Influence of wall luminance and uniformity on preferred task illuminance

Citation for published version (APA):

Document license:
CC BY-NC-ND

DOI:
10.1016/j.buildenv.2017.02.026

Document status and date:
Published: 15/05/2017

Document Version:
Publisher’s PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:

• A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher’s website.
• The final author version and the galley proof are versions of the publication after peer review.
• The final published version features the final layout of the paper including the volume, issue and page numbers.

Link to publication

General rights
Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

• Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
• You may not further distribute the material or use it for any profit-making activity or commercial gain.
• You may freely distribute the URL identifying the publication in the public portal.

If the publication is distributed under the terms of Article 25fa of the Dutch Copyright Act, indicated by the “Taverne” license above, please follow below link for the End User Agreement:
www.tue.nl/taverne

Take down policy
If you believe that this document breaches copyright please contact us at:
openaccess@tue.nl
providing details and we will investigate your claim.
Influence of wall luminance and uniformity on preferred task illuminance

Sanae Chraibia a, b, *, Lisan Crommentuijn a, Evert van Loenen b, c, Alexander Rosemann b

a Philips Lighting, Eindhoven, The Netherlands
b Eindhoven University of Technology, Eindhoven, The Netherlands
c Royal Philips, Eindhoven, The Netherlands

A R T I C L E   I N F O

Article history:
Received 7 December 2016
Received in revised form 11 February 2017
Accepted 28 February 2017
Available online 1 March 2017

Keywords:
Lighting
Open office
Personal control
Brightness perception

A B S T R A C T

Literature suggests an influence of the luminance from non-horizontal surfaces in our visual field on our visual and psychological assessments of an office space. These assessments are believed to directly relate to our expressed preferred task illuminances.

This paper describes an evaluation in a mock-up of office, wherein wall conditions with a non-uniform and a more uniform light distribution of 3 different average luminance levels have been evaluated regarding their effect on users’ preferred task illuminance. Each condition is evaluated starting from three different initial desk illuminances.

For all test conditions, a wall with a non-uniformly distributed average luminance of 200 cd/m2 lead to significantly lower selected desk illuminances than a uniformly lit wall with the same average luminance level. In all cases, preferred task illuminances set were significantly lower when offering the lowest starting level for dimming of 300 lx. The range of preferred illuminance levels between subjects was also found to be smaller for dimming with the starting level of 300 lx at desk level.

The study suggests that when providing users with personal control they will control the total perceived brightness in their visual field, even though they are only directly affecting their task illuminance level. Triggering the selection of lower preferred illuminance levels due to a personal control starting level of 300 lx, will positively influence the energy used for lighting. The smaller range of preferred illuminance levels between subjects at the starting of 300 lx could reduce the risk of lighting preference related conflict between people. However, more research is needed to confirm that these smaller differences are also perceivable by users.

© 2017 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).

1. Introduction

With the changing character of office work, the majority of our tasks today include non-horizontal surfaces in the visual field. Literature indicates relations between the brightness of these non-horizontal surfaces and the users’ visual and psychological assessments of the space. Increasing wall luminance has led to a more stimulating room [1], increased assessment of brightness acceptability and pleasantness [2], and high brightness perceptions have been linked to improved assessments of comfort and spaciousness [3]. Besides the improved assessments, increased wall luminance has also been linked to lower preferred desktop illuminances [1,3], offering the potential to support energy efficiency. Reinforced by standards certifying and monitoring the performance of building features that impact health and well-being [4], users’ feeling of satisfaction and comfort becomes equally relevant.

Personal control is recognized as a means to enhance user satisfaction [5–8] and energy efficiency [9–12]. When applied in shared open office spaces, personal control becomes consensus control. In a recent field study, providing users with consensus control over a group of luminaires resulted in lower energy usage and improved satisfaction with light quality and quantity, compared to a situation without control [13]. Even though consensus control did improve satisfaction compared to a no-control situation, some users did experience conflicting preferences with their neighbours regarding preferred illuminances. A challenge remains, in designing office lighting that limits the risk of
conflict between people due to differences in lighting preference, while maintaining the energy saving benefits.

1.1. Background

When offered control, people are given the ability to alter the illuminance on their desk. Besides the benefits of lighting within the preference of users [5], Sadeghi et al. recently reported a relation between occupant perception of control and the acceptability of a wider range of visual conditions [14]. This increases in relevance when dealing with multiple users in one open office space. However, the experiments of Sadeghi et al. were conducted in private offices. In 2013 and 2014, field studies were performed evaluating personal control in an open office. The first study is published in Ref. [13]. In the interviews the participants shared their self-assessed lighting preference, which could be generalized in a bright, medium, or dark preference category [15]. This self-classification could be based on the users’ preference for task illuminance levels for the visual task, but could also be their preference regarding the office appearance. Fotios also appoints the importance of office appearance, stating that even though it has been shown that tasks on self-luminous displays could be carried out on lower illuminance levels, this is not done because people like a bright and visually interesting environment [16]. If perception of brightness could be maintained at a lower desk illuminance level, energy consumption could be reduced.

Due to a strong tendency of subjects to assess the brightness of all areas similarly, Moore states that occupants view the luminous environment as a whole [17]. This suggests that control may have the potential to influence opinions of other areas than those directly controlled. Moore did not find any relationships between the users liking the environment and an increasing or decreasing assessment of brightness in the reported study. In a study performed by Manav, a strong increase in the desk illuminance did lead to improved user assessments of comfort and spaciousness [3]. When increasing the desk illuminance from 500 lx to 2000 lx, the users’ brightness evaluation of the wall opposite the user also increased, which was evaluated positively. Changing the correlated color temperature of the lighting did not affect the perceived brightness in this study.

