Thermal VR: Assessment of complex fenestration's effects on visual and thermal comfort

Author(s):
Grobe, Lars Oliver; Chiu, Chen; Schlueter, Arno; Waibel, Christoph

Publication date:
2025-11

Permanent link:
https://doi.org/https://doi.org/10.3929/ethz-c-000788260

Originally published in:
Journal of Physics: Conference Series 3140(10), https://doi.org/10.1088/1742-6596/3140/10/102003

Journal of Physics: Conference Series **3140** (2025) 102003 doi:10.1088/1742-6596/3140/10/102003

Thermal VR: Assessment of complex fenestration's effects on visual and thermal comfort

L O Grobe[1,2*], C Chiu[1], A Schlueter[1], C Waibel[1,3]

[1]Chair of Architecture and Building Systems, Institute of Technology in Architecture, ETH Zurich, Stefano-Franscini-Platz 1, 8093 Zurich, Switzerland
[2]Competence Center Building Envelopes and Civil Engineering, School of Architecture and Engineering, Lucerne University of Applied Sciences and Arts, Technikumstrasse 21, 6048 Horw, Switzerland
[3]Flemish Institute for Technological Research (VITO), Boeretang 200, 2400 Mol, Belgium

E-mail: grobe@arch.ethz.ch

Abstract. This paper investigates the integration of thermal feedback into virtual reality (VR) environments to enhance architectural design processes. While traditional VR simulations focus primarily on visual experiences, this work expands the scope to incorporate thermal sensations, offering a more immersive and holistic design tool. The development of a "Thermal VR" system, combining heat emitters with VR goggles, allows architects to assess both the thermal and visual qualities of their designs more intuitively. The system was tested using various facade designs in a virtual office setting, specifically simulating solar radiation and its impact on indoor conditions. The results demonstrate the feasibility of integrating thermal feedback in VR and highlight its potential to enhance spatial perception and decision-making. However, challenges remain in the flexibility of generalizing the approach to different designs. This research contributes to the emerging field of climate-aware architectural design, offering valuable insights into the potential of VR as a tool for simulating combined visual and thermal experiences.

1. Introduction

1.1. Background

Virtual Reality (VR) as design platform in architecture offers unprecedented levels of visual immersion. However, we really only use one of our many bodily senses: the sense of sight. According to the philosophy of embodiment, intelligence was only formed due to a direct link to the physical world via sensors and actuators [1]. It is questionable whether our arguably primitive approach to designing buildings with mostly relying on what we see on the computer screen, plans or through Head-Mounted Displays (HMDs) truly exploits our full creative potential.

Looking at the brain regions responsible for our different senses, we can observe that the sense of touch occupies similarly large parts as the sense of sight, and our other senses obviously also are integral parts of how we perceive space. How would building designs change if we had real-time interactive feedback on the haptics of concrete surfaces; if we could smell the timber of load bearing structures; if we could hear sound propagation of an orchestra in a concert hall; if we could feel the soothing summer breeze on a shaded patio and feel the warm sunlight in winter coming through a window? How would our designs change if we could sense all of that already while drafting our architectural visions?

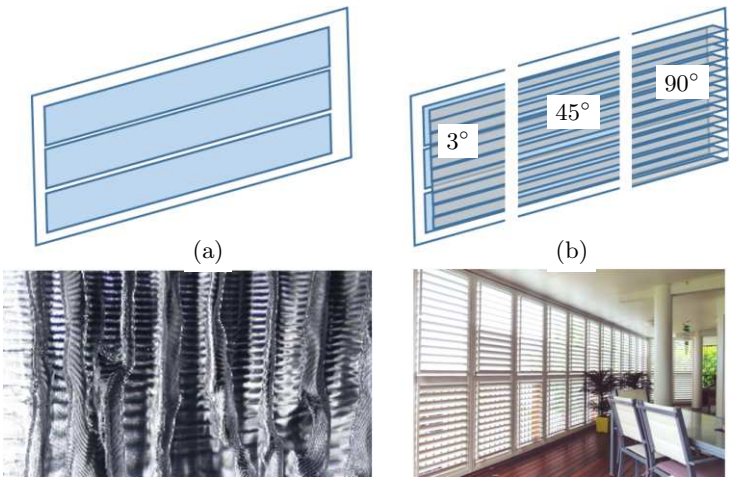


Figure 1. Evaluated fenestration systems applied to three window zones: 3D printed translucent facade (a), internal roller blinds (b) with tilt angles 3°, 45°, and 90°.

