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Satisfying light conditions: A field study on perception of consensus light in Dutch open office environments

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ABSTRACT

Workplace innovation has been changing the European office landscape into mostly open spaces, where enhanced interaction between people is combined by efficient use of square meters. However, challenges are found in offering individual preferred environmental conditions in these multi-user spaces, especially when dealing with shared systems like the general lighting installation.

Previous studies clearly show the benefits of offering personal control as a means to achieve individual preferred lighting. Most of these benefits were demonstrated in private offices or situations where users have a clear “personal” light source.

Lighting systems in open offices are often designed as a regular grid of luminaires to deliver uniform lighting in the space. This results in a ceiling grid of luminaires that does not match the desk arrangement in most cases. Users in the open office do not have a personal luminaire, which makes it challenging to offer personal lighting controls. By combining luminaires in control groups users could be offered consensus control. The question is whether consensus control would bring advantages rather than disadvantages.

This paper presents the results of a field study evaluating consensus light control in an open office. In a within-subject comparative experiment with repeated measures, 14 users experienced a reference no-control condition and a condition in which they were offered control over a zone of luminaires. Data was collected by objective measurements as well as subjective surveys and interviews.

In this study it is shown that consensus control in an open office improves satisfaction of individual users with the quantity and quality of light. Even though the controllable light is shared, consensus among users results in an improved lighting environment for the majority of the users. Selected illuminances in the condition with light controls were on average lower than in the reference condition, resulting in lower energy usage by lighting.

Keywords: Personal control; lighting perception; experimental study; satisfaction

1. Introduction

European workplace design has experienced a transformation over the last decades with the majority of today's modern offices being open office spaces. Despite the often expressed concerns of lower worker productivity and satisfaction the trend does not seem to slow down. Therefore, in today's offices it becomes even more relevant for the worker to create office environments that meet individual needs.

1.1. Benefits of personal lighting control

Standards provide lighting recommendations for different visual tasks to ensure a comfortably lit environment. However, different studies have already shown satisfying light conditions to differ significantly between individuals. Preferred desktop illuminances for office tasks range from 80 lx [1] to around 1500 lx [2] between individuals. With a fixed light 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% [3].

Why would we want to offer lighting that serves the preferences of individuals? An exploration in a laboratory study with a cubicle office setup, in 2001 showed that by offering illuminances close to people's own preferences a significant improvement in ratings of mood, lighting satisfaction, and environmental satisfaction can be established [4]. In 2004, Newsham and colleagues conducted an experiment in a mock-up office where they placed participants in a cubicle office setup under a lighting design for a single day, without any control over the lighting until the second half of the afternoon when all participants were offered a means to control the lighting. The results showed improved ratings when introducing individual control over lighting, but also that these are not simply due to the availability of control. Exercising control to achieve preferred conditions improved mood, satisfaction, and comfort. Participants that made the biggest changes to the lighting conditions after they were given control tended to register the largest improvements in subjective measures [2].

Field studies showed that offices with lighting control achieved higher ratings of lighting quality and comfort. Veitch et al. demonstrated in an office setup with cubicles, that people, who perceived their office lighting as being of higher quality, rated the space as more attractive, reported a more pleasant mood, greater well-being at the end of the day, and improved motivation and vigilance [5]. In 2010 Veitch et al. conducted a field study on four floors of an office building with cubicles in Canada leading to the finding that the availability of individually-controllable lighting results in more favourable office appraisals and higher levels of environmental satisfaction, with an indirect link to higher job satisfaction [6]. Moore et al. performed an evaluation in existing office buildings with and without controls and found that the presence of lighting controls seems to lead to a higher degree of satisfaction with planar illuminance [7]. In another analysis of an office building with user control, Moore and colleagues showed an increased importance of lighting control as levels of discomfort are raised. However, the study also shows that around one-third of the occupants reports a negative perception of controls, suggesting a partial failure of current lighting control systems [8].

In a study performed in 4 identical private offices, Sadeghi and colleagues showed a higher comfort rating from the users that evaluated the offices with control (wall switch or web application). A higher frequency of lighting control actions was observed when offering the more easy-to-access web interface [9]. However, it did not affect the comfort experience. A study performed by Aghemo and colleagues showed lower rating of the lighting conditions in the office when control was extended from on/off to regulation of the luminous flux [10]. Participants did however indicate that their control actions in the extended situation mainly occurred when the automatic system was not working properly, which was absent in the manual on/off situation.

Benefits are not only limited to the contentment of users. When given control, office users would on average select a lower light level than the recommended 500 lx desk illuminance resulting in energy savings [3, 11, 12]. A review of 88 publications by Williams et al. reported the average lighting energy saving potential by personal control to be 31% [13]. A field study by Galasiu and colleagues reported energy savings by personal control over downlights to be 11%, increasing up to 42% when combined with other control strategies like daylight harvesting and occupancy control [14].

