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External validations of a non-obtrusive practical method to measure personal lighting conditions in offices

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ABSTRACT

Health symptoms may be influenced, supported, or even controlled via a lighting control system which includes personal lighting conditions and personal factors (health characteristics). In order to be effective, this lighting control system requires both continuous information on the lighting and health conditions at the individual level. A new practical method to determine these continuous personal lighting conditions has been developed: location-bound estimations (LBE). This method was validated in the field in two case studies; comparisons were made between the LBE and location-bound measurements (LBM) in case study 1 and between the LBE and person-bound measurements (PBM) in case study 2. Overall, the relative deviation between the LBE and LBM was less than 15%, whereas the relative deviation between the LBE and PBM was 32.9% in the best-case situation. The relative deviation depends on inaccuracies in both methods (i.e., LBE and PBM) and needs further research. Adding more input parameters to the predictive model (LBE) will improve the accuracy of the LBE. The proposed first approach of the LBE is not without limitations; however, it is expected that this practical method will be a pragmatic approach of inserting personal lighting conditions into lighting control systems.

1. Introduction

One of the immediate effects of light exposure to the human eye is an increase in alertness (i.e., indirectly via the circadian melatonin suppression or directly as an acute effect) [1]. Researchers have studied the influence of light on human alertness often in the context of office lighting [2]. However, the majority of these light effect studies assessed the effect to average or incidental lighting measurements. Since human health is individualized, the (micro) environment around these individuals should be analyzed independently as well. Several environmental conditions (e.g., air pollution) were already investigated at the individual level [3]. It is recommended to measure lighting conditions per individual as the impact of light should not be generalized. Light captured by the photosensitive cells on the retina (i.e., ipRGcs, rods, and cones [4]) causes image-forming and non-image-forming effects. In order to investigate these light effects, it is essential to assess the light which enters the eyes. It is expected that the relationship between office lighting and human alertness could be better investigated including **personal lighting conditions** (i.e. the light which really enters individual's eyes).

Health effects (e.g. alertness or mood) may be influenced, supported, or even controlled via a lighting control system which includes personal lighting conditions and personal factors [5] (health characteristics, measured either subjectively or objectively). In order to be effective, this lighting control system requires continuous information both on the lighting and health conditions at the individual level. Health effects are one example of effects relating to the individual (amongst others, e.g., productivity, behavior, and lighting preferences) and these individual-related effects highlight the relevance of gathering personal lighting conditions. This paper focuses on the assessment of personal lighting conditions.

1.1. Various measurement methodologies

The amount of light entering the eyes of an individual office worker can be measured, simulated, estimated, or determined based on a combination of options (see Fig. 1). Estimations can be made using both measurements and simulations.

Person-bound measurements (**PBM**) record personal lighting conditions and are performed using wearable photometers, for example Actiwatches [6], Daysimeters [7], or Lightlogs [8]. A large advantage of this method is that the lighting conditions can be continuously

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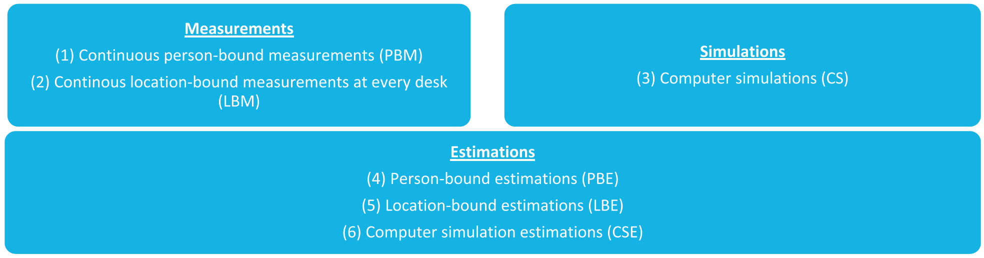

Fig. 1. Various methods to gather personal lighting conditions.

measured. In addition, since the device is worn or carried by the office worker, the measurements are not disturbed by (varying) location. Disadvantages of this method are the high performance errors of these (small) portable devices [9], the high costs of the devices, and the burden for office workers to continuously wear these portable devices [10]. Another method to retrieve personal lighting conditions is to continuously measure the lighting conditions at every desk with location-bound measurements (**LBM**). However, a disadvantage of this method is that the work space may not be used while the instruments are taking measurements.

Computer simulations (**CS**) are another method to record personal lighting conditions which may be less invasive for office workers. A validated simulation model of the office building may provide information of the office lighting conditions at all locations, heights, and in all possible viewing directions. However, developing such a detailed simulation model requires time and resources and must be created for each office building separately. In order to calculate personal lighting conditions, the location and viewing direction of the office worker is essential information which will then be combined with the simulation model. Gathering the location data of each office worker requires location-tracking (e.g., camera recordings) inside an office building and this may lead to privacy issues.

The advantages and disadvantages of the measurement and simulation methods to determine personal lighting conditions are organised in Table 1.

1.2. Location-bound estimations

To overcome the disadvantages of the PBM, LBM, and CS, a new practical method is proposed: the location-bound estimations (LBE) [11]. This method consists of a number of **reference measurements** performed at **reference locations** inside the office environment. **Trend lines** (i.e., predictive models) between reference locations and **outcome locations** were determined. Outcome locations are the locations throughout the entire office environment for which the lighting conditions will be estimated. Fig. 2 demonstrates the six-step process to execute this method [11].

Table 1
Advantages and disadvantages of the measurement- and simulation methods to determine personal lighting conditions.

	Advantages	Disadvantages
PBM	• Continuously collecting data • Location of office worker included in measurements	• High performance errors • High costs • Burden for office workers
LBM	• Lighting conditions at all locations, heights, and in all possible viewing directions	• Office workers cannot work at the working places where the measurement instruments are placed
CS	• Minimal disturbance for office workers • Lighting conditions at all locations, heights, and in all possible viewing directions	• Requires time and resources • Building dependent • Requires location-tracking

The measurement instruments may be of high quality because these are permanently placed inside the office environment. This method is not thought to be obtrusive for office workers when the measurement instruments are placed in well-considered reference locations. A disadvantage of the LBE is that the measurements are location-bound, so information about the occupant's location is required in order to calculate their total light exposure during the day. However, Chang and Hong (2013) demonstrated that more than 60% of the office workers remain in their cubicle (working place) within daily working hours (except for arriving at and leaving the office) [12]. The biggest advantage of this method is that it is ready to be implemented in future data systems. Reports show that the number of devices connected to the internet is expected to increase up to 50 billion by 2020 [13]. A certain lighting control system including big data such as personal lighting conditions, for example to enhance human health or productivity, will be one of these Internet-of-Things (IoT) connected devices. The measurement method to determine personal lighting conditions as input for IoT connected devices, should be non-obtrusive for the office workers, cost-effective for the company, and accurate for the strategy itself. The discussed LBE covers these three requirements and is therefore investigated further.

The LBE was internally validated by Van Duijnhoven et al. [11]. The current paper comprises two **external validations** using measurement data from case studies to investigate the relative deviation of the LBE against two alternative methods to determine personal lighting conditions (i.e., PBM and LBM). The CS, PBE, and CSE (see Fig. 1) will not be included in this paper.

2. Method

This paper describes two external validations of the LBE in two different case studies (realistic office environments). The first small-scale case study was performed to validate the LBE against location-bound measurements (LBM) whereas in the second large-scale case study the LBE was validated against person-bound measurements (PBM).

