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DYNAMIC LIGHTING FOR WINDOW-LIMITED INTERIORS:
A LAYERED FRAMEWORK OF DAYLIGHT CUES, ARTIFICIAL LIGHT,
AND FRACTAL LIGHT-IN-MOTION

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DYNAMIC LIGHTING FOR WINDOW-LIMITED INTERIORS:
A LAYERED FRAMEWORK OF DAYLIGHT CUES, ARTIFICIAL LIGHT,
AND FRACTAL LIGHT-IN-MOTION

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Abstract

Background: People spend the majority of their time indoors, yet many interior environments provide limited access to natural daylight and outdoor views. This lack of daylight can reduce temporal awareness, visual comfort, and connection to natural environmental rhythms. Although dynamic lighting is increasingly used in practice, most systems remain limited to programmed changes in illuminance or correlated color temperature (CCT), without fully capturing the spatial, directional, and patterned qualities of daylight. This gap highlights the need for a more comprehensive approach that integrates temporal, spatial, and perceptual dimensions of light in window-limited interiors.

Method: This study adopts a research-through-design methodology to develop a layered dynamic lighting system that integrates daylight cues, artificial lighting, and fractal light-in-motion. The research combines field observation, simulation (AGI32 and DIALux), visual synthesis, and physical prototyping within a full-scale lighting lab environment. Daylight behavior—including direction, intensity, temporal variation, and spatial gradients—is analyzed through sun path simulation and translated into controllable lighting parameters such as beam angle, tilt, illuminance, color temperature, and pattern behavior. These parameters are applied to a layered system consisting of ambient lighting, directional lighting, and fractal pattern projection, enabling the translation of daylight characteristics into artificial lighting conditions.

Discussion, and Future Directions: The findings demonstrate that artificial lighting can reproduce key daylight characteristics such as direction, intensity, and temporal variation, while the integration of fractal light-in-motion introduces additional spatial complexity and enhances temporal legibility. The study defines three evaluation criteria—perceptual clarity, temporal legibility, and spatial impact—to assess the effectiveness of daylight simulation. Results indicate

that a coordinated, parameter-based layered system can simulate daylight behavior more effectively than conventional static or CCT-based dynamic lighting approaches. However, the system remains limited by the absence of sensor-based control and motorized optical technologies, and findings are based on design evaluation rather than empirical user testing. Future research should focus on adaptive control systems, real-time environmental integration, and human-centered evaluation to further validate and expand the applicability of the proposed framework.

Terms and Definitions

Dynamic Light: Naturally occurring temporal variation in light—including changes in intensity, spectrum, direction, and pattern—caused by solar movement, sky conditions, and environmental reflections.

Dynamic Lighting: A designed electric lighting system that intentionally varies light distribution, direction, or pattern over time in coordination with daylight cues. It extends beyond conventional adjustments in correlated color temperature (CCT) or illuminance to include spatial and temporal variation.

Daylight Cues: Observable characteristics associated with daylight (e.g., directional highlights, shadow progression, and broad luminance gradients) that communicate time-of-day and orientation.

Fractal Light-in-motion: A controllable lighting condition in which projected or emitted light patterns evolve over time, referencing the visual complexity of natural phenomena (e.g., dappled canopy light, water caustics, cloud modulation). In this study, it is used as a design strategy within artificial lighting systems, defined by parameters such as pattern family, scale, speed, and contrast.

Artificial Lighting: Light generated by human-made sources (e.g., electric lighting systems), used in this study as the primary medium for simulating and translating daylight conditions in interior environments.

Layers of Light: Multiple lighting conditions operating simultaneously within an interior environment, including daylight cues, electric lighting (ambient, task, and accent), and fractal light-in-motion, to support temporal legibility, perceptual clarity, and spatial impact.

Temporal Legibility: The degree to which lighting changes over time are readable and consistent enough to communicate time-of-day progression through visible cues (e.g., shifting highlights and shadow direction).

Perceptual Clarity: The degree to which the intended daylight cue and lighting hierarchy remain visually readable (i.e., not muddled or competing) when multiple layers operate together.

Spatial Impact: The degree to which lighting contributes to perceived depth and articulation of surfaces through luminance variation, contrast, and shadow modeling

Keywords: Dynamic Lighting, Artificial Lighting, Daylight Cues, Light-in-Motion, Fractals, Interior Lighting Design

Acronyms Used:

CCT: Correlated Color Temperature

CRI: Color Rendering Index

UGR: Unified Glare Rating

CNC: Computer Numerical Control

SAD: Seasonal Affective Disorder

LED: Light Emitting Diode

Chapter I: Introduction

Background

People spend the majority of their time indoors (Klepeis et al., 2001; Roberts, 2016; Franco, 2019), yet many interior environments provide limited access to natural daylight and outdoor views (Ulrich, 1984). Exposure to daylight and views plays a vital role in supporting mental health, alertness, and a sense of time through its daily and seasonal rhythms (Thursfield & Ven, 2022).

At the same time, large portions of the built environment—circulation zones, basements, interior rooms, and deep plans—receive little or no daylight, which can impair circadian balancing and contribute to stress-related concerns. In these spaces without windows, occupants often experience a loss of temporal awareness, reduced alertness, and emotional fatigue, conditions that are exacerbated in environments designed primarily for function rather than experiential quality (Boubekri et al., 2020). Due to spatial constraints, programmatic requirements, and building typologies, these interior environments without daylight are built for functionality rather than quality. As a result, designers face a critical challenge: how to create interior spaces that feel connected to time, nature, and movement when daylight is physically absent.

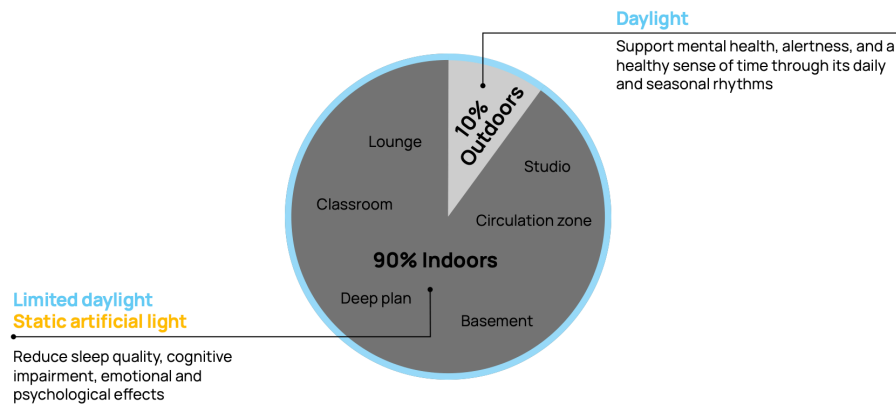
While architects often design with natural light through orientation, massing, and site planning, these decisions are typically established early and may be beyond the control of interior designers. In such scenarios, lighting designers play a critical role in reconstructing natural light behaviors through artificial systems that promote wellness, temporal awareness, and spatial richness. One promising approach is the integration of dynamic lighting, which extends beyond simple adjustments in color temperature or intensity to incorporate temporal change,

spatial variation, and perceptual cues associated with natural environments. By replicating aspects of daylight and outdoor exposure through technological means, dynamic lighting has the potential to enhance user perception and improve the experiential quality of windowless or limited-window interiors. Despite its growing use in practice, “dynamic lighting” is widely discussed in current applications, yet many implementations remain limited to programmed changes in illuminance and/or correlated color temperature (CCT) through preset scenes. These approaches introduce temporal variation, but they often underrepresent other daylight-associated cues—such as directional emphasis, shadow movement, and patterned modulation—through which daylight communicates orientation and time. Emerging strategies (e.g., gobo projection, luminous panels, perforated screens) begin to explore these qualities, yet they are frequently applied as isolated effects rather than integrated into a coherent interior lighting system. This gap highlights the need for a more holistic approach that combines temporal, spatial, and perceptual dimensions of light.

Accordingly, this thesis seeks to bridge architecture, interior experience, and lighting design by creating a dynamic lighting design framework informed by daylight behavior, fractal light patterns, and emerging technologies. It investigates how dynamic lighting strategies can be employed to simulate the qualities of daylight—particularly its rhythmic and patterned nature—and sense of outdoor exposure to support spatial perception and occupant experience in environments with restricted access to natural light.

Diagram 1

Distribution of Indoor Occupancy and Limited Access to Daylight in Typical Built Environments



Significance of the Study

Existing research and approaches have explored circadian lighting, biophilic design, and daylight simulation; however, these domains are often addressed independently rather than synthesized into a comprehensive lighting strategy. This fragmentation limits the ability of lighting systems to function as meaningful spatial and temporal cues. This study positions lighting not as a static or purely quantitative system, but as an experiential medium capable of conveying time, movement, and environmental connection within interior spaces. By treating light as an integrated design language—rather than a set of independent performance targets—this research emphasizes how lighting can communicate “where the day is” and how space can feel animated even when daylight is absent. This perspective also highlights the potential for lighting to bridge the gap between environmental conditions and human perception, particularly in spaces where natural daylight is limited or unavailable.

From an architectural and interior design perspective, although architects deliberately use daylighting strategies (atria, voids, well-oriented windows), many interior spaces simply cannot accommodate these features (Evans & McCoy, 1998). Orientation, time of day, and seasonal variation further limit access to daylight or the appreciation of natural light phenomena.

From a lighting design perspective, research and practice often label “dynamic lighting” primarily as varying correlated color temperature or illuminance through preset scenes (Kompier et al., 2022). These schedules often remain generic rather than coordinated with the real time/season daylight context of the space, and evidence for experiential benefits in window-limited settings is limited.

From a lighting manufacture perspective, a growing number of products aim to mimic natural light through full-spectrum fixtures, color-changing lamps, gobo projections, and ceiling illumination systems (Moreno O. et al., 2024; PacLights, n.d.). However, these systems are often manually adjusted, not responsive to changing environmental conditions, and frequently implemented as isolated solutions rather than as components of an integrated system, limiting their effectiveness in creating coherent and adaptive lighting environments.

Consequently, while current strategies across architecture, lighting design, and manufacturing attempt to address aspects of daylight and artificial lighting, these strategies are often developed independently. This creates a gap in integrating spatial, temporal, and biophilic lighting qualities within interior environments. To address this, this study proposes a layered dynamic lighting framework that synthesizes daylight cues, artificial lighting, and fractal light-in-motion into a unified system. This approach positions lighting as a spatial and temporal medium capable of conveying environmental change and enhancing human perception in window-limited interiors.

Diagram 2

Interdisciplinary Perspectives Defining Dynamic Light, Dynamic Lighting and Identifying Research Gap

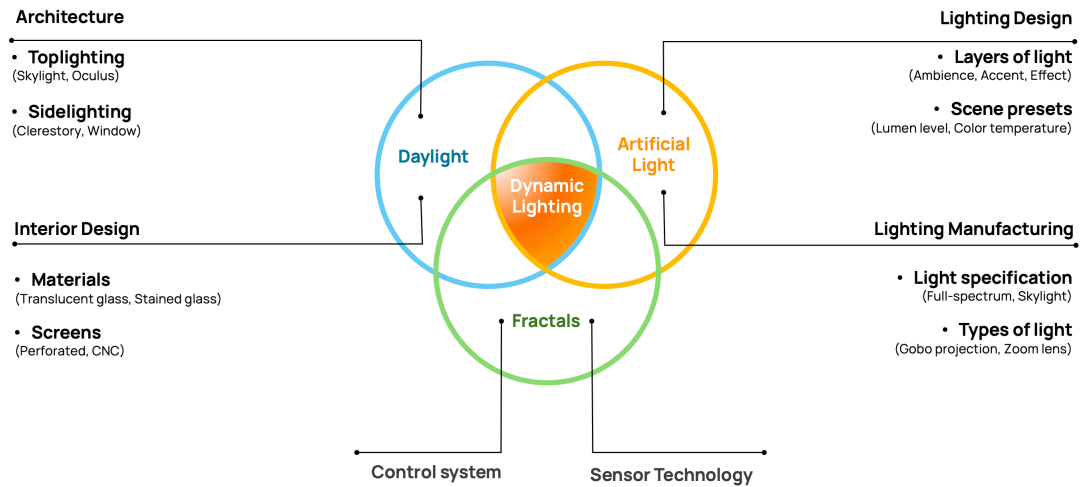
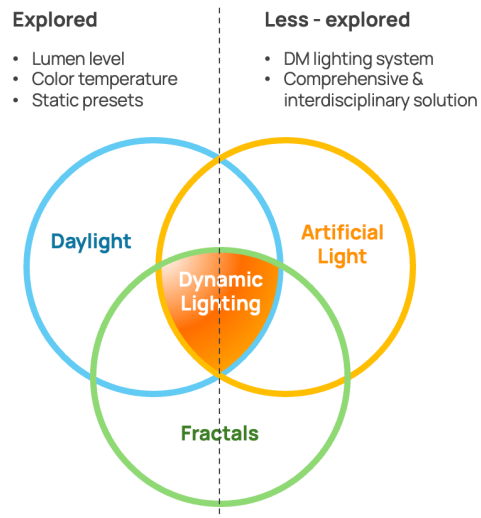


Diagram 3

Explored vs. Less-Explored Aspects of Dynamic Lighting Affecting Human Well-Being



Research Purpose

Therefore, this study develops and demonstrates a layered dynamic lighting system integrating daylight cues, artificial lighting, and fractal light-in-motion to simulate the spatial and temporal qualities of daylight in window-limited interiors. The research focuses on design simulation, prototyping, and framework creation to guide implementation in early design phases or retrofits.

