Title: Virtual Reality for assessing visual quality and lighting perception: a systematic review

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Abstract

The achievement of a good visual environment is key to guaranteeing human satisfaction indoors. In this context, it is crucial to assess the visual environment through the measurement of human perception. However, the assessment of the visual environment through human perception is often complicated. Using real spaces or mock-ups is time consuming, costly, and does not allow the control of all possible variables (e.g., daylight). Photorealistic rendered images present several limitations, starting from the veracity of the visual stimulus presented to participants. Virtual Reality (VR) is emerging as a valid alternative for evaluating the perception of the indoor visual environment due to the ability to control selected variables, analyze cause-effect relationships, and save time and cost, especially for the evaluation of daylit spaces. The high level of immersion and the possibility of interaction provide an opportunity to study users' perceptions and behaviors. However, some aspects of light assessment in VR need further investigations, such as the comparability of the perception of light in real and virtual environments. This paper reviews the available literature on the topic, highlighting the advantages and disadvantages related to the use of VR for lighting research and design. Previous research is classified into 1) studies focused on the comparability between lighting conditions in VR and real environments; 2) studies about users' perception and behavior with respect to lighting scenarios in VR; and 3) studies exploiting VR for lighting design. Hardware and software used in existing literature are further analyzed. This paper highlights that more studies are needed to define a common investigation protocol to make VR a valid investigation tool for lighting research studies aimed at evaluating visual quality and lighting perception.

Keywords

Virtual Reality; Light; Daylight; perception; preference; human behavior.

1 Introduction

Virtual Reality (VR) is used in many fields, from industrial design [1] to healthcare facilities [2]. Because of its ability to immerse participants in the virtual environment and isolate them from the outside world, it has great potential for conducting lighting research studies [3]. This is the primary reason the authors decided to run this systematic review, covering the theme of VR for assessing visual quality and lighting perception.

1.1 Lighting perception assessment methodologies

As it may be related to different domains, the visual quality concept has not a unique definition. Within the building/architecture domain, it is associated with visual comfort, defined by EN 12665 as "a subjective condition of visual well-being induced by the visual environment" [4], [5]. According to the International Commission on Illumination (CIE) definition, light is "radiation within the spectral range of visible radiation, i.e., the optical radiation capable of causing a direct response of the visual system to stimulation" [6]. Therefore, the presence of a visual system able to perceive luminous stimuli is the necessary condition for light description. Without the human visual system, the very concept of light would be meaningless. Although this observation may seem obvious to those typically dealing with light, it is of fundamental importance since it is the base of the primary goal of lighting design: a luminous environment thought for human well-being. Although in recent decades the term "human-centric lighting" has become widespread to refer to lighting aimed at eliciting so-called non-visual effects, good lighting is by definition human-centric, as suggested by Houser et al. [7].

This implies that any study on light cannot overlook the human factor and that parameters describing the quality of the luminous environment must be based on human responses to light. For this reason, much of the research in this area has focused on studying human perception mechanisms in response to a wide variety of lighting aspects (e.g., glare sensation, color perception, occupants' preferences regarding different lighting conditions).

Irrespective of the specific goal, the common elements of all these studies are the need to set realistic luminous conditions and gather information on users' reactions to them. Crucial in this context is the setup of the visual condition to be tested (i.e., the implementation of the experimental set-up), which should be as close as possible to real conditions. The more realistic the setting, the more reliable the results of the experiment, as confirmed by Boyce [8]. Different methodologies are used to achieve this goal.

Some studies are developed in real spaces (i.e., field studies), where people perform their usual activities. The research approach, defined by Heydarian and Becerik-Gerber [9], consists in administrating a questionnaire to occupants (survey-based study) or directly observing people's behavior (observational studies). The goal is to test preferences regarding several aspects of the visual environment (e.g., illuminance levels, Correlated Colour Temperature, glare) or to understand how occupants interact with building systems like lighting controls or shading devices in response to specific visual conditions. Many studies exist on the topic, as reported in the systematic review of Logadóttir et al. [5]. Undoubtedly, studies in real spaces provide the possibility to test the most realistic visual conditions. However, they present two main limitations. First, a significant amount of time and resources must be spent to gain access to real buildings and obtain owners' consent. Second, field studies are affected by a reduction in control over environmental conditions, as it is difficult, and sometimes impossible, to manipulate specific variables while controlling others [9]. Therefore, it is challenging to identify cause-effect relationships correctly (e.g., if visual sensation changes throughout the day, is it due to the difference of time, illuminance levels, or a combination?).

Full-scale mock-ups are used as an alternative to real spaces as they allow better control of the luminous scenarios during an experimental time. As a result, they provide a more accurate method to determine the cause-effect relationship. Mock-ups can be used to simulate the lighting conditions of any typology of space, from an office [10–12] to a single-aisle aircraft, as considered by Albers et al. [13]. The mock-up method provides key information regarding the correspondence between the phenomenon manifestation and the causes determining it (i.e., cause-effect relationship). Mock-ups must be built explicitly, taking into account space restrictions and consuming a relatively large amount of time and money. In addition, only limited configurations can be tested [9], reducing the complexity of real spaces in which multiple stimuli occur in combination.

Another experimental alternative consists in using photorealistic rendered images, generally shown on a screen. Some studies report positive results with this method, which also presents the benefit of reducing setting time and costs. Newsham et al. [14] conclude that evaluating images can be valuable for research and design activities. Nascimento and Masuda [15] demonstrate that image-based analyses can be conducted even when the represented subject is very complex, such as artwork. The need to distinguish a rendering from a photograph has been highlighted in some studies. Nishimura et al. [16], evaluating the luminance and chroma on an HMD and display screen, and Siess and Wölfel [17], have focused on adjusting color temperature, saturation, and contrast on a PC screen and an HMD in relation to personal preferences.

Some limitations exist in this approach as well. First, considering the results of the study conducted by Mahdavi and Eissa [18], it is still not clear if the subjective responses obtained by looking at two-dimensional images are comparable to those reported in a real environment. The elicited sensation from the reproduced luminous environment is entirely different from the real one since the subject, while looking at the images, is also located in a space characterized by lighting conditions different from those of the test spaces representing the image. Second, the chromatic appearance of an object can be different if the object is seen in person or through an image, which is also affected by the lighting conditions of the space. Finally, traditional 2D or 3D images present static outputs, lack interaction, and cannot be used to experience all lighting conditions such as glare [19].

VR represents a potential tool to evaluate subjective responses to visual conditions addressing limitations of the other experimental methodologies.

1.2 VR applications for the built environment

VR is a technology that permits immersion of the user within the digital content, making them part of the simulated scenario, and replacing the physical world through different devices, such as CAVEs (Cave Automatic Virtual Environments) or HMDs (Head Mounted Displays) [20]. VR is part of the larger family of Extended Realities (XR), i.e., a group of modeling and visualization technologies able to provide the so-called Immersive Virtual Environments (IVEs). XR technologies, besides VR, are predominantly represented by Augmented Reality (AR) and Mixed Reality (MR) [21]. AR allows overlay of digital content and information onto the physical world using screen-based interfaces such as mobile devices and dedicated glasses. MR, a technology still under development, aims at merging both the physical and the virtual world, providing digital content in the form of responsive assets to the surrounding physical environment, and focuses on the interaction between user and environment reproduced on the device [21].

In the last two decades, VR has found applications in many fields, such as clinical and rehabilitation [22], training and education [23], and design and manufacturing [24]. Specifically, for engineering and architectural applications, its use was exported to fields from interior design to construction site organization [21]. In the latter, for example, it has been employed as an educational tool for workers' training [25]. Moreover, it has been seen that IVEs could be employed as a support tool related to Building Information Modelling (BIM) software and Building Performance Simulations (BPSs) [26]. Additionally, thanks to its ability to reproduce the real environment inducing emotions and moods [27], VR has recently found applications supporting environmental design studies on occupants' behavior [28].

Due to the mentioned reasons, and in response to the 2002 comparative study performed by Billger and d'Elia [29], a tool which permits a higher grade of interaction and immersion in a reproduced space has gained the interest of lighting researchers and designers as well, who are increasingly utilizing this technology [30]. VR provides the possibility to create and assess specific virtual mock-ups in a more straightforward, faster, and cheaper manner compared to physical mock-ups [31]. Moreover, Ergan et al. [32] quantified how the versatility of modeling tools allows for simple manipulation of all the involved variables at will, either one in turn or in a combined way, to make the management of the experiment easier and to provide the possibility of understanding cause-effect relationships. In addition, it must not be neglected that simulation software allows for the design of virtual spaces with varying degrees of interaction. Consequently, users might be simple observers judging luminous scenes previously selected by the researchers, such as the studies by Siobhan Rockcastle, Kynthia Chamilothori [33], and Amirkhani et al. [34], or they could interact with the virtual space by changing several variables (e.g., luminous flux emitted by luminaires, the color tone of light, optical properties of the surfaces) and selecting the luminous scenario they prefer using BIM as performed by Natephra et al. [35] and Wong et al. [36]. This allows the possibility to perform both survey-based experiments aiming at defining occupants' preferences, and observational ones, in which participants' behavior may be studied. VR can also be a valuable tool in the study of daylit spaces. Daylight continuously changes over time and space, and in standard experimental studies it is impossible to show the same condition in different moments of the day and year to various subjects. Virtual reality presents a possibility to deepen the study of daylight, analyzing its complexity, users' perception, impression, and behavior, and even its effects on energy savings in buildings [19][31][33]. Indeed, the possibility to identify occupant preferences may lead to an optimization in the use of lighting and shading systems, with a consequent reduction of the lighting-related energy consumption, as confirmed by the study performed by Heydarian et al. [37].

With reference to lighting design applications, Hong and Michalatos [38] and Lee [39] demonstrated how VR could be a helpful tool for designers, helping them in the decision-making phase, and for customers, who could be better involved in the design process.

Despite the increasing use of VR in lighting research and design, it is not completely clear how perceptions in real and virtual environments compare. Several factors should be considered in this comparison. Some of them are strictly connected to the way light and materials are simulated in VR [30] and the luminous stimulus produced by the technological tools used to reproduce virtual spaces (e.g., the head-mounted devices) [40]. Other factors, not necessarily directly influencing the luminous sensation, interfere with other spheres of perception and may affect the sense of presence (i.e., the "the subjective experience of being in one place or environment, even when one is physically situated in another" [41]) and consequently the visual perceptions and evaluations. A more realistic scene translates into optimal modeling and accurate simulation of the environment in terms of geometry, color, shading, and texture. Beyond the proper geometrical modeling of the scene, Gerschütz et al. [42] note that factors affecting the VR perception are 1) spatial perception (i.e., appraisal of object size and distances [43,44]), 2) realistic interaction with the model, in turn divided in realistic manipulation (i.e., haptic feedback from interaction tools such as keyboards, gamepads or more sophisticated hand controllers) and realistic navigation, and 3) cybersickness. The last is a side effect of the use of VR, causing headaches, eyestrain, nausea, or disorientation [45]. It may be due to the mismatch between visual motion cues and motion cues sent by the human sense of balance.

1.3 Study goal

This paper aims to analyze the available literature in which VR is used to support lighting research and design. The analysis focuses specifically on factors strictly connected to the visual sensation of the luminous environment. It neglects those related to the other spheres of perception, such as the appraisal of object size and distances, already well discussed in previous works [9,42]. For example, the study focusing on the fidelity of the visual appearance of real objects displayed in VR [40], despite the analysis encompasses the use of two lighting conditions under which the objects are illuminated, is not included in the review as the study does not focus on the perception of the luminous environment but only on the evaluation of the represented objects (e.g., color, shading, texture, definition, geometry, chromatic aberration, and pixelation).

The rigorous systematic review methodology used to collect papers dealing with this specific topic is explained in Section 2. A general overview of the collected articles is described in Section 3. In Section 4, the detailed description of the selected papers is reported. Articles are classified according to the specific type of investigation in three subsections. Studies in Section 4.1 face the problem at a basic level, comparing virtual environments with real ones, to understand if the luminous sensation in VR can be representative of real sensation. Articles discussed in Section 4.2 assume that the visual sensation in VR is reliable and utilizes VR to investigate users' preferences about several aspects of lighting or their behavior in interacting with the luminous environment. Finally, works in Section 4.3 show how VR may be an important tool during the design process. Section 5 focuses on hardware and software due to the crucial role played by the technology in the definition of the IVEs.