It was already in 1987 that Ooyen et al. showed that the preferred work plane illuminance depends on the wall luminance. With increasing wall luminance, a lower desktop illuminance was preferred, and vice versa [1]. They stated that the wall luminance contributed most to the way the room was experienced, where increasing the wall illuminance lead to a more stimulating room. Carter et al. suggest an influence of wall luminance on the user’s perception of horizontal illuminance through increased assessment of acceptability of brightness and pleasantness when increasing the wall luminance [2]. Berruto et al. showed with their first phase experiments in 1994, that participants preferred wall luminances to be minimized behind the monitor when performing a PC task [18]. However, the task did consist of white characters displayed on a dark background, which is not common in current regular office tasks. In the second phase of the study, in 1997, they used a standard Word document task with black characters on a white background, and reported that subjects preferred a screen immediate surround luminance inferior or equal to the screen background luminance [18]. In the same study, they also showed that subjects who set low horizontal illuminance levels (respectively high illuminance levels) tended to also set low luminances on walls (respectively high wall luminances). They concluded that, regardless of the task performed, the wall luminance was shown to have a significant effect on users’ satisfaction, and appeared to deserve more attention.

In a study performed by Durak and colleagues in 2007, different lighting arrangements were evaluated on their impact on impressions of the space [19]. Regarding the evaluation of spaciousness and visual order, the arrangement including illumination of walls by wall washing scored the highest. Islam et al. showed in their acceptance studies, that users’ preferred light conditions were influenced by the task illuminance, which was found to relate to the spatial brightness [20]. The term spatial brightness relates to the perceived brightness of a space [21]. The users preferred the conditions under which they found the lighting environment to look brighter and more spacious [20]. In a laboratory study performed by de Vries et al. with 37 participants [22], three wall luminance conditions were assessed with average luminance levels of 11, 36, and 73 cd/m² respectively. Increasing wall illuminance levels lead to increasing room appraisal by the subjects, regarding attractiveness as well as illumination. The higher wall luminance made the overall appearance more spacious and more attractive.

In a study by Sheedy et al. [23] the effects of the luminance surrounding of a computer monitor were evaluated. When performing tasks on a monitor with a luminance of 91 cd/m², optimal performance by the users occurred when the surround luminance was 50 cd/m² or higher for the younger group of subjects (23–39 years) and 91 cd/m² or higher for the older group (47–63 years). The preferred surround luminance was 87 cd/m² for the younger and 62 cd/m² for the older group, both below the luminance of the screen. In the study performed by Yang et al. the preferred background luminance intensities were found to be linearly correlated with screen luminance intensities [24]. However, in this study the computer screen was position directly against a wall, and only the direct surround of the screen was taken into consideration.

In the latter study of Sheedy, the wall was uniformly lit using a projection. In a study performed by Tiller and Veitch [25] rooms with a non-uniform luminance distribution appeared brighter for the subjects than the uniform variants. The non-uniform rooms required less work plane illuminance to reach a brightness impression equivalent to the rooms with a uniform luminance distribution. Sullivan and Donn reported in their literature review that the majority of studies suggest that more uniform lighting appears brighter than less uniform lighting [26]. In the pilot study presented in the same paper, Sullivan and Donn show that less uniform spaces were evaluated to appear brighter [26], similar to the results of Tiller and Veitch. Disagreement in literature about the direction of this effect raises the possibility that the relationship between uniformity and spatial brightness may be more complicated than this. ‘Brightness’ (perceived luminance) and ‘visual interest’ (variation in luminance) are stated by Moore et al. as two features associated with visually preferred environments [8]. There is however a limit. Newsham et al. showed in an earlier study that people want spaces that are somewhat uniform, but not monotonous [27]. Veitch and Newsham [28] state that a difference might exist between the preferred luminous conditions and the interestingness of a space, which increases with a wider variation of luminance.

Most studies do suggest walls to be particularly important to affect the apparent brightness. This may however also be due to their dominance in the observed visual field, or their lead role in performed studies. Sullivan and Donn report that it is ‘plausible’ that the walls are of particular importance to the brightness impression of a space, but that literature does not provide sufficient evidence to support such claims [26].

In an open office, the walls enclosing the office are shared by the users of the office as part of their visual field. Based on previous studies, the walls are believed to influence the brightness perception of the office space, and with that influencing the preferred task illuminance of users, as expressed by personal control. This paper
describes the results of a laboratory study in which the effects of the wall luminance and wall uniformity on the preferred task illumination are evaluated.

1.2. Hypothesis

Based on previous studies, the authors believe that when providing office workers with task lighting control, users do not only select a preferred task illumination to meet personal requirements for their visual task. They furthermore see in the personal control a means to set a visually preferred lighting environment. This includes the task lighting but also the surrounding luminance distribution. Consequently, it is hypothesized that the wall luminance in the visual field of the user will influence the user’s preferred task lighting.

High wall luminance levels are believed to lead to lower preferred task illuminances, due to a higher brightness perception. High wall luminance levels are believed to reduce the difference in preferred task illumination between occupants.