This method section was divided into six subsections. Section 2.1. explains the different LBE methods applied in the two external validations. The study designs for both case studies (i.e., external validations) were described in 2.2. Section 2.3. demonstrates how the trend lines between reference locations and outcome locations were determined and section 2.4. shows the applicability of these trend lines to derive the LBE estimations. Section 2.5. provides information on the external validations (i.e., the method how the LBE was compared to alternative methods LBM and PBM in case study 1 and 2, respectively). Finally, section 2.6. describes the post-analysis performed on the relative deviations of the LBE. Each subsection is divided into two parts: case study 1 and case study 2.

2.1. LBE methods

As briefly mentioned in section 1.2. and described in full detail elsewhere [11], the LBE consists of reference measurements, **relation measurements** (i.e., measurements at unoccupied outcome locations in

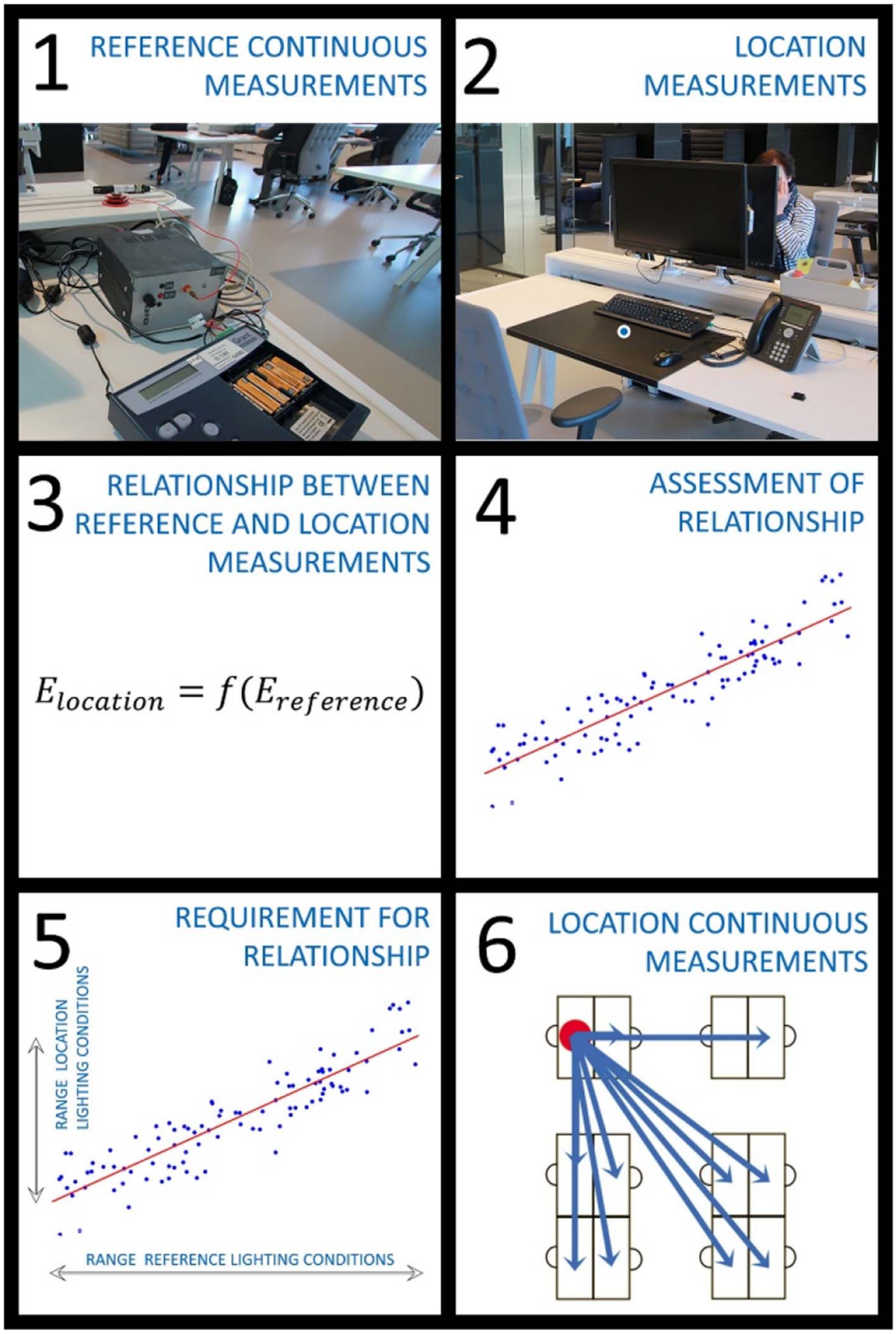

Fig. 2. Six-step process of location-bound estimations (LBE) (after [11]).

order to determine trend lines between the reference locations and the outcome locations), trend lines, and the **estimations** (i.e., application of the trend lines on the reference measurements) of the lighting conditions at the outcome locations inside the office environment. These are all properties of the LBE which can be adapted towards the specific needs for the LBE accuracy. Examples of variability in these properties are:

1. The number of relation measurements (the minimum is set to three).
2. The trend lines can be determined based on the measured illuminances at the reference locations and the outcome locations (i.e. a combination of daylight and electric light, see Equation (1)) or on a part of the measured illuminance. An example is to perform measurements outside daylight hours in order to measure the illuminances from electric light only. During these measurements, both the luminaires at the outcome location and the reference locations need to be switched on. In the situation where the electric lights are dimmable, the illuminances from electric light need to be measured for each applicable dimming level. By subtracting these illuminances (i.e. corresponding to the dimming level of the electric light sources at that specific moment, see Equation (2)) from the measured illuminance, the contribution of daylight can be calculated.

$$E_{tot} = E_{DL} + E_{EL} \tag{1}$$

In which:

E_{tot} = Total measured illuminance at a specific location

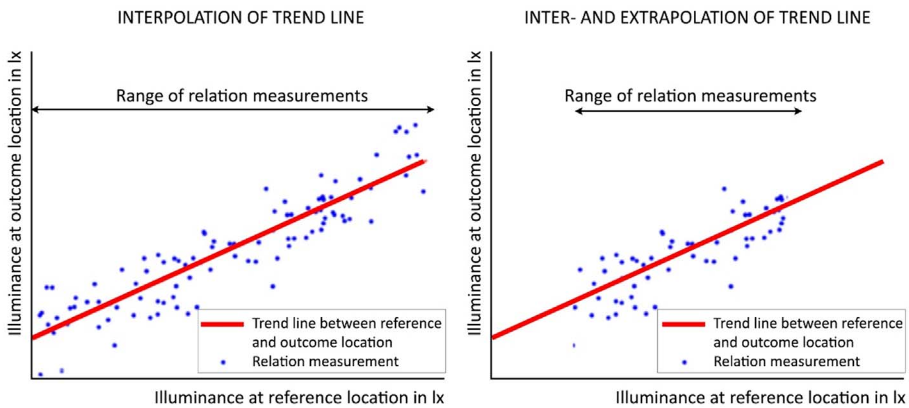

Fig. 3. Two graphs showing the differences between applying the trend line between reference location and outcome location either based on interpolation of the data points or based on a combination of interpolation and extrapolation of the data points.

E_{DL} = Illuminance from daylight only
E_{EL} = Illuminance from electric light only

$$E_{EL,\delta} = \delta \times E_{EL,MAX} \quad (2)$$

In which:

$E_{EL,\delta}$ = Illuminance from electric light only, for dimming level δ
δ = Dimming level of electric light
$E_{EL,MAX}$ = Illuminance from electric light only, for dimming level 100%

3. An assessment criterion can be the goodness of fit of the trend lines, using the coefficient of determination (R^2) for the relationship between reference location and outcome location. If, for example, R^2 takes the value of 0.70, it means that 70% of the variation in data is explained by the fitted model [14]. An R^2 value of 0.7 is recommended to come to reasonable conclusions.
4. The trend lines between the reference locations and outcome locations can be determined based on interpolation of the data points only or based on inter- and extrapolation of the data points (see Fig. 3).

