The effect of lighting environment on task performance in buildings – A review

Iason Konstantzos [a], Seyed Amir Sadeghi [b,c], Michael Kim [b,c], Jie Xiong [d], Athanasios Tzempelikos [b,c,*]

[a] Durham School of Architectural Engineering and Construction, University of Nebraska, 1110 South 67th Street, Lincoln, Omaha, NE 68182, USA
[b] Lyles School of Civil Engineering, Purdue University, 550 Stadium Mall Dr., West Lafayette, IN 47907 USA
[c] Center for High Performance Buildings, Ray W. Herrick Laboratories, Purdue University, 140 S. Martin Jischke Dr., West Lafayette, IN 47907, USA
[d] Commercial Buildings Research Group, National Renewable Energy Laboratory (NREL), 15033 Denver West Parkway, Golden, CO 80401, USA

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ABSTRACT

The effects of indoor environmental conditions on human health, satisfaction, and performance have been the focus of research for decades. This paper reviews and summarizes the impact of lighting environment on task performance, specifically for the built environment audience. Existing studies included a variety of performance tests on cognitive performance and perception, visual acuity and reaction, memory, reasoning, and labor productivity. Illuminance, luminance ratio and correlated color temperature were found to affect performance in different ways, reflecting the impact of experimental techniques, conditions, performance evaluation methods used and data analysis methods. These were reviewed and categorized, with discussion on limitations related to sample size, modeling approach, carryover effects and other factors affecting individual differences in performance, with recommendations for future improvement. Although no universal conclusions can be made, in general, task performance seems to improve with higher illuminances, contrast ratios in the range of 7–11:1 (while always making sure that glare will not occur in the space) and higher correlated color temperature, while spectral tuning in the red or blue wavelengths has also shown positive effects. To obtain more generic evidence, future studies should be more consistent in terms of experimental procedures and overall light conditions, and also consider the effects of vertical illuminance, daylight provision/control, and outside views on task performance. Finally, studying performance with multi-factorial designs in a human-centered optimized manner (such as deploying variable lighting scenarios optimized for various tasks) can lead to deeper understanding of lighting effects on task performance, and ultimately to improved lighting design and operation in buildings overall.

Contents

* Corresponding author at: Lyles School of Civil Engineering, Purdue University, 550 Stadium Mall Dr., West Lafayette, IN 47907 USA.
E-mail address: ttzempel@purdue.edu (A. Tzempelikos).

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1. Introduction

Lighting conditions have a significant impact on all aspects of human life and health. They affect our physiological and psychological health, and their dynamic changes have positive effects on several aspects of human well-being [15]. A review on the impact of environmental conditions on health [85] showed that there is a large number of studies on the effects of lighting conditions on human physiology. Due to the significance of the topic, the focus of the built environment academic community has expanded [99] from the impact of daylight and electric lighting on building performance and energy use to the effects on health, well-being and comfort. While the effects of electric lighting have been studied more, Munch et al [64] identify the difficulty in addressing knowledge gaps in daylight research because "the implications of daylight go far beyond isolated and specialized research areas", such as physics, engineering, architecture, environmental sciences, medicine, psychology, economics, occupational and social sciences. Moreover, the authors emphasize the lack of knowledge regarding the "*quantity and quality of daylight needed for "optimal" physiological and psychological functioning*".

Non-visual effects of daylight are well recognized in the built environment research field and new approaches have been proposed for circadian daylight metrics [43], alertness, mood and rest cycles [62,13,12] and multi-criteria assessment of daylight-driven human responses [4] considering nonvisual health potential, visual interest and gaze behavior. Knoop et al. [42] reviewed human responses to daylight and identified current knowledge gaps. The article discusses human responses related to visual performance, eyesight, circadian entrainment, non-image forming effects, room and object appearance, comfort, outdoor views, energy efficiency and economic benefits. Aries et al. [6] investigated recent research on the daylight exposure on human health. Vision, myopia, eyestrain, migraine, autism, seasonal effects on physiology and behavior, exposure and impact on alertness and cognition, melatonin suppression, hyperactivity and seasonal affective disorders, and even gonadal functions are identified as individual topics. The study found limited statistically significant and well-documented scientific proof for the link between daylight and its potential health consequences.

Lighting preferences vary among individuals [30,29,70,60,28,115] and they are usually studied as a function of lighting stimuli [66,52,77,116]; [118] (Despenic et al., 2017). Physiological, psychological and contextual factors associated with space layout and fenestration systems properties and settings affect visual perception as well [5,84,83,13,71,28,24]; therefore, illuminance parameters alone are considered insufficient to characterize lighting preferences, and sometimes multivariate effects cause preference trends to be not statistically significant [103]. Outside view is also an important aspect of the visual environment, that affects preferences and satisfaction. Studies have shown the impacts of the connection to the outdoors on well-being, job stress, and physical and mental health recovery [86,50,75].

Apart from the effects on human health and well-being, the lighting environment affects task performance [14,15]. Recent studies show that the salaries of occupants are higher than costs of building operation and maintenance [48]. According to an extensive study by Heschong [33], elementary school students in classrooms with the most daylight showed a 21% improvement in learning rates compared to students in classrooms with the least daylight. Therefore, along with energy efficiency practices, increasing occupants' comfort and performance in the workspace are also of great significance. Consequently, there is a need for a comprehensive understanding of the occupants' needs and preferences as well as the factors influencing their performance in indoor environments, two topics that are not necessarily overlapping. Lighting has shown to affect melatonin suppression [10], alertness [19,18,94,93,84,83] and cognitive functions [55,102,79,87], including positive spectral tuning effects [17,63,22,79]. Barkmann et al. [8] summarized the general evidence on how lighting affects work performance as follows: (i) vision improves with increased illuminance (ii) there is an arousing effect of light exposure at night (iii) cooler CTT at high illuminance can lead to increased concentration levels, and (iv) at lower illuminance and especially warmer color temperatures, communication and social behavior seem to improve. However, there are studies that provide contradicting results, both for electric light and daylight applications, as discussed later in this review.

This paper presents a review of literature on the effects of lighting environment on human performance in the workspace, specif-

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ically for the built environment research audience. In general, investigating lighting preferences and performance relates to monitoring the underlying variables such as environmental, physiological, and psychological factors, as well as designing and conducting performance tests, assessment tools and surveys. Section 2 describes the lighting metrics used to assess performance, the experimental methodologies and research approaches followed in different observational studies, and points out the advantages of each method. Section 3 presents the methods of evaluating human performance including subjective and objective measures, along with suggestions on the suitability of each metric for performance evaluation. Data analysis methodologies, limitations, and suggestions for improvement in future studies are explained in Section 4, followed by a summary of findings in Section 5.

2. Experimental methods and performance evaluation

The most efficient way to assess human performance is direct experimentation with human subjects, involving subjective and/or objective methods of evaluation. This section describes the lighting metrics commonly selected to capture the impact of lighting environment on human task performance, the experimental design and process, participants and settings, as well as the main task performance evaluation and assessment methodologies.

2.1. Lighting metrics

2.1.1. Illuminance

By definition, this metric refers to the density of luminous flux incident on a surface. Due to its simplicity in terms of measurement, illuminance is a widely used method to capture light adequacy used in lighting standards [108]. For the same reasons, it is also widely investigated as a potential variable that influences human performance [57,78]; Juslén, 2005; [61,14; 38,68,88,9,104,109].

