Occupancy-based lighting control in open-plan office spaces: A state-of-the-art review

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ABSTRACT

Lighting accounts for a significant amount of electrical energy consumption in office buildings, up to 45% of the total consumed. This energy consumption can be reduced by as much as 60% through an occupant-dependent lighting control strategy. With particular focus on open-plan offices, where the application of this strategy is more challenging to apply due to differences in individual occupancy patterns, this paper covers (1) to which extent individual occupancy-based lighting control has been tested, (2) developed, and (3) evaluated. Search terms were defined with use of three categories, namely 'occupancy patterns', 'lighting control strategy', and 'office'. Relevant articles were selected by a structured search through key online scientific databases and journals. The 24 studies identified as eligible were evaluated on six criteria: (1) study characteristics, (2) office characteristics, (3) lighting system characteristics, (4) lighting control design, (5) post-occupancy evaluation, and (6) conclusions, and this was used to answer the research questions. It was concluded that the strategy has not been tested yet with field studies in open-plan offices, but that it needs further development before it can be applied in these type of offices. Although lighting currently tends to be controlled at workspace level, many aspects of the strategy can be further developed; there is potential to further increase energy savings on lighting within open-plan office spaces. Individual occupancy-based lighting control requires further validation, focussing on the factors influencing its energy savings, on its cost effectiveness, and on its acceptability for users.

Contents

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1. Introduction

Artificial lighting accounts for a significant fraction of global electrical energy consumption. In office buildings in particular, lighting comprises 20–45% of their energy consumption [1]. To promote energy savings on lighting use, aside from the use of more energy efficient luminaries such as LEDs [2], various lighting control strategies have been designed and implemented in office buildings. Examples of such strategies include daylight-linked automatic lighting control, dimming control and occupancy-based lighting control. Linking a light system with occupancy sensors is a cost-effective and easy solution for reducing lighting energy use. Their implementation has been demonstrated successfully in a number of studies, where energy used for lighting has been reduced by between 20% and 60%, depending on the configuration, type of space and type of occupancy sensor used [3–5]. Occupancy-based lighting control has been extensively studied in the private, single user office as this formed the dominant office type for a long time. However, in the 1950s, open-plan offices were designed and adopted by many companies in the 1970s [6]. Due to buildings' average age of 50 years, open-plan office spaces still tend to prevail in commercial office buildings [7]. In these type of office spaces, occupancy-based lighting control still encounters some challenges. Such offices are shared by employees who differ in their occupancy patterns in multiple aspects, from arrival and departure times to the number and duration of breaks during the day [8–10]. These differences are likely to increase even more due to the introduction of flexible working styles that allow employees more flexibility in their working times and working location [11]. In addition, desks no longer belong to one employee, but can be used flexibly by everyone [12]. Consequently, occupancy patterns of workspaces also vary from day to day. As a result, it becomes more challenging to fully align lighting use with the real-time occupancy of the individuals within the open-plan office, or in other words, to establish 'optimal lighting use'. In these type of offices it is also more difficult to account for the individual lighting preferences of all the occupants, but this falls outside the scope of this paper.

Because occupancy-based lighting control strategies play an important role in the reduction of the energy consumption of offices, their state of art has been reviewed by several studies over the years [13–15]. Haq and colleagues [13], for example, provided an overview of the occupancy detection techniques currently available, the amount of energy they can save on lighting and the factors affecting their performance. Guo and colleagues [14], on the other hand, provide an overview of the energy savings that earlier studies found to result from the implementation of occupancy sensors. Although both studies state that energy can be saved in irregularly occupied spaces, like open-plan offices, they pay only limited attention to the application of occupancy-based lighting control in these type of spaces. They do not distinguish them from private, single user offices, although open-plan offices need a different approach to establish optimal lighting use. Within open-plan offices, three different lay-out types can be distinguished, namely (1) cubicle lay-out with high partitions (1.524 m or higher), (2) cubicle lay-out with low partitions (1.524 m or lower), and (3) open lay-out with no or limited partitions (after Kim and de Dear [16]). In this paper, the term multi-occupant office will be used when referring to all types of open-plan offices and the term open-plan office when

referring to type 3 specifically.

With advancement in information and communication technology, detection systems are becoming more sophisticated. In contrast to Passive Infrared (PIR) sensors, which are the dominant detection systems used in office buildings, modern detection techniques are able to provide information on occupant activity, location and number, in addition to information on user presence [17]. Radio-frequency identification (RFID) tags, for example, track occupants continuously throughout the building [18]. These developments make optimal lighting use in multi-occupant offices achievable.

To our knowledge, the user is typically of second interest or not considered at all by studies investigating occupancy detection techniques. However, the comfort of users and acceptance of any control strategy is of great importance, given that the primary role of buildings is providing comfort and safety to occupants. Moreover, when this is neglected, they often take actions to restore their comfort which might in some situations negate the intended energy savings, as for example was found with automated blinds [19]. Therefore, this paper also evaluates whether users are involved in the post-occupancy evaluation of the occupancy-based lighting control strategy.

This study focusses thus on multi-occupant offices. Through a structured and thorough search of literature, three research questions are answered, namely.

(1) Is individual occupancy-based lighting control in the multi-occupant office fully tested and if not, how does it still need testing?
(2) Is individual occupancy-based lighting control in the multi-occupant office fully developed to achieve optimal lighting use, and if not, on which aspects can it be further developed?
(3) Is individual occupancy-based lighting control in the multi-occupant office fully validated, and if not, on which aspects does it still needs to be validated?

To answer (1), the study and office characteristics are analysed, so that it can be determined whether there is still a need for a certain type of study in a certain type of office. To answer (2), the lighting system characteristics and lighting control design are analysed, so that it can be determined on which aspects the strategy can be further developed. To answer (3), the extent to which studies performed a post-occupancy evaluation is assessed, so that it can be determined whether the usability of this strategy already has been proven. The authors focus on the energy savings, costs and evaluation by the user. Finally, the conclusions of the identified studies are analysed to further clarify these research questions.

In the subsequent section of the paper, a detailed explanation of how the literature search was conducted is provided as well as the selection and evaluation criteria (2). The outcomes of the evaluation of the eligible studies are presented and explained in the Results section (3). Based on these outcomes, future research, development and evaluation directions are provided as well as a recommendation on which design approach to take (4). A summary of the findings concludes this paper (5).

2. Methodology

This section provides an explanation of why the six criteria mentioned in the Introduction were chosen (2.1), how the resulting data was analysed (2.2), how the search was performed (2.3), and the inclusion and exclusion criteria used (2.4).

2.1. Assessment criteria

Eligible studies were evaluated on different subcategories within the six criteria, except for the last criterion, 'Conclusions', because subcategories are not applicable here. The subcategories are specified in Table 1.

It is now explained why these specific criteria were chosen as well as what they exactly entail.

2.1.1. Study characteristics
To be able to fully understand the design of the occupancy-based lighting control, the context of the studies is first determined. Studies were categorized as one of three 'study types', namely as (1) computational modelling, (2) laboratory study, or (3) field study. With the study characteristic 'duration', it was determined for field studies (as not applicable to the two other study types) for how long and when exactly the lighting control system was tested as the season might have some confounding effects.

