Personal lighting conditions to obtain more evidence in light effect studies

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Personal lighting conditions to obtain more evidence in light effect studies

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Abstract. Research demonstrated a large variety regarding effects of light (e.g. health, performance, or comfort effects). Since human health is related to each individual separately, the lighting conditions around these individuals should be analysed individually as well. This paper provides, based on a literature study, an overview identifying the currently used methodologies for measuring lighting conditions in light effect studies. 22 eligible articles were analysed and this resulted in two overview tables regarding the light measurement methodologies. In 70% of the papers, no measurement details were reported. In addition, light measurements were often averaged over time (in 84% of the papers) or location level (in 32% of the papers) whereas it is recommended to use continuous personal lighting conditions when light effects are being investigated. Conclusions drawn in light effect studies based on personal lighting conditions may be more trusting and valuable to be used as input for an effect-driven lighting control system.

Keywords: Light effects, measurements, methodological issues, individualized, light exposure.

1 Introduction

Research demonstrated a large diversity regarding effects of light (e.g. health, performance, or comfort effects). In the majority of the studies investigating the health effect, the health effect was often related to the photometric quantity illuminance or correlated colour temperature [1]; however, these aspects were mostly measured and included in the data analysis as average values (i.e., averaged over time or locations). Since human health is related to each individual separately, the environment around these individuals should be analyzed individually as well. Other environmental conditions (e.g., air pollution [2]) were already investigated at individual level. It is recommended to measure lighting conditions per individual as well since the impact of light is not identical for all people.

Health effects may be influenced, supported, or even controlled via a lighting control system which includes personal lighting conditions and personal health characteristics (either subjective or objective). In order to succeed, this lighting control system needs continuous information on the lighting and health conditions, both at individual level.

This paper provides an overview of the currently used methodologies for measuring lighting conditions in light effect studies as reported in literature. The methodological aspects that are being identified are the light aspects, and how, when, and where the light measurements were performed.

2 Method

The literature search was performed in September 2017 and did not have any restrictions on publication year to ensure all relevant articles were included in the search. The base of the literature search was the word combination: 'Alertness', lighting parameters (i.e., 'Lighting', 'Daylight', 'Light exposure', or 'Light'), and 'Office'. All three search aspects had to be present in potentially eligible articles. These search terms led to four possible combinations (i.e., Alertness – Lighting – Office, Alertness – Daylight – Office, Alertness – Light Exposure – Office, and Alertness – Light - Office). Inserting these four search combinations in four different scientific databases (ScienceDirect, Google Scholar, PubMed, and Web of Science) resulted into 141 hits of which 122 were eligible (based on abstract reading). After removing the duplicates, 22 papers were found to be relevant. See Fig. 1 for the search process.

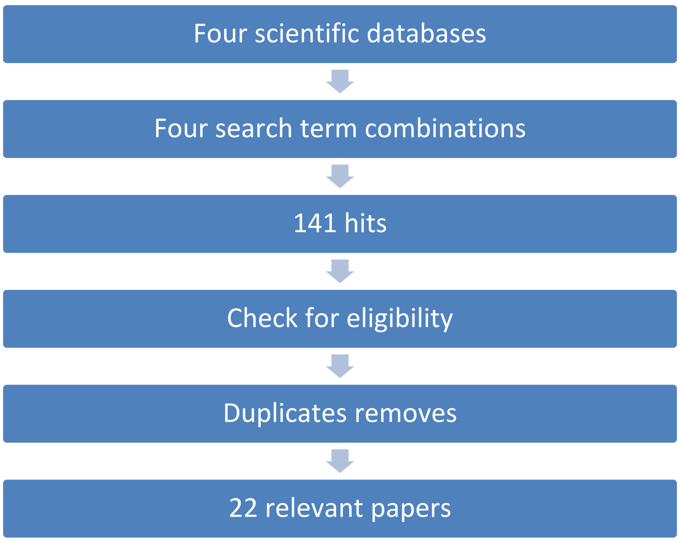

Fig. 1. Literature search process

3 Results

While mapping a certain luminous environment by measuring the lighting conditions, multiple aspects need to be taken into account. Which light aspects are being measured and how, when, and where are these measurements performed? Based on the performed literature study, the questions will be answered in the next paragraphs.