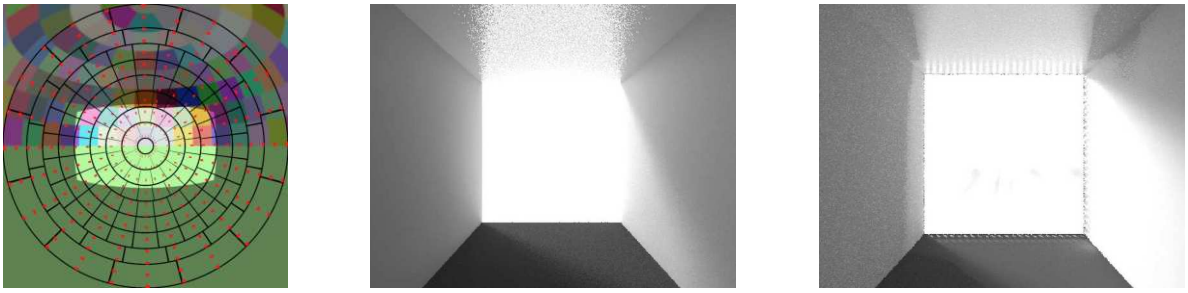
To explore this research question, we propose Thermal VR [2]. The utilization of VR in architecture is being studied by various research groups already [3], in particular with regard to lighting and fenestration [4, 5]. The additional element we propose is to extend VR from being a merely audio-visual experience to also using the other bodily senses. Specifically, heat emitters will be spatially distributed in a VR room, such that environmental/climatic factors would be perceived by the VR designer and the impact on thermal comfort of design decisions could be experienced in real-time. Physics and data-based simulation models, as well as decision support concepts from computational intelligence (optimization and generative design) will be coupled with Thermal VR. A conceptually related study is presented by Chinazzo et al. [6], who experimentally investigate thermal perception based on colours experienced in VR.

This project contributes to the development of future innovative decision making processes in architecture. The global environmental crisis with climate change as its inexorable consequence is demanding for more sustainability in the built environment as one of climate change's major drivers. In Switzerland, particularly, this means a drastic increase of mean temperatures and overheating risk in building – as can already be undeniably experienced on summer days in many buildings not designed for heat waves. However, thermal comfort is one of the major factors determining health, wellbeing and productivity in work spaces [7]. The question arises whether thermal comfort of many buildings would be better, had they been designed with a platform such as Thermal VR.

2. Modelling of a sample room with complex fenestration systems (CFSs)

An existing office room at the Institute of Technology in Architecture at ETH Zurich (HIB 35) presents the context for the experiment. A 3D-model of the room was prepared in Blender. To constrain the visual assessment, all the walls but the facade were replaced by opaque surfaces. The scene was enriched by detailed objects of some furniture, e.g. chairs, and 3D-scanning. While these objects do not contribute to the thermal model, high resolution modelling is imported for visual immersion in VR in particular for views from short distance.

Two CFSs were compared in the experiment. A translucent 3D-Printed Facade (3DPF) (Figure 1 a) diffuses and deflects incident light [8]. The tunable solar-optical properties of this mono-material facade, caused by its geometrical structure, have been determined employing computational methods and measurements on prototypes [9]. The second facade systems comprises horizontal louvres installed on the inside of a Double-Glazing Unit (DGU) (Figure 1



(a) (b) (c)

Figure 2. Discretizations (a) applied to the sky distribution (Tregenza, coloured patches), the BTDF (Klems, black grid), and the regular grid of the IES LM-63-1995 description (red dots). Simple test room illuminated by direct sunlight transmitted by fenestration modelled by its BTDF (b) and by an IES LM-63-1995 description (c). The latter shows artefacts due to light-source subdivision (along the ceiling), and the chosen, low angular resolution (left wall).

b). The solar-optical properties of this CFS can be adjusted by mechanical movement, e.g. retraction and tilting of the slats, and have been computed for tilt angles of 3°, 45°, and 90° [10]. The facade was modelled as a flat surface, subdivided into three vertical window zones. While this allows refined modelling of the CFSs, e.g. partial retraction of the louvres, the presented research assumes that identical solar-optical properties of one CFS are mapped to the three window zones in the subsequent simulations.