Depending on the luminaires used, walls can be illuminated with a different level of uniformity. As shown by Tiller and Veitch [25] and Sullivan and Donn [26], a non-uniform wall luminance distribution is expected to increase the brightness perception compared to a more uniform illuminated wall. Due to this higher brightness impression, a non-uniform wall luminance distribution is believed to lead to lower preferred task illuminances. A non-uniform wall luminance distribution is believed to also reduce the difference in preferred task illumination between occupants.

Conditions that lead to lower preferred task illuminances create energy saving opportunities. Reducing the difference in preferred task illumination between occupants, will reduce the risk of conflict between people due to lighting.

2. Methodology

In a simulated work environment, an experiment has been carried out to evaluate the hypotheses. A lighting system was installed to create different lighting conditions. Participants were invited to experience these conditions and make adjustments expressing their preferred lighting.

2.1. Test bed

The user study was conducted in a laboratory in the Netherlands, where a full-scale mock-up office of 7.2 × 7.2 × 2.8 m was built. The participant's visual field included multiple desks, the ceiling and a wall, simulating a situation in an actual open office space. Fig. 1 shows an impression of the space. Four desks were equipped with a mouse, a keyboard and a Philips 24” Brilliance LCD monitor, set to an identical screen luminance with an average of 100 cd/m². The participant's desk (desk 4) also had a user interface to select the desired task illumination. The fifth desk (desk 5) was equipped with two laptops and a control panel for the researcher to switch between light conditions. Screens in front of the windows blocked the daylight in order to exclude the impact of exterior light variations on the experiments.

The electric lighting system consisted of twelve dimmable recessed ceiling Philips PowerBalance LED Luminaires (600 × 600 mm, 4000 K, Ra > 80, UGR < 16, 345, 3400 lm) and ten Philips StyliD Compact power LED spots (4000 K, Ra > 80, SLED17, 2000 lm). The lighting system was divided in five luminaire control groups, as shown in Fig. 2, to obtain the desired light settings during the experiment. Three luminaire groups illuminated the walls; 6 recessed luminaires (group 1) and 5 spots (group 2) illuminated the ‘test wall’ in front of the user, and 5 spots illuminated the wall behind the user (group 3), to avoid an uncomfortable dark background. Two luminaire groups illuminated the desks in the office space; the ‘control group’ existed of 2 recessed luminaires controllable by the participant (group 4), and 4 recessed luminaires were commissioned to illuminate the other desks at a constant level during the test (group 5). The ‘control group’ consisted of 2 luminaires to simulate shared control in open office environments [8,13], and allow for a dimming range from approximately 300 lx–700 lx average desk illumination. Fig. 3 shows the luminous intensity distribution of the ‘control group’ luminaires.

2.2. Participants

A total of N = 54 subjects participated in the study. N = 30 were male, and N = 24 were female, with an age varying from 18 to 29 years. Participants did not work in the field of lighting application or perception and had no visual disabilities that were not compensated by lenses or glasses.

2.3. Study design

The experiment was conducted in August and September of 2015, on weekdays between 9am and 6pm. Each experimental session included one participant at a time with a total duration of 1.5 h. Each test day had four experimental time slots.

Participants were seated at desk 4, and started with unconscious adaptation to the baseline light setting, commissioned at an average horizontal desk illuminance of 500 lx. Both, the ‘test wall’ and the wall behind the user, were non-uniformly lit, with a first luminance condition of the ‘test wall’ set in accordance with the participant's experimental sequence. During this adaption time, the researcher explained the experimental procedure, and the participant filled in an online survey on the PC. The survey included demographic questions and a self-assessed distraction level.

During the test the participants were asked to perform a reading task provided on the PC monitor. The reading task consisted of a page with randomly picked “did-you-know” facts. The simple reading task was selected to avoid deep visual focus on the PC monitor, and enable observation of the office environment. Every 60 s the participant was interrupted by the researcher to set a preferred illumination using the provided user interface. When the desired illumination was obtained, the participant pressed one of the buttons in the top bar of the user interface (Fig. 4), to log the preferred level. After setting and storing the preferred illumination, the researcher switched the system to the next light condition. The participants could move to the next reading page on the PC, until interrupted for a next preference selection. This was repeated until all conditions were evaluated twice. The interaction with the slider...
directly dimmed luminaire control group 4 up or down (Fig. 2), influencing the task illuminance of the participant based on the selected dimming levels in each condition. The finally set preferred illuminance was logged for each condition. At the end of the experiment, in a conversation between the researcher and the participant additional experiences the participant wanted to share were captured.

2.4. User interface

To avoid that the user interface had any influence on the selected illuminance, the slider was designed to not have an anchor point nor a reference to the last selected level (Fig. 4). Previous studies [29] have shown that people are not consistent in the choices they make when selecting a task illuminance. The range of the provided control interface as well as the starting position when offered control were shown by Uttley et al. to have an influence on the selected illuminances [30]. Additionally, participants might self-classify their lighting preference, as “I like bright light”, or “I

Fig. 2. Floorplan simulated work environment.

Fig. 3. Photometric diagram 'control group' luminaires (Philips PowerBalance).

Fig. 4. User interface position on the desk – layout of the slider for light control.
prefer dimmed lighting", which could influence them to select their preference on a similar end of the scale [13].

