Lighting preference profiles of users in an open office environment

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Lighting preference profiles of users in an open office environment

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ABSTRACT

Offices are transforming into multi-user, open space environments to stimulate interaction between people and optimize the usage of space. Due to design practices, lighting systems in these multi-user environments are implemented as a regular grid of luminaires that often does not match the furniture layout. Consequently, purely personal control over general lighting is not achievable in most cases. As a result, a single luminaire affects several neighbouring desks, creating shared lighting controls and conditions. Therefore, providing satisfying lighting conditions to everyone becomes a challenge. This paper proposes a first method for modelling lighting preference profiles of users based on their control behaviour and preference information. Based on objective measurements and subjective data obtained in two field studies, users can be profiled based on their control behaviour, regarding characteristics as activeness, dominance, lighting tolerance, and dimming level preference. The results show significant differences between lighting preference profiles of users. This paper also proposes a first method for discovering and triggering submissive users to express their preferences in order to derive their profiles as accurate as possible. This will help to secure users’ comfort by offering satisfying lighting conditions to their preference. By knowing the lighting preference profiles of users, the probability of conflict between users can be predicted and minimized.

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1. Introduction

Offices in modern, commercial buildings are rapidly transforming into multi-user environments that stimulate a collaborative way of working. Closed offices are converted into open offices, low partitioned spaces, or flex environments where users do not have assigned workplaces. Furthermore, the Gensler model, envisioned to enhance user satisfaction and productivity by offering activity based workplaces is gaining in popularity [1]. Employees make transitions more often between work modes at their desks and between locations compared to traditional ways of working [2,3,4]. Standards provide lighting recommendations to ensure a comfortably lit office environment [5,6], but they do not take into account that lighting requirements between neighbouring users might differ due to their mood, activity, or preference. Providing everyone with satisfying lighting conditions becomes a challenge.

1.1. Benefits of personal lighting control

Several studies showed that lighting preferences of people differ significantly. In a windowless open-plan office with cubicle workstations, Veitch and Newsham [7] evaluated the preferred lighting conditions of 94 participants when performing office tasks. The study showed that the range of the individual lighting preferences, corresponding to the horizontal illuminance, was between 83 and 725 lx. In another laboratory study of Newsham and colleagues [8], participants worked in a mock-up office for one day. They had no control over lighting until the latter half of the afternoon. Participants chose desktop illuminances ranging from 116 lx up to the maximum achievable 1478 lx. In the laboratory study performed by Boyle et al. [9] in windowless offices, 18 participants were offered controllers to dim the light output of the luminaires in a large control range (12–1240 lx), or a small control range (7–680 lx). The study showed that for the same task, individuals chose different illuminance levels. The median workstation illuminance chosen ranged from 110 to 1230 lx for the larger and from 80 to 630 lx for the smaller control range. In a later performed study by Boyle et al. [10], 57 temporary office workers spent a day in an office with the freedom to adjust the lighting of the cubicles they occupied.
A longitudinal field study of Moore et al. [11] included 45 office workers in 4 different buildings in UK, where occupants were able to vary the illuminance on their workplace. The study showed that the mean daily workplace illuminance was 288 lx, with individual averages ranging from 91 lx to 770 lx.

Besides the varying horizontal illuminances, the different facilities in which the experiments were conducted also resulted in varying luminance distributions. The luminance distributions are linked to the brightness perception, and will influence the preference of users. The horizontal illuminance is used as an indicator for the given dimming level of the luminaire, which creates the individually preferred luminance distribution for a given situation. Due to the broad range of individual lighting preferences, it is a challenge to create satisfactory lighting conditions in a multi-user space by providing fixed lighting conditions to all users. With a fixed illuminance level installation, Boyce and colleagues demonstrated that the maximum amount of occupants that would be within 100 lx of their preferred illuminance is only around 65% [10]. This percentage can be increased by providing personal lighting control for office users.

Benefits of personal control are not limited to satisfaction of individual illuminance preferences. Studies have shown that when users can adjust the illuminance level on their desks, it has a positive effect on their satisfaction with the environmental conditions [8,12–19], with lighting quantity and quality [20], mood, improved motivation and vigilance [21], and indirect positive effects on their productivity [8,20,22]. Besides, occupants who have more opportunities to adapt their environments to their own needs will less likely experience discomfort [22]. On the contrary, having a workspace without some degree of control over the environment, leads to increased discomfort and stress [23]. Therefore, personal control for office lighting is believed to enhance users’ satisfaction and comfort in modern office buildings.

1.2. Challenges in open office environments

Due to the design practice for office lighting systems, multi-user environments are commonly deployed with a regular grid of luminaires that often does not match the furniture layout. Subsequently, in most open office spaces it is impossible to offer desk specific lighting when only using the ceiling mounted general lighting system. A single luminaire would in many cases influence several neighbouring desks, thus the lighting conditions as well as the lighting controls have a shared nature and are referred to as consensus control. The common practice in such cases is to combine luminaires into control groups, such that all luminaires in one control group act as one. Multiple users get shared control over a group of luminaires affecting their desks. Analyses of 14 open-plan offices by Moore et al. showed that occupants become increasingly reluctant to make changes to the lighting as control groups become larger [24]. The researchers suggested that the control group size should be the smallest possible, to enhance user satisfaction and maximize the benefits of lighting control, while equally empowering users. The follow-up study [19] showed that even when sharing controls, the majority of users experienced the benefit of having controls. Satisfaction with lighting quality and quantity was rated higher than in situations without control. In a field study evaluating personal control in an open office space [25], similar results for improved lighting quality and quantity were demonstrated. However, a small portion of the users did indicate to have experienced difficulties in finding consensus with colleagues in the same control group, due to opposing lighting preferences. When asked to express a preference at the end of the study, 10 out of 14 users opted for shared controls, one preferred a situation without controls, and 3 did not express a preference.

The difficulties in finding consensus might be caused by differences in individual preferences for lighting as shown in the previously mentioned studies [7–11]. In interviews, users who participated in the performed preference study [25] indicated preferences ranging from bright light, which made them feel more energized to dimmed light, which was more relaxing for their eyes. A group of people indicated not to have a specific preference beyond being able to perform a visual task. Some indicated not to be critical towards a light level, and some indicated to more quickly experience discomfort glare than their colleagues. Influenced by the users’ character and sensitivity to light, a difference might exist in how critical users are in their selection of preferred lighting. User data logs of the light controls demonstrated different ranges of illuminances that users accepted without initiating a change. Some users showed a broad range of selected illuminance dimming levels, while others demonstrated more invariable choices. Similar to what was shown in the study of O’Brien and Gunay [22], a conflict avoiding behaviour was observed in the study of Chraibi et al. [25]. O’Brien and Gunay showed that people are profoundly affected by the presence of others to take actions that might cause discomfort to colleagues. People have different personalities which can also influence how they interact with their environment in the office. Some people might be more dominant or vocal and feel less hesitation to express their preferences, while others might show a more conflict avoiding behaviour.

1.3. Research motivation

Personal characteristics are believed to have an influence on users’ preferred and selected lighting, when given a choice. A number of studies evaluated occupants’ lighting preference and the effect of their personality on interaction with lighting systems [26,27]. Newsham et al. [28] showed that there is a great variation within individuals around their preferred illuminance values, and many participants chose illuminances that differ by more than 25–50% at various times of the day. Boyce and colleagues [9] also showed that there is a large difference between different occupants regarding their control behaviour. Some people adjust illuminance levels a little, while others adjust illuminance levels over the whole range available. The frequency of adaptive measures significantly decreases in shared offices compared to private offices, due to occupants’ timidity to take adaptive actions that would potentially disrupt the comfort of others [22]. People who experience conflict have decreased satisfaction with lighting quality and are more likely to avoid using controls than those who do not experience conflict [29]. This study of Moore and colleagues also showed that stronger personalities dominate in conflict situations.