2.1.2. Office characteristics
Additionally to the study context, office characteristics affecting users' perception of the space were in particular of interest. Therefore, (1) the size of the office space, (2) the type of office (cubicle or open plan), and (3) the number of workspaces in the office space were included. These numbers are reported per office space (if possible). If a study considered multiple type of spaces, for example private, single user offices in addition to multi-occupant offices, only information regarding the open offices was included.

2.1.3. Lighting system characteristics
This study focusses on how lighting can be controlled more efficiently in relation to individual occupancy patterns so that energy can be saved. Therefore, only characteristics related to this issue are considered. First of all, lighting energy use is affected largely by the used type of luminaires (1). Their spatial relationship to the desks determine how efficiently the luminaires deliver lighting where it is needed, in other words, the desk. Therefore, (2) the number of luminaires per office space, (3) the positioning of the luminaires (e.g. ceiling mounted, recessed), and (4) the extent to which the luminaires are aligned to the position of the workspaces (see Table 2). Other lighting characteristics, for example correlated colour temperature (CCT), are consequently not considered.

2.1.4. Lighting control design
It was also identified in the reviewed studies how exactly the lighting was controlled in response to occupancy. When implementing occupancy-based control, it at first needs to be determined at (1) which spatial level occupancy will be measured and lighting consequently controlled. Additionally, a system is needed consisting of (2) an occupancy detection technique to measure presence and/or absence with (3) an intelligence level, meaning whether lighting will respond to occupancy reactive, proactive, or anticipatory, (4) a time delay setting after which the lighting responds due to absence, and (5) illuminance settings to which lighting is set due to presence and/or absence (see Table 2).

2.1.5. Post-occupancy evaluation
The applicability of a design is not assured until its performance has also been evaluated. Therefore, all studies were reviewed on which measures they used to evaluate the system's performance. They were specifically evaluated on the amount of energy savings gained and the costs associated with the applied strategies. In addition, it was determined whether or not these studies involved users within the evaluation (see Table 2). In case they did, studies were further evaluated on:

Table 1
Overview of subcategories of the assessment criteria (1) study characteristics, (2) office characteristics, (3) lighting system characteristics, (4) lighting control design, and (5) post-occupancy evaluation. For (6) conclusions, subcategories were not applicable, so therefore this criterion is not included the table.

Study characteristics	Office characteristics	Lighting system characteristics	Lighting control design	Post-occupancy evaluation
Study type	Size of office	Type	Spatial level	System performance measures
Duration*	Type of office	Number of luminaires	Occupancy detection technique	Energy savings
	Number of workspaces	Positioning of luminaires	Intelligence level	Cost-effectiveness
		Alignment of luminaires with desks	Illuminance setting for occupancy	Number of participants**
			Illuminance setting for vacancy	Job type of participants**
			Time delay setting	Methods**
				Measures**
				Statistics**

Note: * only applies to field studies, ** only applies to studies that performed a post-occupancy evaluation with the occupants.

Table 2
Overview of final search terms of the three categories 'Occupancy patterns', 'Lighting control strategy' and 'Office' that were combined.

Occupancy patterns	Lighting control strategy	Office
Occupancy	Lighting control	Office
Absence	Intelligent lighting	Commercial building
Presence	Adaptive lighting	Non-domestic
	Smart lighting	Non-residential
	Illumination control	
	Lighting system	

(1) The number of participants,
(2) The job type of these participants,
(3) The methods,
(4) The measures, and
(5) The statistics.

2.1.6. Conclusions sections

To identify future research directions, the analysis did not only include the aspects mentioned above, but also the conclusions of the studies. These were categorized according to their main topic to identify important research directions. This led to a more complete overview of research questions the scientific community is eager to tackle.

2.2. Data analysis

For most of the subcategories, the results were displayed in tables. Each of the lighting system characteristics or lighting control design aspects was plotted against the type of study and type of office (if applicable). For each of the resulting levels, it was determined how many studies were performed in order to identify areas where research is still lacking. The energy savings of the studies were plotted against the spatial level, so that it could be determined whether more energy is saved when controlling at lower spatial levels. In some instances, the data was just described, because studies took a very similar approach, e.g. regarding the type and positioning of the luminaires, or because most studies did not handle this aspect, for example the intelligence level of the lighting control system.

2.3. Search process

The search was executed in four steps. At first, three general databases, ScienceDirect, SAGE, and Google Scholar, were used for a broad investigation. These databases were chosen because they together cover all relevant accessible publishers. Subsequently, the search was narrowed down by continuing the search in two topic-specific databases. With ICONDA (1) studies from the built environment were covered, and with PsychInfo (2) studies from the user perspective, together covering the ground of this study. Then two topic-specific journals were consulted, 'Lighting Research and Technology' and 'Journal of the Illuminating Engineering Society'. Finally, references of literature review(s) found during the earlier searches were further explored. Fig. 1 shows in which databases and journals was searched.

To specify the search, three categories of search terms were determined. The 'Lighting control strategy' is of main interest (category 1) and 'Occupancy patterns' form the problem that needs to be handled by this strategy (category 2). As only applied studies were of interest, the context was set to the 'Office' (category 3). For these three categories, multiple search terms were defined. For example, 'Occupancy patterns' contained the terms 'Occupancy', 'Absence', and 'Presence'. For a complete overview of used terms, see Table 2.

In addition, the search was limited to articles from 1984 onward as in this year the first application of occupancy-sensing control in building was identified according to the literature [20].

With the resulting 72 combinations (3 'Occupancy patterns' terms * 6 'Lighting control strategy' terms * 4 'Office' terms), searches were performed within the journals' 'Abstract, Title, and Keywords' in ScienceDirect and SAGE. The search in Google Scholar was only aimed at matches in the title as the only other search possibility this engine provides is the full text. Therefore, in this search engine was only searched with terms of 'Lighting control strategy' and 'Occupancy patterns'. Slightly different search strategies were applied in step two and three of the search process. As PsycInfo is a non-technology based database, it was decided to use the broader umbrella terms 'lighting' and 'illumination' for 'Lighting control strategy' and 'building' for context. In ICONDA, the office related search terms were not included in the combinations as this database already is limited in itself to publications from the building environment. The issues of Lighting Research and Technology were "full-text searched" to assure that all relevant articles were included. Initially, this was also done for the Journal of the Illuminating Engineering Society, but as this resulted in too many irrelevant articles, it was decided to only search in the 'Abstract', Title, and Keywords'. In addition, terms from the category 'Lighting control strategy' were discarded from the combinations as this journal already only contains lighting related articles. Table 3 shows an overview of the search strategies used for the different databases and journals.