Fig. 4 shows four examples of LBE methods. In the two case studies described in this paper, these different LBE methods were applied. In the rest of the paper these are referred to as **LBE method A, B, C,** and **D**. Case study 1 applied LBE method B and in case study 2 the LBE methods A, C, and D were applied. From A to D, the four properties of the LBE (as described above) improve towards a higher expected accuracy (i.e., a higher number of relation measurements, more specifically determining the trend lines, setting R^2 requirements, and both interpolation and inter- and extrapolation of the data points).

2.2. Study designs

This section describes the setup of the two case studies mentioning the applied LBE methods, measurement locations, instruments and overall procedures.

2.2.1. Case study 1

The first external validation was performed on LBE method B compared to the alternative method LBM. This study was performed in a rectangular office landscape (Eindhoven –September 2017). The building consisted of an office landscape containing 18 desks of which five were included in this validation. Furthermore, the closest window to these desks was oriented at the east side of the office landscape and that was the same for all the desks. These five desks were all assigned to reference locations and measurement equipment (i.e. a monopod with each two Eltek photometers and transmitters attached) continuously (every 30 s) measured horizontal illuminances at desk level (i.e., 0.7 m) and vertical illuminances at eye height (i.e., 1.20 m) for the entire measurement period of eight working days (see Fig. 5 for the measurement setup).

The reference locations were chosen based on their characteristics (i.e. distance to window and viewing direction of an imaginary office worker working at this desk). The reference locations differed in distance to window (minimal 3.3 m and maximum 7.8 m away from window) and in viewing directions (four different viewing directions).

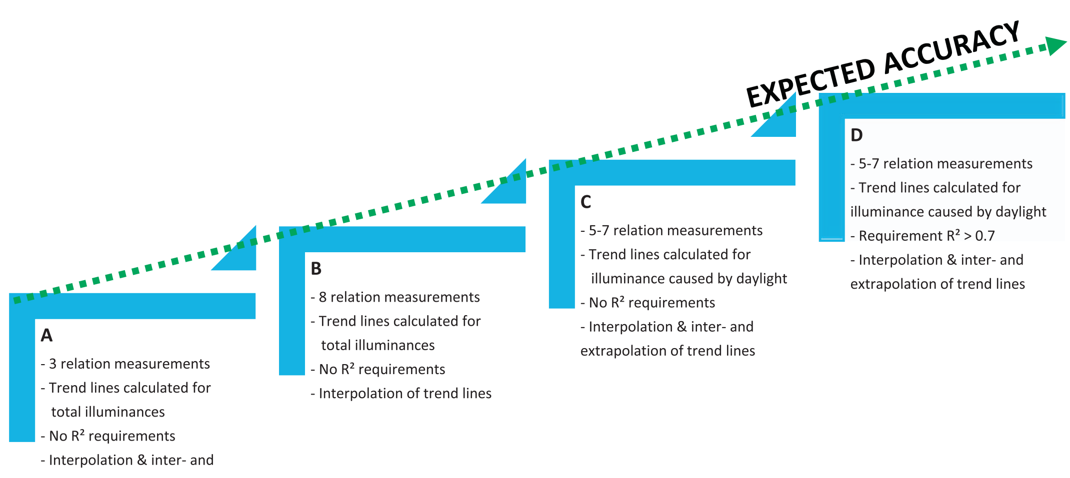

Fig. 4. Several LBE methods categorized by expected accuracy.

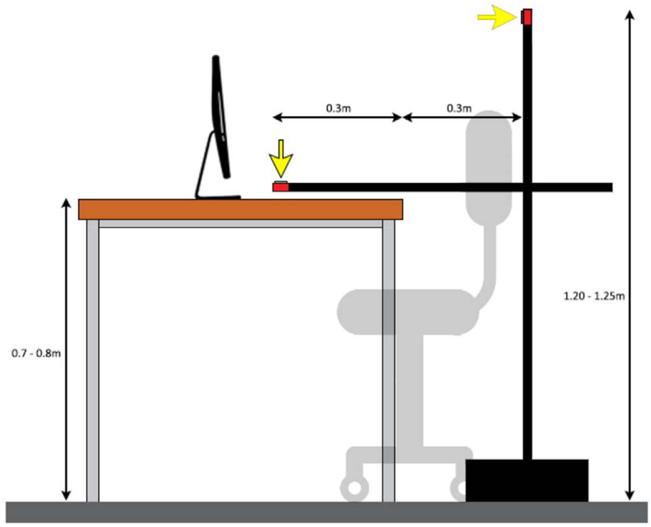

Fig. 5. Measurement setup for case study 1 and 2. The red squares indicate the photometers to measure horizontal illuminance at desk level and vertical illuminance at eye height. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

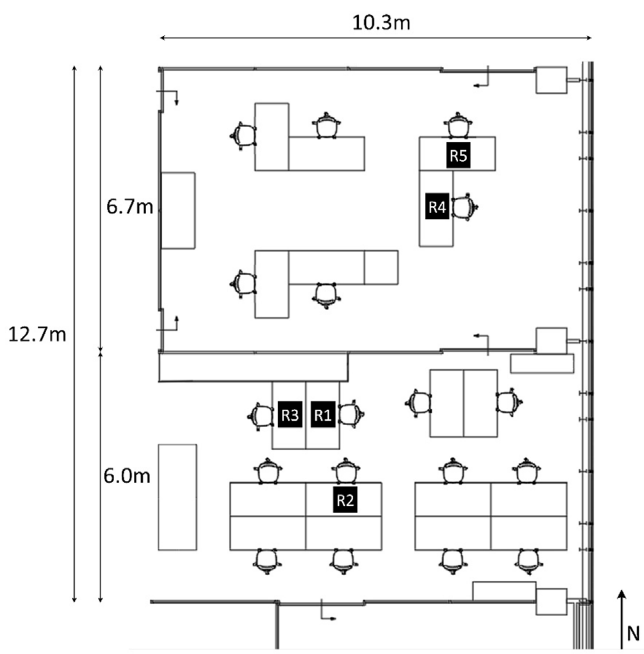

Fig. 6. Floor plan of office environment including the reference locations R1 to R5 (case study 1).

Fig. 6 shows the floor plan of the office environment. The references locations were labelled from R1 to R5.

2.2.2. Case study 2

The second external validation was performed on LBE method A, C and D compared to the alternative method PBM. This study was performed in a large office building (Alphen aan den Rijn – May 2017). The building consisted of five floors containing office landscapes and an atrium situated at the South façade. The office landscapes contained in total 356 desks out of the total 468 desks in the entire office building. All of these 356 desks (outcome locations) were included in this external validation to determine trend lines between five reference locations and the 356 outcome locations. The reference locations were located on different floors and had different orientations (regarding the orientation of the closest window and the viewing direction of an imaginary office worker working at this desk). Fig. 7 shows the floorplans of the office building in which the reference locations are indicated with colored dots. At these reference locations, similar to case study 1, horizontal illuminances and vertical illuminances were continuously (every 10 s in the first week and every minute in the second week) measured using the same measurement equipment (i.e., Eltek, see Fig. 5). This validation study had a duration of ten working days.