2.1.2. Luminance

A fundamental lighting metric, luminance is by definition reflecting the amount of luminous flux emitted by a unit surface. Luminance spot meters have been traditionally used to measure point values, and they are expensive. More recently, High Dynamic Range Imaging (HDRI) sensors and methodologies have been introduced to obtain a detailed luminance distribution over the surfaces of interest (Inanici, 2014) ranging from small (screen, window, wall) to large areas (entire visual field, sky, ground). While usually studied for glare evaluation, only a few studies have evaluated this metric for human performance studies. [96,72].

2.1.3. Luminance ratio or luminance contrast

Using luminance ratios is an effective way to capture the potential influence of contrast between different surfaces/areas of interest. Such approach is mostly effective when used in the cases of virtual display terminals (VDT) [11,51,112,106,117,53], where the optimal luminance ratio is ranging between 7:1 and 11:1.

2.1.4. Type and color of light

The type of luminaires used is a broad concept that could affect light intensity, light uniformity, spectral composition and Correlated Color Temperature (CCT) of the indoor visual environment, potentially impacting occupant's performance. Several studies [1,105,74,39] have proved the effects of different types of lamps and light fixtures on worker's productivity in the industrial workspace. The color of light has also been found to influence alertness, sleep quality, cognitive effort and work performance [59,92,110,47,8,31]. This effect is partially a result of the operation of the Intrinsically Photosensitive Retinal Ganglion Cells (IPRGC), that are more sensitive to short-wavelength blue light at the order of 480 nm[54]; This causes the spectral manipulation of light to impact melatonin suppresion, attenuating non-visual responses in humans [76].

2.1.5. Outside view

Although not a conventional metric of the luminous environment, outside view out or connection to the outdoors is an attribute related to daylight access and occupant satisfaction. The subjective nature of it makes its assessment quite complex. Connection to outdoors includes the quality [32], quantity and clarity of outside view, which is related to window and shading optical characteristics[44]. Outside view has been reported to influence occupants' visual satisfaction and overall well-being, physical and mental health [87,50,75]. Aries et al. [5] showed that perception of glare is lower as connection to outdoor was more satisfactory. Tuaycharoen and Tregenza [98] have also reported that perception of glare was reduced for "interesting" scenes. The importance of window views has been acknowledged by building standards, such as LEED 4.1 [111], EN 17037 [21], and WELL [37]. However, the impact of outside view on human performance has not been only systematically studied.

2.2. Experimental procedure

2.2.1. Experimental design

Factorial design has been the most common strategy in lighting-performance research, mainly because it provides flexibility and efficiency (instead of conducting a series of independent studies, it allows combining multiple studies into one). Moreover, factorial design is an effective way to examine interaction effects between independent variables. Two factor-analysis is most common in lighting-performance literature, in which at least one factor is related to the visual conditions (e.g. illuminance, luminaire type, lighting power density, panel reflectance, etc.). The factorial design used in lighting-performance studies can be divided into within-subjects and between-subjects design, depending on how subjects are treated in the experiments. In within-subjects design, all subjects can be tested under each of the treatment conditions [90,24], while different groups of subjects are tested for each treatment in between-subjects design [9,105]; Boyce [14,15].

The result of a within-subjects design is as many data sets as the number of conditions for each subject, whereas in between-subjects design all subjects undergo one pre-set only. Although within subject design can lead to carryover effects (where subjects' responses on later tests are influenced by their experience in earlier tests), this method was chosen to remove subject variation associated with individual differences and thereby to increase statistical power and decrease the probability of beta errors (see more discussion on Section 3.2). Consequently, the type of design is often determined by the number of the subjects available for the study. In the lighting-performance literature, studies with factorial within-subjects design have less than 40 participants, while between-subjects studies typically have more than 90 participants. Exposure time to the treatments is also important in designing the experiment. In studies that have a large pool of subjects and require exposure times longer than a few hours, the between-subjects design is more practical than within-subjects design.

Mixed factorial designs, studying more than one important factor, can provide more insights and useful results. In addition, variation of lighting conditions during the study is important, and there are systematic methods to follow in this regard. Hawes et al. [31] examined the visual perceptual, affective and cognitive implications with fluorescent and three advanced LED lighting systems of varied color temperature and luminance. LED lights with

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higher color temperatures showed better task performance results. Similarly, Barkmann et al. [8] studied the effects of variable lighting in terms of illuminance and color temperature in two schools (7 controlled scenarios) using a variety of student performance and attitude measures, where one school was used as the intervention group and the other was used as the control group. In their study, Sleegers et al. [87] conducted two field studies and an experiment to examine the effect of dynamic lighting (designed to support the rhythm of activity) on the concentration of pupils in elementary schools. These approaches allows a better understanding of the interactions and effects of different variables as well as aligns with improved human-centered lighting principles.

In summary, when determining the type of factorial experimental design in lighting-performance studies, the following factors need to be considered:

Number of subjects available for the experiment
Impact of carryover effect, fatigue and practice effects on performance tasks
Impact of individual differences
Required exposure time to the treatments
Considered factors and single, multiple, or variable controlled lighting conditions

Table 1 lists representative lighting-performance studies with details on factorial design type, experimental settings and participants.

2.2.2. Participants

Participants of most lighting-performance studies are mainly office employees or college students. They are usually compensated on an hourly basis, while some of the studies involve volunteers (mostly college students in this case). The following characteristics are frequently required in the lighting-performance literature:

Minimum age of 18 years old, except for studies with young elementary school students
Normal or corrected vision, no color blindness
No general health problems
No extreme chronotypes especially in studies with dependent variables related to circadian rhythm, sleep, or nighttime performance
Experience with word processing or spreadsheets when measuring typing task performance

2.2.3. Experimental settings

In most of the studies, experiments are performed in mock-up office environments equivalent to small private office rooms [9,40,105,91,92,90,24]. Studies that performed experiments in actual office areas are scarce (Boyce [14,15]). This is mainly because of the logistic complexities as well as the poor controllability of experimental settings that allow changes of the lighting conditions as required. Studies that are focused on K-12 students are most often performed in the actual classrooms [34,8,41,87,46].

2.2.4. Experimental procedure

There is a major difference comparing within- and between-subjects design studies: in within-subjects design, subjects are exposed to all lighting and other environmental conditions (e.g. 8 conditions if it is 4 2 factorial design) if possible, while each of the subjects is assigned to only one of the conditions throughout the experiment in between-subjects design.

Table 1
Representative experimental design methods, settings and participants in the lighting-task performance literature.