2 Methodology

The methodology used for collecting the papers consists of three steps: 1) identification of the database for the query, 2) query definition, and 3) identification of other studies acquired by other sources.

As a first step, the search engine Scopus developed by Elsevier was selected from the various databases available (e.g., PubMed, Web of Science, Google Scholar), whose resources include the Institute for Scientific Information (ISI) and Scopus-indexed papers primarily focused on the domain of physical and social sciences over the period 1966- April 2021 [46], which is consistent with the purpose of this research as the first paper linking VR with lighting-related issues [47] is dated 2014.

The search engine of Scopus is flexible: it allows basic or advanced search functionality. The latter function allows to code with operators to make a customized and specific query. A detailed search guide can be found in [48]. The query was set in line with the goal outlined in Section 1.3. Figure 1~~Figure 1~~ shows its structure.

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AUTHKEY ((visual OR lighting OR daylighting OR daylight OR sunlight OR "indoor comfort" OR "Indoor lighting design" OR "color fidelity") AND ("virtual reality" OR "Immersive visualization") AND (perception OR preference OR feedback OR "occupant behavior"))

Figure 1. Scopus' query structure consisting of 3 sections

The AUTHKEY field code was considered so that only documents in which the selected words appear in the keywords assigned to the document by the author(s) were selected. The search considered only AUTHKEY because no other characteristic of a paper (e.g., title, abstract) has the same power to describe the essence of the article in a few words [49]. The following sections characterize the query:

1. The first set of keywords (in red) covers indoor comfort in general and lighting-related aspects. The operator OR joins the words such that at least one of the considered terms is included.
2. The second set of keywords (in green) is connected to the first set with the AND operator and is characterized by two target keywords referred to VR.
3. The third set of words (in blue), also connected with the AND operator, considers the human-centric perspective related to this area of research.

The timeframe for publications was not specified in the general structure of the query, thus allowing to exclude a biased sample due to arbitrary constraints on the year range. For the same reason, no geographical location limiters were considered.

This configured query returned 167 papers (assessed in April 2021).

Following the PRISMA diagram, usually reported in review study to assure reproducibility and transparency of selection criteria [50], 27 additional studies, not identified by the above-reported query and identified through other sources, were considered. They were acquired by the authors in previous studies about the topic and considered crucial even if not intercepted by the systematic review process. Figure 2~~Figure 2~~ shows the followed flow diagram, reporting the information on how manuscripts were acquired and analyzed. As it can be seen in Figure 2, the final number of papers (N=33) is the result of a selection process consisting in two phases of screening aiming firstly at removing duplicates and secondly at excluding works not perfectly matching the topic of the research, identified by reading the title and the abstract. Finally, the eligibility of the remaining papers is analyzed via full-text reading.

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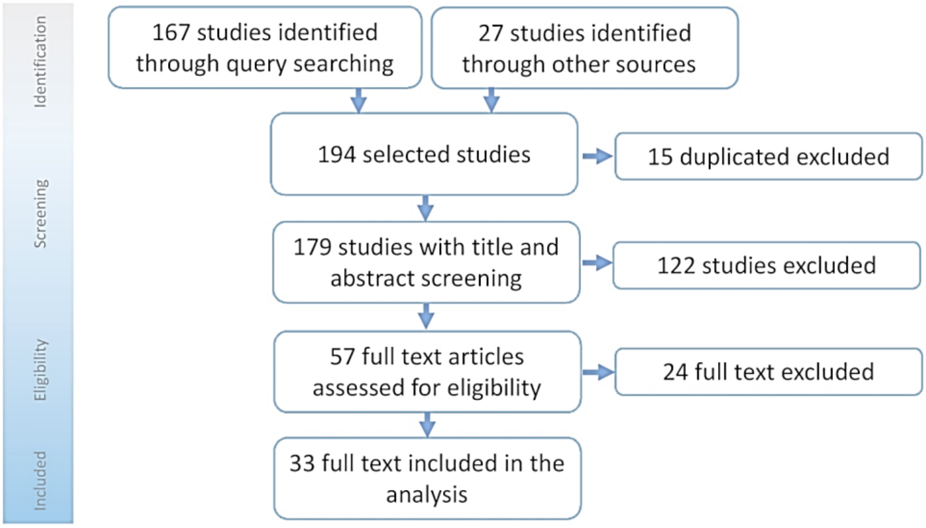

Figure 2. PRISMA flow diagram

It is possible to highlight how the duplicate papers were 15, and the total number of papers considered in the following steps was 179. The screening process and eligibility assessment could be affected by bias [51]. This may be due to a unilateral decision by only one author [52]. To avoid these circumstances, all the authors performed a tedious and time-consuming data extraction and then reached a consensus over discrepancies through discussion [52].

Of a total of 33 selected manuscripts, 84% are indexed on Scopus, while only 16% were derived from other sources.

To verify the effectiveness of the selection process as described above, an Explanatory Data Analysis (EDA) was performed considering the titles and the abstract of the selected documents. For this purpose, the text of the title and abstract of each selected paper were considered: each sentence was tokenized, then all punctuations marks, stop words, and words less than 3 letters in length were removed. A lemmatization process was then performed, consisting in converting a word into its base form. This method differs from the stemming process because it considers the context and converts the word to its meaningful base form, whereas stemming only removes the last few letters, often resulting in incorrect meanings and spelling errors (e.g., 'caring' lemmatized is 'care,' whereas in stemming the base form is 'car'). Then bigrams and trigrams were formed, each referring to two or three words frequently occurring together in the selected text (e.g., virtual_reality, lighting_design). Finally, the EDA was performed using the wordcloud package for Python, where the importance of each word is displayed in terms of frequency of occurrence with font size (Figure 3Figure 3). Figure 3Figure 3 shows the fifty most frequent words in the text of the title and abstract, ensuring that the screening process and eligibility assessment were performed correctly and that the selected papers were consistent with the aim of the research. The most frequent words are lighting, design, perception, virtual reality, and building.

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Figure 3. Exploratory Analysis with wordcloud of the most used terms in the title and abstract of the selected papers

3 General overview of studies

Table 1~~Table 1~~ reports a summary of the main statistics of the considered papers.

Table 1. Main information

Parameter	Description	No.
Documents	Total number of documents	33
Sources	The frequency distribution of sources as journals	21
Author's keywords (DE)	Frequency distribution of the authors' keywords	115
Keywords Plus (ID)	Frequency distribution of keywords plus (ID) generated by Scopus system	299
Period	Years of publication	2014:2021
Authors	Authors' frequency distribution	93
Authors appearances	Number of author appearances	146
Authors of single-authored documents	The number of authors of single-authors articles	1
Authors of multi-authored documents	The number of authors of multi-authored articles	93
Authors per article index	Ratio between Authors and Documents	2.85
Co-Authors per article index	Average number of co-authors in each document	4.45
Average citations per article	Average number of citations in each Article	13.85
Collaboration index	Ratio between total authors of multi-authored articles and total multi-authored articles [53], [54]	2.91

Even if in Table 1~~Table 1~~ an analysis period covering the last 15 years is reported, from Figure 4~~Figure 4~~ it is possible to highlight trends of scientific production covering the considered topic. The Annual Growth Rate was 32.05%. Figure 4~~Figure 4~~ also reports the cumulate occurrences of articles published in the most relevant sources. The author's interest in journals which deal with environmental fields is increasing in recent years, as shown by the values recorded by the Building and Environment journal.

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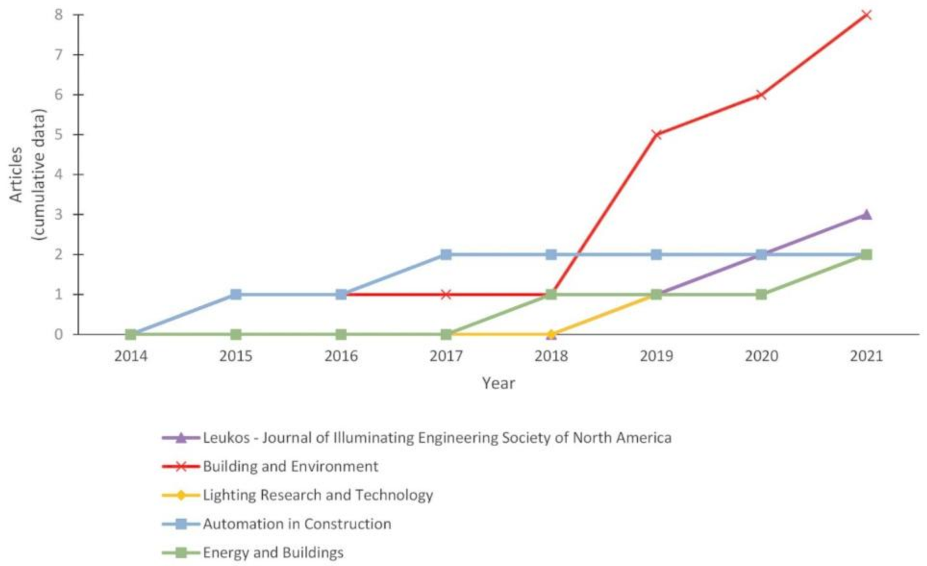

Figure 4. Annual Scientific production and Source Dynamics

Among the 33 analyzed peer-reviewed scientific articles, it is possible to highlight how Building and Environment and LEUKOS - Journal of Illuminating Engineering Society of North America, were the preferred journals with a predominant concentration of articles published on the considered topic (Figure 5Figure 5a). Figure 5b identifies the 10 most important authors, considering the selected topic, ranked in descending order of importance as a function of the number of published articles.

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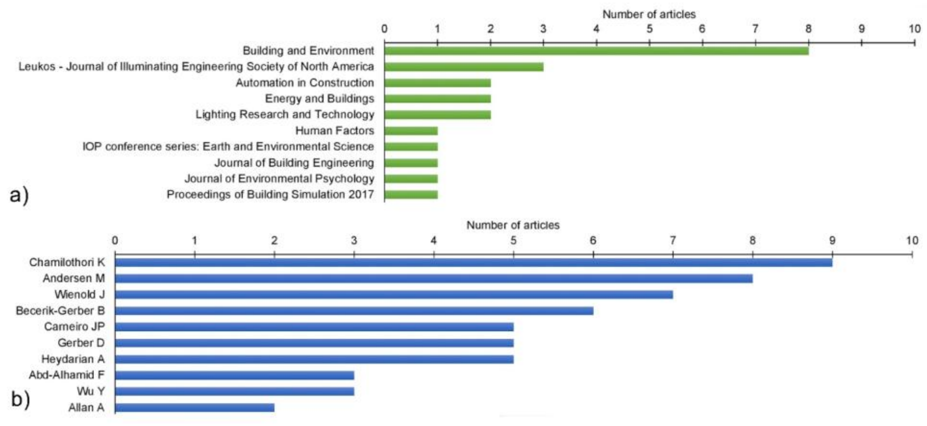

Figure 5. a) Top 10 most relevant sources; b) Top 10 authors ranked by number of articles

4 Review

The following sections report in-depth analyses of the selected studies by dividing them according to the different research steps, as described in Section 1: comparison between luminous conditions in VR and real environments; VR for lighting research: evaluating users' perception and behaviour; VR for lighting design.
It must be underlined that this classification is not random but rather based on the evolution in the investigation procedures adopted by research groups that have published more than one work on the topic. Generally, they concentrated the primary efforts in verifying the capability of the VR in representing the luminous environment and then used it as an analysis tool for research purposes. For example, Heydarian et al. started with studies comparing real and virtual environments [47], improving in the second work [55] the analysis method by increasing the number of participants in the tests. Then, once they verified the reliability of the VR as an evaluation tool, they used it to study users' perception in different daylit scenes, their interaction whit shading systems, and the effect of their actions on energy consumptions [37,56]. Similarly, Chamilothori et al. [31] performed a comparison between real and virtual spaces. Then they used VR to investigate users' preferences about several daylight patterns obtained by using different shading systems [57,58]. In this case, the analysis procedure was improved in the more recent study [58] by adding objective evaluation parameters (e.g., measurements of heart rate) combined with subjective surveys.
On the other hand, other researchers [19,35] focused on the use of VR for lighting design.