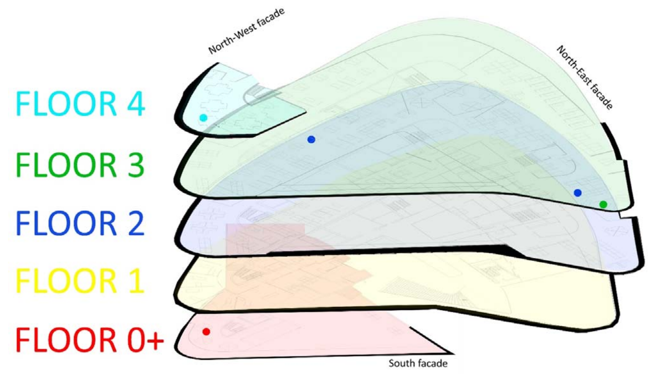

Fig. 7. Overview of the floor plans of the office building used for case study 2. The colored dots indicate the reference locations at the floors corresponding to the same color. One reference location was at floor 0+, two at floor 2, one at floor 3, and one at floor 4. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

2.3. LBE trend lines

In both case studies, trend lines were determined between reference locations and outcome locations. In the first approach, linear trend lines (see Equation (3)) were applied to check the R^2 values of the trend lines. In the majority of the cases, R^2 was within an acceptable range and therefore, a more complicated fit for the trend line was not necessary. The trend lines were later used to derive the LBM estimations.

$$E_{LBE,outcomelocation} = a*E_{ref} + b \tag{3}$$

In which:

$E_{LBE,outcomelocation}$ = LBE of illuminance at outcome location
a = slope coefficient of trend line between reference location and outcome location
b = y-intercept of trend line between reference location and outcome location
E_{ref} = Measured illuminance at reference location

2.3.1. Case study 1

In case study 1, five reference locations were linked to each other to investigate when the fit of the trend line was the best (e.g., when the distance to window was equal at the reference and outcome location). Throughout one cloudy day, eight data points measured at reference locations were taken from the complete set of continuous reference measurements. These eight data points were then linked to the other reference locations (now interpreted as outcome locations) to determine the trend lines in which x represents the reference location and y the outcome location.

The formulas of all possible trend lines between the horizontal illuminances measured at the reference locations and at the outcome locations are shown in Appendix I, Table 6, with the corresponding R^2 values of these trend lines shown in Appendix I, Table 7. The formulas and corresponding R^2 values of the trend lines between the five reference locations and outcome locations for the vertical illuminances are shown in Appendix I Table 8 and Table 9.

2.3.2. Case study 2

All outcome locations (i.e., 356 desks) within the office building were linked to the most appropriate reference location (according to the orientation of the closest window façade). The R^2 values (between reference locations and outcome locations) for LBE method A ($356\ desks,\ \ \bar{R}^2 = 0.55 \pm 0.37$) were slightly higher compared to the R^2 values for LBE method C ($173\ desks,\ \ \bar{R}^2 = 0.36 \pm 0.29$), but lower than the R^2 values for LBE method D ($27\ desks,\ \ \bar{R}^2 = 0.83 \pm 0.08$). One of the aspects of LBE method D was that the R^2 lower limit was set to 0.7. This explains the highest R^2 values for this method.

2.4. LBE estimations

The trend lines described in 2.3.1 and 2.3.2 were applied to the complete data set (reference measurements) to derive the LBE estimations for all outcome locations inside the office environment.

2.4.1. Case study 1

The LBE estimations were derived based on the formulas from Table 6 and Table 8 (Appendix I). Reference measurements from a period of eight days were used for the x-input of the formula. The Y outputs are the LBE estimations for the outcome locations. Since LBE method B was applied in this case study, only interpolations of the trend line were applied (see Fig. 3). When the reference measurement was between the minimum and maximum measurement value for which the trend line was calculated, only then the LBE estimations were calculated. This method was applied for the horizontal and vertical LBE estimations.

2.4.2. Case study 2

Similar to case study 1, the LBE estimations were determined based on the formulas of the trend lines. In LBE method A, the linear trend lines (see Equation (3)) were applied whereas in LBE methods C and D, the contribution of electric light was first subtracted from the total measured illuminances before applying the formula of the trend line. At the end, the contribution of electric light at the outcome location was added (see Equation (4)).

$$E_{LBE,\ outcome\ \ location} = a*(E_{ref} - E_{EL,ref}) + b + E_{EL,\ outcome\ \ location} \tag{4}$$

In which:

$E_{LBE,outcomelocation}$ = LBE estimation of total illuminance at outcome location
a = slope coefficient of trend line between reference location and outcome location
b = y-intercept of trend line between reference location and outcome location
E_{ref} = Measured total illuminance at reference location
$E_{EL,ref}$ = Measured illuminance at reference location in situation with only electric light
$E_{EL,outcome\ \ location}$ = Measured illuminance at outcome location in situation with only electric light

For all three LBE methods, two options were evaluated: (i) only interpolating the trend line, and (ii) interpolating and extrapolating the trend line (see Fig. 3).

The period for which the LBE estimations were derived consisted of ten working days. The LBE estimations were determined for 356 desks, 173 desks and 27 desks respectively for LBE methods A, C, and D.

2.5. External validations

The LBE estimations were derived using the determined trend lines (see section 2.4.1 and 2.4.2.). These LBE estimations were, in the last step of the external validation, compared to alternative methods (i.e., LBM and PBM) to determine the relative deviation of the LBE compared to these alternative methods. The first external validation compared LBE method B with the LBM whereas the second external validation compared the LBE methods A, C, and D with the PBM. In the PBM method, participants were wearing a portable photometer and when they were working at a certain outcome location, the PBM values were compared to the LBE estimations for that specific outcome location.

2.5.1. Case study 1

In this external validation, the LBE estimations were compared to the location-bound measurements (LBM) method.

2.5.1.1. Comparisons. The LBE estimations, calculated via the formulas of the trend lines (see Table 6 and Table 8 in the appendix), were compared to the location-bound measurements (LBM) performed at the outcome location at the same time. This resulted in the relative difference e_{rel} (see Equation (5)).

$$e_{rel}[\%] = \frac{|E_{LBE} - E_{LBM}|}{E_{LBM}} \times 100\% \tag{5}$$

In which:

e_{rel} = the relative deviation between LBE and LBM
E_{LBE} = LBE at the outcome location
E_{LBM} = LBM at the outcome location

For each combination of reference location and outcome location, these relative deviations were calculated. Every combination was analysed using a single value: the median of all relative deviations for the entire measurement period of eight days.

2.5.2. Case study 2

In this external validation, the LBE estimations were compared to a person-bound measurements (PBM) method.

2.5.2.1. Person-bound method (PBM). 37 office workers voluntarily participated in this validation study. On average, 9.8 measurement days per participant were included in the data set. The participants were continuously (only during awake times) wearing a small portable measurement device (Lightlog, see Fig. 8). Instructions were individually given to each participant about how (i.e. at the right chest) and when to wear the Lightlog. In addition to the Lightlogs, participants were asked to keep a diary and activity log to check when the participant started wearing the device and when it was taken off. In addition, their locations (within the office building) were reported in the diaries. The Lightlogs took measurements every 5 min.

Based on participant's diaries, moments were determined when the participant was working at an outcome location (desk) in an office landscape within the office building. In the rest of the paper these moments will be called **sessions**.

For each session, start and end date and time, work day of the participant (between 1st and 10th), and desk number within the office building were derived to create an overview of all sessions for which the LBE could be compared to the PBM (see Table 10 in the appendix). One session had a duration of minimal 5 min (the measurement interval of the PBM). Short breaks to the coffee corner or toilet were not asked to be reported in the diary. Participants reported to work (inside the office building) on average at 5.4 different desks per experiment period (maximum 10 work days). A location change was reported when they were at that location for 30 min or longer.

2.5.2.2. Comparisons. For each session, when a participant was working at a desk inside the office building, the LBE was compared to the PBM. Every session consisted of one or multiple measurements. The comparison of both methods was performed for all measurements per session (from now on called **AM** (i.e., All Measurements)), but also for single values per session (averages, medians and sums of AM). Fig. 9

Fig. 8. Portable photometers (Lightlog, developed by G. Martin (2016) [8]).