In this study, the interface was offered on a tablet, placed vertically on the desk. It was decided not to present the interface on the PC monitor, to trigger people to look away from their monitor and observe the office space. To avoid reflections of the luminaires on the interface screen, but allow for easy interaction, the user interface was positioned under an angle, as shown in Fig. 4. The simplicity of the interface interaction enabled the participants to maintain their viewing direction when using the interface. Participants received instructions on the use of the interface during the introduction at the start of the experiment. To avoid centring bias [30], the user interface design did not provide a reference to the centre of the range. Sliding from the middle to the right dimmed the lighting up and sliding from the middle to the left dimmed it down. Major sliding movements from the middle to the end translated to changing the dimming level by a step of 6% of the maximum luminaire output. Minor sliding movements led to a dimming step of 3%. Multiple sliding movements back and forth formed the centre, could be made by the participants, until the preferred level was set.

2.5. Light conditions

To evaluate the influence of wall luminance and uniformity on the preferred task lighting, the participants were asked during the test to select their preferred illuminance for different light conditions. These conditions consisted of three different average wall luminance levels, offered in a non-uniform distribution as well as a more uniform distribution. The uniformity describes how evenly the light is spread on a surface, i.e. in this study the uniformity of the wall luminance. To create wall conditions with a uniform luminance distribution, a combination of five recessed luminaires and five spots is used (group 1 + 2, Fig. 2). The light conditions are commissioned to obtain as much uniformity as possible with the lighting installation, for three different luminance levels. To achieve non-uniform wall luminance distributions, only the five wall spots directed at the wall are used (group 1, Fig. 2), for three different luminance levels. Table 1 presents the luminance characteristics of the six different conditions. (Note that the absolute luminance values can be influenced by the resolution of the camera.) The conditions were commissioned using the average wall luminance, measured with a luminance camera (LMK5 Color with software package Technoteam LMK LabSoft Standard Color v12.7.23). The lighting installation was designed to meet the proposed average wall luminance as well as the default desk illuminance of 500 lx. Fig. 5 and Fig. 6 show impressions and luminance distribution images of the different conditions, with the level of uniformity $U_i (> L_{\min}/L_{\avg})$ of the "test wall".

For each wall setting three different start-points are used from which the participants dimmed up or down to select their light preference. The study of Uttley et al. [29] demonstrated that besides the influence of the offered range on the selection of preferred luminances, the start-point has an influence as well. They showed that when offering a low start position, illuminance levels selected were lower than when offering a high start position. Results of the ratings of satisfaction with the illuminance did not suggest an effect of the different ranges or start positions offered, despite the significant difference in illuminances.

The three start positions used in the current experiment were: the default of 500 lx as by standards recommended [31]; a maximum setting of 700 lx by which 90–99% of people are expected to achieve their preferred illuminance [9]; and the minimal luminaire output of the control group. Table 2 shows the different conditions, and the corresponding average horizontal task (desk) illuminance of desk 4, being the participant’s workplace. In each setting, users could select their preferred illuminance in the range corresponding to the presented values from minimum to maximum.

The luminaires above the other desks are commissioned to deliver a desk illuminance of 500 lx on average in the default start position, and are kept constant for all 3 start positions of that wall setting.

Each participant was asked to set the preferred task lighting in a first and second trial for all wall lighting conditions, to evaluate the consistency of the users. Table 3 shows the average horizontal illuminance at desk 4 for the different dimming levels of the controllable luminaires. The conditions were presented to the participants in different sequences to avoid an order effect. The 6 different sequences used during the test are presented in Table 4. Each condition was first evaluated from the default dimming start position, followed by the minimum and the maximum start position, before continuing to the next condition. For sequence 1 this meant $N_{50,\min}$, $N_{50,\max}$, and $N_{50,\max}$, followed by $U_{50,\min}$, $U_{50,\max}$, and so on.

2.6. Analyses

The preferred illuminance was selected by the participants on a continuous scale. Given the large sample size and the normal distribution of the data, differences between conditions are analysed using a paired samples $t$-test and a repeated measures analysis of variance. A repeated measures analysis of variance is used to analyse an effect of self-rated sensitivity to distractions on preferred desk illuminance. A one-way between-groups analysis is used to assess effects of demographic characteristics or independent between-groups variables on preferred desk illuminances. For the significance tests a significance of $p < 0.05$ is used. Analyses are performed using IBM SPSS Statistics.

3. Results

3.1. Control variables

A repeated measures analysis of variance test with two within-subject factors showed no significant interaction effect between start-point and trial for the different wall conditions ($p > 0.05$), and no significant main effect for trial in which the preferred illuminance was selected in each condition ($p > 0.05$). In further analyses the average value of the preferred illuminance selected by each

Table 1

Properties of the different wall conditions.

<table>
<thead>
<tr>
<th>Non-uniform</th>
<th>Luminance in cd/m²</th>
<th>$U_i$</th>
<th>Uniform</th>
<th>Luminance in cd/m²</th>
<th>$U_i$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Min</td>
<td>Max</td>
<td>Range</td>
<td>Avg</td>
<td>Min</td>
</tr>
<tr>
<td>N50</td>
<td>23</td>
<td>111</td>
<td>88</td>
<td>52</td>
<td>0.44</td>
</tr>
<tr>
<td>N100</td>
<td>28</td>
<td>217</td>
<td>189</td>
<td>104</td>
<td>0.27</td>
</tr>
<tr>
<td>N200</td>
<td>48</td>
<td>600</td>
<td>552</td>
<td>253</td>
<td>0.19</td>
</tr>
</tbody>
</table>

$U_i (= L_{\min}/L_{\avg})$. 
participant in the first and second trial is used. The start-point did show a significant main effect on the illuminances selected by the users in all conditions \((p = 0.000)\). The start-points will not be combined, and will be analysed separately for all conditions, resulting in 18 different conditions.