4.1 Comparisons between luminous conditions in VR and real environments

An accurate simulation of lighting conditions is more important than ever when VR is used to study the luminous environment. Before conducting such investigations, it is necessary to validate how much VR can realistically reproduce the lighting conditions of the real environment and its influence on users. Despite the importance of this validation, only a few studies related to the built environment have been conducted in this area. The following analysis focuses on the studies in which human subjects experience real and virtual environments by being physically located in a space or by using a head-mounted display (HMD), respectively. Specifically, according to the described methodology, only 7 works have been selected.

In the selected studies, comparisons between real and virtual luminous environments are performed to investigate the validity of the virtual luminous environment and to guarantee reproducibility of the experiment, as well as to ensure that the feedback received by users about the visual environment in the virtual space is reliable and equal to the feedback they would have given in a real space. This latter validation is important if VR tools are to be integrated into the design phase of projects with the goal of acquiring users' feedback in early design decisions, as confirmed by Heydarian et al. [47].

The considered studies report two types of luminous environment comparisons: direct and indirect. The direct evaluation compares the luminous environment displayed in VR with that of the real space through subjective evaluations (i.e., questions related to the lighting conditions or space). Various aspects are investigated through questions on a unipolar, 5- or 7-point scale or visual analogue scale, including the luminous environment appearance (i.e., brightness, CCT, distribution, contrast, evenness, glare) and high-order perceptions of the considered room (i.e., pleasantness, interest, spaciousness, excitement, complexity, sense of inner space, sense of privacy, sense of openness, and satisfaction with the amount of view in the space). The indirect evaluation compares the real and virtual luminous environments by evaluating their *effect* on participants with objective (e.g., performance) or subjective (e.g., perceived symptoms) indicators. The sense of presence can be classified in the latter category (indirect-subjective) as it is estimated through multiple questions but is not directly related to the luminous environment. For example, Heydarian et al. [55] used 32 questions, including focus, gaming, control factors, and distraction factors, to estimate the sense of presence in the virtual scene (e.g., "Did the virtual environment become more real than the physical environment?"). The great majority of the considered studies investigated the sense of presence: [31], [59], [60], [47], [55], [61]. Besides the sense of presence, some studies reported direct comparisons only ([60], [61], [62]), indirect comparison only ([44], [47], [55]), or both comparisons, including subjective indicators only [31] or both objective and subjective indicators [59]. Most of the studies conducted experiments with 20-50 participants, except for two investigations in which 9 and 112 people took part in the study ([47], [55], respectively). The lighting conditions differed across studies, with the majority of them considering electric light only ([59], [62]), daylight only ([31], [61]), or a mix of them ([60], [47] and [55]).

Given the restricted number of studies and their different methods and goals, it isn't easy to compare them. However, some consistencies can be found in the reported results. All studies highlighted the strong presence of participants in VR [31], [59], [60], [47], [55], [61] and some noted discomfort after the use of the HMD [31], [59]. From the studies reporting direct evaluations, it resulted that, despite the reference to specific lighting conditions, the luminous environment of the virtual scene was perceived as similar to the real one, i.e. the evaluations of the two environments did not differ in terms of lighting appearance and high-order perceptions [31], [59], [61]. This was true for both daylit and electrically-lit environments, especially when the latter was well-lit and was not too dark or presented high contrast scenes [62]. The studies reporting indirect evaluations showed no differences in human performance on everyday office-related tasks in a physical environment and VR under different illuminance conditions, even though participants took longer to complete their task in VR [47], [55], [59]. Finally, VR was reported to be superior to other media (photos and videos) for lighting visualization [60]. These results suggest that VR is a suitable representation of the physical environment and may be used as a surrogate to real environments for the evaluations of luminous scenes.

Despite the positive outcome of the analyzed studies, it is important to highlight some of their limitations that could limit the comparison across real and simulated environments. Limitations are divided into technical, experimental, and related to the modeling.

The limited luminance of the VR display is one of the most observed technical limitations across studies, especially when light sources are present in the scene, as in the case of the research study of Krupinski [63]. The virtual scene is displayed on a screen whose luminance and dynamic range are top-down limited. Consequently, the luminance values above the screen range are reduced to the maximum capability of the display. The other technological limitation concerns the resolution of the virtual scene, which may sometimes be limited either by the method to obtain the digital representation of the real space (e.g., scanned and not modeled such as in Chen et al. [60]), or by the display capabilities. As an example, Abd-Alhamid et al. [59] indicated that the resulting lower evaluations of the VR in terms of "details," contrast," and "colorfulness" were associated with the limited resolution of the utilized VR, noting that participants described the virtual experience as seeing the actual room through "fuzzy glass."

The experimental limitations are related to experimental design, measured parameters, and the studied population. The comparison might be weaker in a between-subjects experiment, such as in Rockcastle et al. [62], where participants experienced the real space or the simulated one, resulting in reduced power of the sample. Similarly, in the study of Heydarian et al. [47], each participant performed the tasks in two lighting conditions (bright and dark), but either in the real environment or in the simulated one. In addition, the study does not describe the actual luminance or illuminance values of the different real and simulated conditions, which makes the comparison between the two environments difficult. In the study of Chen et al. [60], the virtual scene was not calibrated with photometric measurements from the real one. Moreover, in terms of the studied population, it has been highlighted that the generally young age of participants could have biased the results, as young people are more inclined to new technologies, and hence they could be more used to VR [55].

Finally, differences between the real environment and its virtual representation in terms of modeling and simulation could make the experience less immersive, e.g. the failure to define some details like small objects or the view to the outside, to freely move in the space [47], [55], or to model the dynamics of the natural light [31]. Given the promising results of the analyzed studies and the numerous limitations highlighted, further investigations are encouraged.

The selected works described in this section are summarized in Table A1 in Appendix A.

4.2 VR for lighting research: evaluating users' perception and behaviour

In this section, 20 studies in which VR was used to support the analysis about users' perception and behavior are analyzed. They are divided into 3 subcategories as a function of the hypothesis statement: 1) analysis of the daylight perception as a function of different façade patterns, windows size or other variables such as indoor environment features and sky type (e.g., clear, cloudy); 2) analysis of the correlation between lighting colors and thermal perception; 3) analysis of how light and control systems can influence users' behavior.

4.2.1 Correlation between daylight perception and façade pattern, windows size, or indoor features and sky type

In this section, the authors focused on the investigation of the effects of façade pattern, windows size, or indoor features and the consequent effects on daylight distribution and users' perception in social or working spaces.

For constant opening ratio (that in the studies of Chamilothori et al. was equal to 25% in [57] and [58], or 40% in [64]), different façade patterns are tested by adjusting regularity (with the same number, size and shape of apertures but different distribution of the same). The number of façade patterns varies from 3 [57, 58], where the configuration with blinds is compared with two other patterns with different apertures distribution, to 20 [64]. The 6 façade patterns judged to be the most exciting in one study [64] are tested by Sawyer and Chamilothori [65] and combined with color of furniture/materials and furniture configuration, with constant brightness level, considering a total of 30 different scenarios. Rockcastle and Chamilothori [33] studied how view direction and sky type can influence visual interest within eight architectural spaces, with differing internal daylight composition, from direct sunlight penetration to diffuse and uniform daylight conditions, to cover a range of typical high and low contrast daylight conditions.

In all these studies, the participants expressed their feedback verbally using a 5 or 11 unipolar scale. In Chamilothori et al. [57] and Sawyer and Chamilothori [65], only data on perception was analyzed, while in Chamilothori et al. [64] and Chamilothori et al. [58], the heart rate and the skin conductance variabilities were also analyzed. Although in one study [64], the results did not reveal a correlation between biometric data and responses of users in different scenarios, the other study [58] found a correlation between the participants' perception of the façade and both the sunlight patterns and the mean heart rate. In Rockcastle et al. [33], besides verbal questionnaires, head tracking permitted the analysis of the vertical and frequency distribution of view direction of all participants; the authors were able to compare subjective data with quantitative predictors to validate the use of image-based algorithms in predicting impressions of visual interest by varying sky conditions and view direction. The number of the participants varies between 30 [57] to 100 [65], with Chamilothori et al. [64] using 80 architects in a first survey and 80 non-technical participants in a second survey, thus comparing the answers of experts, who are usually aware of the issues analyzed, with those of users who are not particularly familiar with the topics. The results show how participants' responses agreed with architects' intuitions in the case of non-complex patterns, while differed in case of complex patterns. The irregular façade pattern was evaluated as more pleasant, interesting and exciting [58]. In Sawyer and Chamilothori [65], the color was the more influential variable and satisfaction was correlated not only with brightness but also with the outside view, complexity, and overall quality of the environment. Head tracking and eye tracking may provide a finer detailed analysis of view behavior and support the development of future imaged-based prediction algorithms [33].

There are other studies where the window size is the primary variable, but it is changed with other variables. Moscoso et al. [66], considered the following variables: three windows size (small, medium, large), two space types (small, large), two spatial contexts (socializing, working), and three sky types (overcast sky, clear sky with high sun angle, clear sky with low sun angle). The participants involved are 150. A higher number of participants (406) is used in a follow-up study [67], replicating the same experiment in three different latitudes: northern, southern, and central latitude in Europe (Norway, Switzerland, and Greece, respectively). Using a unipolar 11 points scale, with a verbal questionnaire, pleasantness, calmness, interest, excitement, complexity, spaciousness, amount of view, and brightness were examined. Window size has shown to be statistically significant in correlation with most of the attributes, and in particular with brightness. Different feedback was obtained depending on the latitude by varying the size of the window in terms of assessing how pleasant, calming, exciting, and bright a space is perceived to be. Otherwise, window preferences seem to not vary in different latitudes: larger windows are preferred over smaller ones to achieve more pleasant, visually interesting, exciting, complex, and spacious rooms.

In other studies, VR is used to investigate how variation in terms of outside view can influence users' perception. Hong et al. [61] analyzed how different percentages (15%, 30%, 45%, and 60%) of the Window-to-Wall Ratio (WWR) influenced the sense of presence and occupant satisfaction, investigating how the variation of the view outside influence the impact on the sense of openness and privacy. Abd-Alhamid et al. [68] investigated how the distance from a window and the variation of the sky view can influence psychological and physiological aspects and stress. Rodriguez et al. [69] analyzed how the variation of the outside view and lightness improve observers' preference, restoration, imageability, and variability responses with respect to identical views with no lightness changes. Flor et al. [70] investigate the view perception and emotional response towards ETFE double-skin façades: three double-skin facade scenarios with different ETFE cushions (clear, fritted, and switchable sample) were evaluated and compared to a single-skin façade with double-glazed windows.

The rise in WWR favored the increase of occupant satisfaction with the senses of visual comfort, inner space, and openness, but did not raise the occupant satisfaction on the sense of privacy, which was more affected by the view outside than the window size [61]. The proximity of the window had many positive effects (lower stress level, higher parameter of view perception, higher satisfaction, more stimulating working environment), and this might be due to the view of the sky [68]. Furthermore, in Flor et al. [70], participants preferred window views with clear ETFE facades, often penalizing energy and daylighting performance. The technique to capture the view stimuli may also be implemented with dynamism [69]. However, the range of luminance was limited, and the glare and brightness cannot be accurately evaluated, and further investigations to understand how different views influence outcomes may be necessary [68].