1.2. Consensus control in the open office

Many benefits of personal control have been demonstrated in studies with private offices, cubicles or situations where users have a clear “personal” light source providing lighting in their workspace. These studies are often performed with luminaires positioned directly above the office worker and with the ability to be individually controlled. With trends like Gensler’s activity-based workspaces, the open office concept is becoming commonplace in the office landscape [15]. Lighting systems in (open) office spaces are often designed as a regular grid of luminaires to satisfy the local regulations, building codes, and design guidelines for lighting with respect to illuminance levels and uniformity in the most efficient way. The number of required luminaires is calculated (based on regulatory and cost constraints) and can be visualized as a regular grid of luminaires providing uniform general lighting in the office space. The furniture layout in the same office is often not known or not being considered during the lighting design process. It is also likely to change throughout the lifespan of the lighting installation. As a result, the ceiling grid of luminaires does not match the desk arrangement in most cases. Even though the lit environment is designed to meet user needs, the lighting grid is often designed using the space dimensions as primary input and not the users.

A space-based organisation of luminaires makes it challenging to offer lighting controls for open offices in a truly personal way. After an exploration in 14 existing office buildings, Moore et al. already discovered that problems with user-controlled lighting will arise after an attempt to introduce personal control into open-plan environments [16]. For some users, it will be obvious which luminaire is linked to their workplace, others could have workplaces positioned in between luminaires or may even have the feeling of controlling “someone else’s light”. By combining luminaires in control groups, such that all luminaires in one group act as one, users could be offered consensus control. Multiple users get dimming control over the same group of luminaires in their proximity which delivers light to a cluster of desks. Based on the analyses of the existing installations, Moore and colleagues suggest to reduce the likelihood of conflict through the use of small control groups and locally situated control [16]. With a minimum number of luminaires per control group the benefits of consensus control can be maximized, while equally empowering users.

1.3. Problem statement

When sharing the control over office lighting, difficulties might arise when trying to reach a consensus over the preferred light level, due to the variety of individual light level preferences. This collective way of consensus control might therefore lead to conflicting light preferences between users. The benefits office users could experience from lighting within their individual preferences would then be defeated by the potential dissatisfaction when needing to reach consensus with people having different profiles regarding lighting preference or behavioural patterns. It is expected that consensus in workplace lighting levels will improve the appreciation and light perception of office users in an open office environment compared to a situation without controls. The study described in this paper evaluates the added value of personal control in an open office context.

1.4. Research hypothesis

The authors hypothesize that office users experience a higher satisfaction with lighting in the office when they are offered a means to control the group of luminaires affecting their workplace compared to a situation offering no control over lighting to the users while the system delivers a fixed uniform light level to the entire office space.

This paper will address occupant evaluations in a reference condition without lighting control compared to an experimental condition with lighting control assessed in a field study. The methodology used, the results, and a reflection on the results will be discussed. The paper concludes with leads for future research.

2. Methodology

In general, people are recognized as being unreliable sensors for light comfort, where discomfort is often easier to evaluate [17]. The perception of discomfort is often related to pain and negative extremes while the perception of comfort is related to feelings of well-being, luxury, and plushness, and changes little over time. Evaluation becomes challenging when it does not concern extreme shifts, but small positive changes of satisfaction over a situation where users have experienced acceptable lighting in offices without control. To deal with this anticipated positive shift from neutral or satisfied correctly, a longitudinal field study has been designed.

2.1. Test bed

The experimental test bed used for the field study was developed in an office space on the 4th floor with a south facing façade in Eindhoven, the Netherlands. Figure 1 shows the top view of the test bed facility and Table 1 an overview of material characteristics. The lighting system consisted of conventional fluorescent lamps (Philips TL5 49W) operated with DALI high frequency dimmable ballasts with a linear dimming curve. The dimming curve is derived by measuring the illuminance at a target spot for various relative light output levels of the luminaire. The relative light output of the luminaire will be further referred to as the dimming level.

The twelve inner luminaires were controllable by the users with a personal user interface, while the four luminaires adjacent to the walls were controllable by the researchers and fixed at a default level to maintain sufficient and uniform wall illuminance and not influence overall space appraisal negatively [18]. Using recommendations from literature, the controllable luminaires were combined in a minimum control group size [19] of two luminaires each, as shown in Figure 2, to provide equal sense of control [7] to the maximum of three users in every control group. Had the luminaires not been grouped the middle person would be disadvantaged compared to his neighbours, who have luminaires above their desk. Luminaires in one control group were commissioned to behave identically. Daylight harvesting was disabled during the entire length of the study in an attempt to remove the potential noise of artificial light changes in response to daylight. The occupancy-triggered light control in the test bed was controlled for the whole space, turning all lights off when the space was unoccupied and switching the lights on at the last selected level when the first person re-entered the space. The participants had their desk equipped with one or two PC monitors for their office tasks. The luminance of the PC monitors with a blank white screen display ranged from 100 to 150 cd/m², measured in the reference condition (average illuminance of 500 lx on the desk surface, excluding the daylight contribution).