This paper presents insights gained from analysing light preference data of the users, obtained in two field studies. The authors show that users can be profiled based on their light preference and control behaviour in the following ways:

- **Activeness** – The level of activity of each user can be determined based on the number of user control actions. The user’s control actions are a good basis to derive the user’s preference profile. Having only a few control actions of a user, makes derivation of the user’s profile difficult.
- **Tolerance** – A tolerant user will select a broad range of illuminances meaning that he can work under a larger variety of lighting conditions. Contrarily, an intolerant user will demonstrate a more consistent preference for illuminance levels. When weighing users’ light preference profiles to offer satisfying lighting to multiple users, the tolerance of the users should be taken into account. The preference of an intolerant user asks for
a higher weight, meaning that the proposed illuminance level should be shifted towards the light preference profile of the intolerant user. Users with a high tolerance will less likely experience conflict.

- **Dominance** — Dominance is observed via the correlation between a particular user preferred illuminance level and the prevailing luminaire output in that zone. The dominance of a user is determined as a fraction of time the luminaire output matched the illuminance level set by that user. If the output of the luminaire is set according to the user’s preference for most of the time, the user is dominant in that control zone. Submissive (non-dominant) users are intimidated by others and manifest conflict avoiding behaviour, resulting in not changing the illuminance level even when dissatisfied.

- **Preference** — The dimming level preference of a user is the control setting that is most comfortable for that user, leading to the highest user’s satisfaction with lighting conditions. Having opposing lighting preferences in one control zone might introduce dissatisfaction of the users and pose a risk of conflict.

The authors hypothesize that intolerant users will be more active to achieve their preferred lighting, unless they are submissive in relation to their neighbours in the same luminaire control zone. In those cases the risk of dissatisfaction is high. Tolerant users, who will prefer a broad range of selected illuminance levels, are expected to be less active in their lighting control behaviour, and will have a lower risk of dissatisfaction. Furthermore, submissive users are assumed to be in general less active than dominant due to their conflict avoiding character.

Based on the lighting preference profiles of the users occupying a control zone and the zone luminaire output, the control zones can be classified. Knowledge of the control zone classification is required to automatically evaluate and, via appropriate control actions, to subsequently enhance users’ satisfaction with the lighting conditions in that zone. This knowledge also allows the prediction of potential conflict between users in the same control zone and to facilitate the process of making consensus choices in order to improve overall user satisfaction.

This paper proposes a first method for modelling lighting preference profiles of users and classification of control zones based on users’ control behaviour to offer satisfying lighting to a group of users. It investigates cases that require additional feedback from the users to secure or enhance users’ comfort by offering satisfactory lighting conditions.

## 2. Methodology

In 2013 and 2014 two field studies have been conducted in an open plan office to evaluate whether benefits of personal control would still be observed when applied as consensus control in an open office environment [25]. In these studies, objective and subjective data was collected concerning the lighting environment experienced and the usage of the individual light control devices. This paper describes the second phase, in which the data obtained in 2013 (*study 1*) and 2014 (*study 2*) was used to explore different lighting preference profiles of users. The test-bed installation was set up in an office building located in the Netherlands. Both studies were conducted as field studies in order to explore and validate user benefits of using lighting controls in a realistic setting. A longitudinal design allowed social dynamics to evolve during the course of the studies. The following sections provide essential details of the test-bed implementation and study design of the two conducted studies.

### 2.1. Test bed

Fig. 1 shows a schematic representation of the test-bed office. The test-bed was located in an open office on the 4th floor, with a south facing façade. The façade consisted of four segments of 2.5 m high and 3.2 m wide windows. For daylight and direct sunlight management, the test bed provided motorized internal as well as external blinds. The external blinds could be set to manual or automatic control mode, and the internal blinds could only be controlled manually. The internal as well as the external blinds were divided in four controllable segments mapped to the windows, with windowsill mounted control interfaces per segment. The interfaces for the segments were for general use and the control means for the blinds did not change during the test. The external blinds are lowered automatically if the rooftop light sensors detect illuminances higher than 16 klx and raised at fixed times (21:00) or with wind speed exceeding 30 km/h. The external blinds were operated in both modes, but it has been observed that they were mainly operated manually throughout both studies, primarily by the participants adjacent to the windows. The participants worked in their normal office environment. There were no instructions or other mentions of the (manual) blind control in order to ensure that all participants keep interacting with the space the same way they normally would.

As in most open office spaces, due to the office layout and the predefined grid of luminaires, it was impossible to offer truly personal control over a luminaire to each user. In order to give the participants an equal sense of control, luminaires were combined into control zones, such that one control zone would be offered to the smallest possible number of users as suggested in Ref. [24]. This resulted in combining two luminaires per zone, shown as green rectangles in Fig. 1, leading to a total of 6 control zones with 2–3 users per zone. This way, the control of lighting is not personal, but labelled as consensus control.

To implement the test-bed, an existing lighting installation with 16 T5 49 W lamps, was modified in accordance with the study requirements. All 16 lamps were equipped with DALI high frequency dimmable ballasts (Philips TD 1 285/49/54 TLS E.), to allow dimming of the luminaires in the 6 control zones. The 12 central luminaires were controllable by user interfaces. The outer 4 luminaires adjacent to the walls were held in a fixed light output to maintain sufficient and uniform wall luminance. This was done to avoid sharp contrasts on the walls that could result from daylight entering the office, since sharp contrasts were shown to negatively influence the overall space appraisal [30]. Combined light and occupancy sensors (Philips PLOS-CM-KNX) were mounted on the ceiling next to each of the 12 central luminaires. The lighting in the entire space was switched based on occupancy controls. When the first person entered the office, all lights turned on. After the last person left the office, all lights turned off with a set time delay of 30 min. In both studies participants were offered personal user interfaces to control the lighting of their zone. The personal user interfaces are further explained in Section 2.2.

### 2.2. Study design

The analysis of this paper is based on data of the study conditions in which the participants were offered lighting controls, commissioned with a “memorizing” system behaviour (October 21st until November 29th 2013 and October 27th until November 14th 2014). During the “memorizing” personal control condition the default dimming level of the 12 controllable luminaires was set to 60% at the start of both studies. This created an average desk illuminance of 300 lx by artificial lighting with the ability to be changed by each participant. Escuyer [31] showed that in presence...
of daylight, users who worked behind computer screens preferred illuminance levels between 100 and 300 lx. Moore’s study [24] showed that the higher the percentage of time office users spent behind a computer screen, the lower the selected desk illuminance was recorded, being on average 300 lx. The results of a study performed by Reinhart and Voss [32] showed that the probability of manually switching on lights decreased below 0.1 when 300 lx was offered to the users. In accordance with these findings and provided that the participants spent most of their time on screen based tasks, the default desk illuminance was set to 300 lx. Participants could change the artificial lighting control group in a range from off to full luminaire output (leading to an average desk illuminance of 500 lx). The luminaires within every control group stayed at the previously set dimming level until the next control action was performed. The dimming level could be overwritten by every user in a zone, at any point in time. After a change was made, the user interface was updated to present the current dimming level of the control group. At the end of each day, the last user selected dimming level was memorized by the system and restored in the zone upon detection of presence the next day.