Research Questions

Research question 1: Design framework – How can a layered dynamic lighting framework—integrating daylight cues, artificial lighting, and fractal effects—be designed and applied in window-limited interiors to simulate daylight rhythms?

Research question 2: System composition – Which layers of light and lighting technologies contribute to the formation of a dynamic lighting environment?

Research question 3: Evaluation criteria – What criteria define an effective simulation of daylight in interior spaces, in terms of perceptual clarity, temporal legibility, and spatial impact?

Chapter II: Literature Review

Introduction

This chapter reviews the research on dynamic lighting—daylight cues, artificial lighting, and fractal effect—and explores the relationship between layers of light to create a dynamic lighting system. It also highlights human responses in terms of well-being, space and time perception. The literature spans several sections from theories on biophilic design, daylight–artificial light integration, and fractal light in motion, to foundation of dynamic lighting variation and its impact on human space–time perception. Sources were identified through the University of Oklahoma library databases, Google Scholar, and LEUKOS, The Journal of the Illuminating Engineering Society, prioritizing peer-reviewed studies (2016–2025).

The literature review is divided into five sections as follows:

Literature Review

Theories on Biophilic Cues and Fractals

Biophilic Cues. Biophilic design emphasizes the connection between humans and nature within the built environment. The connection to nature is important and the science supporting biophilic design is still emerging. As outlined in the “14 Patterns of Biophilic Design”—Terrapin Bright Green, nature can be integrated in three main categories: Nature in the space (visual, non–visual, non–rhythmic sensory, thermal–airflow, water, dynamic–diffuse light, natural systems connection), Natural analogues (form–patterns, material, complexity–order) and Nature of the space (prospect, refuge, mystery, risk/peril). Each has different roots of pattern, relation and design consideration. This study focuses on dynamic–diffuse light and related sub-patterns such as visual complexity, natural systems, and form patterns. Earlier work on dynamic–diffuse light strategies emphasized even illuminance, productivity, and positive moods, while recent studies

extend to illuminance fluctuation, visual comfort, human factors, and perception considerations—linking to the complexity and order of how light and shadow move and capture attention (Terrapin Bright Green LLC, 2014).

Fractals. Fractals are naturally occurring, physically complex patterns found throughout nature. Due to the infinite variety of fractal forms, they are generally categorized into two main types: statistical fractals (repetition with randomness, resemble natural textures) and exact fractals (perfectly repeating rules) (Abboushi et al., 2019; Bies et al., 2016; Hagerhall et al., n.d.). This study focuses specifically on statistical fractals as they are more representative of natural environments, including foliage/dapple, water caustics, branch/vein lattices, cloud textures. Key parameters include fractal dimension, gap texture, recursion depth, symmetry, coverage/contrast, and motion speed.

Daylight–Artificial Light Integration Layer

Integration of daylight and artificial light can shape visual perception, mood, and well-being in indoor environments. One study showed that people generally prefer daylighted environments over electric-only lighting conditions, particularly in terms of visual comfort, lighting quality, and psychological response (Borisuit et al., 2015). Nikookar investigated the combined effects of daylight and electric light under different conditions—sky type (sunny vs. overcast), blinds position (open vs. closed), and correlated color temperature (2700K, 4000K, 6500K) (Nikookar et al., 2024). Their results highlighted that integrated lighting conditions—especially those involving variable daylight access and CCT—significantly influenced how participants rated the ambiance of a space.

Fractals Light-in-motion Layer

Recent laboratory research has demonstrated that nature-derived dynamic light patterns, such as tree-like movement, can reduce physiological stress and are perceived as more natural and engaging compared to static or uniform lighting conditions (Karaman-Madan et al., 2025). These findings are supported by earlier studies on fractal geometry, which suggest that fractal-based patterns contribute to visual preference, aesthetic interest, and psychological restoration (Abboushi et al., 2019; Bies et al., 2016). Together, this body of research indicates that motion and multi-scale spatial structure play a critical role in shaping human perception, beyond simple adjustments in brightness or color. However, many existing studies do not sufficiently report key parameters such as pattern type, motion speed, or contrast, limiting their applicability to design practice. Pattern-motion research often focuses on a single pattern family (e.g., tree dapple) and a fixed motion condition, providing limited insight into how different parameters influence spatial experience (Karaman-Madan et al., 2025). Fractal patterns are typically perceived indirectly through light interactions—for example, sunlight filtering through tree canopies produces continuously shifting patterns that combine geometry and motion. These dynamic fractals differ fundamentally from static decorative motifs, as they convey environmental change and temporal variation. Despite growing interest in fractal architecture and environmental psychology, applications within electric lighting remain limited. Most studies emphasize visual imagery rather than light-generated fractal conditions, revealing a clear opportunity for design-based exploration.

Dynamic Light, Dynamic Lighting

Dynamic light. Dynamic light originates in nature through changing sky conditions, sunlight movement, and reflections, depending on the altitude and orientation (Knoop et al.,

2020). It stimuli in nature include the sudden appearance or disappearance of sunlight patches due to cloud movements, shadow and light patterns of natural elements, or water caustics appearing by water movement (Karaman-Madan et al., 2025). Sunlight changes color from yellow in the morning, to blue at midday, and red in the afternoon/evening; the human body responds to this daylight color transition (Terrapin Bright Green LLC, 2014). The objective of the Dynamic & Diffuse Light pattern provides not only a visual experience but also maintains circadian system functioning due to the complexity and movement.

Dynamic lighting. In practice and research, the term “dynamic lighting” is used inconsistently. Turley describes it as lighting that changes the spectral power distribution throughout the day to replicate natural daylight properties (Turley et al., 2025). Goudriaan defines it as a lighting system that adjust intensity, color temperature, or distribution based on external factors such as time of day, user preferences, or environmental conditions (Goudriaan et al., 2021). Hansen adds to the system to include changes in light directionality or adjustments in the direct:indirect balance in response to daylight conditions (Hansen et al., 2022).

Building on the above, this thesis defines “dynamic lighting” more broadly as time-varying distribution and pattern coordinated with daylight cues, including fractal light-in-motion (nature-referencing patterns such as tree dapple or water caustics). A key limitation in prior work is the lack of actionable parameters (pattern family, motion speed, contrast, coverage, placement), which constrains replication and design contexts.

Impact on Human Spatial and Temporal Perception

Reviews and experiments increasingly treat light as spatial and temporal structured in dynamic lighting strategies. In spatial context, studies found that dynamic lighting, complementing and responding to the natural dynamics of daylight, could improve the perceived

atmosphere and visual comfort in an office environment and thereby improve work engagement (Hansen et al., 2022). A measure revealed that sunlight patterns with medium to medium-high fractal complexity were more visually interesting than other sunlight patterns projected on a wall (Karaman-Madan et al., 2025). In temporal context, the dynamic direct and diffuse lighting can compensate for the static daylight hours through dynamic light settings, full of change, instability and unpredictability (Hansen et al., 2022). This could introduce a new approach to the understanding of how transition time between lighting scenarios could be seen as visually interesting and stimulating for an environment.

Case studies

This thesis is positioned at the intersection of architectural, interior precedent, lighting design and technology. Rather than evaluating lighting solely through performance metrics, the following case studies are analyzed through their implementation methods—specifically how light is filtered, redirected, diffused, concealed, projected, or programmed to create spatial and temporal cues. Through a structured analysis, the case studies are divided into two categories: Architectural and Interior Design Strategies, and Lighting Design Technologies. In this way, we explore how both physical design elements and lighting systems can work together to enhance human experience.

Architecture & Interior Design Strategies

In this section, we examine how architects and interior designers integrate daylight cues into their designs even when direct natural light is absent. In such conditions, architectural elements—such as diffusers, clerestories, and reflective surfaces—act as intermediaries, softening and redistributing available light to create more uniform daylighting conditions. Architects often use these elements as a medium to shape dynamic lighting experiences.

However, these strategies are rarely translated into contemporary electric lighting frameworks that can be applied in environments where daylight is unavailable. For example, Frank Lloyd Wright’s architecture (Frank Lloyd Wright Foundation, n.d.) frequently employs filtered light and shadow play aligned with natural movement, demonstrating a strong sensitivity to solar orientation. As the sun shifts across the horizon, light interacts with different surfaces—floors, walls, and ceilings—producing temporal variation within otherwise static architectural spaces.

Skylight, skywell, and oculus. Top-lighting introduces daylight from above to deliver a sky-dominant light field (typically higher vertical illuminance and softer shadow direction than side windows). Key design moves include: shaping the aperture (oculus vs. linear skylight), controlling glare with baffles/diffusers, using light wells to extend daylight into deep plans where reflectance and geometry control gradients and perceived height. When designed intentionally, skylights can also create slow temporal variation as sun angle changes, producing moving highlights and shadow edges that signal time. These systems create dynamic lighting conditions because the sun’s position changes throughout the day, causing light patches to move across floors and walls. For example, Steven Holl’s *T Space* projects emphasize overhead daylight, using carefully cut skylight apertures to achieve approximately 25 foot-candles on wall surfaces and reduce dependence on electric lighting (Steven Holl Architects, n.d.). Architect Julian King’s residential addition uses a three-sided skylight above a window seat to intensify the feeling of being “in and of the trees,” with the form and opening shaped through sun-path mapping, consideration of views and the surrounding trees and condensation addressed via thermostat-controlled heat tracing at the frame (Reggev, 2024). Historically, Frank Lloyd Wright repeatedly leveraged top-lighting and precisely shaped openings (e.g., *Taliesin West* and the *Guggenheim Museum*) to choreograph changing daylight and shadow over time (Chusid, 2014; Frank Lloyd

Wright Foundation, 2018). While The Pantheon (Rome) uses its iconic oculus to turn daylight into a moving, time-marking solar beam that reads as both functional illumination and sacred spectacle (Pantheon Rome, 2025).

Clerestory window and window. Clerestory windows place glazing high on the wall to bring daylight deeper while protecting privacy and reducing direct glare. They also create strong orientation cues (where the “outdoor” is) and can be paired with overhangs, fins, or light shelves to redirect light to ceilings and stabilize illuminance. Compared to standard windows, clerestories often yield a more diffuse, “ambient-plus-directional” condition—useful when the goal is daylight quality rather than view. Clerestories demonstrate how filtered, indirect daylight can provide rhythm without direct glare. This supports the idea that artificial lighting can replicate directional but softened daylight cues. Again, Frank Lloyd Wright demonstrates in many of his designs like Pope-Leighey House and Jacobs House (Frank Lloyd Wright Foundation, n.d.).