Figure 1 Top view of the test bed area, with controllable luminaires and non-controllable luminaires adjacent to the walls, the position of the HOBO sensors, the illuminance and motion sensors, and the position of the luminance camera

Table 1 Surface properties

Surface	Material	Colour	Luminous reflectance
Walls	Painted Stucco	White	0.83
Ceiling	Mineral wool tiles	White	0.79
Floor	Carpet	Grey	0.08
Green desk divider	Fabric	Green	0.59

Figure 2 Top view of the test bed with in total 6 control zones, 2 luminaires in each zone

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 using the wall mounted interface underneath the windowsill. Internal blinds could only be controlled manually using a remote control, placed on the windowsill. The internal as well as the external blinds were divided in four controllable segments each. The interfaces for the segments were for general use, but more accessible for the users adjacent to the window. The control means for the blinds did not change during the test.

Figure 3 Test bed – interior impression, with green desk dividers between desks

2.2. Study design

The study was designed to have a reference period as well as a “user control” period. The study started with a reference “no control” condition where all luminaires were set at 100% output delivering an average illuminance of 500 lx on the desk surface, excluding the daylight contribution. This condition was followed by a “user control” condition with a default dimming level of 60%, representing an illuminance of 300 lx. The 12 controllable luminaires were adjustable in a range from 1-100% luminaire output, the 4 non-controllable

luminaires adjacent to the walls were fixed at the default dimming level of 60%. At the end of the study period, the “no control” condition was repeated by removing the controls and setting all luminaires back at a dimming level of 100%.

The study was designed as a repeated set of measures within-subject comparative experiment. To closely mimic office conditions and tasks, it was decided to run the experiment as a field study (as opposed to lab conditions). A longitudinal field study was designed in order to deal with the anticipated small positive shift in user satisfaction, and the influence users’ daily office tasks could have on the evaluations. The longitudinal design also allowed for participants to unconsciously discover their individual lighting preferences as well as their preference as part of a group. To minimize the effect of the highly dynamic changes of the outside conditions, the duration of the experiment covered periods related to different climate conditions. The study started after the holiday period, due to availability of the participants, and ranged from September to December. Counterbalancing the experimental conditions minimized the effect of the changing outdoor conditions, as well as the influence of introducing and removing the controls from the users. At least six weeks of data per experimental condition and participant was captured, excluding the first week of control. Figure 4 visualizes the period of the study on a timeline. The periods followed one another directly.

Figure 4 Design and timeline of the study

During the user-control period, participants were offered personal control by means of a personal smart device placed on their desk as well as a directly accessible widget installed on their PC. Each controller was assigned an identifier that was permanently linked to a particular control group of luminaires. During the user-control period, lighting could be controlled by the users at any point in time by setting the slider to the desired light level (Figure 5). After changing the slider position, the output of the luminaire group was adjusted with a dimming speed (time to reach the final state) of 2 seconds. The controller included sufficient steps to offer a perceived continuous slider. The luminaires of the control group stayed at the set dimming level until the next control action within the control group was performed. The dimming level could be overwritten by every user in the zone, at any point in time. After a change was made, the user interface of the users in the zone was updated to present the current dimming level of the luminaire group.

Figure 5 User interface for light control, iPod application (left) and PC widget (right)

Walls enclosing the test-bed were in the reference condition as well as in the user-control condition illuminated with fixed dimming levels of the wall adjacent luminaires, resulting in an average vertical illuminance of 145 lx on the walls, and an average luminance of $L = 43 \text{ cd/m}^2$ ranging from $L_{min} = 23 \text{ cd/m}^2$ to $L_{max} = 96 \text{ cd/m}^2$, measured in the absence of daylight, with general lighting set to generate an average illuminance of 500 lx on the desks.

Figure 6 shows the luminance distribution of both walls enclosing the office space. Two reference desks at both ends of the space are selected, facing respectively the east and west wall, to describe the luminance scene of the testbed. Measurements were taken from the indicated viewing position of the participants (shown in Figure 1). For the horizontal task, a white paper was placed on the desk surface while measuring the average luminance of the entire desk. For the PC screen-based task, a white screen page was used. The task luminance was measured with the adjacent computer monitors turned off. The luminance ratios experienced by the participants are presented in Table 2 using the average values.