2.4. Inclusion and exclusion criteria

Studies were selected describing lighting control strategies that were occupancy-based, i.e. based on presence, absence, or a combination thereof, and tested in a multi-occupant office. This environment could involve a 'virtual office' (thus a software model), office set-up in a laboratory or a real office building. Studies were
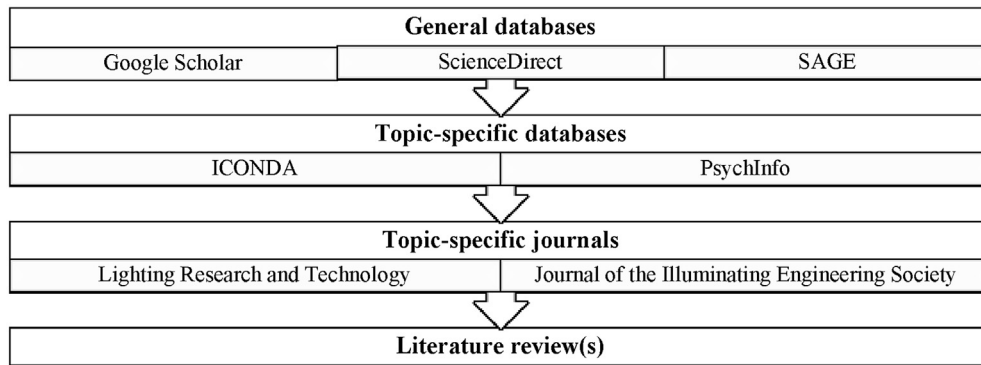
Fig. 1. Search process with the used databases and journals.

Table 3
Overview of the search strategy used for each of the databases and journals (fields searched in, used combination of terms, resulting number of searches and dates of the last search).

Database/journal	Fields	Combinations	Number of combinations	Date last search
ScienceDirect	Abstract, title, keywords	Lighting control strategy & Occupancy patterns & Context	72	06-07-2016
SAGE	Abstract, title, keywords	Lighting control strategy & Occupancy patterns & Context	72	06-07-2016
Google Scholar	Title	Lighting control strategy & Occupancy patterns	18	06-07-2016
ICONDA	Abstract, title, keywords	Lighting control strategy & Occupancy patterns	18	06-07-2016
PsychInfo	Abstract, title, keywords	Lighting control strategy & Occupancy patterns & Office	24	08-07-2016
Lighting Research and Technology	Full text	Lighting control strategy & Occupancy patterns & Office	72	08-07-2016
Journal of the Illuminating Engineering Society	Abstract, title, keywords	Occupancy patterns & Office	12	08-07-2016

not reviewed if they just considered occupancy patterns as input for the calculation of energy savings and not for the design of the strategy (e.g. Refs. [21,22]). Therefore, in addition to these types of studies, books were excluded as well. Literature reviews do not test an intervention themselves, so therefore they were not directly but indirectly used, namely by searching through their references for relevant studies. In addition, only studies in peer-reviewed journals and conference proceedings were selected of which the full article is publicly available in English. Studies were assessed on these criteria by reading abstracts, and, if not clear from the abstract, the whole article.

3. Results

This section first provides an overview of the number of relevant studies identified with each of the databases (Table 4). In total, 24

studies were defined as eligible which were further analysed on the six topics described in the Methodology section (2), and subsequently explained in more detail per topic.

3.1. Overview

The searches in the general databases ScienceDirect, SAGE, and Google Scholar resulted in 10, 2 and 1 eligible unique hits respectively. Although the article of Labeodan and colleagues [23] also met the inclusion criteria, it was excluded from analysis to avoid a conflict of interest. In ScienceDirect as well as SAGE these all resulted from the combination of search terms 'Occupancy & lighting control & office'. Searching on 'Occupancy & lighting control' generated the same eligible unique hit as Google Scholar. With PsychInfo none of the search term combinations as described in the Methodology section resulted in eligible hits. In ICONDA two

Table 4
Total number of hits, new hits, and eligible unique hits found in the different steps of the search process.

Database	Hits	New hits	Eligible unique hits
ScienceDirect	134	125	10
SAGE	9	4	2
Google Scholar	46	16	1
PsychInfo	15	9	—
ICONDA	22	11	2
Lighting Research & Technology	283	80	3
Journal of the Illuminating Engineering Society	30	16	4
Literature review of Guo, X., & Tiller, D. (2010)	45	42	2
Literature review of Haq et al. (2014)	14	5	—
Total	**598**	**308**	**24**

eligible unique hits were found when searching with 'Occupancy & lighting control' and 'Occupancy & lighting control'. From the searches in the topic-specific journal 'Lighting Research and Technology' three unique hits were regarded eligible. Two of these studies resulted from searching with the terms 'Occupancy & lighting control & office'. The other hit was found with 'Presence & lighting control & office'. Within the other topic-specific journal, 'Journal of the Illuminating Engineering Society', four studies were included of which three were found with 'Occupancy & office' and one with 'Occupancy & commercial building'.

In total three literature reviews were found [13–15]. All references of Tiller and colleagues [14] were examined because these authors specifically reviewed occupancy-based lighting control strategies. This resulted in three eligible unique hits. Haq and colleagues [13] reviewed all various types of lighting control systems, including for example daylight-linked systems. Only the references they mentioned in the part about 'Occupancy-based controls schemes' were inspected. However, no eligible unique hits were identified. Also Williams [15] included all types of lighting control strategies in their meta-analysis of lighting energy savings. They did not discuss the different types separately, so therefore the references of this literature review were not further examined.

Table 4 provides an overview of the number of hits, new hits, eligible unique hits that were found in the different steps of the search process. With 'new hits' the number of new hits compared to the previous searches is meant. With 'eligible unique hits' is meant the number of unique hits compared to the previous searches that were regarded relevant.

In the subsequent sections, the results are provided for each of the sub-evaluation criteria. If applicable, tables were created to summarize the results.

3.2. Study characteristics

3.2.1. Study type
Table 5 shows how many field studies, computational modelling studies and laboratory studies were performed in the different type of offices. It can be seen that most field studies were performed in cubicle offices and most computational modelling studies in open-plan offices. The number of field studies in open-plan offices is rather limited.

3.2.2. Duration
Table 6 shows the duration of the different type of studies for the different type of offices. The eight computational modelling studies were discarded from this table as they have no time limit. Granderson and colleagues [34] measured different variables for different time periods for different measures. False negative and positive occupancy detection was measured for 2 months, daylight regulation for 42 days spanning 9 months, and energy savings were monitored for approximately 1 year [34]. Similarly, Aghemo and colleagues [35] tested manual control for two months, while the combination of manual and automatic control was tested for eight

Table 5
Study type of the 24 eligible studies, categorized as laboratory study, computational modelling, or field study, for the different types of offices.

Study type	Type of office			Frequency
	Open-plan	Cubicle	NR	
Field study	[24–26]	[27–34]	[35–37]	14
Computational modelling	[38–43]		[44]	8
Laboratory study	[45,46]			2

Note: NR = not reported.

months. This resulted in a total frequency of 18, as can be seen in Table 6. From the table it becomes clear that most studies lasted between 1 and 6 months, or in other words, the number of lengthy studies is limited.

3.3. Office characteristics

3.3.1. Type
The office types in which the eligible studies were performed varied, as can be seen in Table 7. In open-plan offices mostly computational modelling studies were performed, while in cubicle offices field studies formed the prevailing study type.

