1997**, *20*, 231–239. [CrossRef]
37. Halonen, L.; Lehtovaara, J. Need of individual control to improve daylight utilization and user satisfaction in integrated lighting systems. In Proceedings of the 23rd Session of the CIE, New Delhi, India, 1–8 November 1995; CIE: Vienna, Austria, 1995; pp. 200–203.
38. Bülow-Hübe, H. Energy-Efficient Window Systems. Effects on Energy Use and Daylight in Buildings. Ph.D. Thesis, Lund University, Lund, Sweden, 2001.
39. Galasiu, A.D.; Veitch, J.A. Occupant preferences and satisfaction with the luminous environment and control systems in daylit offices: A literature review. *Energy Build.* **2006**, *38*, 728–742. [CrossRef]
40. Laurentin, C.; Berrutto, V.; Fontoynont, M. Effect of thermal conditions and light source type on visual comfort appraisal. *Light. Res. Technol.* **2000**, *32*, 223–233. [CrossRef]
41. Cuttle, C. People and windows in workplaces. In Proceedings of the People and Physical Environment Research Conference, Wellington, New Zealand, 8–11 June 1983.
42. Heerwagen, J.H.; Heerwagen, D.R. Lighting and psychological comfort. *Light. Des. Appl.* **1986**, *16*, 47–51.
43. Boyce, P.R. Observations of manual switching of lighting. *Light. Res. Technol.* **1980**, *12*, 195–205. [CrossRef]
44. Love, J.A. Manual switching patterns observed in private offices. *Light. Res. Technol.* **1998**, *30*, 45–50. [CrossRef]
45. Maniccia, D.; Rutledge, B.; Rea, M.S.; Morrow, W. Occupant use of manual lighting controls in private office. *J. Illum. Eng. Soc.* **1999**, *28*, 42–56. [CrossRef]

46. Jennings, J.; Rubinstein, F.; Di Bartolomeo, D.; Blanc, S. Comparison of control options in private offices in an advanced lighting control testbed. In Proceedings of the IESNA 1999 Annual Conference, New Orleans, LA, USA, 10–12 August 1999.
47. Lindelof, D.; Morel, N. A field investigation of the intermediate light switching by users. *Energy Build.* **2006**, *38*, 790–801. [CrossRef]
48. Mahdavi, A.; Mohammadi, A.; Kabir, E.; Lambeva, L. Occupants' operation of lighting and shading systems in office buildings. *J. Build. Perform. Simul.* **2008**, *1*, 57–65. [CrossRef]
49. Reinhart, C.F.; Voss, K. Monitoring manual control of electric lighting and blinds. *Light. Res. Technol.* **2003**, *35*, 243–260. [CrossRef]