Besides the “memorizing” user-control condition, study 1 also included a reference condition, in which the participants did not have lighting control. The reference condition of study 1 was designed at the start of the study (August 5th till October 11th), and repeater at the end of the study (December 2nd till December 20th). During the reference condition, all luminaires were set at 100% output delivering an average illuminance of 500 lx on the desk surface, excluding the daylight contribution. In study 2, besides the reference and “memorizing” user control condition, three additional conditions with different control strategies were explored and evaluated. Study 2 started with the reference condition similar to the reference of study 1 (July 28th till August 22nd). This was followed by a second static condition (September 1st till September 19th), where all luminaires were set to deliver an average illuminance of 300 lx on the desk surface, excluding the daylight contribution. Besides the “memorizing” user-control conditions, a “forgetting” user-control condition (Sep 29th October 17th) was experienced, where the user set dimming level was reset on a daily basis. The study was ended with a “set-point controlled” user-control condition (November 24th till December 12th), where the users’ control actions adjusted the set point of the daylight harvesting system. In between conditions, “transition weeks” were designed in the protocol, as also shown in Fig. 2.

Fig. 2 shows the complete study timelines together with the periods of the study protocol included in this analysis.

In study 1 each participant had a widget installed on their PC as
as an iPod Touch device on their desk, both running a light control application (Fig. 3a). The application visualized a slider to control zone lighting from 1% to 100% of the maximal luminaire output, and a button to turn lights off. In study 2 participants received an iPod Touch device with a comparable light control application, to control zone lighting from 1% to 100% of the maximal luminaire output (Fig. 3b). Incorporating the usability feedback of study 1, the user interface was updated for study 2, leaving out the “off” button. The perceptible step between the lowest dimming level of the luminaire group and the off-state was perceived as too large. This did not meet preferred lighting conditions of individuals. Users also felt resistance to initiate well perceivable light changes or to create “dark” ceiling spots, believing that their co-workers would not appreciate this. Due to the limited use, the button was not included in the updated controller of study 2.

### Measurements

The objective measures consisted of data logging from the luminaires and the user interfaces. During both studies log files were created of the light output of the luminaires (logged every 1 min). These are translated into logs of the relative light output, where 100% represents an average desk illuminance of 500 lx from electric lighting, excluding the daylight contribution. The relative light output of the luminaire will be further referred to as the dimming level. Log files of the user actions consisted of the user-selected dimming level, ranging from 0 to 100% in study 1 and 1–100% in study 2. The first week of user-control, labelled as ‘transition week’ in Fig. 2, has been excluded from the analyses due to a novelty effect. During the ‘transition week’ users experimented with controls much more, resulting in a deviation in the behaviour with the controls compared to the rest of the user-control condition. User
actions were initiated by the users themselves, thus no predefined logging rate existed. Actions were logged at the moment they took place. Since users often performed several actions per minute while trying to find the appropriate lighting conditions, actions within a time window of 5 min were filtered out. The assumption is made that only the last user action represents the preferred illuminance. Only these last actions are included as meaningful data points for further processing.

The subjective data used for the analyses described in this paper has been collected via online surveys and interviews. During the entire length of both field studies, users filled in surveys on a weekly basis. Survey questions were presented in English with a Dutch translation underneath each item. In the survey questions regarding the perceived light quantity and the frequency and degree of conflict, due to the use of the shared lighting controls, were adopted from Ref. [29]. The participants were asked to evaluate the light quantity from the artificial lighting on their desk on a 7-point scale, ranging from ‘too little’ to ‘too much’. Besides using the scale to analyse whether lighting was experienced as brighter or darker than preferred, the assessment of light quantity is recoded into 4 rather than 7 steps, allowing for an overall assessment of dissatisfaction with the quantity of light. This approach was chosen in alignment with the one of Moore and colleagues [19]. Here the extremes of ‘too little’ and ‘too much’ are translated into ‘very dissatisfied’, the ‘just right’, middle point into ‘satisfied’, and the steps in between into ‘somewhat dissatisfied’ and ‘dissatisfied’. At the end of each experimental period, after 3 or 4 weeks (see Fig. 2), an interview between each participant and one of the researchers allowed for further elaboration on what was captured in the surveys. All interviews in both studies were conducted by three researchers. Each participant was interviewed by at least two different researchers during the study to avoid limiting the data to the perspective of only one researcher. Interviews delivered complementary qualitative information used to understand the data and the obtained results. In the interviews participants were implicitly asked to describe their lighting preference relative to their colleagues. Subjective data collected in the interviews is found relevant to the preference profiles, and is included in this publication. Other findings of the interviews and surveys are published separately [25].

2.4. Participants

The number of participants in the study was limited to the capacity of the test bed. In study 1 a group of 14 administrative workers was relocated to the test-bed for the study duration. The participants were offered fixed workplaces in the open plan office with 14 desks (Fig. 1). The participants ranged from 30 to 65 years of age (mean = 48.6, SD = 9.49), and consisted of 3 females and 11 males. They worked on their actual job tasks while experiencing the study conditions. As part of the inclusion criteria, participants were present in the office during the majority of their work time. For this experiment this amounted to at least 3 days a week and at least 4 h a day. Most of the participants worked 8 h a day, excluding lunch breaks. Working hours varied between 7.30 a.m. and 6 p.m. The participants were naïve regarding lighting knowledge, and they were at the same corporate hierarchical level. All participants were Dutch speaking (as a first or second language) and had good English reading and speaking skills, therefore they had no linguistic barriers for interaction.

Due to relocation of organizational departments, in study 2 a second group of office workers was allocated to the test-bed, which had 16 workplaces (Fig. 1) at the time of study 2. Fourteen subjects participated in the study, and all had a fixed desk position. The remaining 2 desks, located in zone 4, were used by employees with limited presence. These users did not participate in surveys or interviews, but were provided with a device for light control. Prior to the study, most group members did not share an office together or have worked in an open office. The group included participants ranging from students to senior employees, but none of the participants had their organizational superior in the subject group, in order to rule out possible conflict avoiding behaviour arising from such a situation. Participants of study 2 ranged from 25 to 65 years of age (mean = 44.3, SD = 11.58), and consisted of 1 female and 13 males. Similar to study 1, the participants in study 2 maintained their working habits and conducted their office tasks as usual while experiencing the study conditions. The participants had no lighting or perception domain knowledge. Thirteen participants were Dutch speaking (as a first or second language). All participants had good English reading and speaking skills.

In both studies, the study design and objective were not shared with the participants beforehand. They were informed to be part of an evaluation regarding their experience in the open office, and would receive study details afterwards, to avoid subject bias. Participants were briefed about the lighting control option at the moment they received the user interface. As discussed in Section 2.2, prior to the user-control condition, participants experienced a reference study condition without user control over lighting. During this baseline period, the participants (n = 28) could get used to the office and their neighbouring colleagues, before the lighting control was introduced. Prior to the study, the participants were only acquainted with the control possibilities of the external blinds.

2.5. Clustering

For tolerance and dimming level preference the number of classes is unknown. Therefore, classification of users regarding these features is done by unsupervised learning. The task of unsupervised learning is to infer classes by properly describing a hidden structure of unlabelled data. For this task, the K-means clustering algorithm is used [33].