Transparent, translucent & diffuse material. Material selection determines whether daylight enters as viewable clarity (transparent) or as luminous ambiance (translucent/diffuse). Translucent/diffuse systems (etched, sandblasted, channel glass, polycarbonate, laminated diffusion layers) convert exterior luminance into a soft, even “glow” that supports comfort and makes interiors feel brighter without visible sources. This is a *daylight-cue strategy* that can be simulated electrically via luminous surfaces and controlled luminance ratios. These materials scatter light, reducing contrast while increasing spatial depth. A key precedent is Hiroshi Nakamura & NAP’s *Optical Glass House*, where an “optical wall” of thousands of glass blocks filters the urban exterior into a hypnotic play of softened shadows, and a glass-bottom reflecting pool above the entry produces caustic-like light patterns that animate the ground floor—

demonstrating how diffusion and refraction can create both comfort and temporal visual interest (Hiroshi Nakamura & NAP, n.d.). A closely aligned example is Jun Murata's *Glass Art Gallery* (Japan), where reflective and slit-lit conditions amplify limited light into a soft, crystalline interior glow without direct sun penetration (ArchDaily, 2015). By comparison, Steven Holl Architects' *Institute for Contemporary Art at VCU* (Cornachio, 2018) and the *Geelong Arts Centre* façade (ArchDaily, 2020) illustrate a more envelope-scale approach: matte/translucent or sandblasted low-iron glazing produces a shifting, softly luminous skin whose appearance changes with daylight and becomes lantern-like when lit from within—evidence that diffuse materiality can stabilize visual comfort while still delivering dynamic perceptual change across the day.

Stained glass. In addition, color and index refraction of stained glass add another interesting characteristic to the lighting effect created by natural light and translucent material. An award project is *The Split Light* (Spain) by Elisa Valero (architect) with Arkilum (lighting design), which integrates dichroic glass lamellas within skylights so that diffuse skylight remains largely neutral, while direct sun—arriving at a tilted morning angle—triggers a short-duration phenomenon where the spectrum is split: transmitted color appears on one side and the complementary reflected component is redirected to the opposite wall, restoring symmetry and producing a controlled, evolving color play ([d]arc awards, 2023). By contrast, the basilica of *La Sagrada Família* (Barcelona) uses extensive stained glass as a primary daylight instrument, with large areas of colored glazing designed to modulate the interior atmosphere through shifting chromatic light as the sun path changes across the day; its nave is often discussed as a canonical example of how stained glass can choreograph orientation and time through color gradients and moving patches of light (Sagrada Família, 2025).

Screens. Screens and perforated panels filter daylight by introducing patterned interruptions. As sunlight passes through perforations, it produces patterned shadow fields that change with solar angle. Multi-layer screens increase pattern density and complexity. Perforated systems are natural daylight gobos. They generate fractal-like shadow fields and visible motion over time. These strategies inform artificial fractal projection and screen-based lighting systems offering a direct architectural precedent for later artificial fractal projection and screen-based lighting strategies. In the Fractal Chapel at the State Hospital in Graz-Austria, the perforated screen acts as both concealment and choreography: a spiraling surface filters daylight and electric light into drifting shadow fields that make time and motion perceptible, while the surrounding fractal patterns—developed through a collaboration between 13&9 Design and Richard Taylor (University of Oregon and Fractals Research)—align with evidence that mid-high fractal complexity can increase engagement, preference, and perceived complexity without proportionally improving (and sometimes reducing) relaxation/refreshment, underscoring the need to balance arousal and restoration in biophilic installations (Archello, n.d.; Robles et al., 2021). Louvre Abu Dhabi extends this logic at a monumental scale: its layered perforated dome creates a “rain of light,” repeatedly screening sun into a moving, fine-grain light-and-shadow field across streets and galleries, showing how depth, layer alignment, and solar change can produce a calm yet dynamic atmosphere through patterned filtration (Denmark, n.d.). In a residential project, Liang Architecture Studio placed a perforated aluminum panel beneath a glass roof so shifting sun angles animate the interior with moving, dappled light and shadow throughout the day and year, creating playful, surprising spatial moments (Dalton, 2020).

Lighting technologies

The second section focuses on innovative lighting design technologies that actively simulate natural daylight. Techniques like the use of sky wells, gobo projection, mapping, and perforated screen lighting transform artificial light into dynamic, temporal cues. For example, gobo projections and mapping allow designers to replicate fractal patterns like water caustics or leaf shadows, adding movement and depth to otherwise static interiors. Similarly, translucent panels diffuse light to create soft, ambient atmospheres, while shadow play highlights dynamic shifts throughout the day. These technologies demonstrate how lighting itself can become a medium for mimicking natural daylight, providing spatial rhythm and perceptual richness.

Grazer lighting as daylight mimic. Grazer lighting directs light at shallow angles across textured surfaces. This creates strong shadow modeling similar to low-angle sunlight (morning or late afternoon). This implementation includes linear LED grazer mounted on ceiling or close to walls, wallwasher, emphasizing surface depth and increase contrast. Grazing uses linear or narrowly distributed light placed close to a surface to emphasize texture, relief, and micro-shadowing, producing a “raking light” effect analogous to low-angle sun. As a daylight mimic, grazing is most effective when: it establishes a directional cue (one dominant direction), it creates shadow hierarchy without glare, and it works with materials that respond (wood grain, stone, perforations, textured plaster). Slow changes in intensity or direction (via multiple lines) can simulate perceived “sun movement” without literal projection. Museum of Anthropology Great Hall, Canada ([d]arc awards, 2025a) and Regent Resort Phu Quoc, Vietnam (BLINK Design Group, 2022) used this technique to simulate directional solar light and reinforces time-of-day perception through shadow depth.

Translucent panel / Luminous texture. Translucent panels and luminous textures (backlit stretched fabric, etched acrylic, and diffusers with printed gradients) create large-area luminance that reads as an ambient source, similar to an overcast sky or luminous ceiling. This strategy is effective for window-limited spaces because it provides soft vertical illumination, reduced glare, and a stable base layer onto which fractal motion or subtle gradients can be added. James Turrell repeatedly uses this approach to transform light into a perceptual material. In his *Ganzfeld* environments, such as *Ganzfeld Apani* exhibited in *James Turrell: The Substance of Light* at Museum Frieder Burda (Harrison, 2018), concealed high-intensity light sources are diffused through translucent scrims and fine gauze so that spatial boundaries visually dissolve. A comparable architectural translation appears in the award-recognized ZENE digital entertainment space, where the design team simulated natural daylight conditions through site-specific sun-pattern analysis and artificial lighting systems that reproduce skylight cues, light leakage effects, and time-based environmental variation, generating a calm and luminous atmosphere within a windowless environment (LIT Lighting Design Awards, 2026b)

Gobo projection. Gobo projection uses a patterned mask filter in a projector/spotlight to cast controlled textures (leaf, ripple, lattice) onto surfaces. It is a direct tool for producing your target phenomena (tree-dapple, water caustics) and can be made dynamic through rotating gobos, moving lenses, animated shutters, or motorized media servers. Key to human comfort is keeping motion slow, contrast moderate, and coverage limited so it reads as environmental rather than theatrical. In Zayed National Museum – Exhibition Lighting (UAE), lighting is integrated and concealed within sculptural “pods,” using precision optics and tuned levels for clarity and calm, while immersive sequences (notably in the *Through Our Nature* gallery) combine controlled darkness with programmed scenes that project effects such as water and dappled shadow to

suggest movement, scale, and time ([d]arc awards, 2025) .For Gabrielle Chanel: Fashion Manifesto, Studio ZNA proposed subtly shifting light treatments that move visitors through a day-cycle—from morning to night—sometimes as abstract “time-light” (crisp morning tones; beams refracted as if through golden perfume) and sometimes as evocative atmosphere, including gentle dappled motion to support mood and narrative (LIT Lighting Design Awards, 2026). As a conceptual anchor, James Turrell’s projection works show how light alone can construct perceived form and space: *Afrum I (White)* (1967) uses a tightly framed projection in a corner to produce the illusion of a three-dimensional geometric volume and emphasize the “physical presence” of light, while *Wedgework V* (1974) deploys projected and fluorescent light with reflective surfaces to generate a vertiginous spatial expansion beyond the room’s apparent geometry—demonstrating how controlled projection can shift perception as much as it illuminates.

Mapping. Projection mapping registers projected imagery to real architectural geometry—frames, openings, doors, niches—so a surface can read as a virtual aperture or a calibrated environmental cue. Mapping is most useful when it avoids literal “video-on-a-wall” content and instead delivers abstracted daylight signals (sky luminance gradients, slow cloud drift, diurnal brightening/dimming, or moving shadow fields) that imply outdoors and time without becoming narrative media. A clear precedent is HouseEurope!, which maps light and imagery onto the windows and doors of endangered or soon-to-be-demolished houses to create an “occupied” appearance—an aperture illusion that makes passersby read life and presence where none exists, and therefore demonstrates how mapped light can carry social meaning as well as spatial perception. Technically, contemporary tools such as MadMapper and Lazy Lighting lower the barrier to real-time, real-space alignment by providing workflows to warp and

mask content to surfaces, synchronize multiple outputs, and control related lighting elements (e.g., projectors, LEDs, and in some systems lasers), enabling designers to turn a blank wall into a convincing “window” or suggest a clerestory-like glow—useful for transforming windowless interiors while keeping setup effort focused on creative intent rather than calibration (Lazy Lighting, n.d.; MadMapper Home, n.d.).

Chapter III: Methodology

Introduction

This chapter outlines the methodology used to develop a layered dynamic lighting system for window-limited interior environments. The proposed system integrates daylight cues, artificial lighting, and fractal light-in-motion to simulate the spatial and temporal qualities of natural daylight. Daylight cues refer to observable characteristics of daylight behavior, including direction, gradient, shadow variation, and time-of-day legibility. Artificial lighting layers provide ambient, task, and decorative illumination to establish baseline visibility, spatial hierarchy, and functional lighting conditions. Fractal light-in-motion introduces projected or filtered light patterns inspired by natural phenomena, such as dappled foliage light and reflected daylight movement, to create spatial complexity and temporal variation. The methodology focuses on translating daylight behavior into controllable electric-light parameters through simulation, visualization, physical prototyping, and full-scale spatial testing.

Research Design

This thesis adopts a research-through-design approach, combining observation, simulation, physical prototyping, and site mockup to develop and validate a dynamic lighting framework. Rather than measuring subjective human responses, the study investigates how daylight behavior can be translated into artificial lighting systems through visual, spatial, and temporal analysis. While perceptual and experiential effects—such as enhanced sense of time, spatial richness, and environmental connection—are supported by existing literature, they are inferred through design evaluation rather than empirically measured. This approach establishes a methodological foundation for future human-centered or post-occupancy studies.

The thesis evaluates whether the proposed system can generate daylight-referencing behaviors through three primary evaluation criteria: temporal legibility, perceptual clarity, and spatial impact. Temporal legibility refers to the degree to which lighting variation over time communicates recognizable changes associated with time-of-day progression. Perceptual clarity evaluates whether daylight cues and lighting hierarchy remain visually readable when multiple lighting layers operate simultaneously. Spatial impact refers to the extent to which lighting contributes to perceived depth, surface articulation, contrast, and shadow modulation within the interior environment. Experiential claims related to well-being, circadian alignment, stress reduction, or environmental connection are treated as literature-supported design intentions rather than empirically measured outcomes. Therefore, perceptual language within this study refers to inferred spatial qualities based on design evaluation rather than direct human-subject testing.

The proposed system is defined through key controllable parameters, including light source size, distance, intensity, color temperature, beam angle, movement, and fractal pattern. These parameters are coordinated through a control system and can respond to environmental inputs, enabling dynamic lighting conditions that simulate natural daylight behavior.

Research phases

The methodology follows a sequential workflow that translates daylight behavior into artificial lighting conditions and evaluates the results through both simulation and physical implementation. The study is structured around six phases, including: (1) observation, analysis, and photography, (2) site selection and documentation, (3) artificial lighting simulation, (4) daylight reference, lighting translation, and synthesis, (5) physical prototyping, and (6)

framework development. Together, these phases support a practical investigation into how dynamic lighting strategies can be applied in enclosed spaces where natural light is limited.