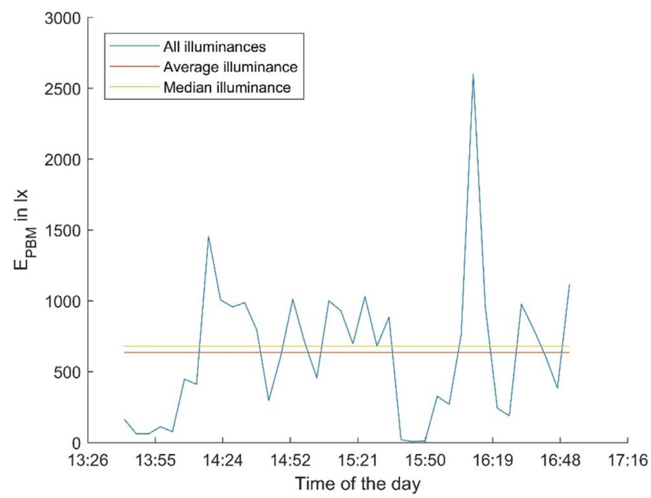

Fig. 9. PBM illuminance measurements for one specific session (the third session of Table 10 in the appendix) for the comparison between the LBM estimations and the PBM measurements.

shows the measured illuminances for the PBM for one specific session.

Three different methods of LBM (A, C, and D), two different ways of applying the trend lines ((i) interpolating, or (ii) inter- and extrapolating)), and four different ways for the comparison (AM, averages, medians, sums) led to 24 comparisons of the LBE and the PBM.

The deviation between LBE and PBM was calculated per session (Equation (6)). The median value of all these deviations was used to compare the different LBE methods.

$$e_{rel}[\%] = \frac{|E_{LBE} - E_{PBM}|}{E_{PBM}} \times 100\% \quad (6)$$

In which:

e_{rel} = the relative deviation between LBE and PBM
E_{LBE} = LBE at outcome location
E_{PBM} = PBM at outcome location

2.6. Post-analysis on LBE deviations

The calculated relative deviations of the LBE (i.e. compared to LBM in the first external validation or compared to the PBM in the second external validation) were tested on (non-parametric Kendall's tau) correlations with multiple aspects (e.g., desk characteristics). These tests were executed in order to potentially explain the magnitude of the relative deviation.

2.6.1. Case study 1

The median relative deviations calculated in the external validation 1 were investigated whether to correlate with:

- The R^2 values of the trend lines between reference location and outcome location
- The number of data points included for the comparisons between LBE and LBM
- The differences in desk characteristics (i.e. distance to window and viewing direction of an imaginary office worker working at this desk) between reference location and outcome location

The desk characteristics of the reference locations are provided in Table 11 in the appendix.

2.6.2. Case study 2

Relative deviations based on comparison of average, median, and sum of illuminances for every session were tested for correlations with several session characteristics. The AM comparisons were excluded because it was not possible to link multiple relative deviations within one session to the session characteristics. Therefore, for 18 different comparisons, correlations were calculated between the relative deviations (per session) and these aspects:

- The R^2 values of the trend lines between reference location and outcome location (the desk of that particular session)
- The differences in desk characteristics between reference location and outcome location (i.e. distance to window and viewing direction of an imaginary office worker working at this desk)
- Maximum LBE within each session
- Duration of each session

The mean relative deviations of the in total 24 different LBE methods were compared based on characteristics of the LBE method (i.e. the number of relation measurements performed, trend line applied to total illuminances or to the daylight contribution, interpolation of trend line or inter- and extrapolation, the number of compared sessions in this method, and the A, C, D methods as wholes) and based on the different ways of comparisons (i.e. AM, averages, medians, or sums). These comparisons of means were performed by applying an independent samples *t*-test.

Table 2
Median relative deviations between LBE Method B and LBM for the horizontal (Hor.) and vertical (Vert.) illuminances.

Reference location (x)	R1		R2		R3		R4		R5	
Outcome location (y)	Hor.	Vert.	Hor.	Vert.	Hor.	Vert.	Hor.	Vert.	Hor.	Vert.
R1	–		0.7%	1.3%	4.6%	1.9%	1.9%	1.8%	3.3%	1.7%
R2	0.6%	3.2%	–		4.5%	2.6%	1.6%	5.4%	3.1%	4.3%
R3	4.0%	7.0%	4.1%	3.4%	–		2.4%	12.0%	1.5%	4.9%
R4	3.4%	10.3%	3.6%	10.7%	6.5%	13.9%	–		4.4%	11.6%
R5	7.5%	6.6%	7.9%	7.3%	4.2%	5.4%	4.5%	11.0%	–	

3. Results

3.1. Median relative deviations of LBE

For both external validations, median relative deviations of the LBE were calculated compared an alternative method to determine personal lighting conditions (LBM and PBM, respectively).

3.1.1. Case study 1

Table 2 provides all median relative deviations for LBE Method B for the horizontal and vertical illuminances compared to LBM.

3.1.2. Case study 2

As described in section 2.5, section2.2, 24 different comparisons were executed in order to get insight in the deviation between LBE and PBM. Table 3 provides the median relative deviations of these 24 different comparisons.

3.2. Post-analysis on relative deviations LBE

The relative deviations of the LBE (either above or below the alternative value) were tested for correlations with aspects which potentially explain the magnitude of the relative deviations.

3.2.1. Case study 1

Only one of the calculated Kendall's tau correlations between the relative deviation of LBE method B compared to LBM and the aspects which potentially explain the magnitude of the relative deviations (see 2.6.1) was found to be significant (see Table 4).

3.2.2. Case study 2

In this validation study, a large data set was used in order to calculate the relative deviation of the LBE compared to PBM as accurately as possible. For the entire measurement period, LBE values of 32/44, 306/359, or 360/461 sessions (respectively for LBE method D, C, and A, see Table 5) were analysed and compared with PBM. All of the separate relative deviations per session were tested against aspects which potentially explain the magnitude of the relative deviations such as the R^2 of the trend line between the reference location and the outcome location of that specific session, and differences in desk characteristics between the reference location and the outcome location.

Table 3
Median relative deviations between LBE method A, C or D for vertical illuminances and PBM.

LBE method	Comparison per session	Interpolation trend lines	Inter- and extrapolation trend lines
A	All values	38.5%	45.1%
	Averages	36.0%	40.0%
	Medians	33.6%	41.5%
	Sums	36.0%	39.9%
C	All values	44.0%	42.4%
	Averages	36.8%	32.9%
	Medians	39.5%	36.7%
	Sums	36.8%	32.9%
D	All values	51.3%	59.3%
	Averages	47.6%	43.8%
	Medians	39.5%	36.7%
	Sums	47.6%	43.8%

The second post-analysis of external validation 2 was the comparison between the different LBE methods A, C and D and some of its characteristics (e.g., number of relation measurements, see section 2.6.2.).

3.2.2.1. Aspects potentially explaining the relative deviations of the LBE. Correlations were calculated between the relative deviation of LBE compared to LBM and aspects which potentially explain the magnitude of the relative deviations (i.e., R^2 of the trend line between reference location and outcome location of that specific session, differences in desk characteristics between reference location and outcome location). The number of data points differed per LBE method and per application of the trend line (interpolation or inter- and extrapolation), ranging from 32/44 to 306/359 to 360/461 data points (respectively for LBE method D, C, and A, see Table 5). Significant correlations are highlighted with an asterisk.