3.1 Which light aspects are being measured?

As briefly mentioned in the introduction, mostly the illuminances or correlated colour temperatures were determined in order to investigate potential light effects. Besides these two light aspects, there are more light aspects which are important to consider while performing a light effect study. In the papers included in this literature study, these light aspects were measured and/or calculated: horizontal illuminance, vertical illuminance, brightness, irradiance, correlated colour temperature (CCT), spectrum, colour rendering index (CRI), reflectance, luminance, flicker, direction, daylight, glare, uniformity, and daylight factor (DF). Table 1 provides an overview of these light aspects per paper and also demonstrates how these light aspects were included (i.e., dark green means included and measured, light green means included but not measured, orange means not included, and red means not reported).

Table 1. Overview light aspects incorporated in light effect studies - based on the literature study. Dark green means included and measured, light green means included but not measured, orange means not included, and red means not reported.

Literature	Light aspects													
	Measured											Calculated		
	Illuminance (Hor)	Illuminance (Ver)	Brightness	Irradiance	CCT	Spectrum	CRI	Reflectance	Luminance	Flicker	Daylight	Glare	Uniformity	DF
[3]	dark green	dark green	light green	dark green	dark green	red	dark green	red	red	red	dark green	dark green	red	dark green
[4]	dark green	dark green	red	light green	light green	red	light green	light green	dark green	red	orange	red	red	dark green
[5]	light green	red	red	red	red	red	red	red	red	red	red	red	red	red
[6]	dark green	dark green	dark green	red	light green	dark green	red	dark green	dark green	red	red	dark green	red	red
[7]	dark green	light green	red	red	light green	red	red	red	red	red	dark green	light green	light green	dark green
[8]	dark green	dark green	red	red	light green	red	light green	light green	dark green	red	orange	red	red	light green
[9]	light green	light green	red	red	light green	red	light green	red	red	dark green	red	red	red	red
[10]	dark green	dark green	red	dark green	red	dark green	red	red	red	red	light green	red	red	red
[11]	dark green	red	light green	red	light green	red	light green	red	light green	red	red	red	red	light green
[12]	dark green	red	red	red	red	red	red	red	red	red	light green	red	red	red
[13]	red	dark green	light green	red	light green	red	red	red	red	red	light green	red	red	red
[14]	dark green	dark green	red	red	light green	red	red	red	red	red	dark green	red	red	dark green
[15]	dark green	dark green	red	red	light green	red	red	dark green	light green	red	orange	red	red	dark green
[16]	dark green	dark green	red	red	light green	red	red	red	red	red	orange	red	red	red
[17]	light green	light green	red	red	light green	dark green	red	light green	red	red	orange	red	red	red
[18]	dark green	dark green	dark green	dark green	light green	dark green	red	light green	red	red	orange	dark green	dark green	red
[19]	dark green	dark green	dark green	red	dark green	dark green	red	red	red	red	orange	red	red	red
[20]	red	dark green	red	red	dark green	red	red	red	red	red	light green	red	red	red
[21]	dark green	dark green	light green	dark green	light green	dark green	red	red	red	red	red	red	red	red
[22]	dark green	dark green	red	dark green	dark green	dark green	red	light green	red	red	red	red	red	red
[23]	light green	light green	light green	light green	light green	light green	red	red	red	red	red	red	red	red
[24]	light green	light green	light green	light green	light green	red	red	red	red	red	red	red	red	red

In the 22 eligible papers, horizontal illuminances was included and measured the most with 15 papers, followed by vertical illuminance in 14 papers. Correlated colour temperature is the light quantity which is often included in the papers but not measured. This is, for example, the case when an intervention study was executed comparing effect in two different light scenarios (e.g., CCTs of 4000 K and 6500 K [9]). The light aspect presence or absence of daylight is the only aspect which is reported to be not included. Light flicker is the aspect which is mostly not reported.

Fig. 2 demonstrates the relative number of times a certain light quantity was included and measured (i.e. dark green colour in Table 1) per publication year. The relative number of times a certain photometric quantity was included and measured means the number of times it was included out of the total papers for that specific publication year (i.e., 1 in 2000, 1 in 2006, 2 in 2007, 1 in 2009, 1 in 2010, 1 in 2011, 3 in 2012, 4 in 2013, 1 in 2015, 1 in 2016, and 6 in 2017). 100% means in all the papers published in that year. Fig. 3 shows the average number of light aspects included and measured per paper throughout all publication years. The dotted line is the linear trend line of these data points.