This study employs a combination of simulation, visualization, fabrication, and physical testing tools to support the research methodology. AGI32 is used for daylight-reference modeling, including sun-path analysis, light distribution, and gradient studies. DIALux is utilized for electric-light simulation, including illuminance studies, beam distribution, and luminaire positioning. Photoshop supports visual synthesis and scenario representation through layer composition and image refinement. CNC fabrication methods, including Universal Laser Systems, are used to translate fractal patterns into physical panels and projection screens. In addition, the lighting laboratory serves as a full-scale demonstration environment for prototype testing and spatial evaluation.

Table 1*Summary of Research phases*

Phase	Method Description	Tools / Resources	Expected Output
1. Observation, Analysis, and Photography	Observe daylight behavior and dappled light patterns at south- and west-facing windows of Gibbs College from 8 AM to 5 PM (summer condition).	Field note, observation,	Identification of daylight
	Translate nature-derived patterns into digital drawings and fabricate CNC-cut panels to replicate and compare dappled light conditions at different scales.	CNC-cut panels, lighting lab setup & photography	behavior, fractal light patterns and applicable lighting technologies
	Conduct controlled lighting experiments in the lighting lab to study artificial reproduction of light and shadow.		
2. Site Selection & Documentation	Select a window-limited site (OU Gibbs Lighting Lab). Document existing spatial and lighting conditions through on-site measurements.	Tape measure, drawings, and site photography	Baseline documentation of windowless space conditions
3. Artificial Lighting Simulation	Simulate the selected space in DIALux under two conditions: (1) windowless baseline and (2) assumed	DIALux	Comparative simulation models of windowless

(Windowless vs Assumed Window)	window condition to evaluate potential daylight penetration, direction, and distribution.		and assumed daylight conditions
4. Daylight Reference, Lighting Translation & Synthesis	• Daylight reference simulated in AGI32 (winter condition), analyzing sun path and temporal variation • Artificial daylight simulated in DIALux by adjusting parameters: illuminance, beam angle, tilt, CCT and direction. • Synthesized fractal lighting condition developed using daylight-informed parameters and refined in Photoshop. • Lighting layout and positioning developed through plan and section drawings	AGI32, DIALux, Photoshop	Comparative analysis of daylight reference, artificial daylight mimic, and synthesized fractal lighting scenarios
5. Physical Prototyping & Spatial Implementation	• Construct a layered lighting prototype consisting of: LED strip (ambient layer), window panel cutout (frame projection layer), fractal panel cutout (pattern layer), zoomable spotlight (directional light source)	SketchUp model, fabrication tools, set up different CNC-cut panels, lighting fixtures	Evaluation of both prototype performance and full-scale spatial lighting conditions, demonstrating

	• Implement system by modifying the lighting lab: replace troffers with recessed downlights (ambient layer), add pendant lighting (task and decorative layer), integrate prototype (dynamic fractal lighting layer)	and materials, photography	integration of ambient, task, and dynamic fractal lighting layers
6. Framework Development	• Synthesize findings from observation, simulation, and prototyping into a parameter-based dynamic lighting framework. • Define relationships between daylight behavior, controllable lighting parameters, and spatial perception. • Propose a system integrating daylight cues, artificial lighting, and fractal light-in-motion, with potential for future integration of sensors, automation, and environmental data.	Diagrams, parameter studies	Parameterized design framework and guidelines for dynamic lighting systems

Phase 1: Observation, Analysis, and Photographic Documentation

The first phase focuses on observing and documenting natural daylight behavior and fractal light patterns through photography in both natural and built environments. Field observations are conducted at south- and west-facing windows of Gibbs College between 8:00 AM and 5:00 PM during summer conditions to capture temporal variations of daylight. These observations examine how light interacts with elements such as vegetation, surfaces, and architectural openings to produce dynamic effects, including dappled light, shadow movement, and changes in intensity and color over time (Figure 1).

To analyze these phenomena, three types of CNC-cut patterns—tree-based, geometric tree-like, and abstract geometric patterns—are translated into digital drawings. These panels are placed at window openings to replicate and compare dappled light conditions at different scales and densities. This allows for evaluation of how closely artificial pattern filters can reproduce natural light behavior (Figure 2). To complement digital simulations, physical testing is conducted using CNC-cut patterns under real daylight conditions (west-facing window) to observe light behavior, shadow quality, and scale effects (Figures 3).

In parallel, controlled lighting experiments are conducted in the lighting lab to investigate how artificial light sources can reproduce similar light and shadow effects through projection, reflection, and directional control. A range of materials—including optical glass, lattice panels, colored film, moss sheer, and a mirror sphere—is tested to evaluate how material properties influence pattern legibility, contrast, and edge softness. Photographic documentation is used as a primary method to record and compare both natural and artificial lighting conditions, establishing a visual and analytical foundation for subsequent phases (Figure 4).

Figure 1

Fractal Light in Nature and Built Environment



(a) Dappled light at 9 AM (November)



(b) Dappled light at 11 AM (August)



(c) Dappled light at 2 PM (February)



(d) Dappled light at 5 PM (February)



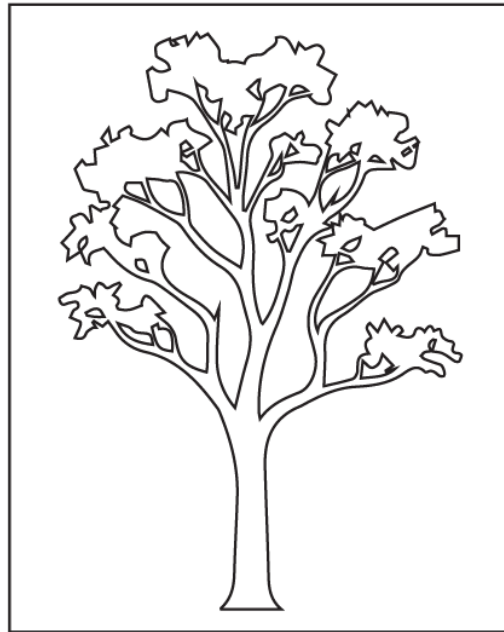
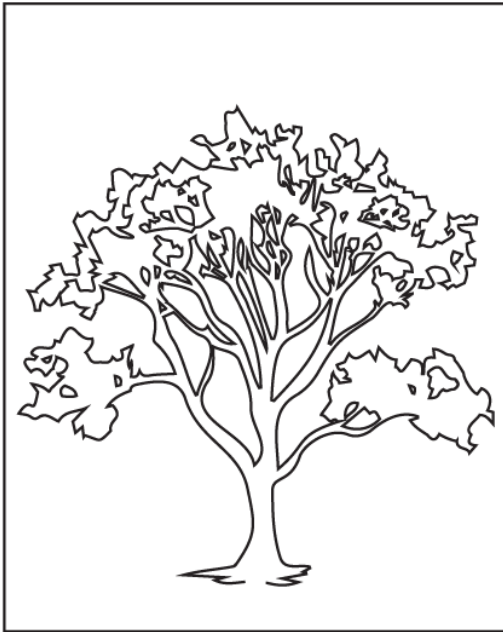
(e) Window with Venetian blinds (large scale)



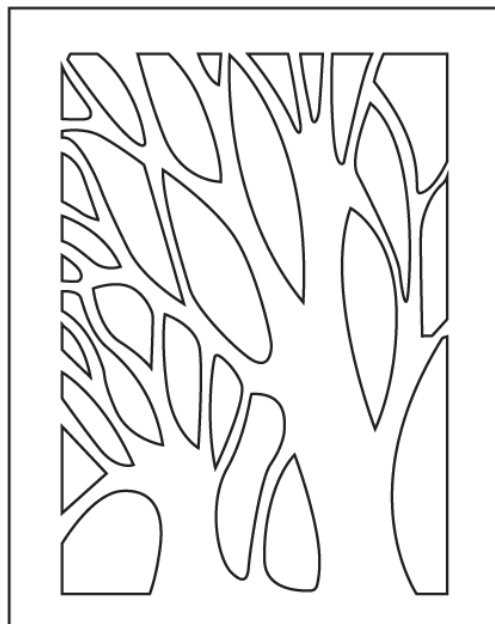
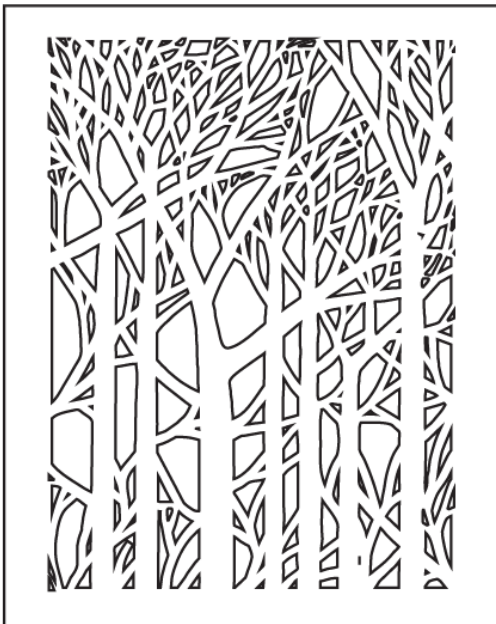
(f) Window with Venetian blinds (small scale)

Figure 2

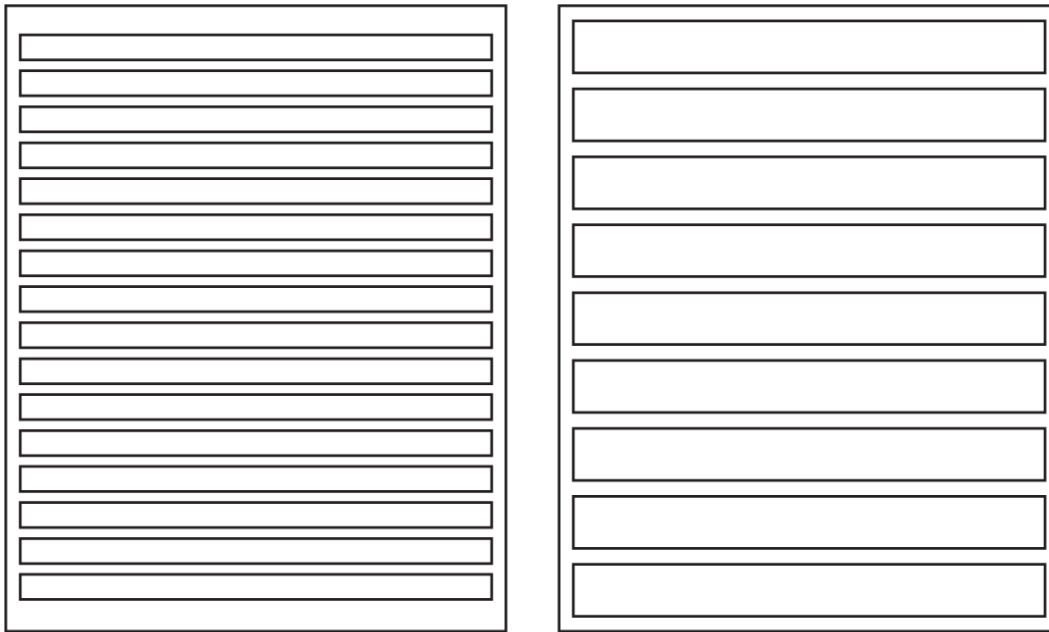
CNC-Cut Pattern Types



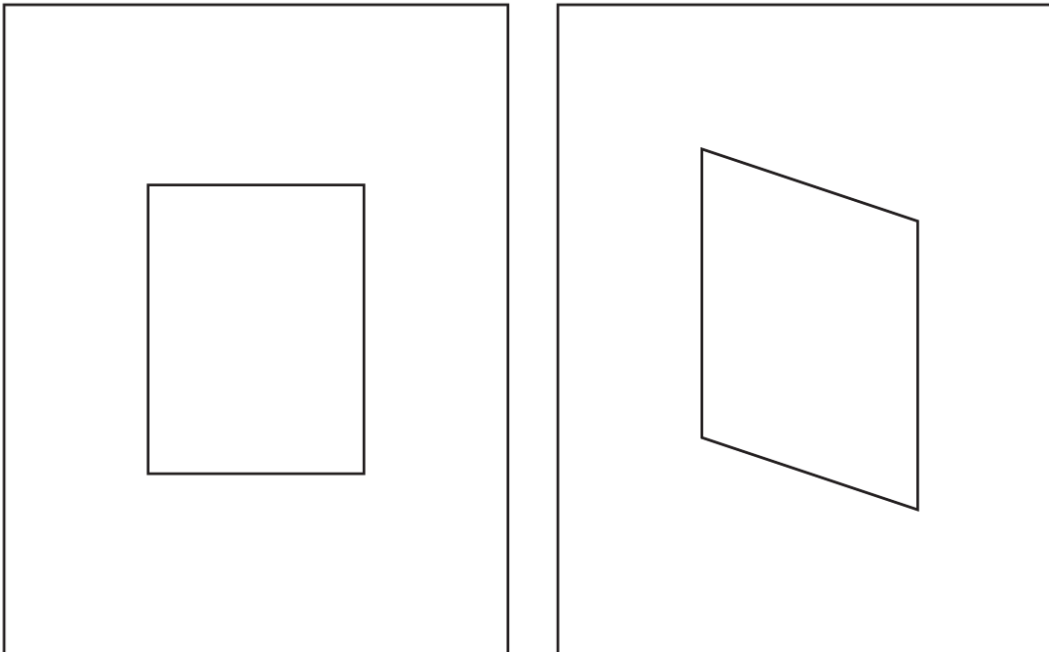
(a) Tree pattern



(b) Geometric tree-like pattern



(c) Linear strip pattern



(d) Rectangular and parallelogram apertures

Figure 3

CNC-cut patterns testing under natural daylight (west-facing window at 4 PM in March).