3.3.2. Number of workspaces
The number of work spaces varied largely among the 24 studies, as can be seen in Table 8. Two studies had office spaces of varying sized and were therefore placed in two categories [24,35], resulting in a total frequency of 26. The office in the study of Rubinstein and Enscoe [33] formed an exception with its 86 cubicles. A large proportion of the studies did not report the number of workspaces.

3.4. Lighting system characteristics

3.4.1. Type and positioning of luminaires
In most studies, the used luminaires are typical ceiling mounted/recessed office luminaires. Some exceptions were identified [25,30,31,33], who investigated the combination of downward and upward lighting. In the studies of Wen and Agogino [28], Galasiu and colleagues [30] and Galasiu and Newsham [31] the luminaires are respectively 1.2 m, 0.3 m and 0.5 m suspended from the ceiling. With two studies additional local task lighting is provided at the desk, namely by a luminaire under a shelf [32] and by a LED shielded task strip built into the furniture [26].

3.4.2. Alignment of luminaires with desks
Table 9 shows in which studies luminaires were directly aligned with the desks. The overview reveals that this characteristic was not reported in 10 of 24 cases. The nine studies with alignment between luminaires and desks have investigated an office space where each workspace has its own luminaire(s). Five of the studies were conducted in cubicle offices and three studies performed computational modelling in an open-plan office. Thus, only one study could be identified as a field study in a real open-office where luminaires and desks were aligned.

3.5. Lighting control design

3.5.1. Spatial level
Occupancy-based lighting can be controlled at different spatial levels, namely (1) at individual workspace level, (2) at zone level, and (3) at room level. At individual workspace level, the lighting only responds to the presence and/or absence of one occupant. When controlled per zone, this means that lighting is switched off as soon as absence is detected at all workspaces within the zone. Lighting can also be controlled together for a whole room, meaning that luminaires are switched off as soon as no one is present in the room anymore. Table 10 shows at which spatial level the lighting was controlled in the 24 studies. Here it can be seen that in most studies the lighting was controlled at individual workspace level. These mainly involved studies applying computational modelling or performed in a laboratory. Only six of the 12 studies tested the system in the field and these were all conducted in an office environment with a cubicle layout.

Table 6
Duration of the 24 eligible studies, categorized according to their length, for the different type of studies and different type of offices. The eight computational modelling studies were excluded from this table. Two studies used different time periods for different measures. This results in a total frequency of 18.

Duration	Study type				Frequency
	Field study			Laboratory study	
	Open-plan	Cubicle	NR	Open-plan	
≤1 day		[28,29]		[46]	3
>1 day and ≤1 week					–
>1 day and ≤1 month					–
>1 month and ≤6 months	[24,25]	[30,33,34]	[35]		6
>6 months and ≤1 year		[27,34]	[35]		3
>1 year		[31,32]			2
NR	[26]		[36,37]	[45]	4

Note: NR = not reported.

Table 7
Office types of the 24 eligible studies, categorized as open-plan, or cubicle, with either high partitions, low partitions, or a mix of both, for the different type of studies.

Type of office	Study type			Frequency
	Field study	Computational modelling	Laboratory study	
Open-plan	[24–26]	[38–43,47]	[45,46]	12
Cubicle - high partitions	[34]			1
Cubicle - low partitions	[27]			1
Cubicle - high and low partitions	[30,33]			2
Cubicle - partition height not reported	[28,29,31,32]			4
NR	[35–37]	[44]		4

Note: NR = not reported.

Table 8
Number of workspaces of the offices of the 24 eligible studies, categorized according to their size, for the different type of studies and different type of offices. Two studies performed their study in offices of two different sizes, resulting in a total frequency of 26.

Number of workspaces	Study type & type of office						Frequency
	Field study			Computational modelling		Laboratory study	
	Open-plan	Cubicle	NR	Open-plan	NR	Open-plan	
2	[24,25]		[35]	[42]			4
>2 and ≤ 10	[24]	[28,29,31]	[35]				5
>10 and ≤ 20		[29]		[39,43,47]			3
>20		[33]		[38,40,41]			4
NR	[26]	[27,30,32,34]	[36,37]		[44]	[45,46]	10

Note: NR = not reported.

Table 9
Frequency of alignment of luminaires with desks in the 24 eligible studies, categorized as yes, no, or not reported, for the different Table 9 of studies and type of offices.

Alignment of luminaires with desks	Study type & type of office						Frequency
	Field study			Computational modelling		Laboratory study	
	Open-plan	Cubicle	NR	Open-plan	NR	Open-plan	
Yes	[26]	[30–33]		[39,42,43,47]			9
No		[28]	[35]	[38,40,41]			5
NR	[24,25]	[27,29,34]	[36,37]		[44]	[45,46]	10

Note: NR = not reported.

3.5.2. Occupancy detection technique

In the 24 reviewed studies, all involved PIR sensors except for Labeodan and colleagues [45], who used chair sensors and Manzoor and colleagues [29], who used a combination of PIR sensors and RFID tags. Both enable lighting control at individual desk level.

3.5.3. Intelligence level

Previously it was mentioned that occupancy-based automatic lighting systems can have three intelligence levels. Rosen [48] defined them as follows:

(1) Reactive: decision making based on real-time information with no explicit regard to the future
(2) Anticipatory: decision making based on real-time information and explicitly taking into account possible future events
(3) Proactive: decision making based on predictions and incorporating a predictive model of itself and/or its environment

When applied to this context, a reactive lighting system (1) controlling at individual workspace level will switch on the lighting as soon as occupancy is detected at the desk. An anticipatory

Table 10
Spatial level of the lighting control of the 24 eligible studies, categorized as 'individual workspace', 'zone', 'room', or 'not reported', for the different types of studies and type of offices.

Spatial level	Study type & type of office						Frequency
	Field study			Computational modelling		Laboratory study	
	Open-plan	Cubicle	NR	Open-plan	NR	Open-plan	
Individual workspace		[28–31,33,34]		[38–40,42,43,47]		[45]	13
Zone	[26]	[32]			[44]		4
Room	[24]	[27]	[35,36]	[41]			5
NR	[25]		[37]			[46]	2

Note: NR = not reported.

lighting system (2) will reason that, if it is 8:55 a.m. and no meeting is scheduled in the agenda of the occupant, there will probably be occupancy soon at the desk, so it switches on the lighting. A pro-active system (3) aims to foresee a condition in the near future and control the lighting system accordingly. For instance, if a desk is unoccupied at 8:55 a.m. but the occupant is typically arriving at 9:00 a.m., the lighting will be switched on in anticipation of the occupant's arrival. In contrast to an anticipatory system, it has an internal model which stores all events.

From the 24 reviewed studies, only one study was found to test an anticipatory lighting control system, namely Oldewurtel and colleagues [44]. All other studies tested a reactive system.