4.2.2 Correlation between light colors and thermal perception

The second group of selected works analyzed the correlation between light color and thermal perception. Chinazzo et al. [71] investigated the interaction effects of temperature and colored daylight (i.e., daylight transmitted through colored glazing) on subjective perception - thermal perception, visual perception, overall perception (comfort, pleasantness, acceptability) - and physiological responses. To overcome the difficulty in testing daylight conditions, a novel hybrid experimental method combining thermal and visual stimuli from real and VR environments was used, with temperature controlled in the real space and the colors in the virtual one. Three types of colored glazing (blue, orange, and neutral) in combination with two temperature levels (24°C and 29°C) were investigated. Vittori et al. [72] studied how three different variables (window aspect ratio, window coating, and electric lighting color temperature) could influence occupants' thermal perception, with possible consequences on energy consumptions. Twelve scenes, divided into 3 main blocks according to the 3 variables selected, were used in VR to investigate the subjects' perception. The electric light is also considered. Salamone et al. in [73] tested 25 participants exposed to a real scenario in a test cell, and the same environment reproduced in VR, to investigate the potential of a new approach based on the management of collected data (users biometric data combined with feedback about their thermal perception along with environmental parameters) with different Machine Learning techniques to predict the Personal Thermal Comfort Perception. Chinazzo et al. [71] found that daylight color significantly affected participants' thermal perception in terms of thermal acceptability, thermal comfort, and temperature estimation, while no color effects on thermal sensation and preference were observed. In [72], the interviewed participants stated feeling relatively hotter in high aspect ratio window conditions and low color temperature. In [73], the results show that, in Real and VR scenarios, the light color is a non-negligible factor in predicting thermal perception. Short exposure time may be a limitation, however, as thermal adaptation was not allowed.

4.2.3 Correlation between lighting control systems and user behavior

Interactions of lighting controls and user behavior were investigated in various studies. Heydarian et al. [74] studied the influence of manual and semi-automatic control systems on lighting usage in a single-occupancy office space. During the experiment, two lighting sources were considered, two electric light fixtures each with three fluorescent light bulbs, and natural light coming through a window. In the VR model, users had different control options: manual switching of lighting sources and manual opening of the curtains; manual switching of lighting sources and manually or semi-automatic opening of the curtains; manual or semi-automatic switching of lighting sources and manual opening of the curtains; manual or semi-automatic switching of lighting sources and manual or semi-automatic opening of the curtains. The same research group, in 2016 [56] and 2017 [37], investigated how default lighting settings could influence users' choice and preference, with consequences on energy consumption. In the first study [56], the choices and preferences of 160 students were analyzed, while in the second study [37], a further step is carried out. The preferences of 89 students were translated into an optimal illuminance level on the working plane and, through generative multi-agent design method, this input was used to generate a façade pattern. Amirkhani et al. [34] investigated how different WWR influence occupants' lighting preferences and intended behaviors, with possible consequences on energy saving. In the VR reality office, four different WWR were considered (15%, 30%, 46%, and 62%) and cool-white electric linear luminaires (CCT of 6500 K) were set up, providing a wall-washing light on surfaces around the window. Users' illuminance satisfaction was recorded, and changes to modify the contrast were investigated. Carneiro et al. [75] investigated how the users' awareness could influence choices and actions with consequent energy benefits. This was done by presenting to the participants a visualization of the energy consumption, or of the light distribution, with the goal to contradict their initial choice. Mahmoudzadeh et al. [76], in an office with natural and electric light, investigated three different control arrangements in terms of user perception, preference, satisfaction, and cognitive load: 1) manual turn on/off electric light and adjustable blinds, 2) automated integrated natural and electric lights, 3) interactive switch allowing occupants to make a choice about the lighting type while keeping the illumination level at a certain amount for energy efficiency reasons.

The number of participants varies between 30 to 160, and in most of the studies they were students. In all the cases, an office scenario was considered.

These studies revealed that users prefer natural light [37] or a combination of natural and electric light [76]. Heydarian et al. [56] show that participants were significantly less likely to change the default lighting setting if the settings had maximum simulated daylight available. Users prefer semi-automatic systems [74] or solutions where it was possible to interact with more energy-efficient lighting systems, which gave them a perception of control (even if they prefer a manual system instead of a fully automated one) [76]. A higher WWR with a supplementary wall washing system improved lighting satisfaction with respect to lower WWR with higher contrast [34]. The energy impact visualization had more influence than the illuminance visualization [75]. The participants enjoyed their experience with the virtual reality technology rather than considering it as a useful device they intend to employ for other purposes [76]. Some limitations due to the quality of the models were also found.

The selected works described in this section are summarized in Table ~~Table~~ A2 in Appendix A.

4.3 VR for lighting design

The following analysis focuses on studies where VR technology becomes an active part of the lighting design process, considering the users' contribution in terms of lighting perception and lighting preferences. Eight studies published from 2016 were selected, focusing both on daylighting and electric lighting applications.

The most followed trend of research is the application of VR for an "inverse design," as defined by Vittori et al. [72], where the desired lighting effect is the initial input for retrieving missing data of light sources. In this context, the interaction between users and the VR environment can follow two methodologies: those where participants were directly involved in the modification of visual properties of the physical elements of the environment and those where users are passive subjects used to identify the effects of a predefined automatized lighting scenarios.

The first group of studies includes the one of Wong et al. [36], where the authors gave the participants the chance to adjust in a VR model the lighting intensity and color. In Natephra et al. [19], a realistic illuminance distribution in VR was achieved by considering a structured GUI (Graphical User Interface) with a comprehensive set of widgets where users can control almost all of the lighting design elements in relation to the lighting energy consumption provided by a real-time display: type, intensity, and colors of electric lights, colors of surface materials and the percent of the window closed by obscurant. In Hong et al. [61], windows size was designed directly in VR according to the user preferences defined as a function of spatial presence or openness feeling and privacy level. Krupinski et al. [63] proposed a lighting design system where participants changed surface luminance values in real time VR images, to represent the environment faithfully. In Hong et al. [61] and Krupinski [63], no significant difference in space perception is detected between real and virtual environments.

Studies falling into the second group include Hong et al. [38] and Lee et al. [39]. In particular, Lee et al. [39] focused on the individuation of areas of interest for a realistic global lighting effect. In LumiSpace system developed by Hong et al. [38], architects could specify daylighting effects and lighting interest areas that drive the sizing and orienting of openings. Verification of the correct space dimension perception in VR by the user was also performed, showing better results in VR than in the equivalent Rhinoceros® model. The results clearly show the feasibility of VR devices for user-centred lighting design, with considerable savings in terms of cost [36] and time [39].

The connection between VR and BIM represents another interest of research [36, 19], aimed at managing building design variables starting from standard lighting simulation produced by BIM-based lighting design tools (primarily Autodesk Revit® and 3D Studio Max®) and users' perception expressed with VR. The methodology described in Wong et al. [36], integrates Industry Foundation Classes (IFC) standard and lighting illumination simulation with VR rendering through DIALux® software. The work by Natephra et al. [19] presents a tool where initial BIM information is updated after user feedback is provided via VR devices; however, exchanging information between BIM and the chosen game engine is limited to only 3D geometry, and information such as the properties of light bulbs, materials, and textures cannot be transferred [19].

The last research interest focuses on the study of correct visualization of the objects in VR environment [77, 78] for design needs and mitigation of VR limitations in reproducing the real scale range of the brightness. In VRGlare system developed by May et al. [77], a real-time VR glare simulator was developed, and different glare visualization techniques were defined, spacing from realistic rendering to false color or symbols superimposed, and considering a suitable refresh rate (45 fps) for a real time calculation of the UGR index, alternating audio and haptic stimulus as well. Potemin et al. [78] investigated how the luminance values change with different techniques for blending objects in a virtual environment with mixed reality applications to minimize the visual discomfort in viewing images. This demonstrates how a video see-thought mixed reality system ensures more uniform luminance values than an optical see-through mixed reality system, minimizing the possible discomfort due to visual perception conflicts.

The works analyzed in this chapter are summarized in Appendix A, Table ~~Table~~ A3.

5 VR software and hardware summary

The choice of hardware and software is crucial for the realistic reproduction of IVEs.

In the analyzed papers, different combinations of hardware and software were utilized for transposing the real environment into the VR experience (Table 2. Software and Hardware used in the selected papers (NR: Not Reported)

~~Table 2~~). Figures 6a and 6b show the software used for 3D modeling and for VR scenes implementation in the considered studies.

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As reported above, the majority of considered studies proposed a virtualization process consisting of 3D modeling with Robert McNeel & Associates - Rhinoceros® (subsequently Rhinoceros) or Autodesk - Revit® (subsequently Revit) or Autodesk - 3D Studio Max® (3DS Max), and VR scene implementation using primarily Epic Games - Unreal Engine (subsequently Unreal) or Unity Technologies – Unity (subsequently Unity). Unfortunately, numerous papers do not report this information, especially regarding VR scene implementation.

Worthy of note is the study proposed by Chamilothori et al. [31], who defined a protocol to generate the virtual environment: the environment is modeled in 3D using Rhinoceros and then exported to Radiance for lighting scene calculation through the DIVA-for-Rhino plugin. To produce highly accurate rendering parameters, material properties were defined from spectrophotometer measurements, and sky generation was based on radiation measurements. The virtual scenes are then created by exporting the radiance renderings in Unity.

In none of the selected papers, the authors justify why Rhinoceros or Revit, or 3DS MAX was used. Generally, Rhinoceros is most often used when creating complex shapes, while Revit is most often used when communication and sharing of information is a requisite. Both have their own parametric engine: Grasshopper for Rhinoceros and Dynamo for Revit. 3DS Max is usually used in combination with Revit because it allows the generation of high-quality renderings thanks to the Vray plug-in, which is widely used for rendering and also among selected papers to produce the virtual reality model as realistically as possible by setting the correct material and object features. The Vray extension for renders is also available for Rhinoceros.

Considering the VR scene implementation and optimization for HMDs, Unity, and Unreal, as shown above, were the most used software. Unreal provides better graphic capabilities and the full source code at no cost. It includes Blueprints as well, a visual programming language to avoid coding. Unity provides some open-source components, but the full engine needs a paid license. It is easier to develop for mobile devices using Unity, while Unreal tends to be oriented for PC and consoles.

These game engines are coupled with several HMDs, including the most used models of Oculus and HTC Vive, which together cover over 70% of the applications surveyed (Figure 6).

Oculus, a subsidiary of Meta, the company formerly known as Facebook , provides both tethered (connected to a PC) and standalone VR headsets, including the Oculus Rift, the Oculus Go, and the Oculus Quest. The Oculus Go (2017, discontinued) includes a 5.5-inch fast-switching LCD display with a resolution of 1440x2560 per eye, equivalent to the Oculus Rift (2016, discontinued), with a previous asset with OLED displays with a resolution of 1080x1200 per-eye and runs at 90 Hz. This device run on an Android-based operating system, as does the Oculus Quest (2018, discontinued), equipped with OLED displays with a resolution of 1600x1440 per-eye and running at 72 Hz or LCD displays with a resolution of 1832x1920 per-eye, running at up to 120 Hz for version 2, released in 2020.

Similarly, the HTC Vive is a growing portfolio of VR headsets developed by HTC and Valve, originally released in 2016. The original HTC Vive (2016, tethered, discontinued) uses Dual AMOLED displays with a resolution of 1080x1200 per eye, running at 90 Hz and requires Windows 7+ OS. In 2018, the system was upgraded to the new HTC Vive Pro with an AMOLED display, a resolution of 1440x1600 per eye and 90 Hz refresh rate. The present version, the HTC Vive Pro 2 (2021) has an LCD display with a resolution of 2448x2448 per eye, up to 120 HZ refresh rate. HTC Vive also provides other high performance VR headsets, such as the HTC Vive Cosmos and HTC Vive Pro Eye, with a special focus on additional sensors such as eye-tracking, providing a wider pool of available data to be collected and processed during the virtual sessions. Standalone headsets are also available, currently represented by the HTC Focus 3, running on a Snapdragon XR2 system-on-chip, with an LCD display, a resolution of 2448x2448 per eye and 90 Hz refresh rate.

Both Oculus and HTC devices have a high sense of immersion, ensuring a 110° field of view, similar to other devices of the same commercial range with the advantage, however, of an "inside-out" motion tracking system, which consists of a series of cameras embedded in the headset. It is necessary to point out that less popular HMDs are already equipped with a wider field of view, from 120° (e.g., the Samsung HMD Odyssey) up to 200° (e.g., the Pimax Vision 8K Plus VR Headset), and as such are more effective in such VR applications as those under discussion, but are also less user friendly and more expensive, preventing widespread usability.