3.2.2.2. Differences between LBE methods. The independent samples *t*-test was applied to test for differences between groups. The following groups were defined:

- Application of trend line: (i) interpolation vs. (ii) inter- and extrapolation
- Calculation of trend line: (i) based on total illuminance vs. (ii) based on daylight illuminance
- Number of relation measurements: (i) less than five relation measurements vs. (ii) equal to or more than five relation measurements
- LBE methods: (i) LBE method A vs. (ii) LBE method C vs. (iii) LBE method D.

In addition, the differences in the individual comparison methods (i.e. AM, averages, medians, or sums) were tested for significance.

None of all calculated differences between groups were found to be significant (all $p > 0.05$); however, the comparisons of means showed some trends (see Fig. 10 and Fig. 11).

4. Discussion

A fully automated health-based lighting control system requires both continuous lighting measurements and health measurements at the individual level. This paper focused on one method to determine personal lighting conditions without interfering with the office worker's regular activities. The two external validations described in the current paper were applied to investigate the accuracy of the LBE.

In the first external validation, the LBE was compared with the LBM. For horizontal illuminances, the relative deviation varied from 0.6% to 7.9% whereas the relative deviation for vertical illuminances varied from 1.3% to 13.9%.

Table 4
Case study 1: Kendall's tau correlations between the relative deviations of the LBM method (both horizontal and vertical illuminances) and the aspects which potentially explain the magnitude of the relative deviations.* indicates significance (p-value < 0.05).

	R^2 trend line between base reference and outcome reference		Number of data points		Differences in desk characteristics			
					Distance to window		Viewing direction	
	τ	Significance (p-value)	τ	Significance (p-value)	τ	Significance (p-value)	τ	Significance (p-value)
Horizontal LBE	0,13	0,434	0023	0,894	−0,043	0794	0,123	0502
Vertical LBE	−0,335*	0,043	−0,115	0507	0,097	0557	0,178	0333

In addition, in the post-analysis of the relative deviations, only one significant correlation was found (i.e., between the relative deviation and the R^2 value of the trend line for vertical illuminances). The correlation was negative and of medium strength (τ = −0.335*, see section 3.2.1.) indicating that a higher R^2 value (i.e., a better fit) of the trend line between reference location and outcome location correlates to a lower relative deviation. This is in accordance with the expectations of Van Duijnhoven et al. [11]. In their internal validation of the LBE method [11], the method was only assessed on the R^2 values of the determined trend lines. In this external validation, the variety of the R^2 values for the horizontal LBE estimations were limited from 0.96 to 1 whereas the range of R^2 values for the vertical illuminance LBE estimations was between 0.81 and 0.98. The small range for the R^2 of the horizontal LBE estimations may cause the absence of a significant correlation between the relative deviation and the R^2 here.

In the second external validation, the LBE was compared with the PBM. Six different LBE methods (i.e., A, C, and D; all with interpolation or inter- and extrapolation) were applied for which four different comparison methods (i.e., AM, averages, medians, sums) were used. The results showed that the LBE method C using the averages or sums to compare the method with the PBM gave the lowest relative deviation (32.9%, see Table 3).

During the post-analysis of the relative deviations, no aspect which potentially explain the magnitude of the relative deviations nor significant differences between different groups were found. Nevertheless, some trends are worth mentioning here. It was expected that by improving properties of the LBE (i.e., a higher number of relation measurements, more specifically determining the trend lines, setting R^2 requirements, and both interpolation and inter- and extrapolation of the data points) the accuracy of the LBE would increase as well. The lower relative deviation for the group ‘ < 5 relation measurements’ compared to ‘≥5 relation measurements’ may be explained by the limited number of data points for the LBE method D. The same applies for the higher relative deviation for the LBE estimations derived using a trend line based on total illuminances compared to the relative deviation when the trend line was based on daylight illuminances. The mean relative deviation for all methods (A, C, and D) with only interpolation of the trend line was slightly lower compared to inter- and extrapolation of the trend line. Fig. 4 shows the expected increase in accuracy of the LBE from LBE method A to D. This expectation was confirmed with the improvement in accuracy (i.e., a lower relative deviation) from LBE method A to LBE method C. However, from LBE method C to LBE method D, the opposite occurred. This may also be explained by the limited number of data points for the LBE method D.

In addition, the median relative deviation also varied for the four different methods of comparison (i.e., AM, averages, medians, sums) described in this paper. These four comparisons are examples of methods to compare two datasets (in this case study the LBE and PBM). The most appropriate method for comparison of the LBE with an alternative method may depend on the effect which will be investigated with the LBE. No significant differences were found between the four different ways of comparison, but the trend showed that comparison of the sums per session would result in the closest fit between LBE and PBM ($\bar{x}$ = 39.49 %). For the calculation of the sum of illuminances per session, the measured or estimated illuminances as well as the duration of the session were taken into account. Duration of light exposure is one

Table 5
Kendall's tau correlations between relative deviation between LBE and PBM and aspects which potentially explain the magnitude of the relative deviations (i.e., R^2 trend line and two types of differences in desk characteristics).* indicates significance (p-value < 0.05).

			N data points in analysis	R^2 trend line between reference and outcome location		Differences in desk characteristics			
						Distance to window		Viewing direction	
				τ	Sig	τ	Sig	τ	Sig
A	Averages	Interpolation	360	0,02	0,568	−0,114*	0,002	−0,049	0183
		Inter- and extrapolation	461	0,068*	0,031	−0,163*	0	−0,021	0529
	Medians	Interpolation	360	−0,001	0978	−0,164*	0	−0,042	0259
		Inter- and extrapolation	461	0,07	0,026	−0,22*	0	0,001	0984
	Sums	Interpolation	360	0,02	0,578	−0,114*	0,002	−0,049	0184
		Inter- and extrapolation	461	0,068*	0,032	−0,164*	0	−0,021	0528
C	Averages	Interpolation	306	0,022	0569	−0,083*	0,036	−0,033	0411
		Inter- and extrapolation	359	0,029	0424	−0,102*	0,005	−0,034	0354
	Medians	Interpolation	306	0,006	0879	−0,13*	0,001	−0,035	0386
		Inter- and extrapolation	359	0,025	0493	−0,145*	0	−0,024	0517
	Sums	Interpolation	306	0,019	0628	−0,096*	0,015	−0,049	0223
		Inter- and extrapolation	359	0,029	0426	−0,103*	0,005	−0,034	0353
D	Averages	Interpolation	32	0,007	0,96	0,239	0087	−0,069	0613
		Inter- and extrapolation	44	−0,04	0,729	0173	0,145	−0,097	0402
	Medians	Interpolation	32	−0,016	0907	0,136	0328	−0,096	0479
		Inter- and extrapolation	44	−0,104	0361	0,099	0406	−0,171	0141
	Sums	Interpolation	32	0,007	0,96	0,239	0087	−0,069	0613
		Inter- and extrapolation	44	−0,04	0,729	0173	0,145	−0,097	0402