3.5.4. Illuminance settings

The illuminance settings of the tested systems varied largely over the studies. Several studies do not specify these settings more than "on" and "off". If the illuminance level was specified, this typically formed a fixed setting, for example 500 lx for occupancy and 0 lx for vacancy. Only three studies were identified in which these levels were variable. In the studies of Wen and Agogino [28] and Galasiu and Newsham [31] the illuminance level depended on the preference of the individual. These studies were either performed with computational modelling or in an office with a cubicle lay-out. In the study of Pandharipande and Caicedo [39] the illuminance level was also variable, but depended on the dimming level of the neighbouring luminaire with which they preserved the spatial uniformity throughout the space. In most of their studies, however, they used 300 lx as illuminance setting for absence, which is in line with the scale of illuminance as stated by the European standard EN 12464-1. If 500 lx is provided at the task area, the recommended maintained illuminance in the immediate surrounding area is a minimum 300 lx. Araji and colleagues [26] also applied dimming, in this case to 30% of the luminaire output, but at zone level.

3.5.5. Time delay setting

Most of the 24 studies did not consider a time delay setting. Within the studies that included time delay, the setting varied from 0 min (chair sensor) to 5–30 min (conventional PIR sensor), but typically it was set at 15 min. Some studies also investigated the effect of different time delay settings on the energy consumption of lighting [3,29,36]. Galasiu and colleagues [30] and Rubinstein and Enscoe [33] incorporated a time frame over which the lighting was dimmed to make the transition from switched 'on' to switched 'off' unperceivable to occupants. Galasiu and colleagues [30] tested two settings: in (1) the time delay was set at 8 min followed by 7 min of continuous dimming and in (2) the time delay was set at 12 min followed by 3 min of continuous dimming. Rubinstein and Enscoe [33] tested a time delay setting of 20 min after which the luminaires were dimmed to 80% for 10 min before they faded off. They did not specify with which dimming speed this fading occurred. They are the only two studies who consider the time delay setting in the design of the lighting control strategy, together with Nagy and colleagues [49], who tested a system with a time delay setting adapted to the occupancy pattern of the room.

3.6. Post-occupancy evaluation

3.6.1. Measures

All studies assessed the system's performance with quantitative measures, except for the study of Escuyer and Fontoynont [25]. They only evaluated the system based on the comments of the users. All of the remaining 23 studies reported how much energy savings were gained by the proposed occupancy-based lighting system. Regarding lighting performance, most studies only measured the illuminance achieved at the work plane. Spatial uniformity was only measured by Caicedo and Pandharipande [47]. Some studies performed additional measurements regarding the costs of installing the strategy [27,29]. Galasiu and colleagues [30] also calculated the power demand reductions the strategy provides as this is a major issue in Canada. The actual performance of the occupancy sensors was only assessed by Refs. [31,34]. Granderson and colleagues [34], in addition, measured the ease of commissioning of the system. Occupancy patterns were measured by almost none of the studies, only by Refs. [36,37]. Nagy and colleagues [24] tested a system with an illuminance threshold adapted to the preference of the occupants and a time delay setting adapted to the room's occupancy pattern, and assessed the time needed before these settings stabilized.

3.6.2. Energy savings

Energy savings of the occupancy-based lighting control were always compared to a baseline case. This baseline case most often involved a traditional system where the lighting is controlled manually (e.g. Refs. [31,33]) or a schedule-based lighting system (e.g. Ref. [37]). Typically, a range was provided as energy savings were not fixed, but depended on time of the day (because of different daylight conditions) [38]; on number of occupants present [39]; on the time delay [24]; on space and assumed lighting power density [27]; on occupancy pattern of the building (homogeneous or heterogeneous) [44]; on optimization approach of dimming levels and spatial uniformity at the workstation [47], occupancy status and daylight availability [28]; on time delay setting, space and occupants' function [36]; and on time delay [37]. In addition, savings were often a result of an implementation of occupancy sensors combined with other sensor technologies, such as light sensors. These savings were categorized as "not applicable = NA" in Table 11 and Table 12. The tables show respectively the amount of energy savings that were found minimal and maximal for the different spatial levels. In these tables it can be seen that savings vary largely across studies as well as spatial levels.

Table 11
Minimum amount of energy saved of the 24 studies for the different spatial levels, categorized according to their percentages.

Minimum energy savings	Spatial level				Frequency
	Individual workspace	Zone	Room	NR	
0–10%	[39]		[27,36,37]		4
10–20%					—
20–30%	[31]				1
30–40%	[30]				1
NR	[29,33,40,41,43]	[26,32,44]		[25,45,46]	11
NA	[28,38,42,47,50]		[24,35]		7

Note: NR = not reported, and NA = not applicable, meaning that studies measured energy savings resulting from more innovations than just occupancy sensors.

Table 12
Maximum amount of energy saved of the 24 studies for the different spatial levels, categorized according to their percentages.

Maximum energy savings	Spatial level				Frequency
	Individual workspace	Zone	Room	NR	
10–20%	[29]	[32]			2
20–30%		[37]			1
30–40%	[30,31,33]				3
40–50%	[39]				1
50–60%		[44]	[27]		2
60–70%					—
70–80%					—
80–90%					—
90–100%			[36]		1
NR	[40,41,43]	[26]		[25,45,46]	7
NA	[28,38,42,47,50]		[24,35]		7

Note: NR = not reported, and NA = not applicable, meaning that studies measured energy savings resulting from more innovations than just occupancy sensors.

3.6.3. Cost effectiveness

As discussed above, only two studies investigated the costs associated with installing local lighting control. Fernandes and colleagues [27] calculated the payback period for both occupancy and dimming as well as just dimming, which were found to be respectively one to eight years and one to ten years. Manzoor and colleagues [29] calculated how much money their strategy would save per day, which they found to be €0.2986. They mention that this is less than the cost of deploying such sensors, but do not provide any details on these costs.

3.6.4. User

Only five studies evaluated the lighting control system with the user, while 19 did not. Two studies were assigned to the 'no' post-occupancy user evaluation category. Although Nagy and colleagues [24] did keep track of users' complaints, they did not ask for their actual opinion. Galasiu and colleagues [30] assessed users' opinion, but did not report the results. Those five studies were evaluated on the items discussed in Table 1, of which the results can be found in Table 13.

In Table 13 it can be seen that the number of occupants tend to be rather small, except for the study of Rubinstein and Enscoe [33], in which 91 users participated. The job type of the participants was only reported by Galasiu and Newsham [31]. Moreover, Table 13 shows that all five studies used qualitative methods, but varying types. The used measures differed largely between studies as well. However, users' experience of the automatic lighting control, of main interest to our study, was addressed by all, except for Granderson and colleagues [34], who did not report any results at all. Participants in the study of Escuyer and Fontoynont [25] explained that they like the automatic system because it means that they did need to care about it (33%). Galasiu and Newsham [31] found users to be more satisfied with this manual interaction than the automatic on/off, but this difference was minimal: with both users scored on average around 3 on a scale of 1–5. The satisfaction of users with automatic dimming was also measured by Aghemo and colleagues [35], on which users scored around 3 on average as well. It should be noted however that this dimming occurred in response to a daylight sensor. None of the studies, however, used statistical tests to analyse the results.