Table 2. Software and Hardware used in the selected papers (NR: Not Reported)

~~Table 2~~'s heading "Others" groups studies utilizing less frequently used software and hardware for 3D modelling and visualizing (e.g., Sketchup, Architecture Interactive, SamsungGear VR) or studies where this indication was generic (e.g., “physically-based imaging method”).

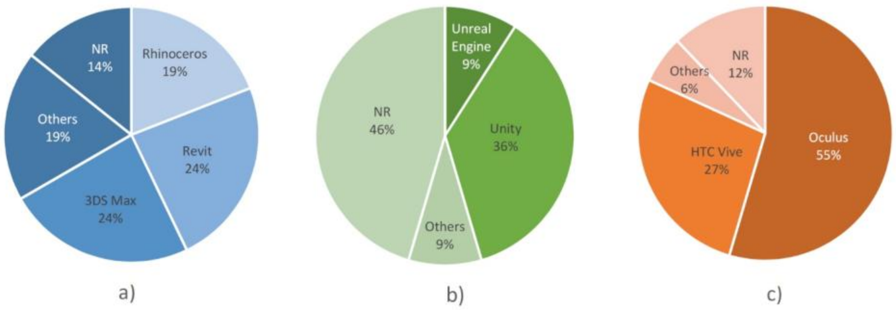

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Figure 6. a) Software used for 3D modeling; b) Software used for VR scene implementation; c) HMDs used

Table 2. Software and Hardware used in the selected papers (NR: Not Reported)

	Softwares used for 3D modeling					Softwares used for VR implementation				HMDs used			
Paper: [Ref. no], First author (year)	Rhinoceros	Revit	3DS Max	Others	NR	Unreal Engine	Unity	Others	NR	Oculus	HTC Vive	Others	NR
[31], Chamilothori et al. (2019)	•						•			•			
[59], Abd-Alhamid et al. (2019)					•				•		•		
[60], Chen et al. (2019)				•				•					•
[62], Rockcastle et al. (2021)				•			•				•		
[55], Heydarian et al. (2015)		•	•						•	•			
[47], Heydarian et al. (2014)		•	•						•	•			
[61], Hong et al. (2019)			•			•					•		
[36], Wong et al. (2019)		•	•				•				•		
[19], Natephra et al. (2017)		•	•			•				•			
[63], Krupinski (2020)					•				•				•
[38], Hong and Michalatos (2016)				•			•					•	
[77], May et al. (2020)				•			•				•		
[78], Wang et al. (2018)					•				•				•
[39], Lee et al. (2017)					•				•				•
[57], Chamilothori et al. (2016)	•								•	•			
[64], Chamilothori et al. (2018)				•					•	•			
[58] Chamilothori et al. (2019)	•								•	•			
[65], Sawyer et al. (2019)	•						•			•			
[33], Rockcastle et al. (2017)	•								•	•			
[66], Moscoso et al. (2020)	•						•			•			
[67], Moscoso et al. (2021)	•						•			•			
[68], Abd-Alhamid et al. (2020)				•					•		•		
[69], Rodriguez et al. (2021)				•					•	•			
[70], Flor et al. (2021)					•				•		•		

[71], Chinazzo et al. (2021)				•				•		•			
[72], Vittori et al. (2021)		•						•		•			
[73], Salamone et al. (2020)					•	•					•		
[74], Heydarian et al. (2015)		•	•						•	•			
[56], Heydarian et al. (2016)		•	•				•			•			
[37], Heydarian et al. (2017)		•	•				•			•			
[34], Amirkhani et al. (2018)			•				•					•	
[75], Carneiro et al. (2019)	•	•							•	•			
[76], Mahmoudzadeh et al. (2021)		•	•				•				•		

6 Discussion

The presented analysis revealed that a common general experimental procedure can be identified in most analyzed papers. This consists of different phases, namely 1) identification of an environment to test; 2) definition of different light scenes to administrate to participants; 3) geometrical modeling of the identified space employing software for architectural design; 4) modeling of lighting characteristics and optical properties of materials; 5) exportation of the model in the virtual environment. When the final goal is to compare the virtual environment and the real one [31,55,60], the scenes are shown in the two forms (virtual and real). Specific tests are then presented to users to verify the correspondence between virtual and real spaces, referring to the sense of presence and the visual sensation. When the goal is to directly evaluate people's preferences or their behavior in VR [58,64,66], the tests are used only to compare the different light scenes.

6.1 Methodological experimental differences

Despite this common experimental structure, a number of methodological differences were found. They can be summarized as it follows:

- Validation: not all the studies described the validation process of the virtual reproduction of lighting conditions to verify the correspondence between simulated and real environments and, when present, different procedures were adopted. Analysing the selected works, four approaches can be highlighted: 1) studies comparing real and VR data, such as Heydarian et al. [55] that compares the measured and calculated horizontal illuminance distribution, Abd-Alhamid et al. [59] and Rockcastle et al. [62] that compare both the vertical illuminance and luminance values, Krupinski [63], Flor et al. [70] and Chinazzo et al. [71] that compare only luminance or Chamilothori et al. [58], Sawyer et al. [65] and Heydarian et al. [74] that compare only vertical illuminance from the view point of the observer; 2) Studies where VR scene is tuning with spectroradiometer measured data ([31], [16],[57], [58], [66], [67]); 3) studies that use a subjective validation of sense of presence of VR scene, like Vittori et al. [72] where the sense of presence is verified showing to the users alternatively as a 360°

picture and a BIM virtual reality spherical model of the same office ; 4) VR scene adjustment with modelled data, as in Heydarian et al. in [56] and [37], or using Honeybee, Radiance, Daysim, and Mahmoudzadeh in [76] using DIALux Evo. Among the 33 works analyzed, only four validate the HDM: Abd-Alhamid et al. [59], Krupinski [63], and Moscoso et al. [66] and [67], as summarized in Appendix A.

- Use of software and hardware: varying types of software are available both for geometrical and lighting modeling and for the virtual environment development. The most used software for geometrical modeling are Revit and 3ds Max [19,35–37,47], whereas Unity is usually employed for the IVE definition [31,56,62,77,78]. The adopted procedures to model light are even more diversified. Light and optical characteristics can be set both in the software used for the design of the geometry [36,61] and in the VR one [77]. However, in both cases, the tools are not specifically designed for lighting analysis purposes, so the setting of the parameters is often not immediate and sometimes it is difficult to understand the correlation between the specific parameter and the corresponding physical quantity. For this reason, some authors, as previously mentioned, proposed to use support lighting software such as Radiance and DIVA [64,65]. In this way, it was possible to produce photorealistic and physically based renders that were then used to generate the virtual space. As with regards to HMDs, despite the differences, Oculus [31,47,55,58,65] and HTC devices are the most used technologies [36,59,61,62,77].
- Selection of participant sample: the number and composition of participants were very heterogeneous; in most of the studies the description of the sample composition was detailed but only sporadic cases provide a correlation between user's information and results. For example, in Chinazzo et al. [71], participants' gender is one of the three confounding factor in the ANCOVA statistical test, and their distributions across temperature-colour combinations are analyzed. Vittori et al. [72] correlated the differences in terms of mean thermal sensation with gender, workplace environment and age. Moreover, sometimes researchers used selection criteria to exclude some participants and obtain a homogeneous sample. For example, in some studies the authors chose participants with the same educational level [75] or age to avoid age-related effects [58] or because of the COVID-19 pandemic [76]. Other authors selected only young and educated participants who passed a test to verify the absence of vision impairments. In two studies by Heydarian et al. [47,74], researchers prevented the participation to the test to participants who manifested motion sickness during a training phase. Moreover, the same authors in another study [55] did not consider participants not matching normal visual acuity criteria. In two studies by Abd-Alhamid et al. [59,68], participants who declared problems of epilepsy, migraine, motion sickness, dizziness, sleep disorders and blurred vision were excluded in the recruitment phase. Furthermore, color blindness was used as an exclusion criterium in other studies [58,71,75].
- Test duration: the duration of the test was on average 30 minutes for many of the studies (e.g., [31], [67], [71]), but this duration often included contemplated preparatory phase before performing the test and the time exposure to a scene is even as low as one minute in one study [58]. In some studies there was a "recovery time" between different scene exposures [68], during which people could remove the HMD from the face. This pause could last from 3 [61] to 5 minutes [59,74] and was essential both to prevent dizziness and to allow the adaptation to the next light scene. Especially in cases where a correlation between color

and thermal perception was analyzed [71], [73] the duration of the activity to be performed included an acclimatization period. The adaptation period was adopted in other cases where subjective impressions of windows size [66] or occupant behavior aspects [56] were analyzed.

- Utilized metrics to perform the evaluation of light scenes: the methods employed to evaluate the scenes were strictly dependent on the task people were required to perform in the virtual environment. When they were simple spectators of the scene, the effect of the virtual environment was evaluated in different ways. In most cases (e.g., [30], [65], [66]), subjective surveys were administrated to people to evaluate some spheres of the perception as pleasantness, interest, calmness, excitement, and complexity. In other cases (e.g., [58], [64], [68]), physiological parameters such as skin conductance and heart rate were measured. Sometimes people were asked to perform a specific visual task in the IVE such as reading a text [37], [56], or defining the color of an object [47], [55]. In the latter cases questions about text comprehension, color perception, or measurements of the reading speed were associated with the typical subjective abovementioned tests.
- Daylight evaluation: in cases of works including daylight evaluation, differences in the view of the outside and sky type, can be underlined as well. Regarding the former, Heydarian et al. [37] have chosen to limit users in their ability to change the shading configurations because they wanted to emphasize the effect on personal sensation due to the outside view, while Rodriguez et al. [69] analyzed the subjective responses toward daylight changes in window views. In both cases, it clearly emerged how personal sensation was influenced by the outside view and window size [66]. Concerning the latter, in some papers 3 skype types are considered (overcast sky, clear sky with low sun altitude and clear sky with high sun altitude [66]), in others 2 (overcast and clear [57][31][33]), in others only 1 (clear sky [19] and direct sun penetration [58]).

6.2 Limitations in the use of VR for lighting research

Based on these observations, it is clear that the primary limitation in the use of VR for lighting research is the absence of a standardized investigation approach. The definition of shared methodologies diversified according to the goal of the study (comparison between reality and VR, evaluation of electric light, evaluation of daylight, assistance to lighting design) would help to reduce limitations found in many of the analyzed studies and reported in the preceding list, fostering the replicability of results [58], [65], [33] and extension of the field of analysis [61], [72], [76].

In this sense, the crucial problems to solve in order to fuel the spread of this promising tool are listed and commented below so as to highlight possible future research steps:

- Modeling of light characteristics: the software used for VR reproduction were developed primarily for gaming. As a consequence, the setting of parameters describing the quality of the sources and the optical characteristics of the materials is driven not by the will to reproduce in a reliable physical way the light distribution, but by the need to make the virtual space fascinating for users. Even the terminology corresponding to the light setting parameters does not correspond to the typical lighting technical language, resulting in complex light characteristics modeling. To overcome this limit, light parameters could be set by means of software specific for lighting evaluations as performed for example in Carneiro et al. [75]. Even more difficult is daylighting conditions reproduction, namely the modeling of the outdoor context [31] and the weather conditions [65,71]. To overcome these limits, it could be useful to analyze the correlation between virtual and real environments in different locations (latitudes), an aspect treated in Moscoso et al. [66] and which other authors want to deepen [68], [69]. Both for electric light and daylight it would be useful to compare different modeling approaches utilized by researchers and to understand which guarantees the most realistic reproduction.