Suppose a given data set \( \{x_1, \ldots, x_N\} \) consisting of \( N \) observations that are \( D \)-dimensional. The K-means algorithm will partition the data into \( K \) number of clusters such that their inter-point distances within a cluster are small compared to distances to points outside the cluster. The \( \mu_k \), where \( k = 1, \ldots, K \), are \( D \)-dimensional vectors, representing the centres of the clusters. The goal is to find an assignment of each data point to clusters, as well as a set of vectors \( \{\mu_k\} \), such that the sum of squares of the distances of each data point to its closest vector \( \mu_k \) is minimal. The formal mathematical representation of the K-means algorithm is given in Ref. [34].

To validate and interpret the consistency within each cluster of data, the silhouette criterion, introduced by Rousseeuw [35] is used. A silhouette is a measure representing how similar a data point is to its own cluster compared to other clusters. The main advantage of the silhouette criterion is that it does not assume that class labels are available, since, in this analysis, labels of users regarding tolerance and preference are unknown a priori. A silhouette value of the \( i \)th point \( S_i \) is given as

\[
S_i = \frac{b_i - a_i}{\max(a_i, b_i)}
\]

where \( a_i \) is the average distance from the \( i \)th point to the other points in the same cluster as \( i \), while \( b_i \) is the minimum average distance from the \( i \)th point to points in a different cluster, minimized over clusters. The silhouette value ranges from \(-1\) to \(1\), where high values indicate that a data point is matched well with its own cluster and poorly to neighbouring clusters. When \( S_i \) is
large, having a value close to 1, it implies that within cluster dissimilarity \( a_i \) is much smaller than the smallest between cluster dissimilarity \( b_i \). Therefore, the \( j \)th point is well-clustered and it is assigned to the appropriate cluster. A different case is when \( S_j \) is close to zero. In that case, \( a_i \) and \( b_i \) are approximately equal and it is not clear whether the \( j \)th point should be assigned to either of the two clusters, since the \( j \)th point lies equally far from both. When the value of \( S_j \) is close to \(-1\), \( a_i \) is much larger than \( b_i \) meaning that \( j \)th point is much closer to the other cluster than to the one it has been assigned to and this point is considered ‘misclassified’. If the majority of the data points have high silhouette values (above 0.5), the clustering is appropriate. If the majority of the data points show low (below 0.5) or negative silhouette values, the clustering configuration either has too few or too many clusters. Values around zero indicate overlapping clusters. The average value of \( S_j \) over all data points in the entire data set is a measure of how appropriately the data has been clustered.

When there is no prior information about the data, the number of clusters being evaluated ranged from 2 to \( \frac{N}{2} \) [36], where \( N \) represents the number of data points. Setting the minimal number of clusters to 1 is meaningless, since the clustering algorithm has no effect when all data is in a single cluster.

The clustering is repeated 100 times to reduce estimation variability. The centre of each cluster is estimated by performing a majority vote over 100 iterations. The average distance between these centres is used to discriminate the users between the clusters.

3. Results

This section describes the results obtained in the two studies. Users are classified based on their personal control behaviour. Classification of control zones is based on the user profiles, and the luminaire output data of that zone. It takes quantitative data into consideration and compares it with the results obtained through surveys and interviews with the participants in the studies.

3.1. Activeness

Each individual user’s level of activity can be determined based on the number of user control actions. A user is assumed to be active if he provides enough inputs such that his profile can be derived. An inactive user will show a lower frequency of control actions, which makes derivation of his profile more difficult.

3.1.1. Classification

In this paper, the proposed method assumes that a user’s profile can be derived if a user provides more than 2 control actions within a given timeframe. This would include an expression of a preference by a first action as well as a reflection on this first action by further actions. Together, these pieces of information form a basis to determine preference and tolerance of a user. If the number of control actions \( N_i \) of a user \( i \) is greater than 2, a user is classified as active, otherwise, a user is classified as inactive. In this study the timeframe concerns 6 weeks in study 1 and 3 weeks in study 2.

The histogram of each user’s control actions during study 1 (blue) and study 2 (green) is represented in Fig. 4. The threshold value of 2 is used for separation of users into two categories and is showed by the solid red line.

As shown in Fig. 4, the population consisted of 14 active users in study 1 and 6 active and 8 inactive users in study 2. Some users in study 2 (IDs 7, 8, 9, 13, 14, and 15) did not perform any control action in the study periods included in this analysis. Users with ID 7 and 8 did not participate in the experiment, but were provided with a device for light control, as mentioned in Section 2.4. Hence, their input is not taken into account in the analysis.

3.2. Tolerance

For classifications of users regarding tolerance, the standard deviation of their selected dimming level is used. It is assumed that offering an illuminance level far from a user’s preferred level would decrease the satisfaction of this user. A standard deviation of selected dimming levels as a measure of tolerance shows how broad the range of preferred illuminance levels is. A tolerant user will accept a broad range of selected illuminance levels meaning that he will perform his work under a larger variety of lighting conditions, without taking an action to adjust them. An intolerant user will demonstrate more consistent choices of preferred illuminance levels resulting in a narrow range [37].

3.2.1. Clustering

For obtaining the number of categories of tolerance, the data from study 1 and study 2 is used. To confirm that data from both studies can be combined, ANOVA analysis of variance is performed. The F-test is used to compare the factors of the total deviation and test the homogeneity of variances. The F-test in a one-way (single-factor) analysis of variance is used to assess whether the expected values of a quantitative variable, within several pre-defined groups, differ from each other. The null and alternative hypotheses are \( H_0: \sigma_1^2 = \sigma_2^2 \) and \( H_1: \sigma_1^2 \neq \sigma_2^2 \). The one-way ANOVA F-test statistic is defined in the following way:

\[
F = \frac{\text{between - group variability}}{\text{within - group variability}}
\]

The “between-group variability” or “explained variance” is defined as:

\[
\sum_{i=1}^{K} n_i (\mu_i - \mu)^2 / (K - 1)
\]

where \( \mu_i \) denotes sample mean of the \( i \)th group, \( \mu \) denotes the overall mean of the data, \( n_i \) is the number of observations in the \( i \)th group and \( K \) is the number of groups. The “within-group variability” or “unexplained variance” is defined as:

\[
\sum_{i=1}^{K} \sum_{j=1}^{N} n_i (x_{ij} - \mu_i)^2 / (N - K)
\]

where \( x_{ij} \) represents \( j \)th observation in the \( i \)th out of \( K \) groups and \( N \) is the total number of observations. The statistic will be large if the between-group variability is large relative to within-group variability, which is unlikely to happen if the population means of the groups all have the same values. The F-statistic follows the F-distribution with \( (K - 1, N - K) \) degrees of freedom under null hypothesis and for which critical value \( F_{critical} \) can be found in the table of critical values for the F distribution at 5% level of significance. If the calculated F-statistic is equal or greater than tabulated value, then a null hypothesis of homogeneity of variance is rejected and the data is heterogeneous in the different studies, otherwise, the data is homogeneous. Furthermore, the probability (p-value) of a value of F being greater than or equal to the observed value can be calculated and the null hypothesis is rejected if this probability is less than or equal to the significance level (0.05).

The F-statistic and p-value are calculated for the data obtained in both studies in terms of the standard deviation of users’ selected dimming levels, resulted in \( F = 0.0464 \) and \( p = 0.8314 \). The value of \( F_{critical} \) for (1,22) degrees of freedom is 4.30 and since, F-statistic has lower value than \( F_{critical} \) and p-value is greater than 0.05, the null hypothesis cannot be rejected, meaning that the data in both
studies is homogeneous and it can be combined.