Table 2 Experienced luminance ratios in the reference condition

Luminance ratios	East wall	West wall
Average wall : direct surrounding (desk divider) : horizontal task	1 : 0.48 : 2.90	1 : 0.35 : 2.52
Average wall : direct surrounding (desk divider) : PC screen	1 : 0.48 : 3.80	1 : 0.35 : 3:35

Figure 6 Luminance distributions of the office space in reference condition – east (top) and west wall (bottom)

2.3. Participants

A group of 14 administrative workers were invited to participate in the study and were relocated to the test-bed for the study duration. The participants did not work on research topics themselves and were naïve regarding lighting or perception knowledge.

The participants were offered fixed workplaces similar to their normal office setup, which was located on the same floor of the building facing the same façade. The position of occupants in relation to the windows as well as to their colleagues was kept identical to the greatest extend. The participants (30 – 65 years, 3 females and 11 males) worked on their actual job tasks while experiencing the study conditions. The participants 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. Prior to the study, the participants were only acquainted with the control possibilities for the external blinds.

The study design and objective was not shared with the participants beforehand. They were informed to be part of an evaluation regarding a general open office environment concept, and would receive study details afterwards, to enhance the study quality. At the start of the user-control condition the users were informed about the lighting control option that they received. The participants received a small participation fee at the end of the study, of which they were not informed beforehand.

2.4. Objective measurements

The objective measures consisted of data logging as well as sensor input. During the study log files were created of the luminaire dimming levels (1 minute logging), the energy usage by Plugwise modules (FW 2.36+) wired into each luminaire (1 hour logging), the use of the light controls (instantaneous logging), and

the use of internal and external blinds (4 minute logging). Sensor input consisted of readings of the 12 ceiling mounted light sensors (Philips PLOS-CM-KNX) (1 minute logging) and 8 desk mounted HOBO sensors (Onset U12-012) measuring the relative desk illuminance, the relative humidity, and the temperature (5 minute logging). Due to the spatial sensitivity of these HOBO sensors, calibration to absolute illuminance was found to be inaccurate. Therefore, the illuminance distributions were analysed relative to each other.

2.5. Subjective measurements

The subjective evaluations were collected via online surveys, interviews, and a paper diary booklet placed at their desk that each participant could write in at any point in time during the full length of the study. The diary consisted of an A5 booklet where participants could make notes of their absence or things they noticed in the office space related to environmental aspects such as electric lighting, daylight, temperature, noise level, air ventilation, or other incidents they wanted to share or capture. Survey questions and the diary headings were presented in English with a Dutch translation underneath each item. At the end of every week, the participants were asked to fill in an online survey. Two types of surveys were used: a short and an extended survey (Figure 4). The short survey had the same items recurring every week for the full length of the study. The short surveys included scales evaluating the perceived lighting quantity, quality, and glare. The participants were asked to evaluate the light quantity on their desk and PC monitor, from the artificial lighting as well as from daylight on a 7-point scale, ranging from 'too little' to 'too much' [7]. Besides using the scale to analyse whether lighting was experienced as brighter or darker than they 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. Figure 7 illustrates the original scale as well as the clustering on the recoded scale.

Figure 7 Original and recoded scale light quantity assessment

The components labelled 'lighting quality' (7 items) and 'glare' (2 items) [20] were created by taking the average of the responses of the contributing items with scores ranging from 1 to 7 with higher values indicating better quality or comfort, respectively. Results from the weekly surveys were aggregated in one average value for each participant per condition.

At the end of each of the four study periods the survey was extended with additional items. Satisfaction with the environmental conditions is evaluated using comfort scales of Osterhaus [21] and Veitch [22] for temperature, acoustics, and air quality in the office. The mood of the participants was evaluated regarding dominance, arousal and pleasure in all conditions using the 3-factor Mood scale of Russel and Mehrabian [23]. The perceived level of control and the level and degree of conflict due to the use of the lighting controls were evaluated in the user-control condition [16].

After each extensive survey an interview between participant and researcher was conducted to further elaborate on what was captured in the surveys or the diary. Interviews delivered complementary qualitative information used to understand the data and the results obtained.

1 The first week of control is excluded from the analyses due to a deviation in the behaviour with the controls
2 compared to the rest of the user-control condition. This study focussed on the user experience when having
3 the ability to select preferred lighting and not in evaluating the user novelty experience with controls.

4 2.6. Analysis

5 Most of the elements included in the surveys were evaluated by the participants on an ordinal scale. Due
6 to the ordinal data and the relative small sample size, the data was analysed using a non-parametric
7 Wilcoxon signed ranks test. For the significance tests a liberal level of significance of $p=0.1$ was motivated
8 by the explorative nature of this study, a relative small sample size, and the use of non-parametric statistics.
9 For the analyses IBM SPSS Statistics is used.

10 3. Results

11 The obtained results will be presented with a distinction between control variables, objective and
12 subjective results.

13 3.1. Control variables

14 Different variables are analysed for their impact on light preference or satisfaction of the participants in
15 this study. No effect is found for age, gender, position of the user in the office space, as well as position of
16 the user related to a luminaire.