3.7. Conclusions from the studies

Four topics were identified that reoccurred in the conclusions of the studies and that were considered relevant to answer the research questions, namely 'occupancy detection technique', 'energy savings', 'cost effectiveness', and 'user'. Table 14 shows the number of studies that discussed these topics in their conclusion, for the different type of studies and type of offices. Additionality to these four topics, several studies had a conclusion about the system architecture of the lighting control strategy, e.g. which kind of PI controller to use [41] and whether to use a central or decentralized controller [38]. As this is not the most important element of the lighting control system for achieving alignment between individual occupancy patterns and lighting use, these conclusions are not included in Table 14. This section also excludes conclusions about performances of luminaires [43] and light sensors [46].

Table 14 shows that most studies discussed energy savings in their conclusion. It was discussed by all type of studies performed in all type of offices. Occupancy detection technique and cost effectiveness received just little attention overall. Conclusions about the user were mainly drawn by field studies that were conducted in both open-plan and cubicle offices. In the subsequent sections, the conclusions will be discussed in more detail per topic.

3.7.1. Occupancy detection technique

Labeodan and colleagues [45] compared the performances of PIR sensors and chair sensors and concluded that chair sensors perform better in controlling lighting based on occupancy. They suggest that they can contribute to reducing building energy use,

Table 13
Overview of number of participants (N), job type of participants, method, measures, and statistics used by the five studies that performed the post-occupancy evaluation with the users.

	N	Job type	Method	Measures	Statistics
[35]	10	Not reported	Questionnaire	Opinion about environmental conditions, satisfaction with system's operation, general and task lighting conditions and manual control	Means + SDs
[31]	17	Students, visiting workers and other temporary staff	Open questionnaire	What they liked the most about the system, liked the least about it, what they would change if they could change one thing	–
[25]	6	Not reported	Semi-directed interview	(1) Importance given to lighting in the office; (2) lighting itself, involving possible comments, preferred luminous levels and the ideal lighting system); (3) the lighting system, involving comments on the automatic system and the ideal lighting control system; and (4)the blinds	Percentage participants mentioned 'essential' sentences for each category
[33]	91	Not reported	Survey with 38 multipoint rating and multiple choice type questions with space for comments	(1) Comfort, with the workspace in general and the lighting conditions; (2) glare, from their work surface, from the light on their computer screen and overall from the lighting; (3) their satisfaction with the amount of control the system provided; and (4) what they would change about the lighting system (11 items)	Percentage participants for each of the answer options
[34]	Not reported	Not reported	Logbooks and debriefing interviews	Perception	Not reported

Table 14
Topics of conclusions of the 24 eligible studies, categorized as 'occupancy detection technique', 'energy savings', 'cost effectiveness', or 'user', for the different type of studies and type of offices.

Conclusions	Type of study and type of office						Frequency
	Field study			Computational modelling		Laboratory study	
	Open-plan	Cubicle	NR	Open-plan	NR	Open-plan	
Occupancy detection technique		[29]				[45]	2
Energy savings	[24,26]	[27,32–34]	[28,36]	[31,42]	[44]		11
Cost effectiveness		[27,29]					2
User	[25]	[30,33]	[35]	[38,47]			6

Note: NR = not reported.

operational costs and overall improvement of the performance of buildings [45]. Manzoor and colleagues [29] used both PIR sensors as RFID tags to control lighting, with which they achieved an accuracy of 91.43%. The authors suggest that they are not only useful for controlling lighting, but that they also allow the monitoring of building energy, use and security. However, their implementation does require changes in building physics and operation, so they ask for a thoughtful consideration.

3.7.2. Energy savings

Ten studies have positive conclusions regarding the energy savings resulting from occupancy-based lighting control [24,26–28,31,33,34,42,44]. Wen and Agogino [28] stress that they even found it to have energy saving potential in open-plan offices with less-than-ideal configurations, with which they mean that luminaires and desks are not aligned. Galasiu and Newsham [31] found it to result in higher energy savings compared to central lighting control, even though the installed lighting power density of individual occupancy-based lighting control is higher. Therefore, they argue that for saving electrical energy for lighting the operation of the lighting system is more important than the installed power density. Nagy and colleagues [24] attribute the large energy saving potential to the calibration of lighting to the use of the specific office spaces.

Jennings and colleagues [32] agree with the studies above, arguing that occupant sensors have the potential to save energy, but also argue that the size depends greatly on occupant habits,

custodial practices, and the baseline of the building. Similarly, Richman and colleagues conclude that their energy saving potential depends on the function of the space, the occupants, the amount of lighting wattage to be controlled, and the applicable utility rate [36].

Fernandes and colleagues [27] argue that most energy savings occurred when occupants arrived early or left the office late. In line with this finding, Pandharipande & Caicedo [42] suggest, as future research, field studies to understand the impact of specific occupancy patterns on the energy savings.

In addition, Fernandes and colleagues [27] provide practical advice on measuring energy savings. They found the measured power consumption to deviate from calculations based on information of the building's lighting control system. Therefore, they advise to use direct measurements for the field evaluation of technologies such as lighting control systems.

3.7.3. Cost effectiveness

Fernandes and colleagues [27] noted that the payback period of dimming controls depends strongly on the occupancy patterns during daytime. Overall, studies stress that a high density of sensors has more value than just saving energy. Pandharipande and Caicedo [39], for example, argue that the sensor data extend the usability of smart luminaires beyond illuminating a space, namely to services as improved building control and better energy management. Similarly, Manzoor and colleagues [29] argue that RFID tags provide facility managers with real-time occupancy patterns,

which can be used to monitor building use and security, in addition to monitoring building energy.

3.7.4. User

Studies did not receive any negative feedback on automatic lighting control [30], but manual control was typically preferred by users [25], which they therefore recommended to provide as well [35]. Escuyer & Fontoynont [25] suggest that the ideal system might involve automatic dimming, but switching off should not occur automatically, as this could annoy some users. Ahgemo and colleagues [35] stress the importance of the correct design and commissioning of the control system.

Rubinstein & Enscoe [33], on the other hand, found that workstation-specific lighting improved users' satisfaction compared to a centralized system. They therefore argue that providing additional corridor lighting and leaving ambient lights on in unoccupied cubicles would further improve overall office lighting conditions but decrease energy savings.

Studies however also acknowledge that the system's evaluation with the user requires more research. Rossi and colleagues [38] investigated the performance of a personal lighting system where each luminaire was equipped with an occupancy and light sensor, but with simulations. They suggest that the different parameters of the system should be tested with users in real office settings. This need for field studies was also acknowledged by Pandharipande and Caicedo [47], who reviewed the lighting control approaches of lighting systems with luminaire-based sensing.

4. Discussion

In this literature review it was investigated to which extent in multi-occupant offices individual occupancy-based lighting control has been tested (1), developed (2), and evaluated (3). First of all, although the search was rather extensive, it only resulted in only 24 eligible studies. The topic was investigated by 25 more studies, but 16 were found to be performed in private offices. The other nine studies only calculated the energy savings that could be gained by implementing an occupancy-based lighting control strategy. These however did not consider the design of the occupancy-based lighting control strategy and its application to the real office environment.