- Validation of the model: to evaluate the correlation of the real and the virtual environment it would be necessary to identify an accurate and reliable validation method. Indeed, when using specific software like Radiance and exporting the renders in the IVE software to build the virtual space, or when the IVE software is equipped with calculation tools (like Unreal Engine Pixel Inspector), it is possible to compare measured data (e.g., illuminance or luminance values) with simulated ones as is done in some studies [59,62,70]. However, the correspondence between these calculated values and the measured ones does not guarantee that the sensation provided by the HMD is comparable to the real one, as that depends on the specific characteristics of the used device. In this case, the validation is generally only based on users' perception analysis, performed by means of subjective surveys. For this reason, it is crucial to establish a shared protocol for the evaluation of the realism of the scene. Otherwise, it would be useful to test a method to measure luminance and luminance contrasts produced by the HMDs and to compare the obtained values with the real ones. This protocol could also include spectral measurements.
- Spatial modeling: spatial modeling is still understudied. Generally, most of the analyzed studies were carried out in the office, social or working activity spaces, and another field that could be further explored is the correlation between human preferences when "immersed" in different environments [70], [33], [61]. In this sense, the recent technical standard EN 17037 defines, for real rooms with natural lighting placed in different geographic contexts, guidelines for achieving an adequate subjective impression of the lightness indoors and an adequate view out and optimal sunlight exposure [79]. VR future developments and applications oriented to the building design will need to follow the EN 17037 approach when dealing with the previous aspects. As a consequence, VR would no longer be independent to the real geographic context of application.
- Evaluation method: as for the evaluation of the light scenes, the most important issues needing further understanding are number of participants, homogeneity of participants sample, typology of the utilized survey and time of exposition. Considering this latter, it must be underlined that the exposition time is generally shorter than experiments in real environments (as noted, even as low as one minute [58]) due to the risks of fatigue and VR-associate discomfort like cybersickness.
- Characteristics of hardware: technological characteristics of the HMD affect the evaluation of the scene. The most important aspects to consider are the headset maximum luminance limitation of 80 cd/m^2 [67], the constrained field of view on distance perception, and the pixel density of the current VR headsets that decrease the accuracy of perceiving glare, brightness, and darkness [19]. Another limitation is that the spectral distribution of the light emitted by HMDs cannot match the real one [80]. Furthermore, light calculation issues reduce VR's experience dynamism because of the frequent use of pre-set and static solar illumination [37]. Indeed, doubling the number of the light sources or using "bendrays visualization" of glare sources, defined as a technique of representation of glare by casting

multiple rays from the user's hand to objects within the user's FOV, significantly slows the image refreshing, while realistic ambient light rendering produced low accuracy in UGR calculation [77].

7 Conclusions

In conclusion, it can be said that VR could be considered a promising investigation tool in the lighting field, both for research purposes and in the design process, as long as the listed limitations are overcome. Indeed, when carefully calibrated, VR may be supposed to assure a satisfactory representation of the physical environment [47], becoming an effective technology to study users' perception and allowing the reduction of time and costs required by real settings [55].

Of course, VR cannot replace real spaces in all lighting investigation fields. Surely, as it has been often repeated, it would be useful to evaluate users' preferences regarding different lighting scenes, to identify the most appreciated setting parameters (CCT, illuminance, typology of the source, daylight conditions) and to observe people's behavior considering the interaction with lighting controls and shading devices. Furthermore, VR could significantly contribute to the study of glare and contrast phenomenon only if the mentioned limits due to hardware and software have been surpassed to reduce the difference between real and virtual environments. Undoubtedly, due to its immediate and immersive representation of reality, VR would be useful for designers to communicate their ideas to customers. On the contrary, the evaluation of non-visual effects of light is a more complicated issue. Although when considering some specific aspects, such as the interrelation between visual perception and thermal sensation, VR has been demonstrated to be a valuable means of investigation [71–73], in regards to other effects, for example circadian rhythms, currently the limitations are too significant. In addition to the previously mentioned issues connected to the intensity of the luminous stimulus provided by the HMDs and the corresponding spectral distribution, one of the most important problems is the impossibility of maintaining immersion in VR for long periods to avoid cybersickness. On the contrary, as commonly known, for the circadian system entrainment, the duration of exposition is crucial.

For all these reasons, further research is necessary and surely future results will provide more information about the potentiality of VR application in the lighting field.

Undoubtedly, in such a new field of research, where technology is advancing rapidly, the use of a reproducible and transparent methodology such as the one described here can be used at any time to review progress in the field, overcoming the possible limitation of this study, which, as explicitly stated, elaborated the papers acquired from the research terminated in April 2021.

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Appendix A

Table A1. Selected works about the comparison between luminous conditions in VR and real environments (ref. 4.1)

Ref.	**Hypothesis statement**	**Methodology**	**Main findings**	**Limitations**
[55] Heydarian et al. (2015)	Test whether IVEs are adequate representations of physical environments and measure user performance in such environments	**Number of participants**: 112 **Environment reproduced**: single occupancy office space **Configurations**: office included two sources of lighting: (1) natural light and (2) two artificial light fixtures. Four different artificial light settings were available through different combinations. The blinds were kept fully open for the bright condition and half open for the dark condition. **Measured data**: perform a set of similar tasks (reading a passage and counting the books in the bookshelf) both in the physical environment and in the IVE. **Sphere of analysis:** 32 questions about: focus, gaming, immersion and involvement, control factors, distraction factors, IVE interaction. **Scale:** unipolar 5 or 7 points scale. **Scene calibration:** comparison between real and VR data **HDM calibration:** not declared	The differences between participants' performance in dark and bright condition is almost equal in physical and virtual environment. So IVE can be a valid tool to investigate user behaviour and performance cause users' felt a sense of presence. IVE can support the design and construction phase of a building acquiring information about users' preferences too.	The navigation through the virtual environment was not perceived realistic: this should influence only the perception of similarities between the IVE and physical environment and not the performance measures. The sample of participants was mainly composed by under graduated students and different results could be obtained by older adults.
[31] Chamilothori et al. (2019)	Investigate the difference in terms of satisfaction, physiological, physical symptom and sense of presence between real and virtual environment.	**Number of participants**: 29 **Environment reproduced**: The DEMONA (Module de demonstration en éclairage naturel), an office with a table and 2 chairs, a grey carpet, a window in the south facade, all the surfaces are achromatic. **Configurations**: 7 scenes were rendered for clear sky type corresponding to every hour from 9:30 AM to 3:30 PM, 2 scenes for overcast sky type using 12:30 PM as the time of the day. **Measured data**: Questionnaire, at the end of the experimental session the participants were invited to discuss their thoughts on the experiment. **Sphere of analysis:** Perceptual Impressions (pleasantness and complexity and a question about the amount of view in the space), Physical Symptoms, Reported Presence. **Scale:** unipolar 5 points scale. **Scene calibration:** VR scene tuning with spectroradiometer measured data. **HDM calibration:** not declared	No significant differences between the responses in the real and virtual environments for any of the studied variables were found, so this technology could have a wide range of applications.	A possible discrepancy between real and virtual environment was the lack of details in the virtual one and the different sky condition. In particular, the view from the window because in the virtual environment the weather conditions couldn't change. The limited luminance range of the head mounted display could limit the investigation of discomfort aspects like glare.
[59] Abd-Alhamid et al. (2019)	Investigate subjective and objective visual responses and participants' interaction with the virtual	**Number of participants**: 20 **Environment reproduced**: An office-like test-room **Configurations**: Two tasks were used in this study: the characters contrast test presented on an achromatic chart	Participants took relatively longer time to complete the same visual tasks when using VR than when it was presented in the real environment. The subjective	Difference in luminance values between the real and virtual environment due to the limited luminance that can be produced with similar types of displays

	environment based on measurements of perceived presence	(with black and white chart characters) and Stroop test with a chromatic chart (with coloured chart characters). **Measured data**: Completing tasks and answering questionnaires. **Sphere of analysis:** luminous environment, brightness, colour-temperature, distribution and high-order perceptions: pleasantness, spaciousness, excitement and complexity, general discomfort and sickness. **Scale:** unipolar 5 points scale. **Scene calibration:** comparison between real and VR data **HDM calibration:** eight different shades of grey were used and their corresponding luminance values were measured at the centre of the full field of the lens using Hagner S3 photometer in completely dark room	assessments showed no significant difference for the perception of the lighting and the perception impressions of the room between the two environments.	
[60] Chen et al. (2019)	Analyse what is the best instrument to evaluate luminous parameters (photo, video, IVEs) comparing lighting perception in different scenes	**Number of participants**: 40 **Environment reproduced**: A physical test room that comprises a "reference room" with a bed, desk, cabinet and a computer, and a "display room" with VR equipment placed to display the reproductions. **Configurations**: 12 lighting scenes which included three reference scenes (in the physical test room) and nine displayed scenes. **Measured data**: five-part questionnaire to compare the VR environment with the physical one. **Sphere of analysis:** Presentation-ability range, perceptual attributes rating, emotional attributes, overall satisfaction. **Scale:** unipolar 5 or 7 points scale. **Scene calibration:** not declared **HDM calibration:** not declared	In IVE was possible to reproduce feelings very close to the true ones in physical scenes. VR can find application to represent lighting environments attributes such as open/close, diffuse/glaring, bright/dim and noisy/quiet and in scientific investigations.	The scene was not very clear, captured scene doesn't permit a good reproduction quality and participants could do limited movement.
[47] Heydarian et al. (2014)	Test whether IVEs are adequate representations of physical environments and measure user performance in such environments. Preliminary study of Immersive virtual environments versus physical built environments.	**Number of participants**: 9 **Environment reproduced**: single occupancy office **Configurations**: office included two sources of lighting: (1) natural light and (2) two artificial light fixtures. Four different artificial light settings were available through different combinations. The blinds were kept fully open for the bright condition and half open for the dark condition. **Measured data**: two tasks of (1) reading a passage on a computer screen; and (2) identifying books of a specific colour in 30 seconds, filling a questionnaire **Sphere of analysis:** sense of presence, good representation, performance affected by the light setting of the room. **Scale:** - **Scene calibration:** not declared	The differences between participants' performance in dark and bright condition is almost equal in physical and virtual environment analysing comprehension, speed and object detection. Participants said they were very immersed in the virtual environment, and it was a good reproduction of the real one.	There was a small sample size. There were a few features of the model that need to be improved.

		HDM calibration: not declared		
[61] Hong et al. (2019)	Investigate if the virtual environment is an adequate representation of the physical environment of windowed spaces	**Number of participants**: 50 **Environment reproduced**: office space. **Configurations**: windowed virtual spaces with different WWR: 15-30-45-60%. **Measured data**: comparison between real and virtual ambient, questionnaire about sense of presence **Sphere of analysis:** general presence, spatial presence, pleasantness, realism. **Scale:** unipolar 7 points scale. **Scene verification:** not declared **HDM calibration:** not declared **Scene calibration:** not declared **HDM calibration:** not declared	A great sense of presence has been measured. The virtual environment is suitable to represent a great sense of presence and a satisfaction similar to the physical one. Higher WWRs increases the occupant satisfaction in terms of visual comfort, sense of inner space and openness and decrease the satisfaction in terms of privacy.	Spaces were too far or too narrow due to the limited field of view of HMDs.
[62] Rockcastle et al. (2021)	Evaluate lighting condition in a real space, comparing it via HDR photographs displayed in a HMD	**Number of participants**: 30 **Environment reproduced**: Studio workplace setting without daylight **Configurations**: 8 light scenes are selected, considering 3 types of light sources: overhead, track, and a lamp desk. **Measured data**: task and oral questions **Sphere of analysis:** visual comfort, pleasantness, evenness, brightness, contrast and glare perception for a range of lighting conditions. **Scale:** unipolar 5 points scale. **Scene calibration:** comparison between real and VR data **HDM calibration:** not declared	Overall response trends are similar for every type of display. Significant differences are in VR with scenes with low average luminance. Scene with the only desk lamp on was considered the one with the largest number of people saying the lighting condition was glaring. No significant differences between visual comfort and pleasantness. Some differences for evenness and brightness, contrast and glare.	The power of the sample was too low. The limited horizontal (150°) and vertical (100°) view angle of the HTC is thought to contribute to the difference in ratings for contrasted and glare rating questions.

Table A2. Selected works VR for lighting research: evaluating users' perception and behaviour (Ref. 4.2)

Ref.	**Hypothesis statement**	**Methodology**	**Main findings**	**Limitations**
[57] Chamilothori et al. (2016)	Investigate the effect of the façade and the resulting daylight pattern on the perceived spatial ambiance.	**Number of participants**: 30 **Environment reproduced**: The DEMONA (Module de demonstration en éclairage naturel), an office with a table and 2 chairs, a grey carpet, a window in the south facade, all the surfaces are achromatic. **Configurations**: Three façade patterns with the same opening ratio but different geometry and regularity (irregular, regular and venetian blind). **Measured data**: verbal questions in random order. **Sphere of analysis:** Perception (how pleasant, interesting, complex and exciting was the space and how satisfied the users were with the amount of view in the space) **Scale:** Unipolar 5 points scale.	Satisfaction with the amount of view was very similar between the two patterns with same geometry and slightly greater for the blinds. A preference for irregular pattern is shown.	