17 3.2. Objective results

18 The study included two times three weeks without control with luminaires set to a dimming level of 100%
19 luminaire output corresponding to an average desk illuminance of 500 lx by artificial light. In the six weeks
20 with user-control preferred dimming levels were set by the users within the range 1 to 100%. Figure 8 shows
21 the distribution of luminaire dimming levels during the user-control period of all six control zones, as shown
22 in Figure 2. Each zone consists of two luminaires, with the same distance from the window. During the
23 control period the luminaires in the office area were 41% of the time on maximum output, and 56% of the
24 time below a dimming level of 60%. Figure 8 illustrates that during the user-control period there were zones
25 that were mostly “dimmed” (zone 2 and 5), mostly “bright” (zone 1, 3, and 6), and a zone that has been
26 labelled “medium dimmed” (zone 4).

Figure 8 Dimming levels of the luminaires in fraction of time of the 6 weeks user-control period

Despite the non-uniformity of lighting over the zones, none of the participants stated to have experienced light level differences between the zones to be disturbing. Often dimming level differences were only observed when looking at adjacent luminaires; not when looking straight forward in the office space.

The frequency in which the controls were used differed during the study. In the first week that the participants were provided with controls, three changes per user per day were made by 12 different users on average. This week is excluded from the analyses due to its variant character. In the remaining six control weeks, actions were performed by changing individuals with three changes a week by on average three users. Similar to previous studies the users in this study showed different usage behaviours ranging from active users to users with limited performed control actions [24]. The majority of control actions took place at the start of the work day (45%) of which two third was to dim down. The other half of the control actions took place throughout the rest of the day (Figure 9), with a small increase again at the end of the day when exterior lighting conditions start dropping, of which little more than half was to dim up. The sunrise in the control period varied from 7:23 till 8:19, and the sunset from 18:31 till 16:34.

Figure 9 Light control actions of the users over the course of a day – fraction of lighting changes of total actions in 6 weeks

Figure 10 presents the frequencies by which illuminance levels were measured by the HOBO sensors placed on the desks (including daylight contribution) on week days from 8 am to 7 pm during the six weeks without control and six weeks with user control. As can be seen in the chart, conditions 2 and 3 are shifted towards lower illuminance values compared to conditions 1 and 4. Due to the spatial sensitivity of the loggers, the distributions can only be analysed relative to each other. The data does not exclude desks that might have been temporary unoccupied during this timeframe.

Figure 10 Desk illuminance distributions, including daylight contribution (All weekdays from 8 am – 7 pm)

The power consumption of the luminaires during the reference period of six no-control weeks was compared to the power consumption of the luminaires during the six user control weeks. The results are presented in

Table 3. The table presents the energy consumption by lighting of both conditions for the 12 luminaires that were controlled by the users, as well as for all 16 luminaires in the testbed, which includes the four wall adjacent luminaires which were not controllable by the users.

Table 3 Energy consumed by lighting during the user-control and no-control conditions

	Condition	Total energy consumption in kWh	Weekly energy consumption in kWh	Relative energy savings in %
User controlled luminaires (12 luminaires)	User control	134.8	22.5	31.9
	No control	197.9	33.0	-
Entire testbed (16 luminaires)	User control	192.6	32.1	27.2
	No control	264.5	44.1	-

3.3. Subjective results

3.3.1. Lighting quantity and quality

The light quantity and quality are assessed weekly. The results presented here are based on 6 weeks no-control and 6 weeks user-control.

In both conditions there is a tendency to report receiving a bit too much light on the desk and the PC screen in general, as well as a bit too much daylight specifically on the desk. However, this tendency is lower for the user-control situation compared to the no-control situation, as can be seen in Table 4, **Error! Reference source not found.** and Figure 11. Levels of dissatisfaction with the amount of light on the desk, the PC screen, and by daylight follow the same pattern for both the user-control as well as the no-control condition. Statistical analysis using a non-parametric Wilcoxon Signed Ranks test shows in the user-control condition compared to the no-control condition a statistically significantly lower dissatisfaction with the light quantity on the desk ($p=0.029$) as well as on the PC screen ($p=0.047$), with both a large effect size (respectively $ES=-0.58$ and $ES=-0.53$). In the interviews the majority of participants indicated to appreciate the possibility of dimming down the illuminance as they felt the preferred dimmed lighting was “more relaxing” for their eyes. Some participants indicated to prefer bright light, for visual performance, “to avoid a gloomy office”, or “to feel more energized”. Despite the diversity in lighting preferences, the frequency in which conflict was reported in the extended surveys remained very low with the exception of two neighbouring participants. However, also for these participants the degree to which the conflict was experienced was rated as low in these surveys and reaffirmed in the interviews.