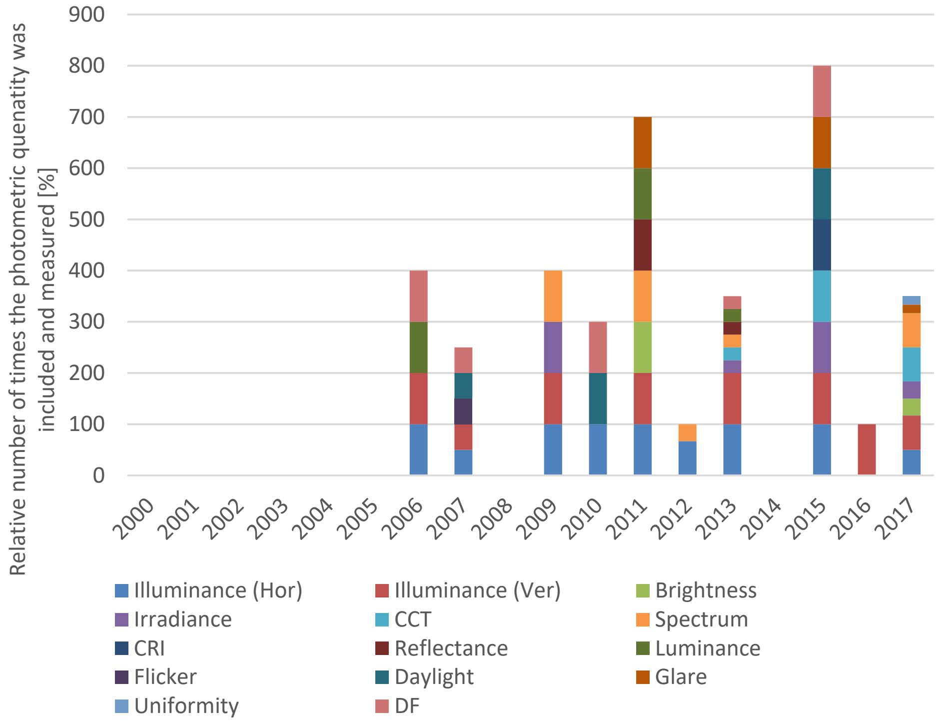

Fig. 2. Graph demonstrating the relative number of times a light quantity was included and measured in the 22 included papers of the literature study. For example, the value 100 for vertical illuminance in 2006 means that in 100% of the papers published in 2006 vertical illuminance was included and measured.

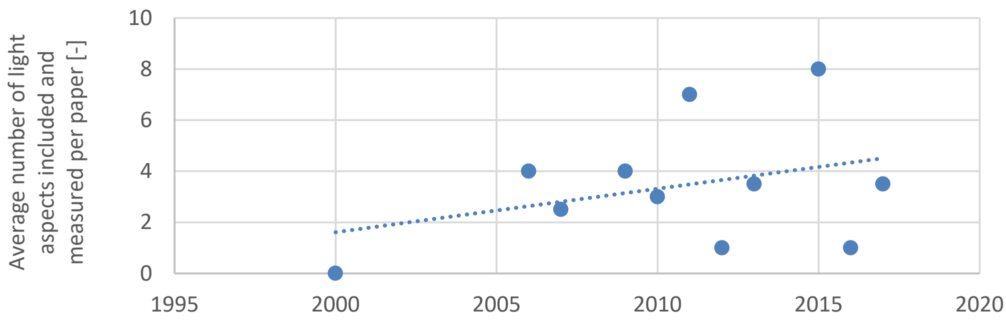

Fig. 3. Graph demonstrating the average number of light aspects included per paper throughout all publication years of the literature included in the literature search. The dotted line is the linear trend line of these data points. 14 light aspects were reported in literature (see Table 1) so that is the highest number possible in this graph.

3.2 How is being measured?

Once the light aspects are determined which will be included in the light effect study, the next question is how to measure these light aspects. The brand and type of the specific measurement instrument were often not reported (in 13 out of the 19 papers including light measurements, no measurement equipment details were provided). Light measurements can be executed using person-bound measurements (PBM, e.g. actiwatches [25], daysimeters [26], or Lightlogs [27]) or location-bound measurements (LBM) [28].

The advantage of the PBM method is that the lighting conditions are continuously measured, at the position of the individual. Disadvantages of this method are the burden for the individual to continuously wear a measurement device [29] and the relatively high performance errors of the current wearables [30]. In order to measure lighting conditions with lower performance errors, highly accurate measurement instruments can be used for location-bound measurements (LBM). A disadvantage of this method is that the lighting conditions are being measured at certain locations only (i.e., not dynamically following the individual) and that these measurement instruments occupy locations (e.g. desks in an office) which cannot be used by building occupants.