As stated in the methodology section, participants evaluated the conditions in one of six different sequences, and during one of four timeslots. A one-way between groups analysis showed no significant effect of the experienced sequence on the selected illuminance \((p > 0.05)\) nor of the participation timeslot \((p > 0.05)\). In further analyses no distinction in the population will be made based on sequence or timeslot.

By means of a one-way between groups analysis, the demographic characteristics of the subjects are evaluated regarding their effect on the preferred illuminances. No significant effect has been found for subjects’ age, gender, visual corrections, ethnic origin, level of education, or the type of work the subjects perform in their daily job.

3.2. Wall luminance conditions

Results of the preferred illuminances of the users are presented in Fig. 7, with from left to right the conditions with an average wall luminance of respectively 50 cd/m², 100 cd/m², and 200 cd/m². Pairs of a non-uniform (N) and more uniform (U) wall condition with a similar average wall luminance and start-point are presented alongside each other.

3.2.1. Uniformity

To analyse the effect of uniformity, pairs are created between the non-uniform (N) and more uniform (U) wall conditions with a similar average wall luminance and start-point. A paired samples t-test has been performed for each pair. The non-uniform 200 cd/m² (N200) conditions showed a significant lower preferred desk illuminance than the uniform 200 cd/m² conditions (U200), for all three start-points (Table 5). No effect of uniformity on selected illuminances is found for the conditions with a wall luminance of 50 cd/m² and 100 cd/m² \((p > 0.05)\). In further analyses, an average preferred illuminance of the uniform and non-uniform conditions is used for the 50 cd/m² and 100 cd/m² wall luminance conditions. These are labelled as conditions X50 and X100 respectively.

3.2.2. Luminance

For the analysis, conditions with a similar start-point and a
different average wall luminance have been paired. The preferred illuminances of the users have been compared by using the paired samples t-test. Preferred desk illuminances did not differ significantly between the X50 to the X100 conditions for any of the 3 start-points (p > 0.05). Preferred desk illuminances did differ significantly for most start-points when comparing the X50 as well as the X100 conditions to the uniform and non-uniform 200 cd/m² conditions. Table 6 shows the results of the analyses. Compared to the X50 and X100 conditions, the selected illuminances are higher in almost all uniform 200 cd/m² conditions and lower in the non-uniform 200 cd/m² condition, as shown by the mean difference in lx presented in Table 6.

3.2.3. Preference spread

The spread of the users’ selected illuminances in each condition,

Table 2

<table>
<thead>
<tr>
<th>Wall setting</th>
<th>Distribution</th>
<th>Desk illuminance in lx at desk 4, at start-point:</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>min</td>
<td>default</td>
</tr>
<tr>
<td>N50</td>
<td>Non-uniform</td>
<td>308</td>
<td>535</td>
</tr>
<tr>
<td>U50</td>
<td>Uniform</td>
<td>311</td>
<td>549</td>
</tr>
<tr>
<td>N100</td>
<td>Non-uniform</td>
<td>312</td>
<td>525</td>
</tr>
<tr>
<td>U100</td>
<td>Uniform</td>
<td>321</td>
<td>560</td>
</tr>
<tr>
<td>N200</td>
<td>Non-uniform</td>
<td>335</td>
<td>528</td>
</tr>
<tr>
<td>U200</td>
<td>Uniform</td>
<td>294</td>
<td>471</td>
</tr>
</tbody>
</table>

Fig. 6. Pictures and luminance distribution images of the non-uniform wall conditions.

Table 3

<table>
<thead>
<tr>
<th>Dimming level in percentage</th>
<th>Desk illuminance in lx at desk 4</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>N50</td>
</tr>
<tr>
<td>1</td>
<td>311</td>
</tr>
<tr>
<td>10</td>
<td>349</td>
</tr>
<tr>
<td>20</td>
<td>391</td>
</tr>
<tr>
<td>30</td>
<td>433</td>
</tr>
<tr>
<td>40</td>
<td>475</td>
</tr>
<tr>
<td>50</td>
<td>517</td>
</tr>
<tr>
<td>60</td>
<td>559</td>
</tr>
<tr>
<td>70</td>
<td>601</td>
</tr>
<tr>
<td>80</td>
<td>643</td>
</tr>
<tr>
<td>90</td>
<td>685</td>
</tr>
<tr>
<td>100</td>
<td>727</td>
</tr>
</tbody>
</table>
as displayed by the boxplots in Fig. 7, does not suggest an effect of uniformity or wall luminance on the differences between people’s preference. The boxplots do indicate an effect of start-point on the spread of preferences. The minimal start-points of all conditions resulted in smaller interquartile ranges than the default and maximum start-points. Table 7 presents the descriptive statistics of each condition, sorted by increasing interquartile range (IQR).

### 3.3. Self-assessed level of distraction

Participants have been divided in 5 groups, based on the self-assessed sensitivity to distractions, expressed in the survey. The five groups represent people that are generally distracted slowly (n = 5), somewhat slowly (n = 0), neutral (n = 15), somewhat fast (n = 27), and fast (n = 7). Fig. 8 shows the mean preferred desk illuminance of each condition for the different distraction categories. The fast distracted people have the lowest mean preferred desk illuminances, and the slow distracted people the highest. A repeated measures analysis confirms an effect for the self-assessed distraction sensitivity on the preferred illuminances (F = 5.434, p = 0.003). A post hoc test showed a significant difference in mean preferred illuminance between fast distracted people and the other categories (slowly: p = 0.001, neutral: p = 0.031, somewhat fast: p = 0.026).