Table 4 Lighting quantity for the no-control and user-control condition

	Assessment of quantity of light (1 = too little, 7 = too much)								
	On desk			On PC screen			Daylight		
	Mean	SD	Median	Mean	SD	Median	Mean	SD	Median
C_{nc} (n=14*)	4.57	0.787	4.63	4.30	0.599	4.38	4.76	0.920	4.62
C_{uc} (n=14*)	4.05	0.598	4.00	4.07	0.586	4.00	4.50	1.121	4.08

* Mean aggregated values per participant for six no-control (C_{nc}) evaluations (n=88) and six user-control (C_{uc}) evaluations (n=83)

*Based on $n=14$ (aggregated per participant from six no-control (C_{nc}) evaluations ($n=88$) and six user-control (C_{uc}) evaluations ($n=83$))

Figure 11 Boxplots of dissatisfaction with light quantity in no-control and user-control condition

The assessment of light quantity on the desk and PC screen show a correlation of $r=0.771$ using Kendall's tau ($p=0.000$). The importance to have control over the lights shows a statistically significant weak correlation with the perceived light quantity on the PC screen ($r=-0.300$, $p=0.039$), but no correlation with the perceived light quantity on the desk.

The quality of light is rated to be above neutral in the reference condition with a statistically significant improvement in the condition with ability to control ($p=0.096$) but with a very small effect size ($ES=-0.05$) (Figure 12). The assessment of light quality shows a correlation with the perceived dissatisfaction with light quantity on desk (Kendall's tau $r=-0.512$, $p=0.000$), PC screen ($r=0.550$, $p=0.000$), and due to daylight ($r=-0.474$, $p=0.001$), as well as the satisfaction of participants with the level of control they had ($r=0.475$, $p=0.001$).

From the surveys, glare was only experienced to a minor extent in both conditions. When occurring it was stated to be caused by direct sunlight, not by the "brightness of luminaires" or reflections of artificial light. The experience of glare was not statistically significantly affected by the ability to control (Figure 12). The assessment of glare shows a statistically significant correlation with the light quality (Kendall's tau $r=0.372$, $p=0.007$) as well as the light quantity on the desk ($r=-0.333$, $p=0.019$), PC screen ($r=-0.306$, $p=0.033$), and due to daylight ($r=-0.481$, $p=0.000$).

*Based on $n=14$ (aggregated per participant from six no-control (C_{nc}) evaluations ($n=88$) and six user-control (C_{uc}) evaluations ($n=83$))

Figure 12 Boxplots of light quality assessment and perceived glare in no-control and user-control condition

3.3.2. Environmental conditions

The environmental conditions are assessed by the participants as part of the extended survey at the end of each 3 week period, resulting in two evaluations of a no-control period and two evaluations of a user-control period.

The air quality in the office was rated as satisfying with no significant difference between the user-control and no-control condition. In both conditions the office was rated to be a bit too noisy, with no significant effect of controls. Participants stated in the interviews to be disturbed mainly by people passing by the open office and having loud discussions. The temperature in the office was rated around neutral, with a significant effect for controls ($p=0.026$) with a large effect size ($ES=-0.60$) when comparing the average temperature evaluation in the no-control condition to the user-control condition. In both no-control periods, participants rated the office to be warmer than they preferred, where in the period when they did have control they felt more neutral about the temperature. However, the perceived temperature ratings of the survey do not show a correlation with the survey results of the perceived level of control over light people felt they had during the study nor with the satisfaction with the level of control. Results are shown in Table 5. The change in perceived temperature might be caused by the actual indoor temperature. The logged average indoor temperatures differed slightly between the conditions being 23.2°C, 22.6°C, and 23.1°C for the first no-control, the user-control and the second no-control condition respectively (including workdays from 8 am to 7 pm, loggers placed on the desks). The 0.5-0.6 K lower average indoor temperature in the user-control condition is likely to have been caused by the lower sun radiation hours in the user-control period compared to the first and second no-control periods.

Table 5 Assessment of environmental comfort during the user-control and no-control condition

Air quality (1=very dissatisfied, 4=neutral, 7=very satisfied)	Acoustics (1=too noisy, 4=just right, 7=too quiet)	Temperature (1=too cold, 4=just right, 7=too warm)
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	Mean	SD	Median	Mean	SD	Median	Mean	SD	Median
C _{nc} (n=14*)	5.14	1.379	6.00	3.25	0.753	3.00	4.50	1.056	4.00
C _{uc} (n=14*)	5.14	1.167	5.25	3.50	0.734	3.50	3.96	1.100	4.00

* Mean aggregated values per participant for two no-control (C_{nc}) evaluations (n=28) and two user-control (C_{uc}) evaluations (n=28)

Table 6 Measured environmental conditions during the first no-control, the user-control and second no-control conditions