The number of categories of tolerance needs to be derived by the K-means clustering, since it is unknown a priori. Taking the data from study 1 and study 2, the number of clusters evaluated ranged from 2 to 4, based on the recommendation that the maximum number of examined clusters shall be \( \frac{N}{2} \), and \( N = 24 \). The silhouette values of each data point for different number of clusters are presented in Fig. 5.

As can be seen in Fig. 5, in case of 3 clusters, the K-means algorithm clustered all data points into 2 clusters. This is caused by the algorithm’s inability to properly cluster the data into 3 clusters based on the squared Euclidean distance measure. Furthermore, for the majority of data points, silhouette values were negative for both cases with 3 and 4 clusters, indicating that clustering is inappropriate. The average value of \( S_i \) over all data points in case of 2, 3 and 4 clusters was 0.73, –0.05 and –0.22, respectively. This means that the best result is obtained for 2 clusters. Only 2 data points among the available 24, have the silhouette values around 0 indicating that they are prone to overlapping. Since the majority of the data points have high silhouette values (above 0.5), clustering into the two given clusters is found appropriate.

The result of the K-means clustering algorithm is presented in Fig. 6, with boxplots showing an intolerant and a tolerant cluster. Results are based on the standard deviation of selected dimming levels of the population of users who had control (\( n = 24 \)) during study 1 and study 2. Crosses represent the centres of each cluster. The discrimination line represents the value of standard deviation for discriminating between two classes of users.

### 3.2.2. Classification

The tolerance of the users in study 1 and study 2 is shown in Fig. 7. As it can be seen from Fig. 6, a threshold of 23% is used. A standard deviation below 23%, classifies a user as intolerant, while a standard deviation above 23% classifies a user as tolerant.

In study 1, there were 7 intolerant and 7 tolerant users, while in study 2, 6 intolerant and 4 tolerant users were observed. The remaining 4 participants of study 2 did not provide any control input to derive their tolerance level.
3.3. Dominance

The dominance of a user is relative to the other users in that control zone. The dominance can be determined by the fraction of time the luminaire output matched the dimming level set by each user. If the user is dominant, the output level of the luminaire in the user’s control zone will be set in accordance with the user’s preference for most of the time. A more submissive user would hesitate to change the illuminance level even when dissatisfied with lighting conditions.

### 3.3.1. Classification

The threshold for discrimination between dominant and submissive users was chosen as

\[
\text{threshold} = \frac{1}{N_{\text{zone,users}}}
\]

where \( N_{\text{zone,users}} \) represents the number of users within a control zone. For a zone with 3 users the threshold would be 0.33, for example. When the user’s set lighting prevails in his control zone, the user is classified as dominant. For a submissive user his set lighting will remain unchanged for a relative time below the threshold (Table 1).

Fig. 8 represents the relative time the output of the zone luminaires had a dimming level set by each user in study 1 and study 2. Based on this classification, the population in study 1 consisted of 6 dominant and 8 submissive users, and in study 2 of 5 dominant and 9 submissive users among 14 participants. Users with IDs 9, 13, 14 and 15 in study 2 did not provide any input during the study and therefore, it is assumed that they were equally submissive.

3.4. Preference

For the dimming level preference analysis, the authors assume that users select illuminance levels that they find comfortable, and most satisfying. This is confirmed by the interviews with users. Each user’s dimming level preference is calculated as a mean value of the user’s selected dimming levels directly resulting from this
particular user’s control actions. The selected dimming levels are used as input for the preference of a user, regardless of the time the set dimming level prevailed in the zone. A group action as a result of an agreement between multiple users is only used as input to determine the preference of the user who performed the action.

### 3.4.1. Clustering

To confirm that the data from study 1 and study 2 can be combined for deriving preference labels, the $F$-statistic and p-value are calculated as described in Section 3.2.1. The obtained values were $F = 0.00021$ and $p = 0.9886$, and compared to $F_{critical}$ for (1,22) degrees of freedom which is 4.30 at 5% level of significance. Since $F$-statistic has lower value than $F_{critical}$ and obtained p-value is greater than 0.05, the null hypothesis cannot be rejected. The results confirmed that the data from both studies is homogeneous and it can be combined for derivation of the preference labels.

Since the number of user preference labels is unknown, again the K-means clustering algorithm is applied to determine the preference clusters (see Section 2.5). Analysing the combined dataset of study 1 and study 2 ($N = 24$) the number of clusters evaluated ranged from 2 to 4. The silhouette values of each data point in case of 2, 3 and 4 clusters are presented in Fig. 9.

<table>
<thead>
<tr>
<th>User type</th>
<th>Fraction of time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dominant</td>
<td>$t_{rel, user, set, lighting} &gt; threshold$</td>
</tr>
<tr>
<td>Submissive</td>
<td>$t_{rel, user, set, lighting} \leq threshold$</td>
</tr>
</tbody>
</table>

#### Table 1
Classification of dominant and submissive users.

**Fig. 8.** Fraction of time the output of the luminaire had a dimming level set by a certain user in study 1 (left) and study 2 (right) in a corresponding control zone.

**Fig. 9.** The silhouette values of each data point for 2 (left), 3 (middle) and 4 (right) clusters.
The average value of $S_i$ over all data points in case of 2, 3 and 4 clusters was 0.74, 0.83 and –0.11, respectively. This means that the best result is obtained for 3 clusters. In this case, only 1 data point has a silhouette value close to 0 and is prone to overlapping. The predominating high silhouette values for the remaining data points indicate that clustering into 3 clusters is found appropriate.

The result of the $K$-means clustering algorithm is shown in Fig. 10. Based on the mean values of users’ selected dimming levels obtained by the clustering algorithm, the users are categorized to have a low, medium, or high perceived brightness preference, as suggested in Ref. [38].

3.4.2. Classification

Fig. 10 shows the discrimination lines between classes of users calculated as the average distances between the centres of the clusters. Table 2 presents the classification approach.

The classification of users based on the mean value of their selected dimming levels in study 1 and study 2 is presented in Fig. 11. In study 1, the number of users with low, medium, and high perceived brightness preference is 7, 3, and 4 respectively. In study 2, 4 users are classified to have low, 4 to have medium and 2 to have a high perceived brightness preference. Four of the users in study 2 could not be classified since they did not perform any control actions during the study period included in this analysis. It can be seen, that user preferences differ largely for users in the same control zone.

3.5. Subjective insights

In both studies the participants assessed the frequency by which they had experienced conflict by means of a survey. This evaluation was done at the end of a three weeks period resulting in two evaluations in study 1 and one in study 2 (see Fig. 2).

Fig. 12 shows the results of the mean frequency of experienced conflict in study 1 and study 2, and Fig. 13 shows the mean degree of the experienced conflict. As can be seen, in both studies some participants did perceive conflict when controlling lighting. Even though, the degree of the experienced conflict was close to “not at all” for most participants, some participants rated the conflict to be close to “moderate”. In interviews these participants indicated that they preferred a different light setting than their neighbouring colleagues. Depending on their dominance, relative to their colleagues, they would either overwrite the lighting to fit their preference, or show conflict avoiding behaviour by not using the light control. Conflict indicated in the survey might not be limited to inter-zone situations. In the interviews of study 1, participants of zone 5 and 6 indicated to experience conflicting preferences between the zones.