Based on the significant effect of the users’ sensitivity to distractions on the preferred illuminance, two groups can be created: an average distracted group (n = 47) and a fast distracted group (n = 7) of people.

For the average distracted group, the results for effect of uniformity, as well as luminance on selected illuminances are similar to the total population. Results are shown in Table 8 and Table 9.

In the small group of fast distracted people, an effect of

### Table 4
Overview of the sequences in which the light conditions were evaluated.

<table>
<thead>
<tr>
<th>Sequence</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trial 1</td>
<td>N50</td>
<td>U50</td>
<td>N100</td>
<td>U100</td>
<td>N200</td>
<td>U200</td>
</tr>
<tr>
<td></td>
<td>U100</td>
<td>U200</td>
<td>U50</td>
<td>U50</td>
<td>N200</td>
<td>U200</td>
</tr>
<tr>
<td></td>
<td>U100</td>
<td>U200</td>
<td>U50</td>
<td>U50</td>
<td>N200</td>
<td>U200</td>
</tr>
</tbody>
</table>

### Table 5
Results paired samples test on wall uniformity.

<table>
<thead>
<tr>
<th></th>
<th>Sig. (2-tailed)</th>
<th>Effect size</th>
<th>Mean difference in lx</th>
<th></th>
<th>Sig. (2-tailed)</th>
<th>Effect size</th>
<th>Mean difference in lx</th>
</tr>
</thead>
<tbody>
<tr>
<td>N50max - U50min</td>
<td>0.411</td>
<td>0.01</td>
<td>-4</td>
<td>N200min - U200min</td>
<td>0.00</td>
<td>0.59</td>
<td>-47</td>
</tr>
<tr>
<td>N50def - U50def</td>
<td>0.054</td>
<td>0.07</td>
<td>-18</td>
<td>N200def - U200def</td>
<td>0.01</td>
<td>0.12</td>
<td>-22</td>
</tr>
<tr>
<td>N50max - U50max</td>
<td>0.540</td>
<td>0.01</td>
<td>-6</td>
<td>N200max - U200max</td>
<td>0.00</td>
<td>0.44</td>
<td>-43</td>
</tr>
<tr>
<td>N100min - U100min</td>
<td>0.956</td>
<td>0.00</td>
<td>0</td>
<td>N100def - U100def</td>
<td>0.22</td>
<td>0.03</td>
<td>10</td>
</tr>
<tr>
<td>N100max - U100max</td>
<td>0.734</td>
<td>0.00</td>
<td>-3</td>
<td>N100max - U100max</td>
<td>0.00</td>
<td>0.00</td>
<td>0</td>
</tr>
</tbody>
</table>
uniformity on preferred illuminances is only found for the minimal start-point of the 200 cd/m² wall condition (p = 0.006) (see Table 9). An effect of luminance on preferred illuminances is only found between the average 50 cd/m² wall condition with minimal start-point and the uniform 200 cd/m² wall condition with minimal start-point (p = 0.007).

4. Discussion

4.1. Study design

The light conditions were not presented to the participants in a completely randomized order, but in one of six sequences.
However, analyses showed no effect of the sequence on the users’ selected illuminances. Additional analyses of an order effect also showed no significant effects of a previously presented condition. It is therefore not expected that repeating the experiment with a different sequence of conditions would lead to different results.

During the introduction phase at the start of the experiment, the participants could get used to the environmental conditions of the tested office. It is not expected that an evaluation in a different period of the year would lead to different results.

Different luminaires have been used to establish the uniform and non-uniform light conditions in this study. The non-uniform light distribution has been achieved by spot light luminaires. Recessed ceiling luminaires in combination with the spots served to illuminate the ‘test wall’ uniformly. In both, the uniform and the non-uniform conditions, an increasing average wall luminance also lead to a decrease of the uniformity U50, as can be seen in Table 1. Even though the uniformity of the N50 condition is comparable to that of the U200 condition, it is significantly lower than that of the U50 condition, and therefore considered and analysed as a non-uniform condition. The effect of the luminaires’ luminances on the participants’ response is minimized by choosing luminaires for the U50 condition, and therefore considered and analysed as a non-uniform condition. The non-uniformity of the U200 condition, it is significantly lower than that of the U50 condition, and therefore considered and analysed as a non-uniform condition. The non-uniformity of the U200 condition, it is significantly lower than that of the U50 condition, and therefore considered and analysed as a non-uniform condition. The non-uniformity of the U200 condition, it is significantly lower than that of the U50 condition, and therefore considered and analysed as a non-uniform condition. The non-uniformity of the U200 condition, it is significantly lower than that of the U50 condition, and therefore considered and analysed as a non-uniform condition. The non-uniformity of the U200 condition, it is significantly lower than that of the U50 condition, and therefore considered and analysed as a non-uniform condition. The non-uniformity of the U200 condition, it is significantly lower than that of the U50 condition, and therefore considered and analysed as a non-uniform condition. The non-uniformity of the U200 condition, it is significantly lower than that of the U50 condition, and therefore considered and analysed as a non-uniform condition. The non-uniformity of the U200 condition, it is significantly lower than that of the U50 condition, and therefore considered and analysed as a non-uniform condition. The non-uniformity of the U200 condition, it is significantly lower than that of the U50 condition, and therefore considered and analysed as a non-uniform condition. The non-uniformity of the U200 condition, it is significantly lower than that of the U50 condition, and therefore considered and analysed as a non-uniform condition. The non-uniformity of the U200 condition, it is significantly lower than that of the U50 condition, and therefore considered and analysed as a non-uniform condition. The non-uniformity of the U200 condition, it is significantly lower than that of the U50 condition, and therefore considered and analysed as a non-uniform condition. The non-uniformity of the U200 condition, it is significantly lower than that of the U50 condition, and therefore considered and analysed as a non-uniform condition. The non-uniformity of the U200 condition, it is significantly lower than that of the U50 condition, and therefore considered and analysed as a non-uniform condition. The non-uniformity of the U200 condition, it is significantly lower than that of the U50 condition, and therefore considered and analysed as a non-uniform condition. The non-uniformity of the U200 condition, it is significantly lower than that of the U50 condition, and therefore considered and analysed as a non-uniform condition. The non-uniformity of the U200 condition, it is significantly lower than that of the U50 condition, and therefore considered and analysed as a non-uniform condition.