	Average indoor temperature [°C] ^a	Average outdoor temperature [°C] ^b	Sun radiation [hours] ^b
C _{nc} – period 1	23.2	12.8	4.5
C _{uc} – period 2+3	22.6	8.8	2.1
C _{nc} – period 4	23.1	4.4	3.5

a. based on temperatures logged on workdays from 8 am to 7 pm, measured with HOBO sensors placed on the desks, b. based on daily average sun radiation data for workdays, KNMI weather station Eindhoven

3.3.3. Mood

At the end of each experimental period, an evaluation of participant mood was included in the extended survey. Unlike Newsham et al. [1] and Boyce et al. [2], there was no statistically significant effect of personal control on the mood of participants. In the interviews some participants indicated that they found it difficult to rate their emotional state in the surveys. The reasons given were the complexity of the emotional states described in the survey items, and the fact that they were not used to reflect on their emotional state in the requested level of detail.

4. Discussion

4.1. Profiles

Based on the illuminance values set by the users during the control condition, the office could be divided in three different brightness zones: zones that are predominantly bright, dimmed zones, and an intermediate zone (as illustrated in Figure 8). The set lighting in these zones did not show large deviations outside the labelled category. This suggests that users within a zone classify themselves in a light preference category, and perform their control actions consequently in that part of the dimming range, which is confirmed by the users in the interviews. However, since control is shared, the placement of a zone in one of the categories can either be the combined preferred lighting of the different users sharing the zone, or the preference of the more dominant, sensitive, or critical user in the specific zone. In the latter case the category placement does not represent the less or non-active user of that zone. Therefore, based on this study, the classification in the categories is concluded on a zone level, and not for individual users. Interactions and classifications of individual users will be further discussed in a separate paper.

Two third of the lighting control actions at the start of the day were to dim down. Where only little more than half of the actions at the end of the day were to dim up. The control actions of the morning were therefore not only a response of the “typical” end of the day setting, but a response on a lighting situation created during the day. Additionally, changes are not daily made, and performed by only a changing subset of participants. More advanced analyses of the data are needed for recommendations regarding optimizing the default switch-on settings of the system and is part of work in progress.

4.2. User satisfaction

The reference condition without light control offered lighting much better in line with the conventional recommendations regarding task illuminance levels than the condition with light control. However, the condition in which users were offered light control was evaluated to have a significantly better “light quantity” on the desk as well as on the PC screen. This was also expected based on the evaluations of Moore and colleagues in buildings with and without light control [7]. In the condition without controls, users on average evaluated the office to be too bright for their preference. The majority of the control actions were performed when exterior lighting conditions were low, at the start of the day when users entered the office space, and at the end of the afternoon. It may be argued that the improved satisfaction with the light quantity could be caused by just the presence of the controls, regardless of their usage. As shown by Sadeghi and colleagues, the acceptability of visual conditions can be influenced by the occupant’s perception of control [9]. However, the shift to lower luminaire dimming levels in the user control condition supports the suggestion that the positive effect is not caused by solely the presence of control.

The condition with user control was also evaluated to have a significantly higher quality of light. Even though the user-set lighting created dimmed and bright zones in the office space, users did not experience lighting in the space as unpleasantly non-uniform. They could be influenced by the absence of extremes in luminance ratios or by the wall adjacent luminaires being fixed at the default 60% dimming level during the user-control condition to maintain a sufficient and uniform wall illuminance.

No relations were found between light quantity and quality evaluations and the age of the participants. The environmental satisfaction and the mood of the participants were not affected by the presence and use of light controls, neither positively nor negatively. A positive effect was expected based on the studies of Newsham and colleagues [2]. Cultural differences could have played a role. Some participants did indicate to have experienced difficulties with the mood survey items. This challenge could be partially caused by cultural or personal awkwardness of sharing emotional states in the survey. Despite anonymous participation in the study, this could be reinforced by the personal contact with the researchers during the interviews, and the fact that the participants were part of the same organization as the researchers.

Even though a significant difference in temperature assessment is found between the user-control and the no-control condition, the data does not support the assumption that the perceived level of control over lights has an influence on the perceived temperature. The outdoor climate data shows a lower number of sun radiation hours during the user-control period compared to the no-control period, which could have influenced the indoor temperature evaluations of the participants.

4.3. Conflict or burden

In this study the experience of conflict, rated as such in the surveys, was limited to two people (out of 14 participants) working in the same zone (zone 5). In the interviews different participants stated that they noticed lighting changes when they were made by colleagues as well as having the impression that their initiated changes were noticed by their colleagues. Small, slow, or gradual light changes were found more acceptable and in general not perceived as negative by the observer, while fast and large light changes were less appreciated. This suggests that there is a difference between the acceptance of a set light level and the acceptance of the dimming speed to achieve this light level. In the interviews none of the participants stated to have experienced serious discomfort caused by fast or large light changes. It could be that it is not the changed light level that leads to lower appreciation, but the distraction from the office task caused by the noticed light change.