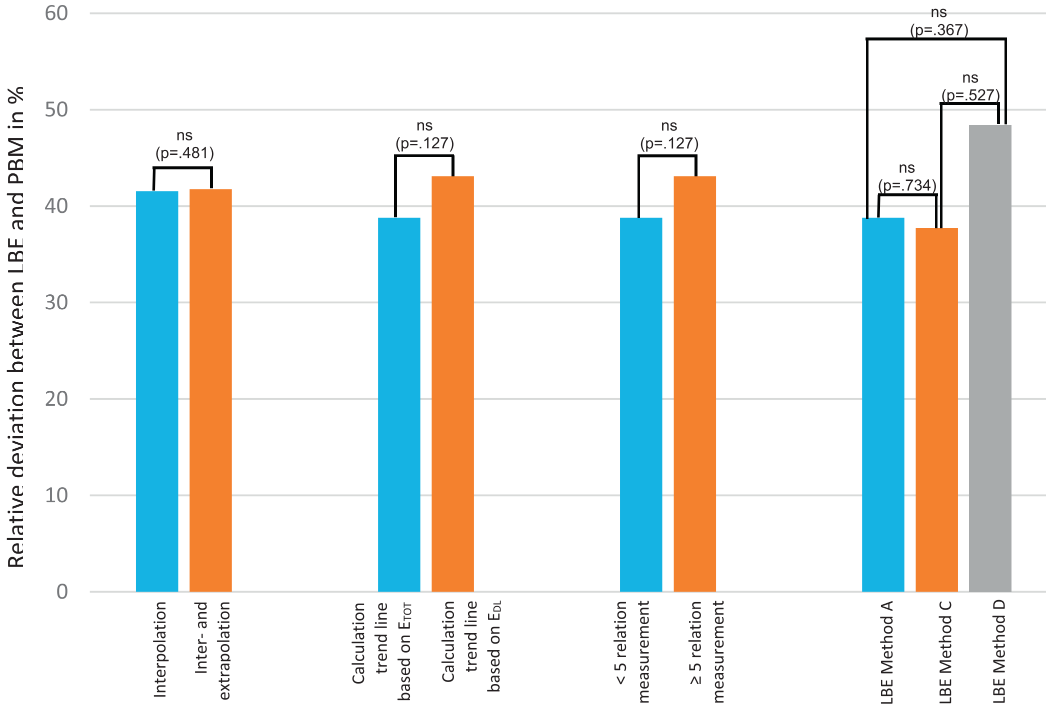

Fig. 10. Statistical tests for differences between groups (i.e., interpolation vs. inter- and extrapolation, calculation of trend line based on total illuminance vs calculation trend line based on daylight illuminance, < 5 relation measurements vs. < 5 relation measurements vs. ≥5 relation measurements, different LBE methods A, C, and D). The bars represent the mean relative deviation in percentages and the p-values of the tests are provided above the bars.

of the six defined light characteristics impacting NIF (non-image-forming) effects of light as described by Khademagha et al. [15].

The magnitude of the relative deviation between the LBE and both alternative methods LBM and PBM depends on several uncertainties of the LBE and uncertainties of the alternative methods. The relative deviation between LBE method B and the LBM may be lower than the relative deviation between the LBE methods A, C, or D and PBM because of the different office environments of both cases. External validation 1 (LBE vs. LBM) was performed in a small-scale rectangular building whereas external validation 2 (LBE vs. PBM) was performed in a large-scale complex building. Determining the trend lines between reference locations and outcome locations in a smaller-scale office environment is easier (regarding achieving the desired fit) compared to setting up these trend lines in a more complex building. In addition to this difference, it may be that the accuracy of the PBM is lower compared to the accuracy of the LBM which may also increase the relative

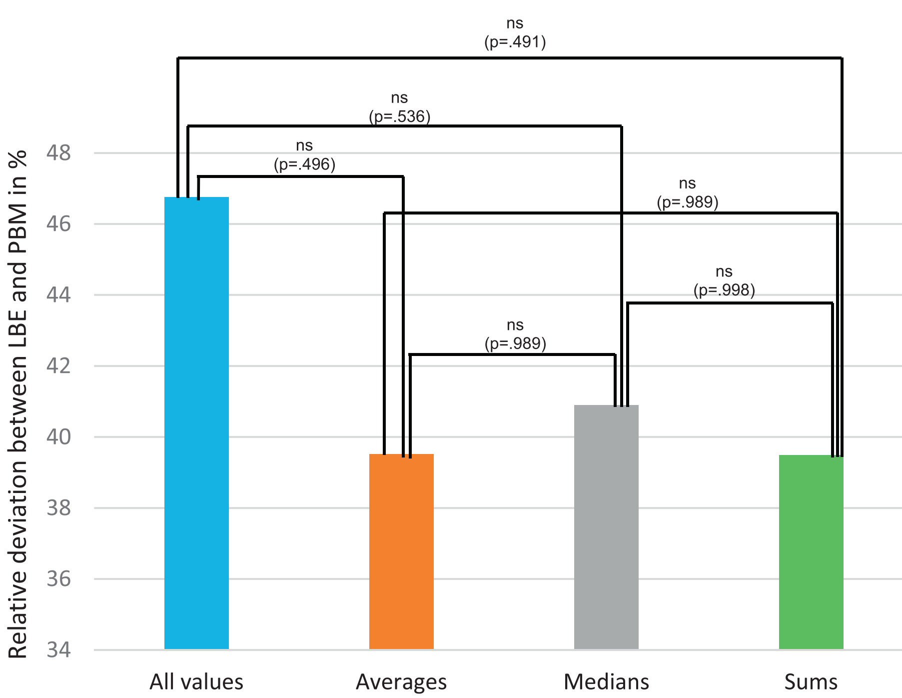

Fig. 11. Statistical tests for differences between groups with different comparison methods (i.e., all values, averages, medians, sums per session). The bars represent the mean relative deviations in percentages and the p-values of the tests are provided above the bars.

deviation of the LBE against the PBM. As with other small portable photometers, the wearable Lightlogs used for the PBM have relatively high performance errors [9], and potentially covering by clothes or hands, or removal from the clothing (i.e. because of annoyance) may also induce measurement errors [10]. Finally, the Lightlog was worn at chest height whereas the reference measurements for determining the LBE estimations were performed at eye height. The illuminances measured at the chest compared to at eye level may deviate up to 17% [9].

4.1. Limitations of the study

As mentioned above, the relative deviation of the LBE compared to an alternative method may be explained by the inaccuracy of the LBE method itself. In the second external validation, the LBE reference measurements were performed every 10 s or every minute whereas the PBM measurements were performed every 5 min. In order to compare the LBE and the PBM, the LBE reference measurements were averaged to get an equal number to the PBM measurements. A second limitation is that the LBE methods in the second external validation consisted of improvements of a combination of properties (i.e., a higher number of relation measurements, more specifically determining the trend lines, setting R^2 requirements, and both interpolation and inter- and extrapolation of the data points). Therefore, the effects of the single properties of the LBE could not be investigated.

4.2. Implications for theory

The trends between the different LBE methods indicate the direction from which the LBE can be further developed in order to increase its accuracy. The LBE method can be seen as a predictive model to estimate personal lighting conditions which consists of several input parameters. One of these input parameters is the quality of the predictive model (trend line) between reference locations and outcome locations. The position of the reference locations may be better distributed throughout the office building in order to ensure that all outcome locations can be linked to a similar reference location (e.g., similar in distance to window, orientation of closest window façade, or viewing direction). The selection of reference desks in case study 1 was based on the variety in distances to window and orientations. The reference locations were close to each other which will probably not happen when the LBE will be applied in a larger office building. Besides, in both case study 1 and 2, the measurement instruments at the reference locations were placed at certain desks. In practice, it would be more efficient to place the reference measurement equipment on the ceiling or walls to prevent occupants influencing the reference measurements by shadowing the equipment.

Within an office environment there are multiple different light sources available such as electric lighting, daylight, and light emitted by visual displays (e.g., computer screens or TVs). During the relation measurements during the day both the luminaires at the reference location as well as at the outcome location were switched on, i.e. the amount of electric lighting was controlled. During the relation measurements outside daylight hours there was no daylight, i.e. the amount of daylight was controlled. In both case studies, the amount of light from visual displays was not controlled which may have had a minor influence on the relation measurements.

In addition, when determining the trend line, the minimum number of relation measurements may be higher than three that needs to be performed in order to ensure a R^2 value above 0.7. For the first approach of the LBE, reference measurements with and without daylight and relation measurements at the outcome locations were performed. More measurement data (e.g., continuous daylight measurements or weather data) can be used as input for the predictive model to increase its accuracy. Another input parameter is related to the office worker itself. In order to determine more accurate personal lighting conditions throughout the entire day, the location and viewing direction of the office worker is required. These locations and viewing directions of the office workers may be recorded by cameras and therefore relatively easy to add as input parameter to the LBE method to determine personal lighting conditions for each individual office worker.