		Scene calibration: VR scene tuning with spectroradiometer measured data **HDM calibration:** not declared		
[58] Chamilothori et al. (2019)	Analyse how the facade pattern and associated daylight distribution influence the subjective environment perception and physiological response.	**Number of participants**: 72 **Environment reproduced**: social and working spaces. **Configurations**: Three facade patterns with the same opening ratio (25%) but different geometry and regularity (irregular, regular and venetian blind). 2 context scenarios (working or social activity) compared with a neutral scene. **Measured data**: Verbal questionnaires and physiological parameters. **Sphere of analysis:** Perception, preference, physiological response. **Scale:** Unipolar 11 points scale. **Scene calibration:** VR scene tuning with spectroradiometer measured data **HDM calibration:** not declared	A preference for irregular façade pattern is shown, resulting as more pleasant, more interesting and more exciting. The façade and sunlight pattern geometry significantly influenced the participant's perception, the mean heart rate, but not their skin conductance.	Participants' age was limited to avoid age-related effects. Limited luminance of the headset that cannot induce discomfort glare.
[64] Chamilothori et al. (2018)	Analyse how the façade geometry and the resulting sunlight patterns affect perception. Compare the perception between lighting/architecture professionals and common users.	**Number of participants**: 80 professionals and 80 common users. **Environment reproduced**: social and working spaces. **Configurations**: 20 façade patterns from existing buildings with the same opening ratio (40%). **Measured data**: questionnaires about perception (such as how exciting and calming the space was perceived) and physiological response. **Sphere of analysis:** Perception and preference **Scale:** Unipolar 11 points scale. **Scene calibration:** not declared **HDM calibration:** not declared	Professionals' surveys reveal a great consensus in perception for the same patterns (up to 49%). Common users were in agreement with professional intuitions for non-complex patterns and different perception for complex patterns.	Some discordant results motivate further research.
[33] Rockcastle et al. (2017)	Investigate how people perceive the immersive scenes and analyse visual interest impressions analysing quantitative predictors (using a headtracking), and subjective perceptual ratings.	**Number of participants**: 65 **Environment reproduced**: 8 different architectural spaces. **Configurations**: Sky conditions and view directions change in every architectural space each with different internal daylight composition, from direct and exaggerated sunlight penetration to diffuse and uniform daylight conditions. **Measured data**: Verbal questionnaires and headtracking. **Sphere of analysis:** Perception. **Scale:** Unipolar 11 points scale. **Scene calibration:** not declared **HDM calibration:** not declared	Subjects explored the 180° scenes with a 45° wide horizontal band, centred in the field of view, highlighting the importance to study the daylight-driven visual interest in architectural design from an occupant perspective.	-
[65] Sawyer et al. (2019)	With brightness level held constant, analyse what influences the environment	**Number of participants**: 100 **Environment reproduced**: Office	The colour is the more influent variable. The satisfaction is correlated with brightness but with outside view,	-

	perception (satisfaction) most.	**Configurations**: The brightness level is held constant changing: shading design pattern (6 configurations), colour of furniture and materials, furniture configurations. In total 30 different configurations are analysed compared with a neutral scene. **Measured data**: Verbal questionnaires to measure users' preference changing the selected variables. **Sphere of analysis:** Satisfaction, perception. **Scale:** Unipolar 11 points scale. **Scene calibration:** comparison between real and VR data **HDM calibration:** not declared	complexity and overall quality of the environment too.	
[66] Moscoso et al. (2020)	Evaluate the interaction between spatial elements and different lighting conditions in spaces with different destinations of use. In particular, evaluate the effect of windows size on daylit impression and how sky type, the use and size of the space may influence window size preferences.	**Number of participants**: 150 **Environment reproduced**: A single office and a multi-use space. **Configurations**: combination of different variables: 3 different window size (small, medium and large); 2 different space size (small and large); 2 different destination of use (social and working); 3 type of sky (overcast, clear with two solar height) **Measured data**: verbal questionnaires. **Sphere of analysis:** Perception, satisfaction. **Scale:** Unipolar 11 points scale. **Scene calibration:** VR scene tuning with spectroradiometer measured data. **HDM calibration:** A black screen with the logos of the two collaborating education institutions was used to verify the correct adjustment of the headset.	Window size has a statistically significant effect on the majority of the attributes. In particular, the space was evaluated as brighter when a participant was exposed to a large window compared to the equivalent small window.	Limited movement in the exploration of the scene; too short time of the experimentation.
[67] Moscoso et al. (2021)	Investigate regional differences in the perception of spaces making variable windows size and sky type.	**Number of participants**: 406 **Environment reproduced**: an office and a multipurpose room. **Configurations**: combinations of different variables: 3 locations (northern, southern and central latitudes); 3 window Size (large, medium, small); 2 space sizes (large or small); 2 destinations of use (social and working); 3 type of sky (overcast, clear sky with low or high sun angle). **Measured data**: verbal questionnaires. **Sphere of analysis:** Perception, satisfaction. **Scale:** Unipolar 11 points scale. **Scene calibration:** VR scene tuning with spectroradiometer measured data. **HDM calibration:** Photometric and colorimetric characteristics of the rendered scenes as presented to the participants in the two VR headsets (the one used in	Window preferences seems to not vary in different latitudes: larger windows are preferred over smaller, but there are no differences in space perception between medium and small windows. There are larger differences between Norway and Greece, but not between Norway and Switzerland.	Limited maximum luminance of the headset.

		Norway and the one used in Switzerland and Greece) were measured to ensure similarity of viewing conditions.		
[61] Hong et al. (2019)	Investigate if the virtual environment is an adequate representation of the physical environment of windowed spaces	**Number of participants**: 50 **Environment reproduced**: office space. **Configurations**: windowed virtual spaces with different WWR: 15-30-45-60%. **Measured data**: comparison between real and virtual ambient, questionnaire about sense of presence **Sphere of analysis:** general presence, spatial presence, pleasantness, realism. **Scale:** unipolar 7 points scale. **Scene calibration:** not declared **HDM calibration:** not declared	A great sense of presence has been measured. The virtual environment is suitable to represent a great sense of presence and a satisfaction similar to the physical one. Higher WWRs increases the occupant satisfaction in terms of visual comfort, sense of inner space and openness and decrease the satisfaction in terms of privacy.	Spaces were too far or too narrow due to the limited field of view of HMDs.
[68] Abd-Alhamid et al. (2020)	Evaluate the importance of the window views.	**Number of participants**: 32 **Environment reproduced**: Office. **Configurations**: repeated measures with the same participants in 3 conditions: Close, Middle and Far from the window in randomly order. **Measured data**: luminance values and physiological response. **Sphere of analysis:** perception, stress, physiological data, sickness symptoms. **Scale:** Unipolar 11 points scale. **Scene calibration:** comparison between real and VR data **HDM calibration:** not declared	Importance to be close to window: higher positive effects and lower stress level, higher parameter of view perception, higher satisfaction, more stimulating working environment); with a certain distance from the window no significant changes are recorded: importance of the sky component. More than the WWR given by standard, the window solid angle or dimensions should be considered (the distance from the window is important).	Limited range of luminance and glare or high brightness contrast can't be accurately evaluated. Only one window view is considered and this can't be representative of typical scenarios. Unwanted simulator symptoms are recorded. Cognitive performance wasn't tested.
[69] Rodriguez et al. (2021)	Analyse subjective responses to lightness changes in outdoor views with respect to different view constructs.	**Number of participants**: 48 **Environment reproduced**: four outdoor views: Corridor, Courtyard, Roof, and Wall **Configurations**: Using a randomization technique, 48 experiments were produced, each presenting unique combinations of dynamic (n = 8) and static scenes (n = 8). **Measured data**: Questionnaires. **Sphere of analysis:** Preference, Restoration, Imageability, Variability **Scale:** Unipolar 5 points scale. **Scene calibration:** not declared **HDM calibration:** not declared	Results showed significant interactions between view type and lightness change factors for the three constructs presented in dynamic format. A significant contribution was observed for the Wall and Corridor categories, indicating that these view types were significantly enhanced with the presence of lightness changes.	The techniques to capture the view stimuli could be refined to cover spatial and seasonal differences for different geographical locations. Likewise, the instruments to assess subjective responses to views could be adjusted to capture occupants' responses to dynamic views for a range of tasks and setting types.
[70] Flor et al. (2021)	Investigate the user acceptance ETFE double-skin façade for energy retrofitting of office buildings.	**Number of participants**: 22 **Environment reproduced**: Office **Configurations**: 3 scenarios with different ETFE cushions, 1) clear, 2) fritted, 3) switchable sample, were evaluated and compared to the 0) original single-skin façade with double-glazed windows.	Participants preferred window views with clear ETFE facades over fritted foil constructions, even if the latter provides better energy and daylighting performance. Otherwise, fritted ETFE facades could be acceptable in spaces	-

		Measured data: Questionnaires **Sphere of analysis:** Satisfaction and perception **Scale:** Unipolar 7 points scale. **Scene calibration:** comparison between real and VR data **HDM calibration:** not declared	where window views are not required or where it is necessary to improve the environmental performance of the building envelope.	
[71] Chinazzo et al. (2021)	Evaluate interaction between thermal and lighting perception on users and the influence on physiological responses.	**Number of participants**: 57 **Environment reproduced**: Office **Configurations**: Three types of coloured daylight (blue, orange, and neutral) in combination with two temperature levels (24°C and 29°C). **Measured data**: Verbal questionnaires. **Sphere of analysis:** thermal, visual and overall perception. **Scale:** Unipolar 5-, 7- and 10-point scale. **Scene calibration:** comparison between real and VR data **HDM calibration:** not declared	Orange scene was considered the worst pleasant in comparison with the neutral and the blue one. Visual and thermal perception have a connection only with the low temperature. General perception hasn't been influenced by colour and temperature.	Short exposure time to the thermal environment, which might not have allowed for full thermal adaptation. The use of a visual stimulus presented in the virtual environment might have been more predominant than a visual stimulus in a real environment.
[72] Vittori et al. (2021)	Occupants' behaviour is strongly influenced by their perception and represents a major variable affecting buildings' energy performance, but its impact is difficult to predict since the early design stage.	**Number of participants**: 50 for the validation, 100 for the colour experiment. **Environment reproduced**: Office **Configurations**: with a constant thermal environment, the following variables are considered: window coating, window aspect ratio, and artificial lighting colour temperature. **Measured data**: questionnaires. **Sphere of analysis:** subjective validation of sense of presence of VR scene. **Scale:** bipolar 5-point scale. **Scene calibration:** comparison between real and VR data **HDM calibration:** not declared	Validation test: 76% of the interviewees declared to prefer the 360° picture with respect to the VR model, even if the same percentage positively evaluated the perceived sense of presence in the VR environment. Core test: window aspect ratio and artificial lighting colour temperature modify the temperature perception of the users: interviewed people declared to feel relatively hotter in high aspect ratio window conditions and low colour temperature	Limits of the headset.
[73] Salamone et al. (2020)	Evaluate the influence of light colour temperature in thermal perception.	**Number of participants**: 25 **Environment reproduced**: Office **Configurations**: maintaining a constant thermal environment, light colour and images projected vary from cold to hot tone in real and VR environment. **Measured data**: questionnaires and biometric data. **Sphere of analysis:** perception. **Scale:** bipolar 7-point scale. **Sphere of analysis:** subjective validation of sense of presence of VR scene. **Scale:** bipolar 5-point scale. **Scene calibration:** not declared **HDM calibration:** not declared	Light colour is a non-negligible factor in predicting thermal perception.	Short exposure time could be a limitation because the thermal adaptation was not allowed.
[74] Heydarian et al. (2015)	Understand occupants' lighting use behaviour by	**Number of participants**: 114 **Environment reproduced**: Office	Semi-automatic systems, for what concern curtains, are preferred, especially	Limitations due to the quality of models, along with the equipment used.