From the 24 studies identified as eligible, first the study design as well as office characteristics are discussed. This provides an answer to research question 1, or in other words, future research directions are provided. Then, it is explained to which extent the lighting system characteristics and lighting control design consider individual occupancy patterns. Subsequently, and answering research question 2, future directions for the development of individual occupancy-based lighting control are given. Then, the extent to which studies performed the post-occupancy evaluation is examined and future evaluation directions are provided. Finally, suggestions are provided for a design approach that could be taken.

4.1. Future research directions

Of the 24 studies, 58% were performed in a real office environment, which is preferable as a test environment because it closely resembles the environment where the strategy is aimed to be implemented. In geographical locations where weather conditions differ significantly across seasons, such a field study should preferably cover multiple, if not all seasons, so that the lighting control strategy is experienced with the full range of daylight availabilities. Therefore, a field study should last at least nine months to one year. However, it was identified that the number of studies longer than the preferable minimum of nine months is still limited (Table 6).

Offices of all sizes were however investigated, but large office spaces formed a minority (Table 8). Open-plan offices were overall studied more than cubicle type offices, but less in field and laboratory studies and more with computational modelling studies (Tables 5 and 7). One short-coming of simulations is that the occupancy scenarios remain static, while in the real office these vary constantly. As a result, the illuminance levels will vary as well. They used 500 lx for occupied zones and 300 lx for unoccupied zones, which means that there will be a reduction of 200 lx when users will leave their desk. Therefore, it is highly important to conduct more user studies in open-plan office environments.

4.2. Future development directions

As lighting control strategy, control at the individual workspace level was applied most. It forms the first step in aligning lighting with the individual occupancy patterns. It was, however, just applied in cubicle offices, not open-plan offices (Table 10). It seems inappropriate to directly transfer this strategy to open-plan offices. In these type of offices users overlook the whole office space, while in cubicle offices users' fields of view are limited by partitions. Consequently, while in the cubicle office only illuminance changes at the neighbouring desk are likely to be noticed, in open-plan offices changes are visible from everywhere and to everyone. Thus, further development of this strategy is required as different parameters might be required, for example for the illuminance settings. Although most studies switched off the lighting completely at workspace level in the case of vacancy, in open-plan offices local dimming might be preferred, for the reason explained above. This was only found to be applied in computational modelling studies [39] or at a higher spatial level [26]. Dimming has the potential to preserve the visual comfort of the co-workers present in the space as it provides a smoother contrast between occupied and unoccupied workspaces, as also argued by Haq and colleagues [13]. However, this has to be further developed and tested with users. For the development, user studies in the laboratory might be more appropriate as they provide a controlled environment. After strategies have been fully developed, they should be validated with users in field studies, as was also suggested by the reviewed studies.

When dimming would be applied, LED luminaires would be most suitable. These were also used by the studies employing dimming control. With conventional luminaires the lifespan is negatively affected by dimming, but this is not the case with LEDs. It might even extend their lifespan [51]. Pandharipande and Caicedo [42] argued that 'substantial energy savings can be obtained by using our proposed strategy' (p. 949), referring to dimming according to location of the individual within the space.

To support control at individual workspace level, luminaires were often aligned with the desks (Table 9). Sensors were used that are able to sense individual's behaviour. However, this was mostly applied to cubicle offices; only Araji and colleagues applied it to an open-plan office [26]. In open-plan offices alignment currently only tends to be simulated, but not applied in the real world. This difference can be explained by the fact that in open-plan offices such a strategy is less straight forward than in cubicle offices, where the layout forces alignment: if the luminaires were not located directly above a cubicle, the partitions would (partly) block the light. The step from simulation to practice in open-plan offices is further complicated by the current building process. While a computer simulation allows complete freedom in designing the lighting in the space, this is typically not the case in reality because lighting is placed in the building before the lay-out of the space is designed or because the space lay-out is altered over time. Luminaires consequently tend to be positioned in a standard grid. To achieve alignment between desks and luminaires in retrofit office buildings,

replacing the desks would be one solution, but this might not always be possible. Wen and Agogino [28] resolved this issue with an optimization framework determining the output level needed for each of the luminaires to establish the illuminance level as preferred by the occupant. Consequently, as soon as an occupant's presence was detected, the luminaires were set to these levels, which, for example, meant that one luminaire was set at 100%, seven between 11% and 73%, and four at 0%. Localized lighting control thus also seems achievable in retrofit buildings, but more cases are required to prove its applicability here.

Almost all studies used PIR sensors, which can be explained by their low-cost availability, but these only enable individual workspace control in cubicle type offices. They have a large view angle and can only sense occupancy binarily. In cubicle type offices this does not result in any issues as here partitions limit the view of the sensors, shown in the study of Rubinstein and Enscoe [33]. In open-plan offices, however, there are no partitions and workspaces tend to be smaller. Here, the PIR sensor consequently is not able to identify individuals. Only two studies [29,45] were found who resolved this issue and used a different type of sensor, namely chair sensors and a combination of PIR sensors and RFID tags, respectively. Other solutions might also be possible and even better fit individual occupancy-based lighting control, but this requires further research.

In addition, the time delay settings of the strategy require more attention from research. It was found that these are adapted to the occupancy pattern of the room, but not to the individual occupancy patterns within the room. This is important because the time delay setting determines the lighting use. If occupants, for example, tend to sit behind their desk all day, the probability that someone will leave and return again soon is low. A long time delay setting would in this case result in energy waste because the lighting remains unnecessary switched on. To achieve optimal lighting use, the time delay setting should be adapted to an individual's occupancy pattern. Although this optimization has been performed for single-occupant offices (e.g. in Ref. [52]), the identified time delay settings by this research are not directly transferable to open-plan offices, because occupants influence each other's patterns here. This was not addressed by any of the 24 studies. This means that also in cubicle type offices lighting use can be further optimized. Additional research is thus required to address the optimization of the time delay setting to individual occupancy patterns within multi-occupant offices.

Theoretically, a proactive intelligence level is expected to result in more optimal lighting use than reactive and anticipatory systems. With such a system it is possible to fully anticipate the occupancy behaviour of an individual. Consequently, there is no need for a time delay, because the system knows that the individual, for example, will not return for the coming 20 min. This consequently results in an optimal fit between lighting use and individual occupancy. However, human behaviour is difficult to fully predict, so the extent to which optimal lighting use can be achieved depends on the prediction accuracy. Consequently, reactive and adaptive system might have the same lighting use. A conclusion cannot be drawn yet as no studies investigated a proactive lighting system and only one system an anticipatory system (in addition to a reactive system) [44]. This last study investigated Model Predictive Control (MPC), a method which considers long-term occupancy patterns. Energy savings were calculated both for a homogeneous occupancy and an alternating occupancy pattern. Based on the results, they recommend to adjust the lighting to instantaneous measurements, so reactive, but not to use sophisticated occupancy predictions as MPC for lighting control. However, they used the same vacancy-to-occupancy ratio to each second room while in reality the whole building may have an alternating ratio, which

would mean that more energy would be saved with such an anticipatory strategy. In addition to saving energy, the comfort of users might be increased with a system that works anticipatorily as lighting will be switched on before occupants arrive at their desk. Consequently, the occupant does not experience any inconvenience of the switching. Clearly, more investigation is required to determine the applicability of anticipatory lighting systems.