(a) Tree pattern



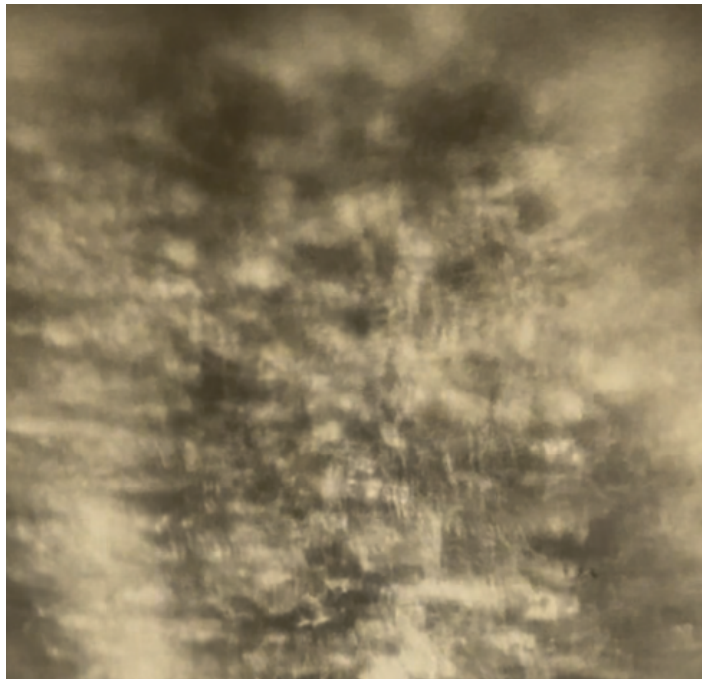
(b) Geometric tree-like pattern



(c) Rectangular pattern

Figure 4

Material-Based Fractal Lighting Experiments



(a) Optical glass



(b) Colored film



(c) Reflective sphere



(d) Moss sheer material



(e) Diffused colored film

Phase 2: Site Selection and Existing Condition Documentation

The second phase establishes the experimental context by selecting a windowless lighting lab within Gibbs College as the primary test environment in the basement. This space represents a typical interior condition where natural daylight is absent, aligning with the research focus on window-limited environments.

The spatial configuration is documented through site plan, (figure 5) floor plans, sections, (figure 6) and photographic (figure 7) records to capture geometry, surface conditions, and existing lighting systems. Measurements are taken to define room dimensions, ceiling height, and fixture placement. This documentation establishes a baseline understanding of spatial and lighting conditions prior to intervention and supports subsequent simulation and prototyping phases (Figures 5–6).

Figure 5

Site Plan of Gibbs College with Seasonal Sun Path and Lighting Lab Location

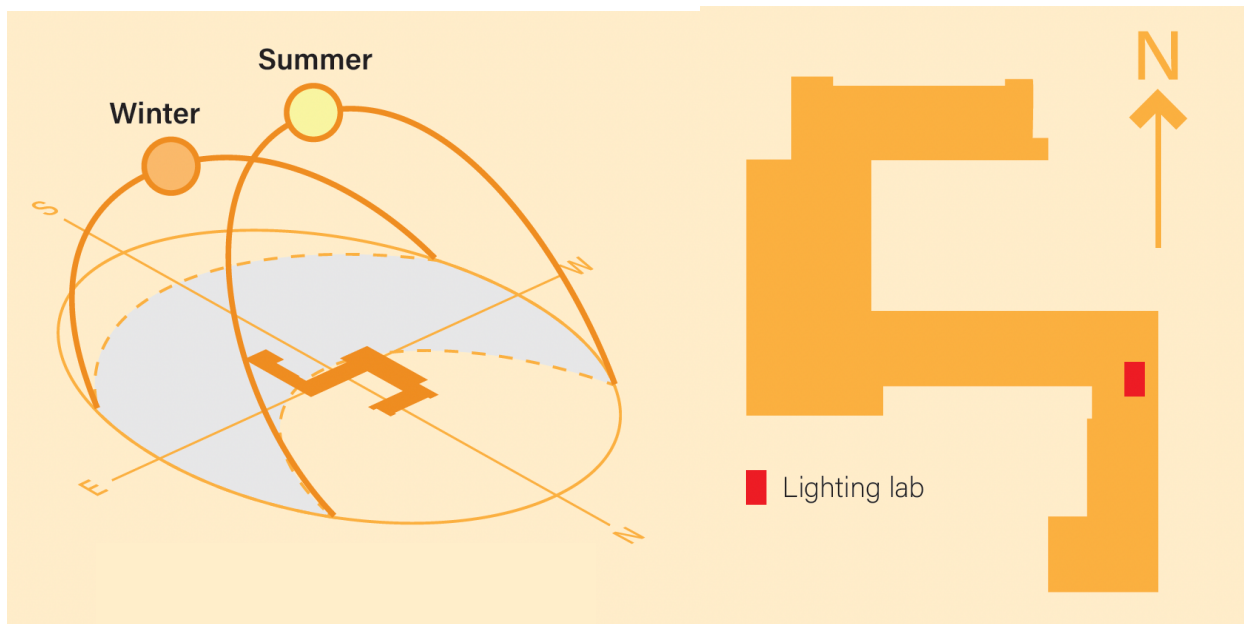
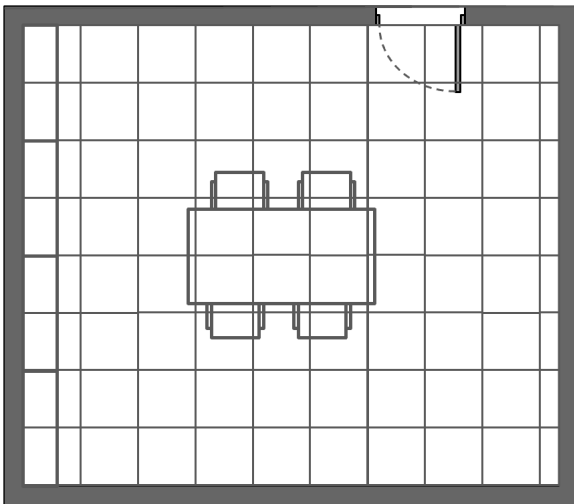
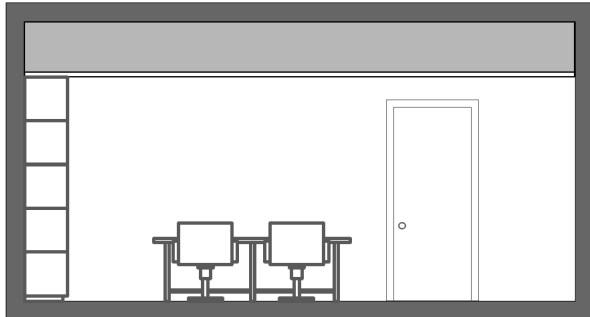


Figure 6

Plan and Section of Lighting Lab



Floor plan



Section

Figure 7

Existing Lighting Lab Condition





Phase 3: Artificial Lighting Simulation – Windowless Condition

In the third phase, the selected space is modeled in DIALux to analyze lighting performance under two conditions: existing windowless condition with artificial lighting and assumed window condition to simulate potential daylight penetration.

The existing windowless scenario models the current condition in which illumination is provided only by static 2×4 troffer fixtures, with no access to daylight or outdoor views. This simulation establishes an electric-only baseline for evaluating spatial light distribution.

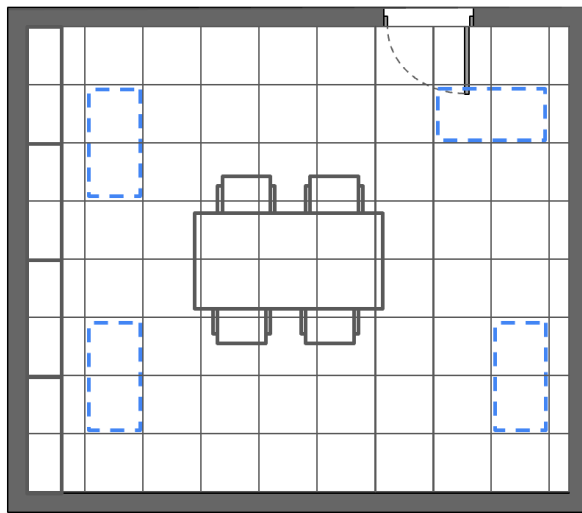
In the assumed window scenario, an idealized window aperture is introduced to approximate potential daylight entry and provide a comparative reference. This condition estimates how daylight could enter the space in terms of direction, distribution, and relative intensity, enabling comparison between a daylight-influenced reference and the electric-only baseline.

The results provide a baseline for understanding spatial light distribution and inform the translation of daylight characteristics into artificial lighting strategies (Figure 8).

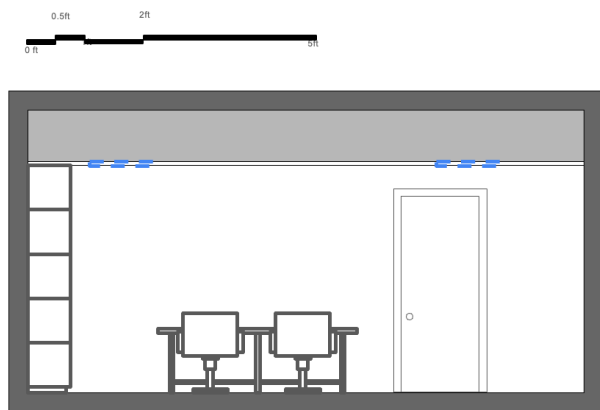
Figure 8

Comparison of Windowless Baseline and Assumed Daylight Condition (DIALux Simulation)

(a) Perspective View of Windowless Baseline Condition



Floor plan

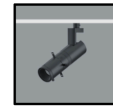


Section

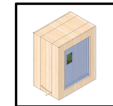
(b) Perspective View of Assumed Window Daylight Condition



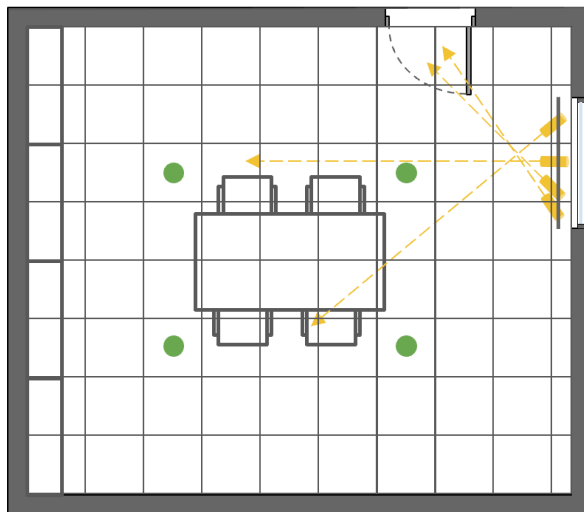
DOWNLIGHT
Beam angle: 92°
CRI: 92
CCT: Dim to Warm
Input power: 12W