	investigating the influence of manual and semi-automatic control systems on lighting-use. Investigate the influence of manual and semi-automatic control systems on lighting use.	**Configurations**: two sources of lighting: (1) two artificial light fixtures each with three florescent light bulbs and (2) natural light coming through a window. Four different control option: manual switching of lighting sources and manual opening of the curtains; manual switching of lighting sources and manually or semi-automatic opening of the curtains; manual or semi-automatic switching of lighting sources and manual opening of the curtains; manual or semi-automatic switching of lighting sources and manual or semi-automatic opening of the curtains. **Measured data**: questionnaires and reading task. **Sphere of analysis:** IVE interaction and gaming familiarity, environmental responsibility, personal preferences. **Scale:** unipolar 7 points scale. **Scene calibration:** comparison between real and VR data **HDM calibration:** not declared	with electric light environments. Users choose the remote option because it's easier to use.	
[56] Heydarian et al. (2016)	Identifying end-user lighting preferences via immersive virtual environment towards user centred building design.	**Number of participants**: 160 **Environment reproduced**: office **Configurations**: five lighting setting with different configurations of artificial lighting and shades. **Measured data**: reading a text, questionnaire about the text, changing of lights settings, evaluation of the ambient. **Sphere of analysis:** Preference and user behaviour **Scale: -** **Scene calibration:** VR scene adjustment with modeled data (Honeybee, Radiance, Daysim) **HDM calibration:** not declared	Participants were significantly less likely to change the default lighting setting if daylighting was available and they performed better.	Time and destination of use limitations
[37] Heydarian et al. (2017)	Collect end-user lighting-related behaviour by using immersive virtual environments (IVEs) as an experimental tool.	**Number of participants**: 89 **Environment reproduced**: Office **Configurations**: five lighting setting with different configurations of artificial lighting and shades. **Measured data**: reading a text, questionnaire about the text, changing of lights settings, evaluation of the ambient. **Sphere of analysis:** **Scale: -** **Scene calibration:** VR scene adjustment with modeled data (Honeybee, Radiance, Daysim) **HDM calibration:** not declared	Participants were significantly less likely to change the default lighting setting if daylighting was available and they performed better.	Not account for dynamic lighting changes or the angle of view in the virtual environment since the solar illumination of the scenes were preset and static.
[34] Amirkhani et al. (2018)	Investigate the impact of the WWR and the power level of an electric wall-washing system on occupants' lighting	**Number of participants**: 53 **Environment reproduced**: Office **Configurations**: four different WWRs: 15%, 30%, 46%, and 62% with a cool-white electric linear luminaires providing wall-washing.	Participants reported higher contrast on the window wall in the space with a lower WWR compared with the other groups of WWR. Increasing the lighting level of the	Current tone-mapping operators are static, whereas the content and contrast of scene in the IVR spaces changes with the users' head movement.

	preferences and intended behaviour. Explore the utility of an IVR space in examining responses to lighting scenarios.	**Measured data**: verbal questionnaires **Sphere of analysis:** Preference and satisfaction **Scale:** Unipolar 5 points scale. **Scene calibration:** not declared **HDM calibration:** not declared	supplementary wall-washing system improves indoor lighting satisfaction	
[75] Carneiro et al. (2019)	User awareness can influence choice and action with energy efficiency benefits	**Number of participants**: 80 **Environment reproduced**: office **Configurations**: Two visualizations were presented to the participants, one relating to energy consumption and another relating to light distribution in the room, depending on the participants' initial choice. If the participant chose natural light as the main source of lighting by opening the blind, an energy consumption related InfoVis shows the impact of heat gain on energy consumption. If the participant chose mainly artificial light as the lighting choice, the illuminance levels in the room is shown to demonstrate that the natural light was sufficient to illuminate the room. The goal was to contradict their initial choice. **Measured data**: Questionnaires **Sphere of analysis:** Preference **Scale:** Unipolar 5 points scale **Scene calibration:** not declared **HDM calibration:** not declared	The energy impact visualization influences more than the illuminance visualization.	Few people changed their initial choice. The effectiveness of the InfoVis can be further improved if user personality is also considered in the InfoVis design. Another limitation of this study is that the participants mainly consisted of students and, since the participants were of similar age and education level, it wasn't possible to analyze the impact of age, experience and level of education on the study outcomes.
[76] Mahmoudzadeh et al. (2021)	Occupants' behaviour has major effect on building energy consumption. The sense of control can influence occupants' choice and performance in office settings.	**Number of participants**: 30 **Environment reproduced**: office **Configurations**: Three different lighting settings, which provided different degrees of control for lighting arrangement, for the same virtual office setting. **Measured data**: Questionnaires, lighting choices **Sphere of analysis:** Perception, satisfactio, cognitive loads, Personality traits **Scale:** 7 questions with a agree-disagree format, 1 question with a 3 points Likert Scale, 1 question with a 6-point Likert scale, 44 questions on 5-point Likert scale. **Scene calibration:** VR scene adjustment with modeled data (DIALux Evo) **HDM calibration:** not declared	The participants were more likely to choose to have natural lighting over artificial lighting when interacting with more energy efficient lighting systems, which gives them a perception of control. Overall, the assessments suggested that the participants were equally satisfied with semi-automated lighting systems. The participants underwent a higher cognitive load when they performed a task with fully automated lighting system compared to the conditions where they had full control or a perception of control over the lighting system. The participants who scored high on openness had a wide range of lighting choices regardless of having different degrees of control over lighting. In case of having full control, participants with bold extraversion	The environmental factors and conditions were static and in favour of having natural light throughout the experiment. Additionally, since this study was designed for virtual environments, the obtained average lux levels in the real work environments might result in different associations. Due to the COVID-19 pandemic, the sample size was kept small.

			dimension mostly chose a combination of both natural and artificial lighting. VR technology is not perceived as a tool for performing serious task. Furthermore, behavioural observations of the participants during the experiment signified that the participants had a strong perception of reality in the IVE.	

Table A3. Works about VR for lighting design (Ref. 4.3)

Ref.	**Hypothesis statement**	**Methodology**	**Main findings**	**Limitations**
[36] Wong et al. (2019)	Matching BIM and VR technologies could be useful for designers and users, to support user interaction and to evaluate lighting design alternatives.	**Number of participants**: - **Environment reproduced**: lecture room **Configurations**: Lighting parameters (i.e., intensity and color) can be adjusted after instantiating the lighting fixtures **Measured data**: - **Sphere of analysis:** Lighting instantiation; Lighting parameter adjustment; Personalized lighting design; Video projecting; Energy consumption **Scale:** - **Scene calibration:** comparison between real and VR data **HDM calibration:** not declared	A feasible calculation method of lighting illumination in Unity is lacked. Both the unit of light intensity in Unity and its conversion relation with the real-world unit of luminous flux are not available in the official documentation. This proposed approach cannot reflect the real lighting effect.	The quantitative analysis in the proposed system cannot be conducted due to the lack of a feasible calculation method of lighting illumination in Unity.
[19] Natephra et al. (2017)	Develop a new prototype that integrates BIM and VR to identify the best design parameters and evaluate if this approch could be useful in lighting design.	**Number of participants**: - **Environment reproduced**:office **Configurations**: 12 artificial lighting sources, natural light added as an actor in the virtual environment. UI tools are implemented in the model. **Measured data**: - **Sphere of analysis: -** **Scale: -** **Scene calibration:** subjective validation of sense of presence of VR scene and comparison between real and VR data **HDM calibration:** not declared	This method permits to explore the virtual space and to perceive lighting distribution and illuminance level as well as in a real environment. It permits to quantify illuminance in real-time.	Different sky conditions could be added. Synchro between BIM and VR could be automatic. False colour view is not realistic, it reaches only 1000 lux.
[61] Hong et al. (2019)	Investigate if the virtual environment is an adequate representation of the physical environment of windowed spaces	**Number of participants**: 50 **Environment reproduced**: office space. **Configurations**: windowed virtual spaces with different WWR: 15-30-45-60%. **Measured data**: comparison between real and virtual ambient, questionnaire about sense of presence	A great sense of presence has been measured. The virtual environment is suitable to represent a great sense of presence and a satisfaction similar to the physical one. Higher WWRs increases the occupant satisfaction in terms of visual comfort, sense of inner space and	Spaces were too far or too narrow due to the limited field of view of HMDs.

		Sphere of analysis: general presence, spatial presence, pleasantness, realism. **Scale:** unipolar 7 points scale. **Scene calibration:** not declared **HDM calibration:** not declared	openness and decrease the satisfaction in terms of privacy.	
[63] Krupinski (2020)	An innovative lighting design system using virtual reality should receive technical information on luminance level and energy consumption supporting designers.	**Number of participants**: 32 participants in first survey and 129 in the second one. **Environment reproduced**: room and external façade. **Configurations**: The spaces were reproduced after an accurate measurement of geometries, lighting and materials. Spaces were compared also with imaging luminance measuring. **Measured data**: Comparison between light perception in the real and the VR environment. **Sphere of analysis:** perception **Scale: -** **Scene calibration:** comparison between real and VR data **HDM calibration:** Measure of the luminance range of the projected image on the VR headset display	Some respondents who observed the real image considered it a computer simulation, or understand through details which image was the virtual one.	All the modelling softwares ignore CRI
[39] Lee et al. (2017)	An integrated lighting design system which comprise direct, indirect and inverse lighting design in VR environments	**Number of participants**: - **Environment reproduced**: virtual museum room **Configurations**: Unlimited. A user can freely identify areas of interest ("lighting goals") on surface to solve the inverse lighting problem. **Measured data**: - **Sphere of analysis:** realism **Scale: -** **Scene calibration:** not declared **HDM calibration:** not declared	Provision of an hybrid lighting design interface including direct, indirect, and inverse paradigms light in VR environment to cope selected design tasks and scenarios	-
[38] Hong and Michalatos (2016)	Evaluate the interaction between users and architecture in 3D models.	**Number of participants**: 20 **Environment reproduced**: generic room **Configurations**: 5 different possibility of interaction. **Measured data**: comparison of objects dimension perception with VR and Rhinoceros software **Sphere of analysis:** perception **Scale:-** **Scene calibration:** not declared **HDM calibration:** not declared	VR has an advantage over Rhino in helping people determine scale. Rhino do a slightly better perception of distance.	Limited range of light of the screen. Small number of samples
[77] May et al. (2020)	Investigate pros and cons of different ways to inform user about the glare intensity through an immersive VR simulator	**Number of participants**: - **Environment reproduced**: living room **Configurations**: - **Measured data**: -	Definition of 6 ways (4 visual-based and 2 non visual-based) to inform user about glare intensity	Acceptable refresh rate (>45 fps) with less than 5 light sources and 1300 meshes. Each way used to inform glare intensity has limitations -semi realistic mode: low UGR accuracy;

	capable of real-time glare analysis.	**Sphere of analysis:** perception **Scale: -** **Scene calibration:** not declared **HDM calibration:** not declared	The glare visualization techniques are: semi realistic mode, heatmap color, bendrays, animated arrows Non visual glare information ways are: glare intensity proportional to an audio signal, glare intensity proportional to vibration on haptic device	-heatmap color: loss of real aspects of objects; -bendrays: slows the refresh rate and rays obstruct the FoV of the user; -arrows: obstruction in FoV, low intuitiveness -audio and haptic: hardness in locating glare sources;
[78] Wang et al. (2018)	Study the visual perception conflict for mixed reality (MR) devices. comparing images of the real, virtual and mixed worlds as seen when using the augmented or mixed reality device along with an expected image of the mixed world.	**Number of participants**: - **Environment reproduced**: living room **Configurations**: 2: MR with optical see-through device and MR with video see-through device **Measured data**: MR scenes Luminance **Sphere of analysis:** realism **Scale:-** **Scene calibration:** not declared **HDM calibration:** not declared	In optical see-through MR system type only increase luminance of the virtual objects is possible to make them clear visible. MR needs a tuning of the virtual world luminance. In video see-through MR systems the absence of indirect illumination makes the shadows uncorrect. An external simulation indirect illumination is needed.	-