Participants referred to different indicators in their visual field that triggered them to notice the light changes. Some participants indicated visible dimming of a light source itself. Others mentioned triggers like a perceived brightness change in their surroundings, a noticeable change of their desk light level, or a shift

of the selected dimming level on their user interface. Due to the desk dividers in the office space, as shown in Figure 3, noticeability of changes at the opposite desks might be limited, e.g. the neighbour exercising the control action, or a change in the light level at the opposite desk.

Users who intended to set a preferred light level were cognisant of other people in their vicinity. This consequently influenced their behaviour. Even though these changes were generally acceptable, neutral comments were still made when observed. This triggered some users to set their preferred light level in a non-noticeable way, i.e. slow and gradual. A difference might exist in an acceptable dimming speed for the observer and the user performing the action, likely influenced by personal character as well.

The size of the control zone may influence the risk of conflict, as was also shown by Moore et al. [16]. The more people that need to reach a consensus on preferred light level the higher the risk of conflict situations occurring. Indications from users in the interviews showed a diversity in their lighting preference and sensitivity. Some participants pursued a dark environment by closing the blinds and dimming the lights, while other participants preferred a very bright environment, or indicated not to have an outspoken lighting preference. 70% of the participants did indicate to prefer the experienced consensus control over no control at all. Further analyses of the social dynamics and conflict results of user control will be published in a separate paper.

All participants in this study were at the same corporate hierarchical level. A reporting difference may influence the perceived conflict of users as well as the tendency to use the controls in these situations.

4.4. User interface effect

Control was offered with a range from 1 to 100% luminaire output (100% corresponding to an average work plane illuminance of 500 lx from artificial light when all luminaires are on). In previous studies it has been shown that the range of the offered control as well as the anchor point of the user interface have an influence on the selected preference of the user [25]. Offering a different range is likely to influence the preferred absolute illuminance, but the distribution of preferences between people will still hold. When the user-control condition was introduced, the controllers were set at an anchor point of 60%. Some users indicated to be pleased with the extended range they were offered after the introduction of controls, assuming the anchor point to resemble the default setting of the no-control condition. Similar to the range of the control, the start position of the control might have influenced the selected preference. Absolute values of the preferred illuminance should therefore only be interpreted in the context of this study. Results from Uttley et al. underpin the authors' assumption that even though an anchor point and range do influence the selected light level, they do not influence the satisfaction of the users with their light preference [26].

4.5. Study design

The study of Moore et al. has earlier suggested that people perceive control as important, that the perception of control could be improved through smaller control groups, and with that, the satisfaction with the degree of control [8]. Luminaire control groups were created perpendicular to the façade, following a desk layout that gave neighboring co-workers an equal level of control. By doing so, it was not possible to separately control the areas near the facade from the areas further away from the windows. Even though the office is only 5.0 m deep, participants sharing a zone were exposed to different lighting conditions due to different daylight contributions on their task surface. This could have influenced participants to take greater consideration of each other. A different partitioning of zones could have influenced among others the satisfaction of the participants with light quantity and the actual selected light levels.

To capture the small anticipated positive shift in user evaluations from neutral or satisfied correctly the study was designed as a longitudinal study. To deal with the changing outdoor conditions during the study as well as the effect of introducing or removing the controls, a counterbalancing study design was chosen. Due to

the summer holiday period and the associated absence of the participants, the experiment started in September. The reference no-control condition covered the longest days of the study in the first experimental period in September as well as the shortest days in the last experimental period in December. The user-control condition covered the autumn days during the second and third experimental periods. Offering user-control to participants earlier or later in the year could have influenced the use of the light controls based on a difference in available daylight.

5. Conclusions

In this study, it was shown that consensus control improved user appreciation of office lighting in an open office. Even though the controllable light has to be shared with colleagues in the same zone, consensus control results in higher satisfaction compared to the condition without control and a fixed average work plane illuminance of 500 lx. Higher satisfaction is demonstrated with the amount of light on the users their desk and PC screen as well as with the quality of the light when offering control. In the condition with light controls, the average preferred illuminance values were shown to be lower than the fixed 500 lx work plane lighting, resulting in 27.2% lower energy usage by lighting in the testbed of this study. Consensus control did not introduce a negative effect on the environmental satisfaction or the mood of the office users.

Users have different lighting preferences and can be subdivided into profiles, based on their lighting preference, sensitivity and character. This supports the requirement that automated control systems should be capable of taking the profiled individual into account, rather than only information such as the time of day. Further analyses with larger user groups is needed to explore user profiles in detail.

The results of this study indicate an influence of lighting dimming speed on the user acceptance of light changes in the shared office space. In order to further refine conclusions on the impact of dimming speed it requires a follow-up exploration.

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