4.2. Wall conditions

Preferred desk illuminances are found to be lower when offering an average wall illuminance of 200 cd/m² in a non-uniform distribution compared to a more uniform distribution with the same average illuminance. For the conditions with an average wall illuminance of 50 cd/m² or 100 cd/m², no significant effect of wall uniformity on the selected desk illuminances is found. The preferred desk illuminances are found to be significantly higher when offering an average wall illuminance of 200 cd/m² in the more uniform distribution, compared to most other conditions (N200 all, X50, and X100 min max). The differences in users’ preferred desk illuminance in the evaluated conditions, may be influenced by a different spatial brightness experience between conditions. As reported in previous studies, the spatial brightness is influenced by among others, the desk illuminance and the light distribution in the office [20,21,26]. However, as also stated by Cuttle, linking appearance to spatial brightness, might involve more [32].

The differences in preferred illuminances between people are expressed by the interquartile range of each condition. The range in which participants set their preferred task illuminance did not show a consistent difference for the two types of uniformity, nor for the three wall illuminance levels. However, the conditions with a low start-point for dimming of around 300 lx did show a smaller interquartile range, compared to the conditions with a start-point of 500 lx or 700 lx. This suggests that offering a low start-point will reduce the difference in preferred task illuminances between occupants. To take people’s non-linear perception of light [33] into account, the results of the selected illuminances of users are presented on a logarithmic scale in Fig. 9.

When user preferences are plotted on a logarithmic scale to represent perceived brightness, the differences in interquartile range between the conditions is still observable but becomes less obvious. This suggests that for higher preferred illuminances, the spread between people may be larger, without people experiencing these differences as larger.

Satisfaction of participants with the different wall conditions has not been quantified in this study. In informal interviews 8 participants indicated to prefer a uniformly illuminated wall over a non-uniform wall, 2 participants indicated to prefer a non-uniformly illuminated wall, and 44 participants did not express a preference. To assess the satisfaction with different levels of wall illuminance and uniformity, further research is needed.

The start-point from which users are asked to set their preference has a significant effect on the selected task illuminance. For each condition the mean preferred task illuminance is found to be lowest for the minimum start-point, followed by the default and

### Table 8
Results paired samples test per distraction group — effect of wall uniformity on the preferred desk illuminance.

<table>
<thead>
<tr>
<th></th>
<th>Average distracted group (n = 47)</th>
<th>Fast distracted group (n = 7)</th>
<th>Average distracted group (n = 47)</th>
<th>Fast distracted group (n = 7)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Sig. (2-tailed)</td>
<td>Effect size</td>
<td>Sig. (2-tailed)</td>
<td>Effect size</td>
</tr>
<tr>
<td>N50min - U50min</td>
<td>0.502</td>
<td>0.01</td>
<td>0.510</td>
<td>0.09</td>
</tr>
<tr>
<td>N50def - U50def</td>
<td>0.112</td>
<td>0.06</td>
<td>0.197</td>
<td>0.30</td>
</tr>
<tr>
<td>N50max - U50max</td>
<td>0.696</td>
<td>0.00</td>
<td>0.550</td>
<td>0.07</td>
</tr>
<tr>
<td>N100min - U100min</td>
<td>0.945</td>
<td>0.00</td>
<td>0.882</td>
<td>0.00</td>
</tr>
<tr>
<td>N100def - U100def</td>
<td>0.366</td>
<td>0.02</td>
<td>0.357</td>
<td>0.17</td>
</tr>
<tr>
<td>N100max - U100max</td>
<td>0.808</td>
<td>0.00</td>
<td>0.252</td>
<td>0.24</td>
</tr>
</tbody>
</table>

### Table 9
Results paired samples test per distraction group — effect of average wall luminance on the preferred desk illuminance.