Author	Experimental design	Settings	Participants
Campbell and Dawson [20]	Between-groups design (2 illuminances: 200/1000 lx)	Simulated plant environment	25 subjects (10 male 15 female)
Baron et al. [9]	2 4 between-subjects factorial design (2 illuminances on desk:150/ 1500 lx 4 lamp types)	Simulated office environment 3.35 3.22 2.45 m	91 undergraduate students (64 Male, 27 Female)
Katzev [40]	Between-groups design (4 different lighting fixtures)	Simulated office environment 4.3 m 3.0 m	24 office employees (6 male, 18 female)
Veitch and Newsham [105]	3 3 between-subjects factorial design (3 lighting fixture and control configuration 3 LPDs)	Simulated office environment 12.2 m 7.3 m	289 subjects (150 male, 139 female) Age range: 18–61
Boyce [14,15]	4 2 between-subjects factorial design (4 lighting fixture and control configurations 2 panel reflectance)	Partitioned cubicles in actual office Office area: 239 m^2 Cubicle: 2.28 m 2.28 m	181 subjects (69 male, 112 female) Mean age: 32 years
Smolders et al. [91,92]	2 2 mixed-factorial design (2 illuminances at eye: 200/1000 lx 2 light exposure time-morning vs afternoon)	Simulated office environment 3.6 m 3.2 m	32 students (19 male, 22 female) Mean age 22 years
Smolders and de Korte [90]	2 2 within-subjects factorial design (2 illuminances at eye: 200/1000 lx 2 antecedent conditions-fatigued versus control)	Simulated office environment 3.2 m 1.8 m	28 students (12 male, 16 female) Mean age: 23
de Korte et al. [24]	2 2 within-subjects factorial design (2 initial radiant heating powers 2 initial indirect illuminances on desk: 97/204 lx)	Simulated office environment 3.6 m 2.7 *m*	20 subjects (8 male, 12 female)
Keis et al. [41]	2 2 within-subjects factorial design and 4 4 between-subjects factorial design	Two real schools	58 students 8–16 years old
Sleegers et al. [87]	2 4 between-subjects mixed-factorial design (2 illuminance targets 4 CCT)	Three real schools, dynamic vs standard lighting conditions	181 elementary school students Grades 4–6
Hawes et al. [31]	4 4 within-subjects mixed factorial design (4 illuminance targets 4 CCT)	Military shelter facility	24 subjects (20 male, 4 female) Mean age: 22
Barkmann et al. [8]	7 7 within-subjects mixed factorial design (7 illuminance targets 7 CCT)	Four classrooms, different sizes	116 young students (8–16 years old)

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The overall experimental procedure is illustrated in Fig. 1. Before measurement sessions, participants complete questionnaires that collect individual information such as demographics, employment or health-related details. In some studies, a simple visual test was also performed to ensure that the participants have no vision problems. After that, participants are instructed about the overall procedure of the experiment and trained on the performance tasks. A training session for performance is particularly important in within-subjects design studies, to reduce learning effects and enhance consistency. In some of the related literature, a "base condition" session occurs before treatment sessions, where dependent variables are measured under different treatments [20,91,92,90]. The procedure of the base condition session is mostly the same to the following treatment session. Subjects are exposed to a base condition (generally in moderate- or low-light level conditions) for a certain amount of time and then complete performance tasks and a questionnaire collecting subjective ratings related to the lighting conditions. Subjects are then assigned to one of the conditions, and they complete the same performance tasks and questionnaire as in the base condition session. In a within-subjects design, where the subjects are exposed to all the conditions, a short break is given between each treatment blocks to mitigate fatigue or adaptation effects on the dependent variables. The sequence of treatment blocks in within-subjects design is decided on a random basis and counterbalance among the subjects. In a between-subjects design, subjects are randomly assigned to one of the experimental conditions. The purpose of the random assignment is to distribute individual difference equally across the groups; therefore, if between-subject differences in outcome measures are found, they may be attributed to the experimental manipulation. Finally, subjects have to complete a post-test questionnaire that collects subject ratings related to the varying lighting and environmental conditions.

2.3. Performance evaluation

2.3.1. Subjective assessment

Subjective assessment of task performance is usually obtained by a designed survey or questionnaire. Compared to subjective comfort assessment, subjective performance assessment is considered more unreliable and most studies focused on self-sleepiness-assessment. Several studies used simple scale rating and description feedback to evaluate sleepiness subjectively [105,92,90], while other studies used a developed assessment system, the Karolinska Sleepiness Scale (KSS) [2]; Juslén, 2007). Sadeghi et al. [81] also included a subjective productivity assessment in the surveys used for user lighting preferences with electric lighting and shading operation. The extent to which subjective assessment could effectively replace performance/productivity objective tests is not yet certain.

2.3.2. Objective assessment

Objective assessment of work performance can be achieved through either measurements or tests. Early studies on the objective effects of visual environment on occupant work performance mainly focused on alertness. Technologies of bio-marker measurements (electroencephalogram, electrocardiogram, heart rate and heart rate variability) that reflect the brain-wave pattern proved the effects of lighting conditions on alertness first at night-time [7,58,23,19,112], and later on daytime [73,18,17,84,83], and also showed their comparison [80,94].

Different psychometric tests were developed in attempts to assess the performance oriented to different neurobehavioral functions. Table 2 describes representative tests commonly used when studying the effect of indoor environment on performance and their corresponding objectives [49]. In studies related to the visual environment, most tasks have three components: (i) visual; (ii) cognitive; and (iii) motor[1].

Selected single task performance tests in existing literature on the visual environment are summarized in Table 3. Some of the studies focused on cognitive and reaction ability, while others concentrated on thinking and memory-related performance. Studies aiming at manufacturing industry investigated labor productivity directly.

There are also studies utilizing developed (or self-developed) test batteries to cover different aspects of performance. For example, Katzev [40] combined four tests (error detection, spreadsheet entry, typing task, mood test) into one test session; Campbell

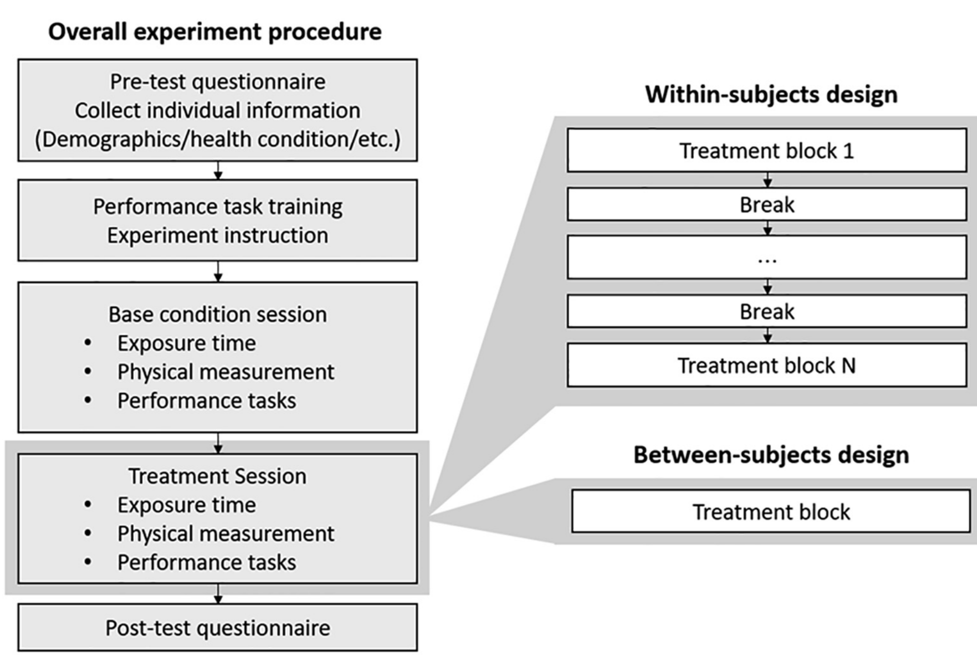

Fig. 1. Overall experimental procedure.