The current literature search only revealed one study that applied person-bound measurements. In this study, a ‘LuxBlick’ was used to measure personal lighting conditions. This study did not report the accuracy of the measurement device and the corresponding advantages or disadvantages of this method [10].

3.3 When is being measured?

The third aspect to be considered before performing the light measurements is the moment when the light measurements will be performed. Measurements can be performed at different measurement intervals: continuously (i.e., measurement interval ≤ 1 hour), regularly (i.e., measurement interval > 1hour), or only once (per light scenario). Only three papers mentioned that they measured lighting conditions with a measurement interval of less than or equal to 1 hour [3][13][20].

3.4 Where is being measured?

The fourth aspect regarding the light measurements is the location of the light measurements. A light effect study can be performed in a laboratory environment (lab study) or a realistic work/home environment (field study). 16 out of the total 22 papers included in the literature study described a light effect lab study.

Within the study environment (either lab or field), measurements need to be performed at certain locations. When these measurements are executed at a sample of locations inside the environment, often these measurements are averaged to determine an average lighting condition for the entire environment. In contrast, measurements can also be performed at the specific locations of the participants of the light effect study to be more accurate about the lighting condition for that specific participant. Measurements performed by person-bound measurement instruments or measurements performed at the specific workplace of that person (either vertically at eye height or horizontally at desk height) are assumed to measure personal lighting conditions. Thirteen papers in the literature study performed measurements at personal level of which 8 were measurements at eye height.

3.5 Overview

Table 2 provides an overview of the three methodological aspects (i.e., how, when, and where are lighting measurements performed) for the 22 included papers in the literature study.

Table 2. Overview methodological aspects (i.e., how, when, and where are light measurements performed) of included light effect studies - based on the literature study.

Literature	How					When				Where				
	Measurement equipment details reported		Measurement method			Measurement interval				Type of study		Measurement location		
	Yes	No	Person-bound measurements (PBM)	Location-bound measurements (LBM)	Not reported	Continuously (measurement interval ≤ 1 hour)	Regularly (measurement interval > 1 hour)	Once (for each scenario)	Not reported	Lab study	Field study	Average	Personal	Not reported
[3]	■			■		■				■			■	
[4]		■		■				■			■		■	
[5]	No light measurements		No light measurements			No light measurements				■		No light measurements		
[6]		■		■					■	■			■	
[7]		■		■				■			■	■		
[8]		■		■					■	■			■	
[9]		■			■				■	■		■		
[10]	■		■						■	■			■	
[11]		■		■					■	■			■	
[12]	■			■			■				■	■		
[13]		■		■		■				■			■	
[14]		■		■				■			■		■	
[15]		■		■					■	■		■		
[16]		■		■					■	■		■		
[17]		■		■				■		■			■	
[18]		■		■				■		■			■	
[19]	■			■				■		■			■	
[20]	■			■		■					■		■	
[21]		■		■				■			■		■	
[22]	■			■				■		■		■		
[23]	No light measurements		No light measurements			No light measurements				■		No light measurements		
[24]	No light measurements		No light measurements			No light measurements				■		No light measurements		

4 Discussion

In the current literature study, the aspects which, how, when, and where do light measurements need to be performed were investigated. This paper gives an overview of these aspects and demonstrate multiple possibilities for each aspect. The decisions which need to be taken before performing light measurements may be based on standards, regulations or other literature. It is expected that, for example, illuminance is often included in light effect studies since this is the mostly used recommendation in current standards.

In 2002, a third photoreceptor was discovered explaining the mechanism of image-forming and non-image-forming effects through this intrinsically photosensitive retinal ganglion cell (ipRGc)[31]. In order to investigate light effects (excluding the biological effects such as tanning or the production of vitamin D due to the UV radiation in sunlight), it is essential to know the amount and type of light which enters the eye, i.e. lighting conditions vertically measured at eye level. In addition, Lucas et al. stated in 2014 that measuring and reporting light with photometric quantities will not be sufficient either [32]. Table 1 demonstrated the number and types of light aspects included in the 22 selected papers in the literature study. Although the CIE recommended to describe the total lit environment instead of individual elements within it [33], this literature study showed that none of the 22 papers included the broad range of light aspects. However, Fig. 3 showed that the average number of light aspects included and measured in the light effect studies increased over the years.