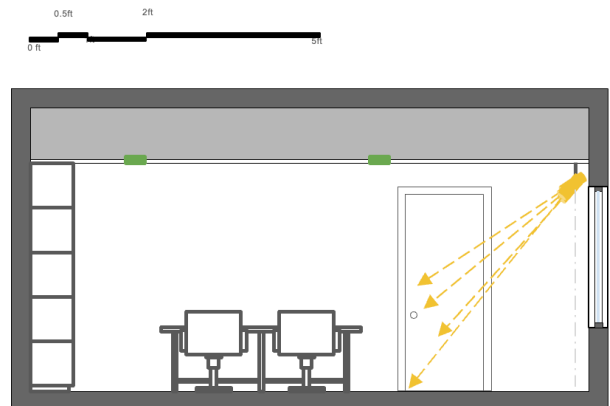
FRAMEABLE SPOTLIGHT
Beam angle: Narrow framing
CRI: 92
CCT: Tunable white
Input power: 6.8W



DYNAMIC PROTOTYPE
Fractal Light-in-motion
CRI: 92
CCT: Turnable white / RGBW
Input power: 4W / 8W



Floor plan



Section

Phase 4: Daylight Reference, Lighting Translation & Synthesis

In the fourth phase, daylight conditions are first analyzed using AGI32 to study solar position and spatial light distribution under winter conditions. The simulation focuses on a south-facing window in Oklahoma (35.0078°N, 97.0929°W) on December 21, capturing temporal variation from 9 AM to 5 PM. These simulations reveal how daylight enters the space at different times of day, producing changes in light direction, intensity, and spatial distribution across interior surfaces. The results provide a quantitative and visual reference for daylight behavior, including illuminance gradients and directional light penetration, which serve as the foundation for subsequent artificial lighting translation (Figure 9, Figure 10a).

The daylight conditions derived from AGI32 are translated into artificial lighting scenarios using DIALux, where a zoomable spotlight is calibrated to approximate daylight behavior. The spotlight is treated as a controllable light source capable of adjusting multiple parameters, including beam angle (20°–40°), tilt angle (30°–60°), correlated color temperature (3000K–6500K), and illuminance levels (approximately 300–800 lux). Through iterative simulation, these parameters are adjusted to reproduce the directional and temporal qualities of daylight observed in AGI32. Rather than replicating the exact geometric shape of daylight patches, the goal is to translate the spatial logic and behavior of sunlight, including direction, gradient, and intensity variation, into an artificial lighting system (Figure 10b).

To ensure spatial accuracy, the lighting configuration is further refined through floor plan and section drawings, where spotlight position, tilt angle, and projection direction are mapped in relation to the architectural space. These drawings document key parameters, including beam angle, tilt angle, light direction, and resulting illuminance distribution on walls and floors. This step establishes a clear relationship between simulation and spatial application, allowing the

artificial lighting system to align with the geometry and orientation of the space. The coordinated representation of lighting parameters in plan and section provides a measurable framework for translating daylight behavior into spatial lighting design (Figure 10c).

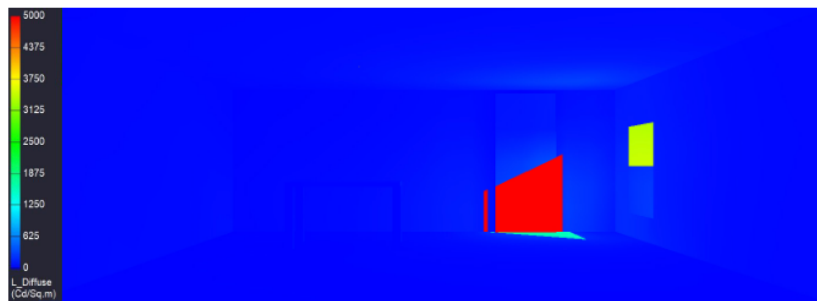
Following simulation and spatial calibration, Photoshop is used to synthesize fractal light-in-motion effects and refine visual output. A window frame is introduced as a projection reference, and fractal patterns—derived from earlier CNC studies—are overlaid to simulate dynamic natural light conditions. This step allows for visual testing of how effectively artificial lighting reproduces dappled light, shadow movement, and spatial variation. Color temperature is further refined across time-based scenarios (e.g., 9 AM – 4000K, 12 PM – 6500K, 3 PM – 5000K, 5 PM – 3000K), and a fractal light-in-motion layer is added to simulate temporal change. This synthesis integrates daylight cues, artificial lighting, and pattern-based dynamics into a cohesive visual representation, bridging simulation and experiential perception (Figure 10d).

Figure 9

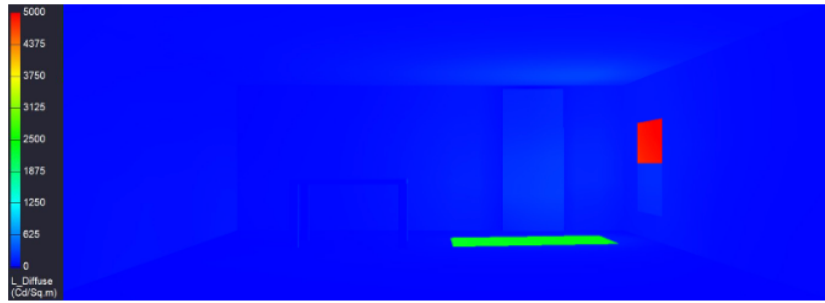
Daylight simulation in AGI32 showing winter sun path conditions for a south-facing window from 8:00 AM to 5:00 PM in Oklahoma (35.0078° N, 97.0929° W).



8AM



12PM



3PM

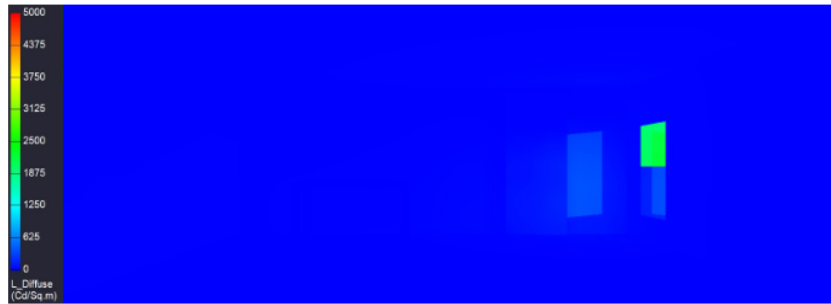


5PM

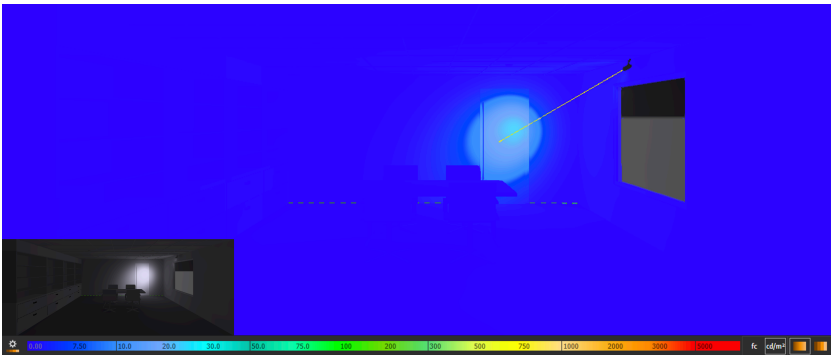
Figure 10

Comparison of daylight reference, artificial daylight mimic, and synthesized fractal lighting condition at 8 AM.

(a) Daylight reference simulated in AGI32 showing natural light distribution.



(b) Artificial daylight mimic in DIALux, calibrated to match illuminance (300 lux), beam angle (20°), and spotlight tilt angle (35° horizontal –65° vertical) demonstration.



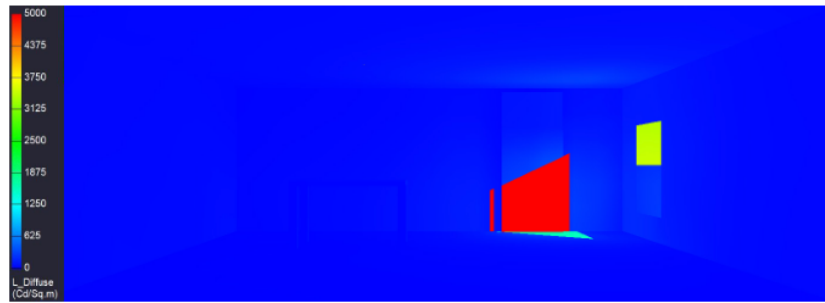
(c) Synthesized fractal lighting condition developed using daylight-informed parameters and refined in Photoshop to integrate color temperature, pattern projection, and spatial composition.



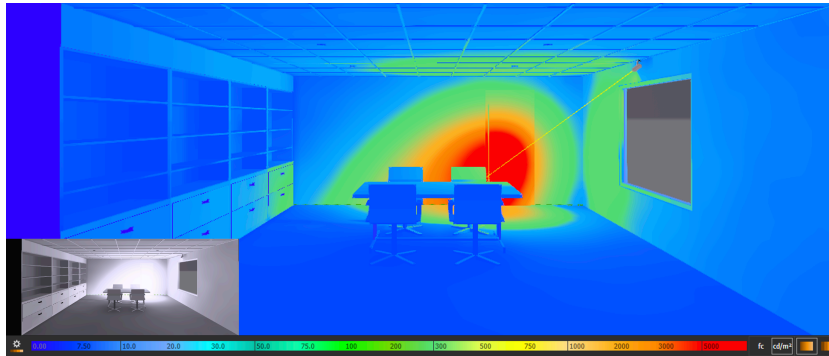
Figure 11

Comparison of daylight reference, artificial daylight mimic, and synthesized fractal lighting condition at 12 PM.

(a) Daylight reference simulated in AGI32 showing natural light distribution.



(b) Artificial daylight mimic in DIALux, calibrated to match illuminance (5000 lux), beam angle (40°), and spotlight tilt angle (45° horizontal –50° vertical) demonstration.



(c) Synthesized fractal lighting condition developed using daylight-informed parameters and refined in Photoshop to integrate color temperature, pattern projection, and spatial composition.

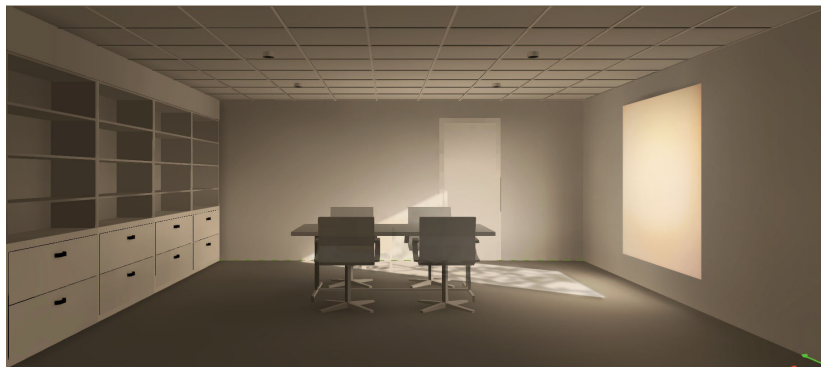
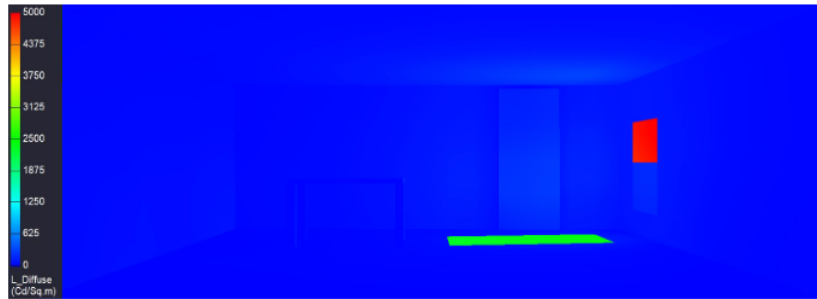


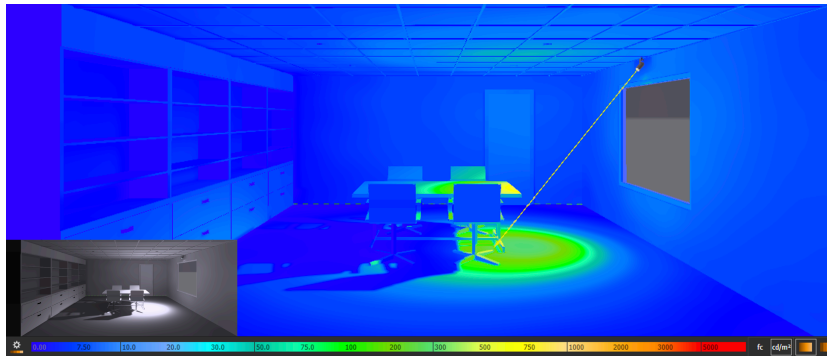
Figure 12

Comparison of daylight reference, artificial daylight mimic, and synthesized fractal lighting condition at 3 PM.