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Table 2
Corresponding functions mainly tested by representative tests [49].

No.	Name of the test	Neurobehavioral functions to be tested.
1	Letter search	Perception - visual search
2	Overlapping	Perception - spatial orientation
3	Memory span	Learning and memory - recall memory verbal memory, attention
4	Picture recognition	Learning and memory -recognition memory, spatial memory, attention, response accuracy
5	Symbol-digit modalities test	Learning and memory, - recall memor, verbal memory
G.	Number calculation	Thinking - mathematic procedures, response speed
7	Conditional reasoning	Thinking - verbal reasoning
8	Spatial image	Thinking-spatial reasoning, imagination
9	Visual choice reaction time	Executive functions - response speed and accuracy

Corresponding functions mainly tested. brepresentative to

Table 3
Commonly used single task performance tests utilized in lighting-perfromance studies.

Test Name	Tested Performance	Literature
Letter identification / Letter counting / Letter Digit Substitution Test (LDST)/d2 concentration test	Cognitive (Perception) Visual acuity (Reaction)	[9,117,51,92,87,31,8]
Landolt-C Test		[11,112]
Necker Cube Pattern Control Test		[92]
2-Back task	Memory Visual acuity (Reaction)	[90]
Standard Ortho-Rater Scoring	Visual acuity (Reaction)	[96]
Go-NoGo Task		[84,83,90]
Psychomotor Vigilance Test (PVT)		[92,90]
Proofreading / Reading Comprehension	Reasoning (Thinking)	[40,105,47,31,8]
Production assembly speed	Labor productivity	[74]

and Dawson [20] adopted Walter Reed Performance Assessment Battery, which includes a logical reasoning task, an index of spatial manipulation and processing abilities and a psychomotor task; Smith et al. [89] adopted a more comprehensive test battery – Automated Neuropsychological Assessment Metrics (ANAM), which includes tasks testing simple reaction time, procedural reaction time, mathematical processing, delayed matching to sample, code substitution, and the Stanford Sleepiness Scale; Sahin et al. [84,83] used a Multi-Attribute Task (MAT) battery. Vimalanathan and Babu [109] used twelve sub-tests to evaluate performance, including letter search, direction, object overlapping, memory span, picture detection, figure-digit, logical sequences, comprehensive reading, numerical addition, logical conclusion, picture match, and reasoning.

Comprehensive guidelines selecting robust task performance tests with respect to the visual environment in workstations remain unclear despite the relatively large number of applications. As performance consists of different neurobehavioral functions, the selection is restricted by the studied work type and the associated performance aspects. Although test batteries try to provide "general" performance assessments, there are different emphases and weaknesses in different test batteries. Different effects of the visual environment on different tests[53,90,109]indicate that different aspects of performance should be analyzed separately.

2.3.3. Objective versus subjective assessment

A few studies combined subjective and objective evaluation of performance in the experimental setups [105,92,90], but no comparative study between these two methods was conducted. As mentioned above, research groups focused on task performance and productivity with respect to lighting conditions should continue this comparison; subjective tests can be more time efficient and, depending on the involved tasks, more cost-effective. However, until we have more evidence about the relative accuracy of subjective assessment, in the form of a validated set of questions, objective tests remain the most reliable way to study human performance and productivity with respect to lighting and other indoor environmental conditions.

3. Data analysis methodologies

All the previously discussed research elements including experimental setup, procedure, lighting and performance metrics, will be eventually presented within one final component: the dataset resulted from the study. Therefore, data analysis methods play a key role when studying occupants' task performance. Inappropriate data analysis might produce misleading conclusions and even cause questions regarding the reliability of the experimental design. This section presents a summary of data analysis methods adopted by researchers to investigate the impact of visual conditions on subjective performance metrics and cognitive functions. A discussion is also presented on limitations of each method and recommendations for improvement towards more accurate methodologies of the data analysis.

3.1. Methods

The following three methods are mainly used in the literature to analyze the datasets in experimental studies and investigate the impact of lighting conditions on task performance. Performance metrics are usually selected as the dependent variable and the effects of other factors are examined independent variables.

3.1.1. Visualization and basic hypothesis tests

In this method, datasets generated from the study are analyzed through descriptive statistics and plotting the dependent variable versus assumed influencing factors [1,100,40,3,27,38,97,95,114]. Trends observed in plots are the main source to introduce and support impacts of lighting conditions on task performance. However, it is also important to statistically justify the significance of observed trends. Therefore, basic hypothesis tests such as Student's *t*-test are coupled with visualization to confirm solidity of findings [110,55,84,83,92,59,16]. Despite the simplicity, which can be an advantage, by following this method, one might not be able to describe the multilayer interactions of factors within a multivariate framework. Thus, other data analysis methods have been adopted in the literature to account for interactions of influencing factors of human performance.

3.1.2. Analysis of variance (ANOVA)

This approach is a statistical method used to test general differences between means and associated procedures of two or more groups. In its simplest form, ANOVA provides a statistical test of whether or not the means of several groups are equal, and therefore, more conservatively generalizes the *t*-test to more than two groups. Moreover, ANOVA is very suitable to study the effects of multiple factors in factorial design experiments and more importantly, has the major advantage of being able to detect the interactions between the factors. Testing one factor at a time (e.g. *t*-test) neglects the interactions of underlying factors and can lead in erro-

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neous conclusions. Due to its advantages and compatibility for factorial experiments, ANOVA is adopted widely by researchers to study the impact of lighting conditions on task performance [84,83,20,7,101] [110,65,79,74,24,87].

ANOVA is commonly based on linear regression and among its main assumptions are homoscedasticity of variances and normal distribution of residuals. These assumptions usually do not hold in the raw data collected from the experiment. Thus, often the data needs to be transformed to datasets that are compatible with ANOVA requirements. When repeated measurements are collected from the same individuals, which is the case in many studies of human performance, ANOVA becomes vulnerable to violation of equality assumption for variances of the differences between all combinations of related groups. In this case, the test becomes too liberal and can cause misleading conclusions. This is a ubiquitous issue when dealing with performance data collection and should be carefully checked. Some researchers have noticed the impact of experimental design which is causing this issue, and have used proper statistical methods such as Greenhouse-Geisser and Huynd-Feldt corrections to account for this matter [7]; Cajochen et al., 2000; [79,24]. Others have also implemented a correction on the data to minimize unwanted effects of individual differences in the performance tests. To this end, for a given dependent variable, the raw data from each subject needs to be averaged, and the ratio of the individual subject average to the grand average is used to transform that subject's raw data. Thus, transformed values have been used as the dependent measures in statistical analyses [84,83]. Another approach to account for repeated measurements and resulting serial correlations is to incorporate the concept of random effects within the modeling framework. For this purpose, an extension of conventional linear regression methods has been used as described below.

