Анализ на точността на виртуалните симулации на осветеност в сравнение с измерени реални данни

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Analysis of the accuracy of virtual lighting simulations compared to measured real-world data

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Abstract:
With the growing need for sustainable design in architecture and construction, lighting simulations are becoming a key tool for predicting energy efficiency and visual comfort. The present study examines the reliability of virtual simulations in the design of interior and exterior environments, focusing on the accuracy of predicted lighting values compared to actual measured data. By comparing results from specialized software platforms and a virtual laboratory created by the authors, with accurate measurements using lux meters under controlled conditions, the report analyzes deviations, their causes, and opportunities for optimization. The study not only demonstrates the potential of 'intelligent light' – a combination of simulation, analysis, and sustainable solutions – but also enlightens the audience about its role in creating energy-efficient, healthy, and functional environments.
Keywords: Lighting education, Lighting virtual laboratory, Virtual laboratory, Lighting simulation, Illuminance measurement, Comparative lighting study.

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INTRODUCTION

As sustainable design becomes increasingly central to architectural and construction practices, the ability to predict lighting performance has grown in importance. Virtual lighting simulations are now widely used to estimate illuminance levels, energy consumption, and visual comfort in both interior and exterior spaces. Digital technologies enable architects and researchers to model and analyze intricate lighting conditions, supporting more informed design choices [6]. Inverse modeling offers a promising approach for simplifying daylight performance predictions in sustainable building design [5], [11]. However, the accuracy of these simulations, particularly when used for educational or early-stage design decisions, remains a critical concern. Previous studies have extensively validated simulation tools such as Daysim, Radiance, and Ladybug against physical measurements under controlled conditions [10], [12]. These comparisons underscore both the potential and limitations of virtual environments in reliably modelling complex light-material interactions and daylight scenarios [4], [3], [8]. Furthermore, studies on the role of technology in education emphasize the importance of interactive and realistic digital tools in professional and pre-service training [1], [2]. To better understand the effectiveness of virtual laboratories in an educational setting, the present study explores the accuracy of a student-oriented simulation platform, developed by the authors as an initial prototype, comparing its results to real-world measurements gathered using a calibrated photometric instrument.

EXPOSITION

The comparative analysis of simulated and real-world lighting measurements provides valuable insights into both the accuracy of the developed virtual tool and the pedagogical benefits of using such systems in educational contexts. The virtual tool demonstrated reliability in predicting illuminance levels, particularly under direct lighting conditions and when interacting with diffuse or matte surfaces. The studies [10], [13] show that simplified lighting models can approximate basic light distribution with acceptable accuracy in standard indoor environments.

In cases where materials had more intricate optical characteristics, like transparency, glossiness, or partial translucency, the differences between simulated outputs and actual measurements became more noticeable. These inconsistencies likely stem from how the educational tool simplifies how light interacts with various surfaces. Unlike advanced photometric simulation engines that incorporate physically based rendering (PBR) techniques, many educational tools rely on basic reflection and shading algorithms that do not fully account for phenomena such as refraction, subsurface scattering, or global illumination [7].

For instance, transparent materials like glass or plastic involve complex light interactions, including refraction and reflection, which depend on surface properties. Approximating these effects can lead to deviations in illuminance and shadow accuracy. Additionally, the tool does not simulate secondary reflections or indirect lighting, limiting realism. While such simplifications are acceptable for basic teaching, they highlight the trade-off between computational simplicity and physical accuracy in educational simulations.

Methodology

This study adopts a dual-method approach combining virtual simulations with real-world measurements to assess the reliability of predicted lighting values. Such comparative strategies are widely used to evaluate the performance of lighting simulation tools in both academic and professional contexts [10].

A custom-developed software environment was a virtual educational tool to support students in the "Lighting Technology" course. Its core function enables users to experiment with various lighting conditions and material types, providing visual feedback on how light interacts with surfaces of different reflectivity, texture, and geometry. The pedagogical value of simulation-based learning environments in lighting education has been well documented [9]. Within the virtual environment, students could place objects composed of predefined materials—such as metal, wood, plastic, and glass—and subject them to various artificial light sources, including point lights, spotlights, and directional lighting.

To validate the predictive accuracy of the simulation, controlled real-world experiments were conducted in a laboratory environment. Physical analogues of the virtual materials were arranged in test scenes that mirrored the digital setup. Illuminance measurements were collected using a calibrated lux meter placed at predefined distances and angles, carefully aligned to match the virtual scenarios. As suggested by industry-standard practices, maintaining environmental consistency—such as minimizing ambient interference and standardizing surface orientation—was essential for ensuring valid comparisons.

Experimental Workflow

The measurements required to analyze specific lighting parameters related to the test object were performed using the OHSP-350C device, developed by HopooColor Technology Co., Ltd. This portable spectrometer is capable of capturing up to 14 photometric and colorimetric indicators, including illuminance (lux), correlated color temperature (CCT in Kelvin), color rendering index (CRI or Ra), spectral power distribution (SPD), and chromaticity coordinates (x, y, u, v). The neutral—colored sphere test object was positioned close to the device's sensor to ensure precise and repeatable measurements under various lighting conditions.