<table>
<thead>
<tr>
<th></th>
<th>Average distracted group (n = 47)</th>
<th>Fast distracted group (n = 7)</th>
<th>Average distracted group (n = 47)</th>
<th>Fast distracted group (n = 7)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Sig. (2-tailed)</td>
<td>Effect size</td>
<td>Sig. (2-tailed)</td>
<td>Effect size</td>
</tr>
<tr>
<td>X50min - U200min</td>
<td>0.000</td>
<td>0.40</td>
<td>0.007</td>
<td>0.76</td>
</tr>
<tr>
<td>X50def - U200def</td>
<td>0.340</td>
<td>0.02</td>
<td>0.714</td>
<td>0.03</td>
</tr>
<tr>
<td>X50max - U200max</td>
<td>0.000</td>
<td>0.26</td>
<td>0.648</td>
<td>0.04</td>
</tr>
<tr>
<td>X100min - U200min</td>
<td>0.000</td>
<td>0.32</td>
<td>0.731</td>
<td>0.03</td>
</tr>
<tr>
<td>X100def - U200def</td>
<td>0.599</td>
<td>0.01</td>
<td>0.975</td>
<td>0.00</td>
</tr>
<tr>
<td>X100max - U200max</td>
<td>0.000</td>
<td>0.34</td>
<td>0.727</td>
<td>0.03</td>
</tr>
<tr>
<td>X50min - X100min</td>
<td>0.230</td>
<td>0.03</td>
<td>0.235</td>
<td>0.26</td>
</tr>
<tr>
<td>X50def - X100def</td>
<td>0.081</td>
<td>0.07</td>
<td>0.820</td>
<td>0.01</td>
</tr>
<tr>
<td>X50max - X100max</td>
<td>0.928</td>
<td>0.00</td>
<td>0.442</td>
<td>0.12</td>
</tr>
</tbody>
</table>
maximal start-points, which is in line with the findings of Uttley et al. [29]. In the interviews, participants indicated not to have noticed that only the task illuminance changed when moving to a next start-point within the same wall condition. They did not notice the sequence of changing wall conditions every three evaluations.

The self-assessed sensitivity for distractions showed an effect on the preferred illuminances of the users. Fig. 8 shows that the more easily users are distracted, the lower is their average selected desk illuminance, with a significant difference between the “fast distracted” people and the other distraction categories. This can be taken as an indication that fast distracted people are also more sensitive to light and therefore prefer lower illuminances. Further research is needed to validate these potential relations.

Exploring the possible explanations for the reported effects, the wall conditions have been inspected in more detail. A high maximum wall luminance (as present in the N200 condition) may have positively influenced the perceived room brightness, leading to a lower tendency to increase the room brightness by increasing the desk illuminance. This is however not evaluated in the scope of this study. A described potential effect of a high maximum wall luminance would be consistent with the observation that the N200 condition led to a lower average selected illuminance than any of the other conditions, although only significantly for X50min, X50def, and X100min. The study of de Vries et al. showed that by increasing the wall luminance, the room appraisal increased both in terms of attractiveness and perceived illuminance [22]. The high wall luminance in the study of Newsham et al. made the space more spacious and attractive [27]. In line with the suggestions of both studies, participants could have been expressing a preference relating to appearance, and to a lesser degree relating to visual comfort. Based on this study it is unclear what the effect of a maximum wall luminance higher than 600 cd/m² will be. Additional research on the relation between the assessment of room appearance and the maximum wall luminance is needed for further qualified statements.

The U200 condition had a minimum wall luminance (94 cd/m²) close to the luminance of the PC monitor (100 cd/m²) on which the participant performed the task. The absence of background areas with a lower luminance than the task could have contributed to the significantly higher selected desk illuminances in this condition. This suggests that when a contrast between task and background is not observable, users might have the tendency to increase their task lighting, in order to achieve this contrast. This is in line with findings of Sheedy et al., where preferred surround luminance levels were found to be lower than the luminance of the task [23]. The effect is not found for the conditions with an average wall luminance of 100 cd/m², which may be due the presence of areas with a lower luminance than the PC monitor, as can be seen in Table 1 and Figs. 5 and 6. Additional research is needed to investigate the suggested effect absence of low luminance background areas could have on selected desk illuminances.

5. Conclusions

In this study it has been shown that for an average wall luminance of 50 cd/m² or 100 cd/m², the uniformity of the wall does not influence the selected task illuminances by users. A wall with a non-uniformly distributed average illuminance of 200 cd/m² leads to lower selected desk levels than situations with an average wall luminance of 50 cd/m² or 100 cd/m². A non-uniformly illuminated wall with a high average luminance of 200 cd/m² has been found to lower selected preferred illuminances of users compared to more uniformly illuminated walls with similar or lower average luminance levels.

Results indicate that when provided with controls, users do not only select the lighting required for their visual task, but incorporate the observations in their visual field in their selected preference. This study showed that the luminance level and uniformity distributions of the wall in the visual field influence the selected preferred task illuminance of users. The results indicate that high maximum luminance values of the wall in the visual field and with it high perceived brightness levels, lead to lower selected desk illuminance levels. The results also indicate that high minimum luminance values of the wall in the visual field, creating little
contrast between the task and the background, lead to higher selected desk illuminance levels.

The start-point for dimming of the task lighting has a significant influence on users’ selected task illuminances. A start desk illuminance of around 300 lx leads to lower selected illuminances by users than a start desk illuminance around 500 or 700 lx. A start-point around 300 lx also leads to smaller differences in preferred illuminances between users.

Offering users of open offices personal control with a 300 lx desk level as a starting position to control their desk illuminance, instead of the by standards recommended 500 lx, results in 26% lower selected preferred illuminances. Triggering lower selected illuminances, leads to lower energy used for lighting. A 300 lx desk level as a start-point has also the potential to reduce the risk of conflict between people due to a smaller range of preferred illuminances. However, more research is needed to confirm that these smaller differences are also perceivable by users.

Acknowledgements

This research was performed within the framework of the strategic joint research program on Intelligent Lighting between TU/e and Philips Lighting B.V. The authors thank dr. ir. M.B.C. Aries and drs. J.W. Bikker PDEng for their input to this paper and drs. T. Lashina for valuable discussions.

References