4.3. Future evaluation directions

All studies except one calculated the energy savings that resulted from the studied occupancy-based lighting control strategy, while only five studies involved users in the post-occupancy evaluation. This confirmed our expectations formulated in the Introduction. In the conclusions of the studies however, 'energy savings' and 'user' received more similar attention: they formed the main topic of the conclusion of 11 and 6 studies respectively (Table 14). These were partly other studies than those involving users in the post-occupancy evaluation. This suggests that although some studies did not yet involve the user in their investigation, they do acknowledge the need to do so.

Moreover, studies tend to evaluate the lighting system's performance on the achieved illuminance at the desk. However, it can be questioned whether this is sufficient. Caicedo and Pandharipande [47] also tested for spatial uniformity, which is in line with the EN-12464-1 norm [53]. This standard not only recommends a minimum horizontal illuminance level, but also sets a limit to glare and asks for a minimum uniformity.

Reported results on achievable energy savings of lighting controls at individual occupancy level are partly contradictory. Studies investigating this type of control found higher energy saving percentages than the baseline case, which was typically lighting control at room level. They ranged from 0 to 50% (Tables 11 and 12). However, studies investigating lighting control at higher spatial levels found energy savings in the same range as with control at individual occupancy level (Tables 11 and 12). These results and the fact that all studies mentioned factors influencing energy savings suggest that it highly depends on the specific space. Varying case studies will thus need to be performed to determine the energy saving potential of individual occupancy-based lighting control. Thereby it seems important to especially determine the influence of individual occupancy patterns, as this was mentioned as future research direction by several studies.

The cost effectiveness did not receive that much attention; it is only mentioned in two studies. Thus, before individual occupancy-based lighting control is further researched, this needs to be investigated more extensively. However, it will be difficult to draw general conclusions due to the drastic ranges in prizes for electrical energy. These analyses thus will need to remain regional. Thereby, the additional value resulting from implementing a fine-grained sensor network should also be weighted. Several other applications of sensors in addition to lighting control were namely suggested by the studies.

From those five studies involving the user in the post-occupancy evaluation, only Rubinstein and Enscoe did this extensively [33]. They used a questionnaire with 38 questions that covered comfort, glare and satisfaction aspects and was filled in by 91 occupants. Job type was also reported by only one study. To obtain valid results it should be the aim to involve occupants with a variety of job types as this will affect their occupancy patterns. This in turn might affect their perception of the lighting control strategy.

It was of specific interest to our study to learn how users experienced the automatic lighting control. However, as the five studies measured this differently, it was difficult to compare their results. Granderson and colleagues [34] did not report their results,

so they could not be included in the comparison. Statistical analyses were also missing in all studies. Across these studies, however, participants seemed to like the automatic on/off switching. Automatic dimming was also evaluated positively by participants in the study of Aghemo and colleagues [35], which suggests that dimming does not form a distraction. However, it should be validated whether this applies to dimming based on occupancy as well.

4.4. Overall design approach

As discussed before, the evaluation of the occupancy-based lighting control systems is currently focussing on energy savings. This focus might also explain why the 24 studies devoted little effort to the design of the occupancy-based lighting system. Typically, recommendations from standards and guidelines were used as system settings. With the illuminance settings, for example, almost all studies used a target illuminance of 500 lx if the occupant is present. Only with the system designed by Ref. [28] the illuminance settings depend on preferences of users. Most studies either modelled the design or tested the design directly in a real office environment. Only Labeodan and colleagues [45] as well as Caicedo and Pandharipande [46] initially tested the applicability of their developed system in a controlled environment before applying it to a real facility. Nagy and colleagues [24] designed a system that learned from behaviour of occupants which they tested in their own offices. Thereby, they indirectly involved users in their optimization process. Fernandes and colleagues [27] also allowed occupants to give input towards the commissioning. The target illuminance of the system was set at 323 lx unless a user requested a different individual setting, which was done only once. This shows that users do not feel inclined to express their preference if the researchers do not actively ask for it. For a user-centred design approach users are to be directly involved in the design process. This approach can be implemented through qualitative user tests, such as focus groups and interviews, or quantitative user tests like measuring task performances. Nagy and colleagues [24] indicate that such quantitative tests are needed to show the system's comfort gains before it can be implemented in other offices. It thus can be concluded that none of the reviewed studies took a full user-centred design approach.

5. Conclusion

The aim of this literature review was to reveal.

(1) Whether occupancy-based lighting control in the multi-occupant office is fully tested and if not, how it still needs to be tested,
(2) Whether individual occupancy-based lighting control in the multi-occupant office is fully developed to achieve optimal lighting use, and if not, on which aspects it can be further developed, and
(3) Whether individual occupancy-based lighting control in the multi-occupant office is fully validated, and if not, on which aspects should it still needs to be validated.

The structured literature search resulted in 24 studies being identified as eligible, which suggests that the research on lighting control in multi-occupant offices is still limited. The most important research direction identified was the need for field studies in type 3 open-plan offices, i.e. offices without partitions separating desks. Field studies have been performed in cubicle offices, but longitudinal studies as well as studies in large office spaces are still limited, providing a clear direction for future research. The analysis of the lighting system characteristics and lighting control design

revealed that controlling lighting at workspace level is the only means by which lighting is currently aligned to individual occupancy patterns. However, it was only applied in cubicle offices, not in open-plan offices. As these type of offices have a different spatial lay-out, the strategy developed for cubicle offices cannot be copied directly. In case of naïvely applying such strategies might negatively impact the comfort of users. Instead of switching luminaires on and off in response to individual occupancies, dimming them might be more appropriate here. This raises the question of what horizontal illuminance levels the lighting system can be dimmed without affecting the comfort of users. No study has addressed this issue yet, identifying a focal point for future research. Research carried out up until now excludes an entire office type, i.e. there is still a large potential to saving energy on the use of electrical lighting. While other aspects of the design of occupancy-based lighting controls also have not been addressed yet, their resulting energy savings might only lead to minor improvements. These aspects involve, for example, adapting the time delay setting to the occupancy pattern of the individuals within the multi-occupant office. Further, the lighting system could be developed such that it anticipates the individual occupancy patterns. This means that lighting is not yet used optimally in multi-occupant offices and energy consumption for lighting can still be reduced further. Validation of individual occupancy-based lighting control is especially required for the comfort of users as they received little attention from current research. Also the energy saving potential of occupancy-based individual lighting control should be investigated further, as results differed largely across studies. Research should focus on the factors explaining these differences, especially on the influence of the individual occupancy patterns, as this factor seems the most determinant. Therefore, case studies in different building types with different occupant types would be needed. The cost-effectiveness of the strategy could then also be addressed. Since this highly depends on local energy prices, general conclusions cannot be drawn easily. The design process of occupancy-based lighting control tends to be minimal: recommendations from standards and guidelines are typically used, while the user-centred design approach was not found to be applied yet. So, in multi-occupant offices, not only the individuals, but also their occupancy patterns need more attention from research and design.

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