In the interviews the participants also shared their self-assessed lighting preference. These lighting preferences differed between users in both studies. The assessments shared in the interviews were generic and consisted of different wording, but could all be translated into three categories: a preference for low, medium, or high perceived brightness. The results of each user are shown in the overview in Table 3. The labels are based on the assessments of the users and do not map to specific illuminance ranges.

3.6. Control zone classification

The classification of the control zones can be obtained based on lighting preference profiles of the users who occupied them and the zone luminaire output. By knowing how a control zone is classified, the satisfaction of the individual users within a particular zone can be automatically evaluated and conflict between the users can be predicted. By analysing the different types of user combinations in the control zones and the actions they performed to set their preferred lighting conditions, we can distinguish 3 cases:

- **Case 1.** All users in a control zone are satisfied, the probability of conflict occurring is low.
- **Case 2.** User(s) in a control zone are dissatisfied, the probability of conflict occurring is high.
- **Case 3.** User(s) satisfaction and the probability of conflict occurring is unknown and therefore, additional input from the user(s) is needed.

A flow chart of control zone classification is given in Fig. 14. If all users in the same control zone are active, their profiles can be derived from the control actions they performed, since they

<table>
<thead>
<tr>
<th>User type</th>
<th>Mean value of user’s selected dimming levels [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low perceived brightness</td>
<td>$\text{mean} \leq 42%$</td>
</tr>
<tr>
<td>Medium perceived brightness</td>
<td>$42% &lt; \text{mean} \leq 66%$</td>
</tr>
<tr>
<td>High perceived brightness</td>
<td>$\text{mean} &gt; 66%$</td>
</tr>
</tbody>
</table>
Fig. 11. Classification of the users to have low, medium and high perceived brightness preference based on mean values of user’s selected dimming levels in study 1 (left) and study 2 (right). The solid red line represents the discrimination line between users with low and medium perceived brightness preference (42%), while the dashed red line represents the discrimination line between users with medium and high perceived brightness preference (66%). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Fig. 12. The mean frequency of experienced conflict study 1 (left) and study 2 (right).
provided enough inputs. If users have matching preferences, it can be assumed that users are satisfied and that the probability of occurrence of conflict is low which represents case 1. If users have opposing preferences, but all of them are tolerant, there will be an overlap between their preferred illuminance levels, which again leads to case 1. If more than one user in a control zone is intolerant, meaning that several users are critical regarding the selected illuminance levels, the occurrence of conflict depends on whether these users have matching preferences (case 1) or not (case 2). On contrary, if only one user in a control zone is intolerant, and this user is also dominant, meaning that his preferred illuminance level is set in a zone for most of the time, he will be satisfied. Since other users in a zone are tolerant, the probability of conflict will be low (case 1). On the other hand, if this user is submissive, he will be dissatisfied with lighting conditions due to his intolerance, leading to a higher probability of conflict occurrence (case 2). If inactive users are present in a control zone, deriving their profiles is difficult due to a lack of inputs from the users. In that case, dominant, inactive users can be identified based on their preference profiles derived from the zone luminaire output data, since there would be a high correlation between their control choices and the prevailing luminaire output. If an inactive user is submissive, there will be insufficient data for a profile derivation and therefore, additional input from the user is needed to obtain an accurate profile of that user (case 3).

Based on the analysed data, the summary of the users’ profiles as well as the control zone classification is provided in Table 3.

3.6.1. Overcoming the limitation of low number of data points
In both studies, the number of data points was generally low. There are a number of potential reasons. The user-control conditions in both studies were commissioned with a “memorizing” system behaviour. Starting from a default light setting with a desk illuminance of 300 lx on the first day of both studies, the luminaires within the control group stayed at the previous set dimming level until the next control action was performed. At the end of each day, the last selected dimming level in a specific zone was memorized and restored in that zone upon presence detection the next day. Due to this system behaviour, is it likely that users regarded it as unnecessary to perform further actions after they had set the lighting according to their preference. As also illustrated in Figs. 12 and 13, the frequency and degree of conflict was very low for most users. However, some users did experience conflict. The submissive users confirmed in the interviews that they applied conflict avoiding behaviour and felt a hesitation to change lighting even when they were dissatisfied. In study 2, 4 users did not perform any control action during the investigated periods. This could have been due to the users’ conflict avoiding behaviour, or due to a broad tolerance of the users. Information about the user’s satisfaction with lighting conditions would facilitate the classification of submissive users, since their submissiveness suppresses accurate classification of their preference profiles. Hence, all control zones in study 2 are classified as case 3 (see Table 3).

When case 3 is detected, additional input is required to derive the user’s lighting preference profile. Fig. 15 presents the proposed flowchart to gain this information from the user. The first input is related to the user’s satisfaction with lighting conditions, acquired in these studies from the survey results, as explained in Section 2.3. If a user is inactive, but satisfied, it means that lighting conditions are in accordance with the user’s preference, i.e., the probability of occurrence of conflict will be low (case 1). In that case, a user’s profile can be generated based on the zone luminaire output data, and there is no need for further input. If a user is inactive, but dissatisfied, additional input in the form of preferred lighting is required. This could be done by a push message requesting the user to set the lighting, or by asking the user to evaluate the existing lighting condition. By means of such requests, the profiles of the submissive users can be determined.

To support the benefits of proposed approach for deriving the preference profiles of inactive users, survey input regarding users’
The satisfaction with lighting conditions represents valuable information when profiles of inactive users need to be derived. Preference of users with ID 0, 14, and 15 are interpreted based on the perceived light quantity and their satisfaction. Users with ID 0 and 15 rated their perceived light quantity towards ‘too dark’. In case of zone 1, the predominating dimming level of the zone was in the low brightness range, while in zone 6, it was medium. Therefore, the perceived brightness preferences of the users with ID 0 and 15 are labelled as *medium* and *high*, respectively. Similarly, the user with ID 14, rated the perceived light quantity as medium.

### Table 3

<table>
<thead>
<tr>
<th>Zone ID</th>
<th>User ID</th>
<th>Objective measurements</th>
<th>Zone classification</th>
<th>Subjective measurements</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Activeness</td>
<td>Tolerance</td>
<td>Dominance</td>
</tr>
<tr>
<td>Zone 1</td>
<td>0</td>
<td>Active</td>
<td>Tolerant</td>
<td>Submissive</td>
</tr>
<tr>
<td>Zone 2</td>
<td>1</td>
<td>Active</td>
<td>Tolerant</td>
<td>Dominant</td>
</tr>
<tr>
<td>Zone 3</td>
<td>2</td>
<td>Active</td>
<td>Intolerant</td>
<td>Dominant</td>
</tr>
<tr>
<td>Zone 4</td>
<td>3</td>
<td>Active</td>
<td>Intolerant</td>
<td>Submissive</td>
</tr>
<tr>
<td>Zone 5</td>
<td>4</td>
<td>Active</td>
<td>Intolerant</td>
<td>Submissive</td>
</tr>
<tr>
<td>Zone 6</td>
<td>5</td>
<td>Active</td>
<td>Intolerant</td>
<td>Submissive</td>
</tr>
<tr>
<td>Zone 7</td>
<td>6</td>
<td>Active</td>
<td>Tolerant</td>
<td>Submissive</td>
</tr>
<tr>
<td>Zone 8</td>
<td>7</td>
<td>Active</td>
<td>Tolerant</td>
<td>Submissive</td>
</tr>
<tr>
<td>Zone 9</td>
<td>8</td>
<td>Active</td>
<td>Tolerant</td>
<td>Submissive</td>
</tr>
<tr>
<td>Zone 10</td>
<td>9</td>
<td>Active</td>
<td>Tolerant</td>
<td>Submissive</td>
</tr>
<tr>
<td>Zone 11</td>
<td>10</td>
<td>Active</td>
<td>Tolerant</td>
<td>Submissive</td>
</tr>
<tr>
<td>Zone 12</td>
<td>11</td>
<td>Active</td>
<td>Tolerant</td>
<td>Submissive</td>
</tr>
<tr>
<td>Zone 13</td>
<td>12</td>
<td>Active</td>
<td>Tolerant</td>
<td>Submissive</td>
</tr>
<tr>
<td>Zone 14</td>
<td>13</td>
<td>Active</td>
<td>Tolerant</td>
<td>Submissive</td>
</tr>
<tr>
<td>Zone 15</td>
<td>14</td>
<td>Active</td>
<td>Tolerant</td>
<td>Submissive</td>
</tr>
<tr>
<td>Zone 16</td>
<td>15</td>
<td>Active</td>
<td>Tolerant</td>
<td>Submissive</td>
</tr>
</tbody>
</table>