(a) Daylight reference simulated in AGI32 showing natural light distribution.



(b) Artificial daylight mimic in DIALux, calibrated to match illuminance 2500 lux), beam angle (25°), and spotlight tilt angle (90° horizontal –40° vertical) demonstration.



(c) Synthesized fractal lighting condition developed using daylight-informed parameters and refined in Photoshop to integrate color temperature, pattern projection, and spatial composition.

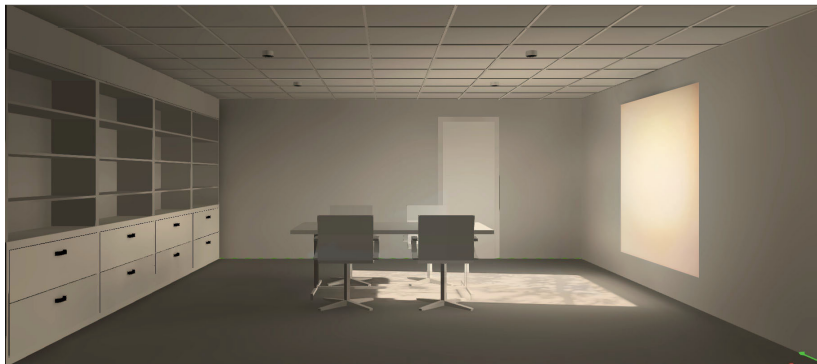


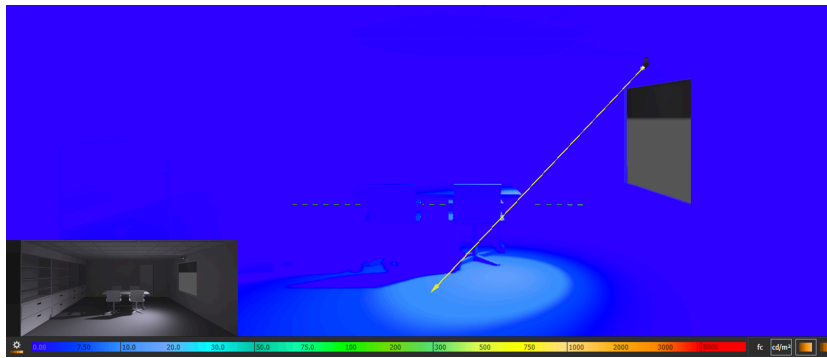
Figure 13

Comparison of daylight reference, artificial daylight mimic, and synthesized fractal lighting condition at 5 PM.

(a) Daylight reference simulated in AGI32 showing natural light distribution.



(b) Artificial daylight mimic in DIALux, calibrated to match illuminance (500 lux), beam angle (30°), and spotlight tilt angle (60° horizontal –60° vertical) demonstration.



(c) Synthesized fractal lighting condition developed using daylight-informed parameters and refined in Photoshop to integrate color temperature, pattern projection, and spatial composition.

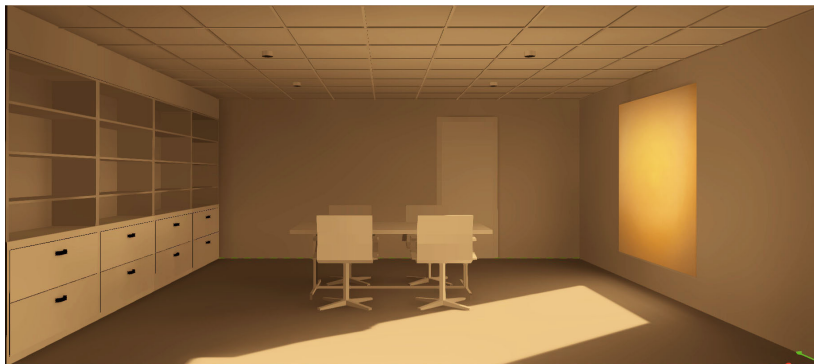


Figure 14

Lighting fixture specifications used in simulation and prototyping



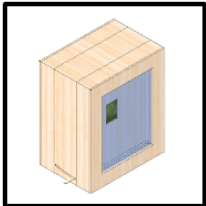
FRAMEABLE SPOTLIGHT

Beam angle: Narrow framing
CRI: 92
CCT: Tunable white
Input power: 6.8W



DOWNLIGHT

Beam angle: 92°
CRI: 92
CCT: Neutral white
Input power: 21.3W



DYNAMIC PROTOTYPE

Narrow framing
CRI 92
CCT: Turnable white
Input power: 6.8W

Phase 5: Physical Prototyping in the Studio Basement

The fifth phase focuses on the construction and implementation of a layered lighting prototype within the lighting laboratory environment. The prototype was developed to investigate how ambient lighting, directional daylight cues, and fractal light-in-motion could operate together as an integrated dynamic lighting system. The system consisted of multiple coordinated components, including LED strip lighting for ambient illumination, a window-frame projection layer to simulate directional daylight entry, CNC-cut fractal panels to generate patterned light effects, and a zoomable spotlight used as the primary directional light source. The system configuration and dimensional relationships between components are illustrated through

three-dimensional assemblies, exploded diagrams, and detailed section drawings in Figure 15. These drawings establish the spatial organization of the lighting layers and demonstrate how light source position, projection distance, and panel arrangement contribute to the resulting lighting effects.

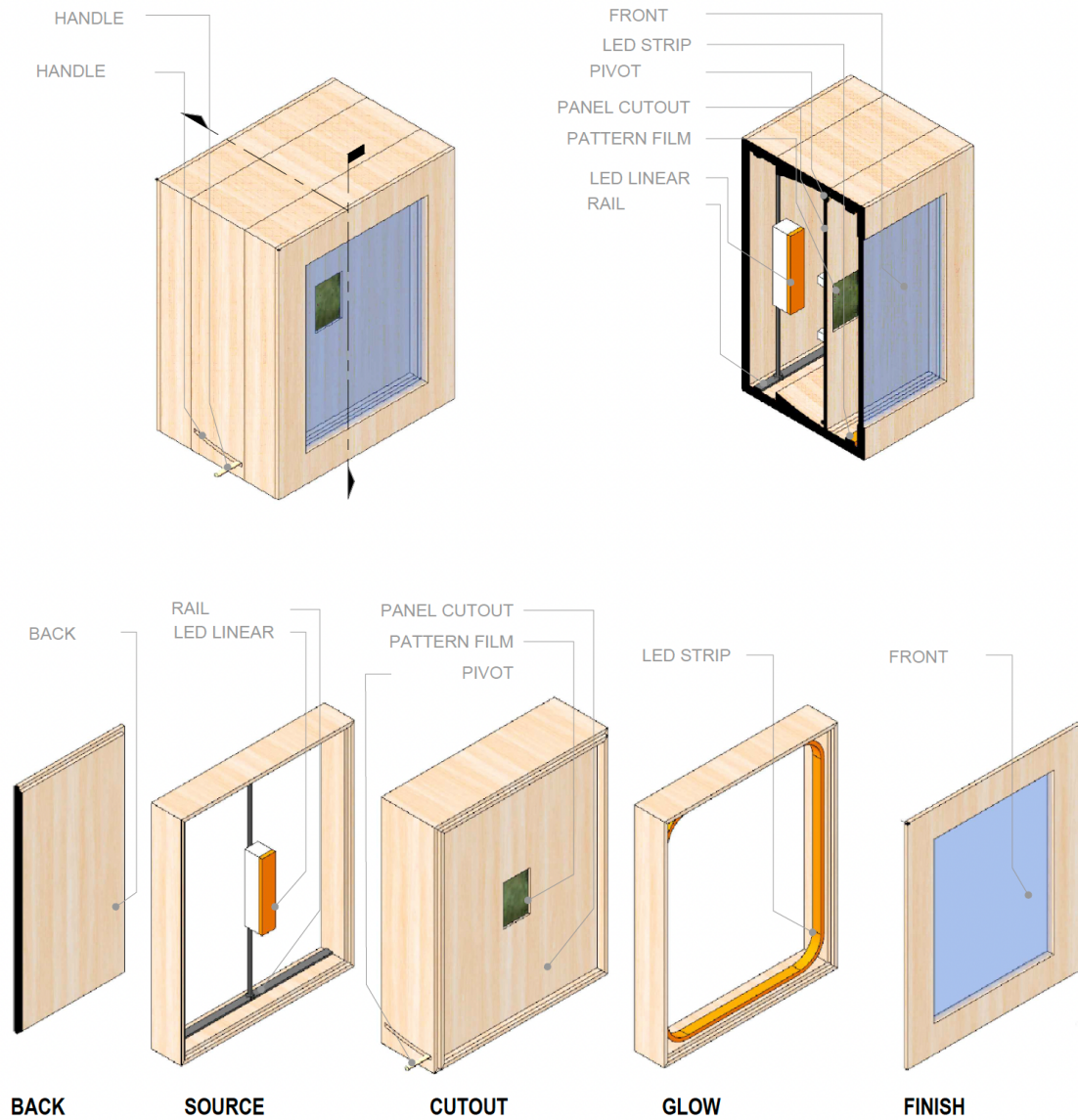
The physical prototype was then fabricated and tested to evaluate pattern legibility, directional projection behavior, color temperature variation, and the relationship between light source, filter layers, and receiving surfaces. Different correlated color temperature (CCT) conditions ranging from 2200K to 5500K were tested to study how changes in light spectrum influence perceived atmosphere and spatial character. The prototype testing documented variations in ambient glow, projection clarity, and visual warmth under different lighting conditions, as shown in Figure 16.

Following the object-scale prototype evaluation, the layered lighting system was implemented within the full-scale lighting laboratory environment to investigate its spatial application in a window-limited interior. The existing troffer fixtures were replaced with recessed downlights to establish a softer ambient lighting condition, while the prototype system was integrated as the dynamic fractal lighting layer. Different directional lighting angles, tilt conditions, and color temperatures were tested within the laboratory to simulate changing daylight conditions throughout the day. Figure 17 documents the resulting lighting scenes under both warm and cool color temperature settings, demonstrating how the integrated layered system contributes to spatial depth, temporal variation, and daylight-like environmental perception within the interior space.

Figure 15

Prototype system showing layered lighting components and detailed section drawing.