3. Modelling daylight conditions in VR

3.1. Annual calculation of daylight emission

Despite the widespread adoption of Physically-Based Rendering (PBR) techniques [11] by VR environments, the irregular transmission properties of CFSs, and complex, climate-based descriptions of sky-conditions are typically beyond these capabilities [12]. To address this limitation, discrete descriptions of hourly sky conditions and tabular Bidirectional Scattering Distribution Functions (BSDFs) of the evaluated CFSs were combined in a pre-calculation pass [1]. The sky descriptions were generated from a weather file for Zurich [2]. Available tabular BSDFs [8, 10] were employed to model the CFSs. The resulting hourly intensity distributions were recorded in IES LM-63-1995 format [13]. Figure 2a illustrates the sampling the combination of a Tregenza-discretization of an hourly sky with the Klems-discretization of a BSDF at the regular angular intervals required by IES LM-63-1995. The light propagation from the sky through the BSDF as calculated by RADIANCE (Figure 2b) can be closely replicated by the pre-calculated intensity distribution applied to an area source (Figure 2c). The approach is inspired by the Three-Phase-Method (3PM) [14, p. 466], but replaces the view matrix by directions to produce the intensity distributions.

3.2. Presenting daylight conditions in VR

The geometric model of the furnished room was imported into the 3D-engine UNITY 3D. UNITY 3D allows to apply luminous intensity distributions to light sources that can be approximated as emitting from a point, e.g. to model the emission from light fixtures. In this case, the contribution by a light source to the local illuminance at any location in the scene translates to a simple look-up in the luminous intensity distribution for a known direction. If light is emitted

[1] The RADIANCE-based pre-calculation was implemented in C++: `https://gitlab.ethz.ch/lgrobe/bsdf2ies`.
[2] `climate.onebuilding.org`; `CHE_ZH_Dubendorf.AP.066099_TMYx.2004-2018.epw`

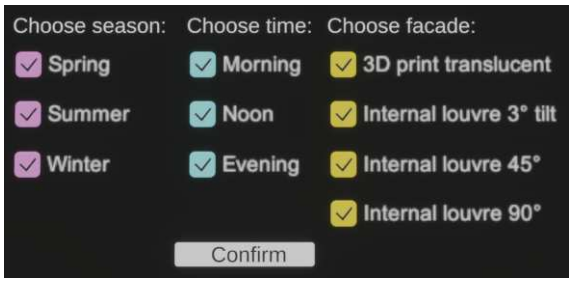


Figure 3. VR user interface.

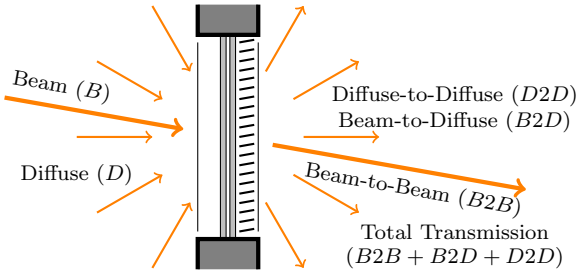


Figure 4. EnergyPlus output variables.

by an area, e.g. facades, this is significantly complicated to the integration over the solid angle covered by this extended light source. To ensure real-time rendering at sufficiently high frame-rates, Unity 3D ignores the assigned intensity distribution in such cases and acts as a diffuse emitter. To overcome this limitation, all light transport was pre-calculated in Blender using the Cycles rendering engine. In computer graphics, this process is known as *light map baking* and commonly applied to accelerate real-time rendering. Assuming purely diffuse reflection by all opaque surfaces, the effective luminance at any point was pre-calculated from the local diffuse reflectance and illuminance and stored as Hight Dynamic Range (HDR) imagery in OpenEXR format, that could be imported as light maps in Unity 3D.

The resulting scene was navigated using a HMD [3]. To avoid disruption of the immersive experience when switching between scenarios during the evaluation, a simple user interface was implemented in Unity 3D. This allows users to select one of the four CFS configurations (Figure 1) and a given time-step (by season and time of day) from within the VR environment (Figure 3).