As it can be seen, the satisfaction with lighting conditions represents valuable information when profiles of inactive users need to be derived. Preference of users with ID 0, 14, and 15 are interpreted based on the perceived light quantity and their satisfaction. Users with ID 0 and 15 rated their perceived light quantity towards ‘too dark’. In case of zone 1, the predominating dimming level of the zone was in the low brightness range, while in zone 6, it was medium. Therefore, the perceived brightness preferences of the users with ID 0 and 15 are labelled as *medium* and *high*, respectively. Similarly, the user with ID 14, rated the perceived light quantity as medium.
towards ‘too bright’ and his perceived brightness preference is labelled as low, since the predominating dimming level in this zone was in the medium range. These users represent the clear case of submissiveness and conflict avoiding behaviour which was confirmed in the interviews. For profile derivation of these users, additional input in terms of preferred lighting is required as presented in Fig. 15.

4. Discussion

4.1. Population size

To be able to classify users according to their activeness the data related to the whole population of users (n = 28) was used. Analyses related to the users’ tolerance levels and preferred illuminance levels are based on a population of 24 users from both studies, since in study 2, 4 users did not perform a single control action during the analysed periods, and a classification of those cases could not be done. The dominance of a user is classified relative to the other users in that zone (n = 2–3), since the characteristic is relative to the dominance of the specific users with whom the zone is shared. Therefore, it cannot be analysed based on the whole population of users who participated in the studies.

4.2. Classification

The values of classification thresholds are derived based on the data obtained in these specific studies and could have different values for a different population of users. However, this paper presents a general approach for clustering and classification that could be applied to any population of users. Since the dominance of a user is determined relative to the other users within the same control zone, it can only be analysed based on the data obtained in that very zone, as already previously mentioned in Section 4.1. Therefore, it would be inappropriate to perform clustering in order to determine the number of dominance categories in a general manner, because the analysis would be based on the data from all control zones in both studies. Obtaining the classification threshold in case of dominance as explained in Section 3.3.1 is invariant to the data used, since it depends only on the number of users in the control zone.

The proposed classes for activeness, dominance, and tolerance represent general categories and are believed to be invariant to the analysed study. Depending on the dataset the distribution of users within the categories will differ. For the preference classification, in a situation where artificial lighting could deliver more than 500 lx on the desk, a wider range of possible illuminance levels might lead
to additional categories. More preference classes might lead to a higher risk of conflict (see Fig. 14).

The authors hypothesized that intolerant users, who prefer a narrow illuminance range, will be more active to maintain their preferred lighting, unless they are submissive in relation to their neighbours in the same luminaire control zone. Tolerant users, who prefer a wide illuminance range, are expected to be less active in their lighting control behaviour, and will have a lower risk of dissatisfaction. The classification results together with results from questionnaires showed that among 28 users, 12 users were tolerant, 13 were intolerant and for 3 users (ID0, 14 and 15 in study 2) the tolerance level could not be determined. Tolerant and intolerant users performed approximately the same number of control actions (75 and 72, respectively) which rejects the initial hypothesis that intolerant users will be more active. Among 12 tolerant users, 10 were satisfied with lighting quantity and 2 were dissatisfied due to their submissiveness, which supports the hypothesis that tolerant users have low risk of dissatisfaction.

Furthermore, it was assumed that submissiveness would suppress users to perform control actions due to their conflict avoiding behaviour. There were 17 submissive and 11 dominant users in both studies, who performed in total 61 and 88 control actions, respectively. The average number of actions/user in case of submissive users was 3.6, while in case of dominant users, it was 8 actions/user, supporting the original hypothesis. This is also in accordance with findings of previous studies [22,29].

4.3. Objective versus subjective preference labels

Table 3 presents the subjective, self-assessed preference labels of the users, as well as the labels derived from the objective measurements. The self-assessed labels, obtained in the interviews, deviate in some cases from the labels derived from the objective measurements. The preference labels are based on calculated thresholds using the objective measurements. On the contrary, users do not categorize themselves using similar thresholds, but
have their own way to describe their preference. The self-assessed labels were often based on personal experiences when performing visual tasks. The majority of the cases do show a match, which suggests that users do possess self-knowledge of their lighting preference, when classifying it in the presented three categories i.e. low, medium and high perceived brightness preference. This also corresponds to the clustering results. Some users did describe their light preference in the interviews, but did not perform any control actions in the analysed period. Their preference description could be based on the experienced lighting condition during the study, but might also be based on these users' previous experiences. By asking these users for additional input in the form of their satisfaction with lighting conditions and/or preferred light level, their preference can be classified.

By taking the information about perceived light quantity and satisfaction with lighting conditions into account, a better match between self-assessed and derived preference labels is found (see Tables 3 and 4). As explained in Section 2.3, in this study, satisfaction with lighting conditions is obtained as an assessment on 4-point scale ranging from 'very dissatisfied' to 'satisfied'. This confirms that these inputs represent valuable information when profiles of inactive users cannot be derived purely based on their control behaviour. Furthermore, validity of the approach presented in Fig. 15 is verified.

### 4.4. Experienced conflict

In the presented analyses it is assumed that conflict has the highest probability within the user’s control zone. By measurements of the desk illuminances in the office, it is confirmed that the zone lighting has a sizeable influence on the desks within the zone beyond daylight. However, this does not exclude the possibility that conflict might occur in the user’s visual field beyond his own control zone.

Based on Figs. 12 and 13, users with ID 5 and 6 in zone 3 in study 2, experienced moderate level of conflict quite frequently, which is confirmed by zone classification (see Table 4). However, users with ID 10, 11 and 13, in study 1, located in the zones 5 and 6, respectively, also experienced conflict, which is not seen in the classification results. In the interviews, users confirmed that have matching preferences with the neighbours in their own zones, but opposing preferences with users in the adjacent zone as presented in Section 3.5. The analysis of the conflict between zones is out of scope of this paper and it will be addressed in the future work.