3.1.3. Linear mixed models

These models are extensions of linear regression models for data that are collected and summarized in groups (panel data). They describe the relationship between the dependent and independent variables with coefficients that can vary with respect to one or more grouping variables. Due to the hierarchical structure of data in human performance studies, Linear Mixed Models (LMM) have been used to allow for random effects by explicitly modeling the covariance structure of the data. In this modeling framework, the participant is added as a random variable to group the data per person, i.e., to indicate that the same participant is measured multiple times. This implies that intercept is not constant anymore but is a random variable changing between individuals. Based on their availability in data collection, personal data such as light sensitivity can be added as covariates to form and control the grouping [92,90]. One of the main assumptions of LMM is the normally distributed random effects and residuals.

3.2. Limitations and recommendations

3.2.1. Sample size

The validity and generalization of findings in experimental studies of human performance and lighting conditions can be significantly affected by the number of individuals participating in the study. Small-sized data sets are likely to provide limited information and cause large uncertainties in results of statistical analyses. In addition, limited data can also be the reason for false conclusions based on findings that only represent the sample and would not be statistically significant if a larger population had been studied. Therefore, sample size can play a key role in correctness and actuality of findings. Most studies in this field have considered rather small samples with almost thirty or fewer participants [84,83,20,92,7,101,65,55]. This might be due to difficulties in recruiting reliable human test-subjects but knowing the variation among individuals[92,84,83], it is important to extend field studies to larger data sets to ensure results of data analysis are not biased.

3.2.2. Proper modeling framework

The normality assumption for ANOVA and LMM is likely to be violated depending on the experimental design and data collection method. Although statistical corrections exist to avoid some of these violations, it is still hard to satisfy all the assumptions as sometimes non-normality is due to the nature of human behavior. To this end, it is important to allow for non-normal distributions for errors within the model structure. Generalized Linear Models (GLM) are a flexible generalization of ordinary linear regression, allowing dependent variables to have error distribution models other than normal distribution[67]. GLM generalizes linear regression by allowing the linear model to be related to the dependent variable via a link function and by allowing the magnitude of the variance of each measurement to be a function of its predicted value. Another important consideration is the proper modeling structure according to the dependent variable. Use of ordinary regression-based methods such as ANOVA and LMM are justifiable when dealing with continuous dependent variables such reaction time or relative accuracy of a cognitive performance task. However, when modeling discrete variables such as subjective assessment of performance based on discrete scales, it can be problematic to rely on these methods, as they assume a continuous nature for the dependent variable and can result in inefficient estimates. Therefore, it is important to assign the true dependent variable type to the model structure. Logistic and probit functions are among the forms which are commonly used in GLM by researchers in other areas to model non-normal and discrete dependent variables representing human behavior such as interactions with window shading devices [30,29].

3.2.3. Individual differences

Different personal characteristics can cause different attributes of performance towards lighting conditions, which is the main reason some researchers have considered the grouping of data sets based on individual variables in linear mixed models[92,90]). This can also be investigated in ANOVA by including the participant as a factor interacting with other independent variables[84,83]. However, this approach does not explicitly identify the categorization of human performance towards different lighting conditions; in random-effect methods, such as linear mixed models, varying intercept does not create sufficient flexibility to investigate and capture the classification, if any, of human performance. Therefore, advanced cluster analysis methods can provide more insight in this direction. Latent class and random parameter models have proved to be promising approaches towards identifying potential categorization within the data set. Latent class models detect a number of different behaviors with an estimated class probability assigned to each group while random parameter models allow for variation of all coefficients including the intercept and search for classification with larger degrees of freedom in comparison to random-effect models (e.g. linear mixed model). Clearly, to apply the advanced models with reasonable confidence intervals, larger data sets are required as more variation is to be captured through these models.

3.2.4. Carryover effects

When dealing with within-subject experimental designs, where data from the same group of subjects are repeatedly collected in more than one treatment, there are two main types of sequence or carryover effects: learning (practice) and fatigue. Participants potentially develop a better skill in experimental tasks and cognitive performance tests throughout the experiment period, which is

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referred to as learning or practice effect. The obvious indication of this effect is a consistent increase in performance over time. Furthermore, there might be a fatigue effect which might happen if participants repeatedly conduct experiment tasks for long periods of time. The obvious impact of fatigue would be the lower performance over time. However, as these effects are not always obvious and identifiable, to achieve a reliable data analysis and findings, it is important to (i) design the within-subject experiments in a way that these effects can be minimized and (ii) to check and correct for them after data collection [87]. Randomization in experiment procedures and Latin-square design [48] are promising methods which can control carryover effects at experiment design stage. After the data collection, carryover effects could be tested and adjusted by setting up the 'sequence' as an independent variable in mixed models or ANOVA apart from other factors. Positive coefficient estimates suggest learning effects while negative coefficients imply fatigue. This is similar to conducting an analysis of covariance where dependent variable scores are adjusted covariates before testing treatment effects. After detecting the carryover effects, corrections of the dependent variable can be applied using Eq. (1):

$$P'_{n,i} = \frac{\overline{P_1}}{\overline{P_n}} P_{n,i} \tag{1}$$

where $P_{n,i}$ and $P'_{n,i}$ are the value of the dependent variable for the i^{th} participant and n^{th} presentation before and after correction respectively, n refers to the sequence of presentation, and $\overline{P_n}$ refers to averaged value of the dependent variable at the n^{th} presentation. Carryover effects need to be adjusted before treatment effects can be thoroughly explored. However, this matter has been neglected in most of the studies that investigate impacts of lighting condition on human performance.

4. Results and discussion

This section discusses results from the reviewed studies in terms of each of the metrics of interest.

4.1. Illuminance and task performance

From the early studies in the 1920s, the effects of light levels on work performance in industrial settings was of particularly of interest. Although the Hawthorne effect - which refers to the fact that the feeling of being observed can lead to improved performance [57,78]– caused waned interest in this type of studies, the belief that brighter illuminance leads to better work performance is accepted until today.

Juslen and Tenner [39] organized all the results found in literature from 1920 to 1980. An important characteristic of illuminance-performance early studies in industrial environments is that the types of task evaluated were closely linked to the visual performance of workers. Fig. 2 shows the clear increase in work output as a function of task illuminance, based on all available early studies according to Juslen and Tenner [39]. Note that there is high uncertainty in individual studies, marked by dotted lines, and therefore the averaged (solid) curve cannot be used with certainty to predict task performance improvement. Nevertheless, in all cases, performance increased with higher illuminance (right end of each line). Note that, since the minimum horizontal illuminance standards were significantly lower in the previous decades, the base case illuminance test scenarios were also low. Therefore, it is expected that output was significantly affected by how well people were able to see, and steeper slopes are observed for illuminances lower than 100 lx. This might have resulted in overly-optimistic expectations of performance improvement with higher task illuminances. For that reason, when the illuminance is sufficient for the visual performance, the relative increase in output decreases.