Fig. 1 illustrates the complete experimental workflow used in the present study, covering both virtual and physical environments. The diagram outlines a systematic process that begins with setting objectives and formulating hypotheses, and proceeds through experimental design, data collection, and result analysis.

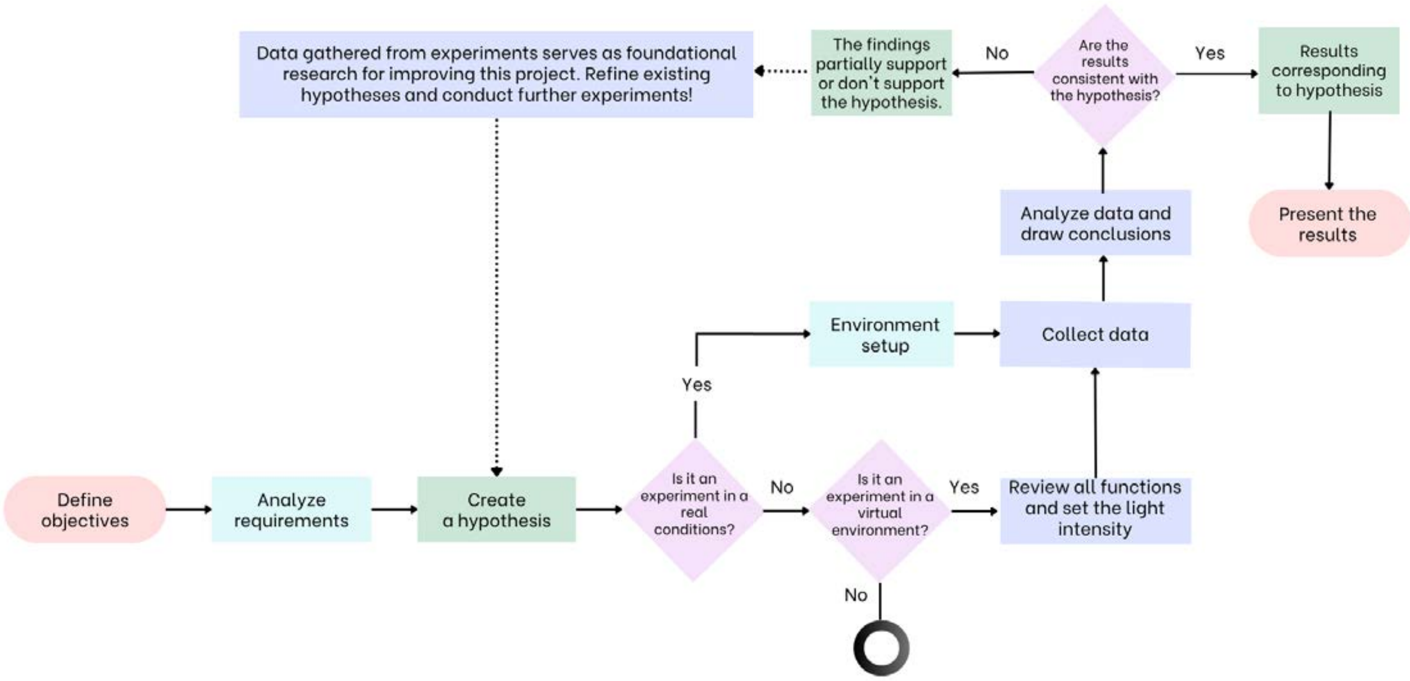

Fig. 1 Experimental workflow illustrating the parallel structure of virtual and real-world lighting investigations

The workflow is bifurcated based on the nature of the experiment—real-world measurements or virtual simulation—allowing for parallel procedures tailored to each context. Environmental conditions are established for physical experiments, and data are collected using calibrated equipment (e.g., the OHSP-350C device). Users interact with the software in the virtual setting by configuring material and lighting parameters and observing the rendered outcomes under different lighting conditions.

This flowchart emphasizes the iterative nature of experimental design, where partial or inconclusive results prompt further refinement of hypotheses and additional experimentation. The diagram offers a clear overview of how both types of experiments were carried out, helping to support the overall research method and show how the two approaches—virtual and real—were used together for a well-rounded comparison.