4. Augmenting the VR model with thermal stimuli

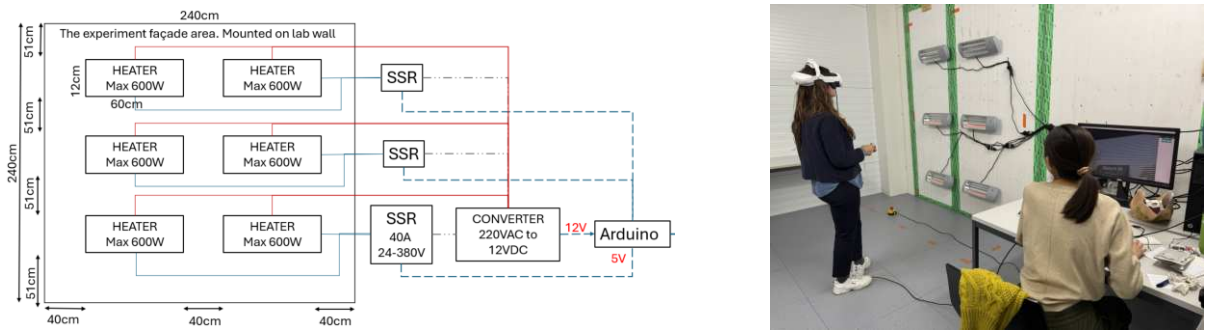
4.1. Annual simulation of solar gains

EnergyPlus[4] was used to model annual hourly energy and radiation variables for the room with existing models of the chosen CFSs [8, 10]. The weather file employed in the daylight simulation was used also for the thermal modelling. Construction parameters and schedules were set according to the Swiss building norm SIA 2024 [15], with cooling and heating controls to maintain a constant 22.0° to 22.5° ambient air temperature throughout the year. The 3DPF (Figure 1 a) was modelled by a tabular BSDF [8] in conjunction with the EnergyPlus objects `WindowMaterial:ComplexShade` and `WindowMaterial:Glazing`. The internal, horizontal louvres (Figure 1 b) were described by the objects `WindowShadingControl` and `WindowMaterial:Blind`. The slats geometry was parametrized with 25 mm width, 18.75 mm separation, 1 mm thickness, and 50 mm distance to the glass. The solar-optical properties were set to 44.9 W m^{-1} K conductivity, beam and diffuse reflectance in the solar and visible light range of 0.8 and 0.7 respectively, and thermal infrared emissivity of 0.9 (front and back surfaces). No angle controls are used. Instead, fixed angles in three states are applied for the whole year: 3° (practically closed), 45°, and 90° (fully opened). The simulation provided annual hourly time-series with variables shown in Figure 4, as well as zone air and operative temperatures.

4.2. A VR-controlled heat wall

One wall of a test room in the Zero Carbon Building Systems Lab (ZCBS) at ETH Zurich was equipped with an array of radiators to mimic the thermal stimuli by CFSs. Quartz heaters

[3] In this research, a Meta Quest 3 was employed.
[4] `http://Energyplus.net/`



(a) (b)

Figure 5. (a) configuration diagram of the heat wall; (b) Photograph of the complete THERMAL VR system including active heaters

were chosen, that heat up in few seconds and provide a moderate lifespan of ≈ 5000 h. The six heaters (Figure 5b), each with a nominal power of 1200 W, are connected to three Solid State Relays (SSRs), that each switches the supply voltage of 230 V for one pair of heaters. The SSRs are controlled by an ARDUINO micro-controller[5]. Figure 5a illustrates the components and wiring of the heat wall. Tuning the effective transmission of each row of heaters was implemented by modulation of their power-supply, e.g. setting the length of the duty-cycle, through the SSRs. Due to the heaters' latency, the frequency could be kept low at ≈ 1.0 Hz. For the typical case of diffuse emission from a fenestration system blocking direct transmission, each heater represents just its corresponding window zone.

5. Results and discussion

5.1. Visual experience

The method renders convincing and realistic scenes in VR (Figure 6). In particular, it produces consistent views from different locations and achieves satisfactory resolution. While lightmaps reduce real-time computation and noise, their discrete resolution can limit texture detail when viewed up close. This limitation can be mitigated with higher-resolution rendering, making it less noticeable to users. The application of dynamic exposure adjustments, mimicking the human eye's automatic adaptation, makes the VR scene appear more natural. Shadows are generally rendered convincingly, with penumbras that respond to seasonal and diurnal sky conditions as well as the configuration of the CFS. However, the use of average BSDF to model the CFS leads to reduced non-uniformity in shadow patterns, which blurs distinctions between systems like the BSDF and horizontal louvres. Additionally, horizontal angular differences are not clearly perceived. A contributing factor to these shadow limitations is the use of IES profile projections via substituted point light sources, which compress the light distribution and reduce shadow clarity. This compression impacts the accuracy of shadow pattern, and could be improved by applying customized shaders to area lights, which would better capture the spatial characteristics of real light sources. Finally, the static outdoor view created by mapping a CFS image to the façade offers some contextual clues but fails to reflect view-dependency and dynamic sky conditions. This causes inconsistencies between the perceived indoor lighting and the visible exterior, which might be addressed by adding a geometric model of the CFS that does not interact with interior light propagation.