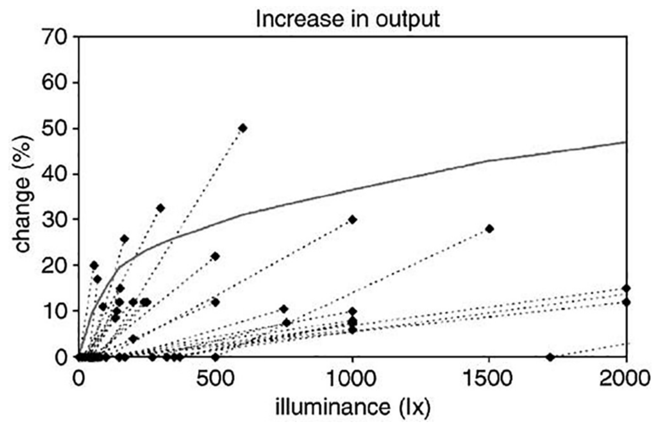

Fig. 2. Lighting change effect for work output. Dotted lines: results of the individual field studies; solid line: calculated average slope [39].

Fig. 3 shows the decrease in errors or rejects, as a function of task illuminance. It is clear that higher task illuminance results in less errors. Comparing Figs. 2 and 3, the averaged solid curves differ in the sense that the decrease in rejects shows a steeper slope than does the increase in output for illuminances above 300 lx. The authors mention that it is possible that other factors block the increase in output for higher light levels, which is certainly true based on more recent research. Also, they state that brain stimulation mechanisms play a role, referring to a study by Cajochen et al., which claims that vertical (eye) illuminance 500–1000 lx is needed to increase alertness during early biological night, which means that the horizontal illuminance should be in the range of 1000–2000 lx. However, this is a significant approximation which might not be true for different work settings and space configurations.

Major findings of other early studies are as follows [113,114,61,14]:

Equal step increases in illuminance are related to smaller improvements in task performance until no further improvement occurs

The saturation point occurs at lower illuminances when the visual stimuli are larger

Further improvements in task performance are achieved by changing variables such as size and contrast than levels of illuminance

With the dramatic increase of office workers in late 20th century, research shifted towards office environments. Unlike in industrial settings, the link between visual performance and overall task performance, in that case, is less obvious. Due to a large number of variables that affect office task performance, the relationship between illuminance and performance in less evident, causing studies to show mixed results. Below, the conclusions of studies are presented in sequence, covering studies showing a positive impact, mixed impact and no impact of increased illuminance, respectively.

Overall, studies show that higher illuminance conditions improve task performance in every type of objective test they performed. More specifically:

Hughes and McNelis [36], reported that increased illuminance (from 500 to 1500 lx) caused 9% performance improvements in difficult paperwork of clerical office workers.

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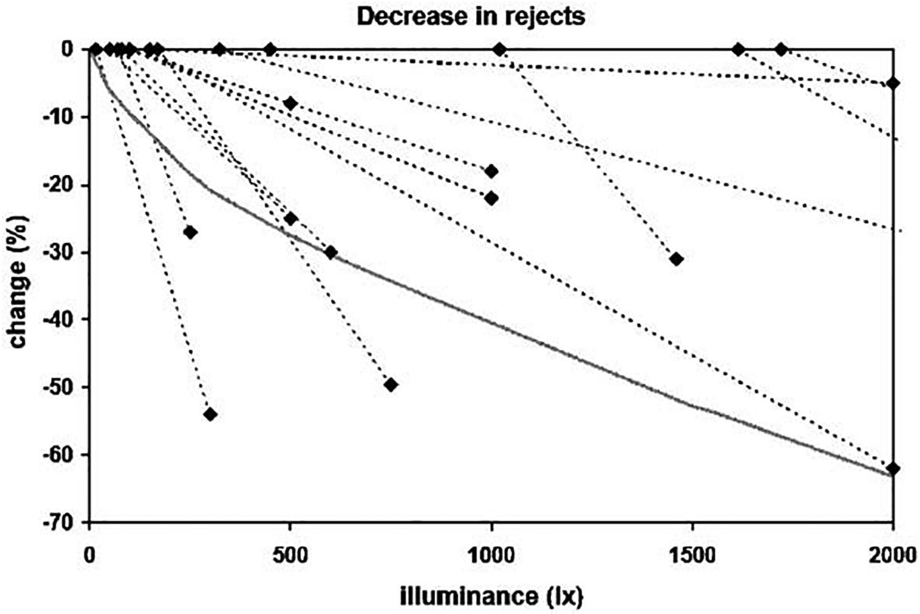

Fig. 3. Lighting change effect for rejects. Dotted lines: results of the individual field studies; solid line: calculated average slope [39].

Vimalanathan and Babu [109] identified that a higher illuminance (1000 lx) contributes to 19.91% and 5.12% of improvement in reaction time and error response of neurobehavioral tests (compared to 500 lx and 750 lx).
Smolders et al. [92] showed effects of illuminance on subjective alertness and vitality, sustained attention in tasks, and heart rate and heart rate variability. Participants felt less sleepy and more energetic under higher light levels, had shorter reaction times on the psychomotor vigilance task and increased physiological arousal. The results demonstrate that even under normal, i.e., neither sleep nor light deprived conditions, more intense light can improve feelings of alertness and vitality, as well as objective performance and physiological arousal.

Nevertheless, research evidence for a positive correlation between illuminance and office task performance is often mixed:

Baron, Rea, and Daniels [9] found that lower illuminances (150 lx) can enhance performance on a complex word categorization task as compared to high levels (1500 lx).
Nelson, Hopkins, and Nilsson [68] found a puzzling effect in which performance on a tracking (which requires hand-eye coordination) was best under 80 lx, worse under 160 lx, and Intermediate under 320 lx. In reading or spatial relations tasks, no illuminance effect was found.
Campbell and Drew [20] observed greater nighttime performance improvements in logical reasoning task (12.7%) and spatial manipulation and processing (23.8%), when shifted from 10 to 20 lx condition to 1000 lx condition, as compared to the improvement shifted to 100 lx (0.5% for logical reasoning and 6.6% for spatial manipulation and processing). On the other hand, no significant difference in psychomotor performance was found between two different changed-conditions.
Katzev [40] also identified varying illuminance effects on different types of tasks. In the computerized error detection and spreadsheet entry tasks, there was no differential impact of illuminance on performance. For computer-based reading comprehension and typing tasks, illuminance affected performance in both negative and positive directions.
Results showed that participants felt less sleepy, more vital and happier when exposed to bright light. Effects on subjective sleepiness and self-control capacity were stronger under mental fatigue. Vigilance benefited from bright light exposure, although this effect emerged with a delay irrespective of the antecedent condition. Other tasks showed more mixed and sometimes even adverse effects of bright light [90].
Tested illuminance levels ranging from 79 to 2996 lx in combination with variable temperature settings were not found to have an impact on cognitive performance tasks [24].

Finally, some studies reported no noticeable effect of illuminance on task performance, considering a wide range of illuminance levels and simple tasks:

Smith and Rea [88] found no impact of illuminance on reading comprehension task ranging from 9.2 to 4540 lx.
Nelson, Nilsson, and Johnson [69] identified no effect of illuminance levels between 100 lx and 300 lx on creative writing performance.
Horst et al. [35] failed to find any illuminance effect on reading and scanning tasks over a range from 100 lx to 800 lx.
Kaye [119] compared task performance under 500 and 1200 lx and found no effects on proofreading or visual search tasks.
Veitch [107] identified that the reading performance was not affected by illuminance in an office environment.