It is expected that the accuracy of the LBE would improve by adding additional input parameters (e.g., daylight measurements or location-tracking data of office workers) to the predictive model. It is also possible to combine more methods (from Fig. 4) in order to gather more input parameters for the predictive model of LBE.

The first approach of the LBE, as described in this paper, considers only horizontal and vertical illuminances. Since it is known that six light characteristics impact NIF effects of light, other light characteristics (e.g. spectral composition, intensity, timing, duration, directionality, and history) need to be considered in the LBE as well [15]. It depends on the effect of light which will be investigated (i.e. using an effect-driven lighting control strategy) which light characteristics must be included in the LBE.

4.3. Implications for practice

The desired accuracy of the LBE estimations is dependent on the effect of light to be investigated. The accuracy of the LBE can be seen as the utility within the concept of Information Quality [16]. Kenet and Shmueli defined Information Quality (InfoQ) as the potential of a particular dataset for achieving a given analysis goal by employing data analysis methods and considering a given utility. The goal of this data analysis was to compare two datasets (i.e. LBE versus LBM and LBE versus PBM), the analysis method were the different ways of comparison between the two datasets, and the utility was the performance measure ‘accuracy of the LBE’. Potentially, the personal lighting conditions can be used as input for different lighting control systems (e.g., health-based, productivity-based, or visual performance-based). Depending on the type of application, the control systems may require lighting input at different levels of accuracy. Since the thresholds for the effects of light on human health, productivity, or visual performance are still undefined, multiple LBE methods were investigated. It is expected that further developed LBE methods (e.g. by adding more input parameters, see section 4.2) may give more accurate results (see Fig. 4). The meaning of the relative deviation (32.9% compared to the PBM) is topic to further research. Without thresholds, it is difficult to determine the range of conditions required to gain an effect or not. The 32.9% relative deviation may be acceptable for illuminances around 1000 lx values whereas this deviation may be crucial for illuminances around 100 lx.

When LBE estimations will be applied as input for different applications in addition to the magnitude of the relative deviation, it is essential to know its direction (e.g. whether the LBE estimation compared to an alternative method to determine personal lighting conditions is higher or lower). All relative deviations in this paper were also calculated as real-number deviations (including a positive or negative direction). The results of this showed that all relative deviations were significantly lower compared to the deviations without any direction.

In addition, current studies often investigate health effects in relation to office lighting after a certain study period. With this LBE method, it will be possible to continuously measure personal lighting conditions and continuously monitor and control these conditions (e.g. via a connected lighting system) towards the office worker's needs and desires.

4.4. Further research

The aspects discussed in sections 4.2. and 4.3. are all topics for further research. Additional external validations are required to generalize the LBE method.

5. Conclusion

The current paper externally validated the non-obtrusive practical method (LBE) against two alternative well-used measurement methods. Comparing the LBE to location-bound measurements (LBM), low relative deviations of 7.9% and 13.9% were found for horizontal illuminances and vertical illuminances, respectively. Compared to the person-bound measurements (PBM), a relative deviation of 32.9% was found. These deviations may seem relatively high. The proposed first approach of the LBE is not without limitations; however, it is expected that this practical method will be a pragmatic approach of inserting personal lighting conditions into IoT connected devices.

In the future, entering an office building must not cause a burden to the office worker to install his or her personally controlled lighting system. A health-based lighting control system, for example, using LBE as lighting input neither requires office workers to wear a portable photometer nor occupies desk space inside the office building. These two main advantages of the LBE show its applicability in the field. Both external validations in this paper focused on office buildings but it is likely that its applicability may be extended to other applications and/or building types as well.

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Appendix I

Table 6
Formulas of trend lines of comparison between horizontal illuminances measured at reference locations R1 to R5 compared to the outcome location R1 to R5.

Reference location (x) Outcome location (y)	R1	R2	R3	R4	R5
R1	–	y = 0.79 x - 4.69	y = 1.17 x - 90.69	y = 0.32 x + 288.63	y = 0.39 x + 271.53
R2	y = 1.24 x + 18.91	–	y = 1.48 x - 107.44	y = 0.39 x + 377.37	y = 0.49 x + 354.39
R3	y = 0.84 x + 86.71	y = 0.67 x + 74.91	–	y = 0.27 x + 327.28	y = 0.33 x + 312.40
R4	y = 3.10 x - 889.73	y = 2.44 x - 902.15	y = 3.64 x - 1176.76	–	y = 1.23 x - 52.76
R5	y = 2.51 x - 674.21	y = 1.99 x - 692.87	y = 2.95 x - 910.64	y = 0.81 x + 44.88	–

Table 7
R^2 values of the trend lines of comparison between horizontal illuminances measured at reference locations R1 to R5 compared to the outcome location R1 to R5.

Reference location (x) Outcome location (y)	R1	R2	R3	R4	R5
R1	–	0.98	0.98	0.99	0.99
R2	0.98	–	0.99	0.96	0.98
R3	0.98	0.99	–	0.97	0.98
R4	0.99	0.96	0.97	–	1.00
R5	0.99	0.98	0.98	1.00	–

Table 8
Formulas of trend lines of comparison between vertical illuminances measured at reference locations R1 to R5 compared to the outcome location R1 to R5.

Reference location (x) Outcome location (y)	R1	R2	R3	R4	R5
R1	–	y = 0.33 x + 102.57	y = 0.15 x + 145.61	y = 0.22 x + 131.46	y = 0.12 x + 148.53
R2	y = 2.88 x - 286.17	–	y = 0.45 x + 129.13	y = 0.61 x + 96.13	y = 0.36 x + 137.01
R3	y = 6.27 x - 898.23	y = 2.17 x - 273.41	–	y = 1.40 x - 80.95	y = 0.81 x + 15.39
R4	y = 4.11 x - 515.53	y = 1.33 x - 85.44	y = 0.63 x + 79.13	–	y = 0.51 x + 89.19
R5	y = 7.41 x - 1068.20	y = 2.59 x - 334.82	y = 1.20 x - 11.83	y = 1.68 x - 108.22	–

Table 9
R^2 values of the trend lines of comparison between vertical illuminances measured at reference locations R1 to R5 compared to the outcome location R1 to R5.

Reference location (x) Outcome location (y)	R1	R2	R3	R4	R5
R1	–	0.96	0.94	0.89	0.88
R2	0.96	–	0.97	0.81	0.93
R3	0.94	0.97	–	0.88	0.98
R4	0.89	0.81	0.88	–	0.85
R5	0.88	0.93	0.98	0.85	–

Table 10
A part of the overview of all sessions for which the LBE was compared to the PBM.

Begin time	End time	Desk number	Workday	Participant	Duration of session [minutes]
'May.10,2017 11:37:00′	'May.10,2017 11:57:00′	143	1	3	20
'May.10,2017 12:02:00′	'May.10,2017 12:27:00′	49	1	3	25
'May.10,2017 13:42:00′	'May.10,2017 16:52:00′	49	1	3	190
'May.11,2017 08:02:00′	'May.11,2017 09:27:00′	50	2	3	85
'May.11,2017 09:47:00′	'May.11,2017 10:27:00′	50	2	3	40

Table 11
Case study 1: Desk characteristics of all five reference locations.

Reference	Distance to window façade	Viewing direction of person sitting at this desk (North = 0°)
A	6.3 m	270°
B	5.9 m	180°
C	7.4 m	90°
D	3.6 m	270°
E	3.3 m	180°

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