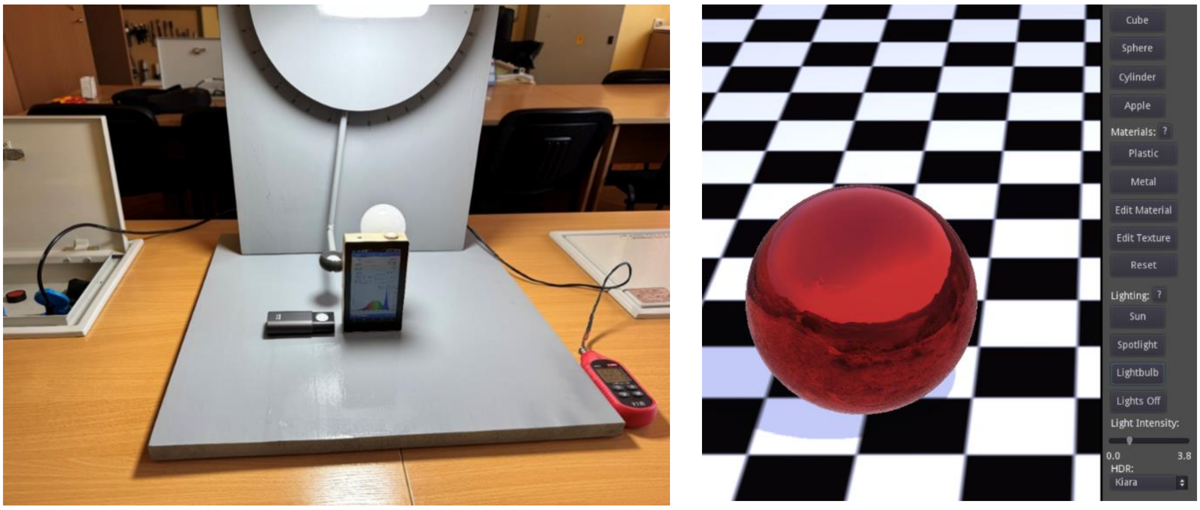

Fig. 2 Comparison between physical lighting measurement setup and virtual simulation environment

To evaluate the effect of various lighting conditions on illuminance, three separate measurements were performed using the OHSP-350C device. Figure 2 illustrates a side-by-side comparison between the physical measurement setup and the virtual simulation. On the left, illuminance is measured using the OHSP-350C device with a neutral-colored sphere under artificial lighting conditions. On the right, the same object is visualized within the custom-developed educational platform, showcasing realistic reflections and lighting behavior under simulated lighting scenarios. The neutral—colored sphere test object was consistently positioned near the device’s sensor to ensure comparable results across scenarios. Each measurement simulates a unique lighting context in architectural and interior environments.

- Ambient Daylight: Measured in a naturally lit room without artificial light, the illuminance was 1540 lux—typical for well-lit interiors and suitable for general tasks.
- Spotlight: A focused artificial light source aimed at the sensor yielded 7610 lux, demonstrating the high intensity of task or accent lighting.
- Direct Sunlight: In full outdoor sunlight, the illuminance exceeded 40,000 lux, reflecting the upper end of natural light intensity.

These measurements provide a baseline for comparing physical lighting conditions and validating virtual simulations.

Virtual Simulation with the Godot Game Engine

A custom virtual lighting tool was developed using the Godot game engine. Though primarily a game development platform, Godot's real-time 3D rendering, PBR material support, and scripting capabilities make it suitable for simulating lighting in educational contexts.

The tool enables users to manipulate 3D scenes with various materials under different light types and settings. While it does not output photometric values like lux, it provides a visually accurate approximation of lighting behavior, including reflections, shadows, and material responses.

Its interactivity allows students to explore lighting principles dynamically—observing how changes in light angle, intensity, and material affect appearance. This qualitative approach supports the teaching of core concepts such as diffuse vs. specular reflection, shadow formation, and material-light interaction. In concise, the Godot-based virtual tool may not function as a calibrated measuring device. However, it fulfils an equally important role: it invites users to experiment, visualize, and reflect on lighting behavior in a controlled, repeatable, and intuitive way

Table 1 Comparative Overview of the Virtual Lighting Simulation Tool and the OHSP-350C Measuring Device

Capability	*Visual tool*	*OHSP-350C*
Visual interactivity and scene control	Supported	Not applicable
Simulating lighting behavior	Approximate, based on rendering engine	Not applicable
Measurement of physical illuminance (lux)	Not applicable	Available (high precision)
Correlated Color Temperature (CCT)	Not applicable	Available
Color Rendering Index (CRI)	Not applicable	Available
Spectral Power Distribution (SPD)	Not applicable	Available
Scientific measurement accuracy	Low	High (calibrated instrumentation)
Educational value	High (interactive, visual learning focus)	Moderate (requires interpretation skills)

CONCLUSION

While the student-oriented simulation platform developed in this study offers substantial educational value, it is not intended as a substitute for physical instruments such as the OHSP-350C spectroradiometer. Built using the Godot engine, the platform enables users to visualize relative differences in light intensity, material reflectivity, and scene composition. Through interactive features such as adjustable light angles, intensities, and material properties within PBR and HDR environments, the simulator supports conceptual learning and exploratory engagement with lighting principles.

However, unlike calibrated photometric devices, the platform does not generate physically accurate data such as lux values, CCT, SPD, or CRI. As a result (table 1), while it provides qualitative approximations of light behavior, it lacks the precision required for scientific measurement or technical validation.

More advanced virtual environments that integrate radiometric calibration, validated HDR maps, or ray-tracing engines may offer improved estimations, yet they still require real-world measurements for verification. Therefore, within the context of educational research, the simulation platform should be viewed as a complementary tool that enhances understanding but does not replace high-accuracy physical measurement instruments.

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