As a meta-analysis study of rich-body literature on the link between illuminance and office task performance [104] showed, studies that compare illuminance levels of higher difference (average 70 lx vs. 1962 lx) identified statistically significant performance differential impact of illuminance, as compared to studies that compared lower contrast illuminance levels. Also, the adaptation time may affect the illuminance-performance relationship. Higher adaptation time reflects more realistic conditions and potentially shows more valid results. The studies designed to include adaption period before beginning the tasks showed a more trivial illuminance effect on performance. Thus, the illuminance-performance may be transitory to some extent.

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Except for response time, the impact of illuminance on task performance can be mediated by many other variables. The age of office workers can be one of them [87]. Smith and Rea [88] asked individuals of different age groups to proofread print over arrange of illuminances. The performance of older subjects (46–62 years old) deteriorated more quickly as illuminance was reduced, compared to younger subjects (18–22 years old). The age difference held up even when the subjects were equipped with corrective lenses.

One important aspect is that in almost all studies, horizontal task illuminance is used as a factor when studying human performance. However, the type of task (i.e., whether to include computer or paper work) should be carefully considered when designing performance experimental designs. Office workers mostly perform computerized tasks, therefore the illuminance on work plane (or other horizontal surfaces) may become less significant, and vertical illuminance on the eye plays a more important role. This has not been studied as a basic illuminance parameter when studying task performance, and future studies should emphasize this direction. Moreover, in some cases, during a computer-based task, a higher value of horizontal illuminance on the desk may even compromise visual comfort regarding glare, potentially decreasing performance levels.

Finally, the vast majority of studies have focused on the impact of electric lighting conditions, and daylight illuminance has been far less studied. There is limited evidence that higher daylight illuminance leads to better task performance, but this has been limited to subjective testing. More effort is needed in this direction and Knoop et al. [42] has identified organized current knowledge gaps with respect to daylight and human response.

4.2. Luminance and task performance

Due to the measurement difficulty and required instrumentation for luminance acquisition, only a few studies included this metric in terms of its relationship with task performance levels, or to study simpler visual tasks. Sturr et. al. [96] studied the visual acuity of 151 individuals of ages 18–87 years, with different target surface luminances (black and white checkerboard was used as target). Fig. 4 shows that visual acuity is decreased with reduced luminance, and that this effect is more evident for people over 60 years old. This acuity test results are useful for evaluating driving ability of individuals, however it is not a workspace performance test. Osterhaus [72] showed that productivity generally decreases when surface luminance in the field of view is increased.

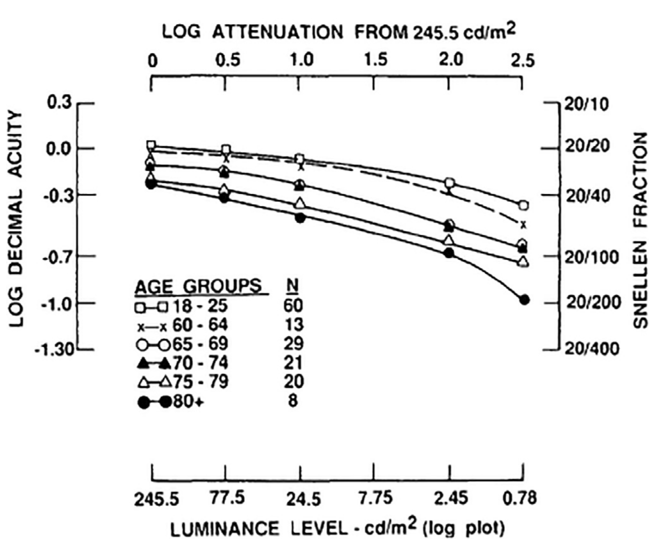

Fig. 4. Visual acuity as a function of age and luminance levels [96].

Several studies [11,51] investigated the impact of different luminance ratios on screen task performance with VDT devices, and there are different suggestions for the optimal ratios, including 8:1 [112] and 10:1[106]. Zhu and Wu [117] studied different combinations of luminance ratios based on background luminance and found that the optimal ratio increases with lower background luminance, from 7:1 (20 cd/m^2) to 11:1 (40 cd/m^2). Linney [53] showed that combinations of window luminance, luminance ratios and window/occupant positions (front/side/back) have different effects on different aspects of performance (error, accuracy, and speed). In overall, the inconsistencies in different studies suggest that larger data sets are needed. This could be achieved by implementing standardized experimental protocols in future studies, that would allow meta-analysis of combined data sets. Glare has not been a part of task performance related studies since glare conditions should not occur in office workspaces. As glare induces compromised vision and creates distraction [45], it can be assumed that disability and discomfort glare conditions would reduce task performance.

4.3. Color

Another metric of the visual environment that was repeatedly evaluated in terms of its relationship with performance and productivity was color, in terms of colors of surfaces and correlated color temperature (CCT). Kwallek et al. [47] investigated the influences of interior colors on worker's productivity and found the effects vary among different people and could have opposite impact on long-term and short-term productivity. Viola et al. [110] reported that blue-enriched white light in the workplace improves self-reported alertness, performance and sleep quality. Blue-enriched white light in the early morning hours was found to improve the speed of cognitive processing and concentration [41]. The long-term effects of blue-enriched light are under investigation.

Recent studies have demonstrated that long-wavelength (red) light can increase objective and subjective measures of alertness at night [25] and during the day[82]. According to a study by Sahin et al. [84,83], red light can increase short-term performance as shown by the significantly ($p < 0.05$) reduced response time and higher throughput in performance tests during the daytime. There was a significant decrease ($p < 0.05$) in alpha power and alpha–theta power after exposure to the white light, but this alerting effect did not translate into better performance. Alpha power was significantly reduced after red light exposure in the middle of the afternoon. There was no significant effect of light on cortisol and alpha-amylase. These results suggest that red light can be used to increase daytime task performance. Due to the temporal characteristics of most available studies, further research should be conducted to investigate the impact of the duration of such interventions in the overall alertness and sleepiness of occupants [26].

Mills et al. [59] conducted a prospective controlled intervention study within a shift-working call center to investigate the effect of newly developed fluorescent light sources with a high correlated color temperature (17000 K) upon the well-being, functioning and work performance of employees. Improvement in self-reported ability to concentrate at study and increase in work performance (19.4%) were reported. Therefore, high CCT fluorescent lights could provide a useful intervention to improve productivity in the corporate setting, although further work is necessary for quantifying the magnitude of likely benefits.

Hawes et al. [31] showed highest visual acuity as measured on symbol identification and color recognition tasks with LED relative

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to fluorescent lighting, and this effect was greatest at higher color temperatures (6000 K compared to 3345 K). In addition, higher CCT led to increased vigor/activity and decreased fatigue scores, while promoting positive mood and mitigating Seasonal Affective Disorder [85].

Barkman et al. [8] showed that students made fewer errors, particularly of omission, on a standardized test of attention under the variable light "Concentrate" program (which is the light that is variable in illuminance and color). Reading speed, as measured using standardized reading tests, increased significantly. Moreover, this study summarized the effect of special lighting techniques on the well-being and performance of people in work settings.