Regarding these different light aspects, it seems, especially for researchers with a non-technical expertise, that it is sometimes difficult to use the correct terminologies for certain light aspects. Van Hoof et al. and Aarts et al. provided tools to correctly measure and report all methodological aspects when performing a light effect study[34][35]. In a previous review, these methodological issues of reporting light measurements were extensively highlighted [1]. In this literature study, the term brightness was reported to be measured in three papers and reported to be included but not measured in six papers. The question immediately arises how researchers defined this terminology and whether this term was related to, for example, illuminance measurements.

Since in 13 out of the 19 included papers (including light measurements), no measurement equipment details were provided, it can also be questioned whether the included light aspects were either objectively or subjectively measured. In two cases, both in the paper of Borisuit et al. [3], they mentioned that brightness and direction of light were subjectively measured (i.e., using an adapted version of the Office Lighting Survey [36]).

For both subjective as well as objective measurements, the choice when to perform light measurements may be influenced by the measurement equipment. For subjective measurements, the length of the questionnaire may influence the number of times the questionnaire is distributed, to limit the annoyance of filling in the questionnaires. For objective measurements, the choice when to measure may depend on the instrument properties. Wearables (PBM), for example, run on batteries and measuring at a shorter sample interval may shorten the battery life.

Besides the measurement equipment details, the moments for performing light measurements or the sample interval may depend on the lighting conditions in the environment as well. If the light effect study includes daylight availability, the ranges of lighting conditions vary more than compared with a situation without daylight. If daylight is available, the weather conditions (clear/overcast sky) also cause more variation in the lighting conditions during spring or summer. A wider range of lighting conditions may raise the necessity to measure the lighting conditions more often.

The decision to perform a light effect study in a laboratory or field environment depends mostly on the outcome measures, the aim or research question of the experiment and its hypotheses. While performing field studies, more measurements may need to be performed in order to identify potential confounders influencing the final results. The advantage of performing a lab study is that many parameters can be controlled to reduce the chances of having many confounders influencing the results. The large advantage of performing field studies is that the results were found and demonstrated in a realistic work/home environment. Then there is no need to doubt the possibility of extending the results to the realistic environment.

4.1 Practical implications

This literature study demonstrated that in nearly all the studies light measurements were performed using location-bound measurement instruments and that these measurements were sometimes averaged over the entire environment. Since all individuals differ, each individual health differs, and this increases the importance to measure lighting conditions at individual level as well.

Many of the currently available wearables measure multiple light aspects (e.g. illuminance, or irradiances in different spectral bands); however, these measurement instruments suffer from higher performance errors compared to the location-bound measurement instruments. Van Duijnhoven et al. [28][37] proposed a new non-obtrusive method to obtain personal lighting conditions using location-bound measurement instruments. This novel method may be a good alternative for less accurate person-bound measurement devices. This new method (location-bound estimations, i.e. LBE) consists of estimations based on location-bound measurements. Measurements at reference locations allow estimations of lighting conditions at other locations inside the building. The LBE was developed as a principle method and various methods of the LBE were already investigated. The accuracies of these LBE methods were determined based on two validation studies in offices. It is expected that, considering an effect-driven lighting system (an effect can be e.g. visual performance, health, or productivity), this LBE method will be a pragmatic approach of inserting personal lighting conditions into lighting control systems. The method may approach reality, is unobtrusive for the building occupants, and can easily be included in an Internet-of-Things-platform.

5 Conclusion

Light effect studies are a combination of measuring lighting conditions and health aspects. This multidisciplinary field of research requires knowledge of both fields. Therefore, it is highly recommended to perform light measurements and report these measurement methodologies as comprehensive as possible. Comprehensive descriptions of measurement methodologies enable researchers to understand, trust, and reproduce light effect studies.

This literature study showed that in ±70% (i.e., 13 out of the 19) of the papers including light measurements, no measurement details were provided. In addition, an average number of 3.4 (i.e., average of all values in Fig. 3) light aspects included and measured per light effect study suggests that researchers are not fully mapping the lit environment during their light effect studies as suggested by the CIE [33]. Furthermore, these light aspects were often averaged over time (i.e., only three studies applied light measurements with a measurement interval of less than an hour) or over location (i.e., six studies performed measurements at one location only).

Light effect studies are investigating potential effects of light, usually per individual. Each individual responds differently to light and lighting conditions should therefore be measured at individual level as well. Person-bound measurements (PBM), location-bound measurements (LBM), or location-bound estimations (LBE) can be applied measuring personal lighting conditions continuously for the entire study period. These obtained personal lighting conditions are essential information to draw conclusion within a light effect study. Conclusions drawn in light effect studies based on personal lighting conditions may be more trusting and valuable to be used as input for an effect-driven lighting control system.

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