[5] The UDUIONO toolkit was employed to address the micro-controller from UNITY 3D: `https://marcteyssier.com/uduino`.

Figure 6. VR scene showing visual effects by (a) the translucent 3DPF; and the horizontal louvers with tilt angles of (b) 3°, (c) 45°, and (d) 90° on March 21st 7:00.

5.2. Thermal experience

Power-cycling at low frequencies allows tuning the heaters with imperceptible fluctuation. Representing the emitting facade by six heaters was adequate at typical distances, the temperature decreases between the heaters was sensible only for positions very close to the heated wall. Directional transmission through the louvres (45° and 90°) could be modelled by dynamically increasing the power of the lower heater row based on the tracked user's distance from the heat wall. Heater output is adjusted using a duty cycle to simulate varying thermal intensity. However, with increasing distance this effect diminished. This suggests the addition of directional heat-sources to separately account for direct solar transmission.

6. Conclusion and future steps

The experiment increased immersion by consistent thermal and visual stimuli and demonstrated the potential of accessing the effect of planning decisions in multiple dimensions and with multiple senses. We hypothesize a drastic rethinking of the quality of architectural spaces, when designers start using thermal sensation integrated into their decision making. Accordingly, we see great potential in architectural education. We imagine practical applications in both specialized labs, as well as design firms, since the setup is relatively easy to install. Following, we aim to conduct comprehensive user studies to quantify physiological responses and most importantly changes in architectural design outcomes when using the system. Combined with ever increasing visual quality of computer graphics and 3D sound systems, a fully immersive, experimental design environment will be created with Thermal VR that captures the full spectrum of what the human body experiences, thus supporting a richer creative process stimulating all senses and fostering truly environmental and contextual designs.

Acknowledgments

The authors thank Elena Bonatesta and Dr. Valeria Piccioni for providing EnergyPlus and BSDF models of the evaluated CFSs, and are grateful for the technical expertise contributed by Dominique Maritz and Erik Jan de Best to the safe and robust implementation of the experiment.

References

[1] Pfeifer R and Bongard J 2006 *How the body shapes the way we think: a new view of intelligence* (Cambridge MA, United States: MIT Press)

[2] Chiu C 2024 *Thermal VR: Climate-aware designing with real-time thermal feedback* Master's thesis ETH Zurich

[3] Milovanovic J, Moreau G, Siret D and Miguet F 2017 Virtual and augmented reality in architectural design and education *17th international conference, CAAD futures 2017*

[4] Scorpio M, Bladowski A, Geisler-Moroder D, Martyniuk-Peczek J, Sibilio S, Pfluger R and Sokol N 2025 *J Build Eng* **102** 112036

[5] Cho Y, Karmann C and Andersen M 2025 *Build Environ* **274** 112757

[6] Chinazzo G, Chamilothori K, Wienold J and Andersen M 2021 *Hum Factors* **63** 474–502

[7] Parsons K 2007 *Human thermal environments: the effects of hot, moderate, and cold environments on human health, comfort and performance* 2nd ed (London, United Kingdom: CRC Press)

[8] Piccioni V 2024 *A multiscale approach to 3D-printed facades: energy, daylight, environmental impact* Ph.D. thesis ETH Zurich

[9] Piccioni V, Grobe L O, Hischier I and Schlueter A 2024 *Energy Build* **314** 114222

[10] Bonatesta E 2022 *Smart adaptive blinds: experimental evaluation and long-term performance analysis for sustainable building retrofit* Master's thesis Politechnico di Milano URL `https://hdl.handle.net/10589/218459`

[11] Pharr M, Jakob W and Humphreys G 2023 *Physically based rendering: From theory to implementation* (Cambridge MA, United States: MIT Press)

[12] Bellazzi A, Bellia L, Chinazzo G, Corbisiero F, D'Agostino P, Devitofrancesco A, Fragliasso F, Ghellere M, Megale V and Salamone F 2022 *Build Environ* **209** 108674

[13] 1995 IES Recommended standard file format for electronic transfer of photometric data and related information Tech. rep. Illuminating Engineering Society of North America New York, NY, USA

[14] Wang T, Ward G and Lee E S 2018 *Energy Build* **174** 464–483

[15] SIA2024:2015 Raumnutzungsdaten für die Energie- und Gebäudetechnik (standard) Schweizerischer Ingenieur- und Architektenverein (SIA) Zurich, Switzerland