As the existence of the intrinsically photosensitive Retinal Ganglion Cells (ipRGC) is a relatively recent addition to our knowledge about the non-viusal effects of lighting, more research is needed towards understanding more details about the way CCT interacts with illuminance levels. Current well-being-focused standards such as WELL [37] use the Equivalent Melanopic Lux (EML), a new metric that also weights the impact on the ipRGC instead of only addressing the rods and cones[56]. In that scope, more controlled studies are needed directly associating performance with color-weighted characteristics of light availability, to bridge the gaps with respect to the interaction between color and illuminance level. In addition, further studies should investigate the impact of the duration of exposure of occupants to different colors of light on alertness and sleepiness. Finally, with many of the aforementioned studies indicating uncommon color characteristics as beneficial for performance, it is necessary to investigate the acceptability of such conditions in the long term and for different space characteristics (commercial, education, healthcare, etc.)

4.4. Outside view

As mentioned in the first section of the paper, window views can visual satisfaction and overall well-being, physical and mental health [86,50,75]. They can also reduce glare perception [98,5] which might indirectly lead to improved task performance, except if there is direct sunlight on the person, even through shades [45]. However, specific studies on the impact of outside view on task performance are almost inexistent.

Heshong [33] reported that ample and pleasant view out of a window, that includes vegetation or human activity and objects in the far distance, support better outcomes of student learning. In a later study that was focused on office settings [34], a significant effect of view has been reported with respect to cognitive tests performance. The study stated as potential reasons for that the mental stimulation or relaxation that can be obtained from having access to outside views can promote mental function. A study by Kuhlenengel et al. [46] that observed 220 K-12 classrooms investigated how student achievement is impacted by three main factors addressing outside view in the EN 17037 European Standard for Daylighting [21]: (i) Horizontal Sight Angle, (ii) Outside Distance of View and (iii) Number of View Layers. Student achievement was assessed based on reading and math scores for the students. The results showed that only the number of view layers metric of EN 17037 was a significant factor for reading task performance, and that future controlled experiments are needed to address the plethora of confounding factors.

5. Conclusion and discussion

This review paper summarized studies focused on the effects of lighting environment on task performance, specifically for the built environment audience. The main lighting metrics affecting performance were horizontal and vertical illuminance, luminance and luminance ratio, as well as color and correlated color temperatures. Different experimental design methods, participants and settings were reviewed and categorized, along with assessment and evaluation methods. Data analysis methodologies were discussed in detail, with discussion on limitations (Table 4) also related to sample size, modeling approach, carryover and bias effects, and ways to consider other factors affecting individual differences in performance.

Table 4
Research gaps identified with respect to main visual environmental parameters.

Illuminance	Vertical illuminance should be investigated as more appropriate for computer-related tasks Daylight has not been thoroughly studied compared to electric lighting Impact of adaptation still not clear Glare implications of excessive illuminance levels need to be considered
Luminance	Discomfort glare needs to be investigated with respect to performanceInconsistencies between studies suggest the need for larger data sets and consistent experimental protocols that will allow meta-analyses of combinations of data sets.
Color	More studies needed to better understand the interaction of color and light levels with respect to performance. Further research needed with respect to the impact of the duration of interventions The acceptability of non-widely-used color temperatures needs to be investigated to prove the feasibility of relevant interventions in design
Outside View	Controlled studies needed to validate the indications of aspects of outside view impacting learning and cognitive performance

Lighting-performance experiments in the workplace have focused on students of all ages and office workers, whereas in the early studies industrial workers were usually studied. Most of the lighting-performance experimental studies are based on factorial design, involving both within- and between-subjects designs. The studies included a variety of different performance tests, focused on cognitive performance and perception, visual acuity and reaction, memory, reasoning, and labor productivity. Only a few studies included self-reported subjective performance. Although these tests can be efficient in terms of time and effort, we have no solid evidence on their relative accuracy compared with lighting-performance objective tests, and more research should be conducted in developing robust rules and validated set of questions for subjective task performance evaluation with respect to indoor environmental conditions.

Many studies included within-subjects design with small sample sizes ($n < 30$), and different methods of data analysis were used to capture the significance of metrics. These included simple visualization or hypothesis testing, Analysis of Variance to test general differences between means and associated procedures and Mixed Model Linear Regression to describe the relationship between the dependent and independent variables with coefficients that can vary with respect to one or more grouping variables. The limitations in different approaches were discussed, with examples of recommendations for future improvements.

Illuminance, luminance and color temperature were found to affect performance in different ways, also reflecting the impact of different experimental techniques, conditions, performance evaluation methods used and data analysis techniques. Illuminance was found in most studies to affect performance. In the majority of the studies, the effects of increased illuminance were positively connected to performance, while there were studies showing contradicting results for different tests and tasks, and some studies showed no significant impact. It is however common that the human variability and the large number of hidden factors can affect results and produce contradicting conclusions in experi-

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ments related to human subjects and all types of performance activities. Horizontal illuminance has been the main variable tested for task performance. However, office workers nowadays typically use computer screens and therefore vertical illuminance on the eye is more important. Vertical illuminance and task performance have not been studied and future studies should emphasize this direction.

Luminance, especially in the form of ratios, reflecting contrast, was found to impact performance, with studies focused on display units recommending an optimal range of 7:1 to 11:1. Luminance and luminance contrast limits usually refer to glare protection, as they should, and they have not been studied extensively for task performance. With respect to color, white lights and high correlated color temperatures were found to increase self-reported and objective task performance, while red light and blue-enriched were found to improve alertness and cognitive performance in different studies. Although the effect of spectrally-tuned lighting on circadian rhythm is the focus of recent research, the long-term effects on task performance is still under investigation. LED lights with higher CCT around 6000 K led to increased visual acuity and decreased fatigue scores compared to fluorescent lights, but more studies are needed in this field to generalize results.

Due to the thin line separating task performance from productivity and satisfaction, it is difficult to identify specific ranges of lighting metrics that optimize task performance in office environments. Nevertheless, the existing research yields towards higher illuminances, contrast ratios in the range of 7–11:1 (while always making sure that glare will not occur in the space) and higher CCT, while spectral tuning in the red or blue regions has also shown positive effects. Although the impact of lighting conditions on performance was evident in most studies, the small sample and different conditions met in different cases does not favor meta-analyses to obtain more concrete conclusions that will apply to design recommendations. Moreover, the impact of daylight has not been studied, and it is expected that, when properly controlled, it can play an important role in task performance (similar for outside view). This signifies the need for future studies, being more consistent in terms of experimental procedures, tasks involved, samples and overall light conditions, which will potentially allow to obtain more useful and generic information on the effects of the lighting environment on task performance.

Hawes et al. [31] correctly state that more robust experimental designs with multiple and carefully controlled lighting parameters and highly sensitive cognitive tasks might reveal detailed and reliable results. As Sleegers et al. [87] mentioned, results from multiple randomized experiments on the effect of dynamic lighting on students' concentration can yield more accurate estimates than any one individual study. Employing variable lighting techniques [8,87] with multi-factorial designs to study task performance, especially in schools, is an innovative approach. Performance and preferences vary depending on the situation and individual needs, and teachers or researchers can deploy different (well-designed) multi-factorial lighting scenarios, that differ in illuminance/luminance and correlated color temperature, optimized for various tasks and learning situations. Studying performance in such a human-centered optimized manner can lead to a better understanding of the interactions between parameters affecting work performance in buildings while aligning with improved lighting design and operation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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