### 4.5. Limitations and possible improvements

In these studies, individual presence information of users was not available. Lighting was controlled based on overall occupancy of the office space, as explained in Section 2.1. Therefore, it was not possible to determine what each user actually experienced during the study, regarding lighting conditions. Having the presence information would help to generate the preference labels more accurately and to better distinguish between user’s preference and acceptance. An illuminance level set by a particular user is clearly recognizable as his preference. If a user experiences an illuminance level set by his zone neighbours, the presence of his colleagues influences the interpretation of this data. If a user is alone in a control zone, without any social obstacles to change lighting, the illuminance level of the zone represents the user’s preference, regardless of the action holder. If a user is not alone, the prevailing illuminance level represents the user’s acceptance, but might not be his preference. Distinguishing between acceptance and preference helps to recognize submissive users. If lighting conditions that

### Table 4

Updated classification of the users and the control zones based on satisfaction data. *" symbols represent interpretation of profiles based on the perceived light quantity and satisfaction.

<table>
<thead>
<tr>
<th>Zone ID</th>
<th>User ID</th>
<th>Quantitative measurements</th>
<th>Objective measurements</th>
<th>Perceived brightness preference</th>
<th>Zone classification</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Satisfaction</td>
<td>Perceived light quantity</td>
<td>Activeness</td>
<td>Tolerance</td>
</tr>
<tr>
<td>Zone 1</td>
<td>0</td>
<td>Somewhat dissatisfied</td>
<td>A bit too little</td>
<td>Inactive</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>-</td>
<td>-</td>
<td>Active</td>
<td>Intolerant</td>
</tr>
<tr>
<td>Zone 2</td>
<td>2</td>
<td>Satisfied</td>
<td>Just right</td>
<td>Inactive</td>
<td>Tolerant</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>-</td>
<td>-</td>
<td>Active</td>
<td>Tolerant</td>
</tr>
<tr>
<td>Zone 3</td>
<td>4</td>
<td>Satisfied</td>
<td>Just right</td>
<td>Inactive</td>
<td>Tolerant</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>-</td>
<td>-</td>
<td>Active</td>
<td>Tolerant</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>-</td>
<td>-</td>
<td>Active</td>
<td>Intolerant</td>
</tr>
<tr>
<td>Zone 4</td>
<td>7</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
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<td>-</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>Satisfied</td>
<td>Just right</td>
<td>Inactive</td>
<td>Intolerant</td>
</tr>
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<td></td>
<td>10</td>
<td>-</td>
<td>-</td>
<td>Active</td>
<td>Tolerant</td>
</tr>
<tr>
<td></td>
<td>11</td>
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<td>Just right</td>
<td>Inactive</td>
<td>Intolerant</td>
</tr>
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<td></td>
<td>12</td>
<td>-</td>
<td>-</td>
<td>Active</td>
<td>Intolerant</td>
</tr>
<tr>
<td>Zone 6</td>
<td>13</td>
<td>Satisfied</td>
<td>Just right</td>
<td>Inactive</td>
<td>Intolerant</td>
</tr>
<tr>
<td></td>
<td>14</td>
<td>Somewhat dissatisfied</td>
<td>A bit too much</td>
<td>Inactive</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>Somewhat dissatisfied</td>
<td>A bit too little</td>
<td>Inactive</td>
<td>-</td>
</tr>
</tbody>
</table>
the user accepts differ from this user’s preference, this is an indication of submissiveness.

Another limitation is that a group action as a result of an agreement between multiple users would be used as input to determine the preference of the user who performed the action. Verbal agreements reflecting the preference of multiple users will not be identified. With individual presence information, this action could be identified as acceptance of the other users and preference of the user performing the action.

Having additional information based on individual presence would provide more detailed information on each classification. This could lead to fewer cases where additional input from the users is needed, as suggested in Section 3.6.1. However, the limited data does show that from the users’ lighting control actions, user’s satisfaction with lighting conditions can be still evaluated and risk of conflict between users can be predicted.

In this paper, preference labels are derived based only on user’s lighting control actions and luminaire output data, and are independent from contextual and environmental data. Using this method, preference profiles could be determined without additional sensorial data. However, people could have different preference depending on aspects such as the time of the day, weather conditions or presence of colleagues in the control zone or office space. Besides, when a user, for example, selects dimming levels in the ‘low brightness’ range, it might be that he does not prefer low light level conditions, but he compensates for high room brightness due to high wall luminance. The blinds control and with that the available amount of daylight can have a significant influence on the choice of artificial lighting condition. The profiling of the specific users could be different in situations with more or less daylight due to blinds control, e.g. by triggering people to be more active if the space has less daylight. Further elaboration on environmental factors that might influence user’s lighting preference is part of work in progress and will be published separately.

In this paper the activeness is determined based on a proposed threshold of 2 actions per user. It is arguable whether reliable classification needs more data points. Additional evaluation is needed to assess the error in profiling based on this limited number of actions. However, with a higher threshold for activeness, the proposed method stays identical, only more users might be asked for additional satisfaction data, resulting in more reliable classification.

The number of participants in the study was limited to the capacity of the test bed. A larger group of participants would further strengthen the proposed classification approach.

It can be observed that profiles of the users significantly differ from each other even for users in the same control zone that experienced similar environmental conditions. This is a clear indication that satisfactory lighting conditions cannot be obtained by providing a fixed illuminance level for all users and that we need to take users’ profiles into account when offering lighting. By knowing the profiles of the users in the space, the satisfaction can be increased by automatically considering their personal as well as preferences of their neighbours.

5. Conclusions

This paper proposes a first method for modelling lighting preference profiles of users based on their control behaviour and preference information to offer satisfying lighting to a group of users. The main advantage of the current method is that users’ satisfaction and conflict can be predicted purely based on users’ control actions and the output of the luminaire, since it cannot be assumed that additional sensorial data (e.g. information about individual presence, daylight contribution, controllable blinds etc.) is available in the majority of the modern office buildings. The results obtained in the questionnaires and interviews support the validity of the approach, even with limited data. Differences in profiles need to be taken into account when offering lighting conditions in open space environments.

It has been shown that users can be profiled based on their activeness, tolerance, dominance and lighting preferences. By knowing lighting preference profiles of the users and zone classification, satisfaction of the users with the lighting conditions can be improved by:

- Predicting the probability of conflict between the users in the same control zone and facilitate in making consensus choices.
- Having the information about conflict by classifying a control zone as case 2, gives the opportunity to allocate users to different zones that match their profiles, in order to improve users’ satisfaction with lighting conditions.
- Offering lighting conditions that meet the preference profiles of the users. A proposed illuminance level could result from a weighted combination of user profiles and by taking into account whether users in the same zone are tolerant or intolerant. A tolerant user can be satisfied with a broad range of illuminance levels and therefore, the weighting needs to be done by shifting a proposed illuminance level towards a preference of an intolerant user.
- Triggering a submissive user to express their preferences. A submissive user will represent an inactive user, whose choices are not correlated with the prevailing luminaire output in his zone. This situation might lead to increased discomfort of this particular user. In that case, additional user input is required in order to derive his lighting preference profile as accurate as possible (see Fig. 15).

A semi-automatic system which proposes lighting automatically by using the lighting preference profiles can support users in finding consensus in addition to the benefits of manual personal control. In this paper it has been assumed that lighting preference of a user can be derived based on user’s control actions only. Further elaboration on environmental factors influencing user’s preference is a subject of work in progress. In that case, the prediction of users’ control actions in terms of offering satisfactory lighting conditions can be performed based on the contextual data collected in the office. Furthermore, access to lighting preference profiles of office users can improve design decision making as well as help facility managers to optimize their building operation strategies.

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