(a) Three-dimensional layered system



(b) Detailed drawing

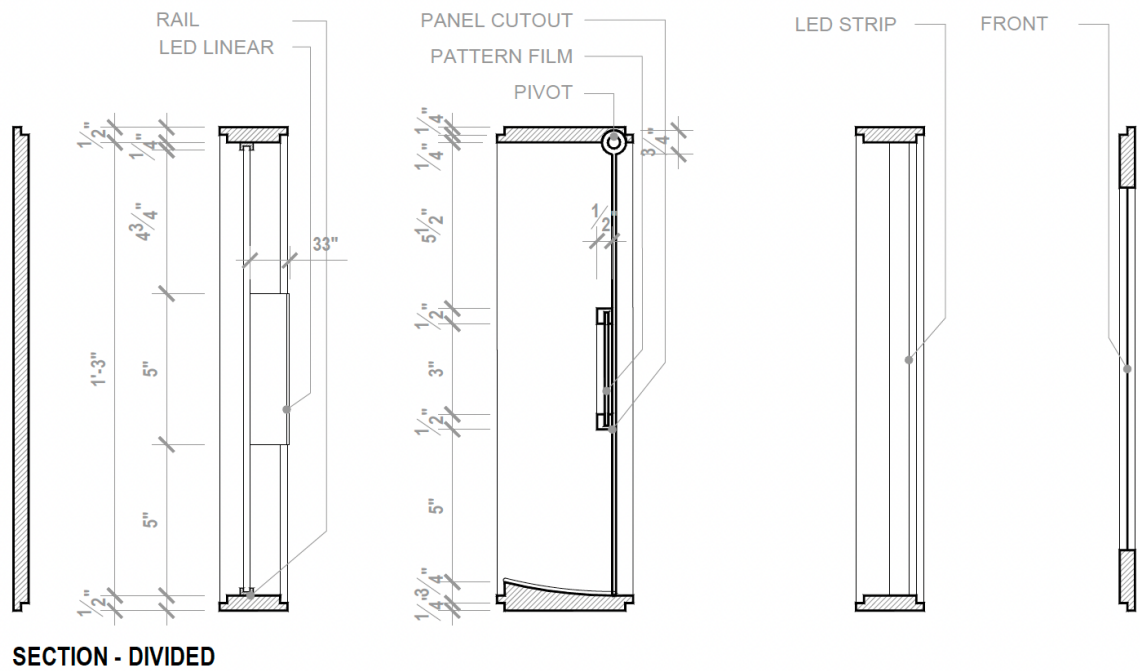
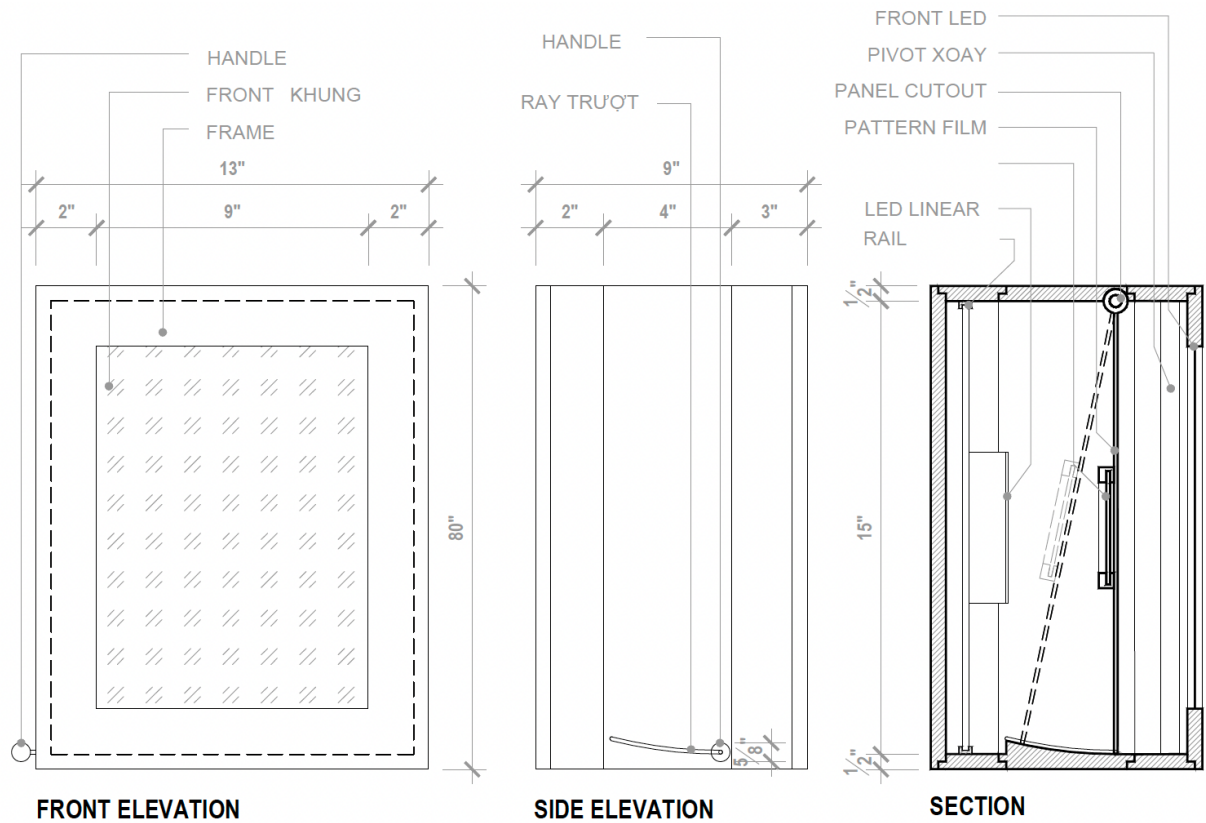
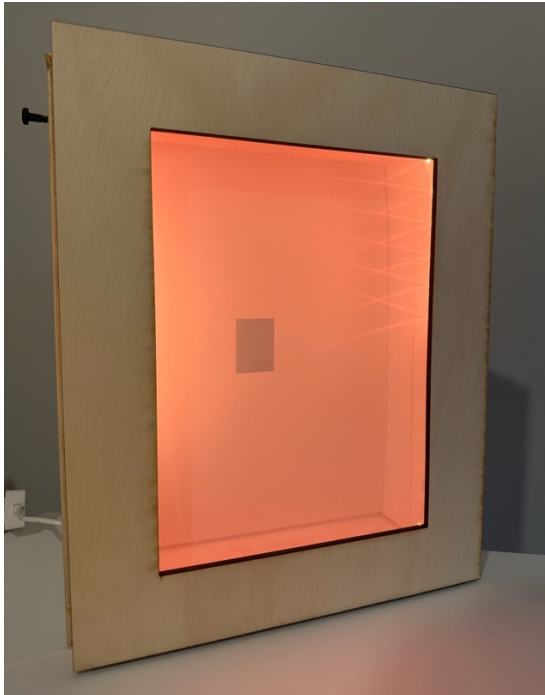
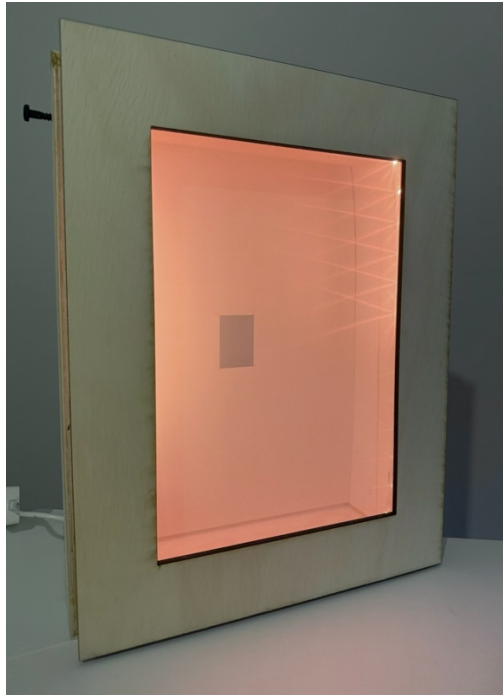


Figure 16

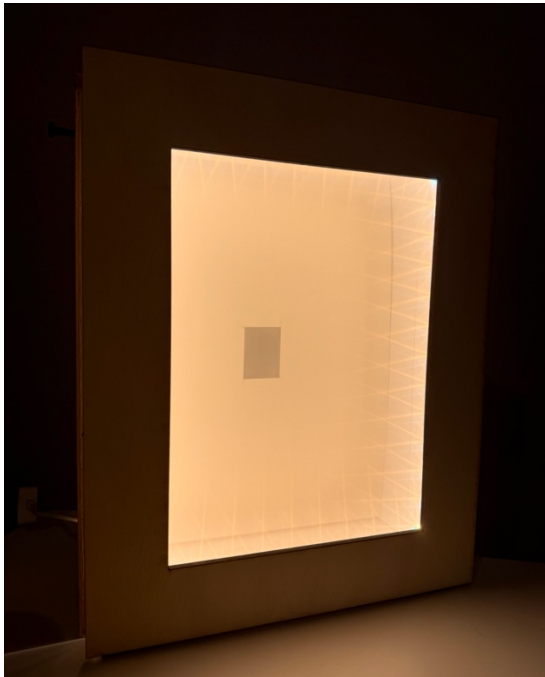
Prototype testing under different color temperatures (2200K–5500K).



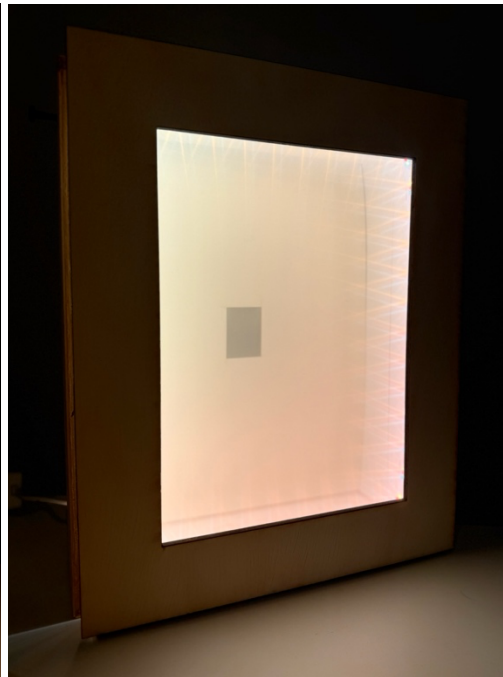
(a) 2200K



(b) 3000K



(c) 4500K



(d) 5500K

Figure 17

Full-scale lighting lab scene demonstrating integrated layered lighting system in different color temperatures (2200K & 5500K) and directional lighting conditions



(a) 2200 K, spotlight tilted 30° toward the west wall, 300 lm



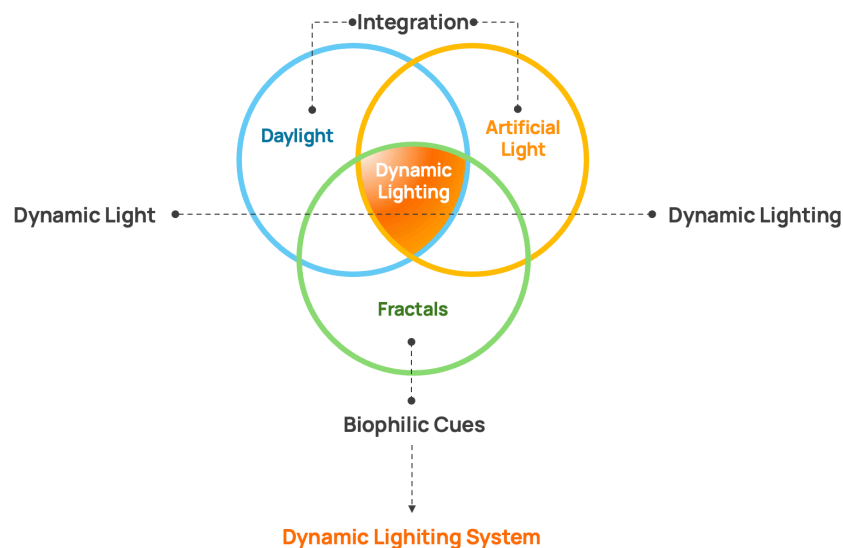
(b) 5500 K, spotlight tilted 90° toward the west wall, 500 lm

Phase 6: Framework Development

The final phase synthesizes findings from observation, simulation, and physical prototyping into a layered dynamic lighting framework for window-limited interior environments. Building on the preceding phases, the study translates key daylight characteristics—including solar movement, directional light distribution, temporal variation, and biophilic shadow behavior—into a coordinated indoor lighting methodology. Rather than proposing a single lighting solution, the framework establishes a repeatable system integrating daylight cues, artificial lighting, and fractal light-in-motion to support spatial and temporal perception. Daylight represents natural directional and temporal lighting behavior derived from solar movement and environmental changes. Artificial light refers to the controllable lighting system that provides ambient (general overall) and functional illumination within the interior environment. Fractals introduce biophilic light patterns and shadow variation inspired by natural phenomena such as dappled foliage light and reflected daylight movement. Diagram 4 illustrates the conceptual relationship between these three integrated lighting layers.

Diagram 4

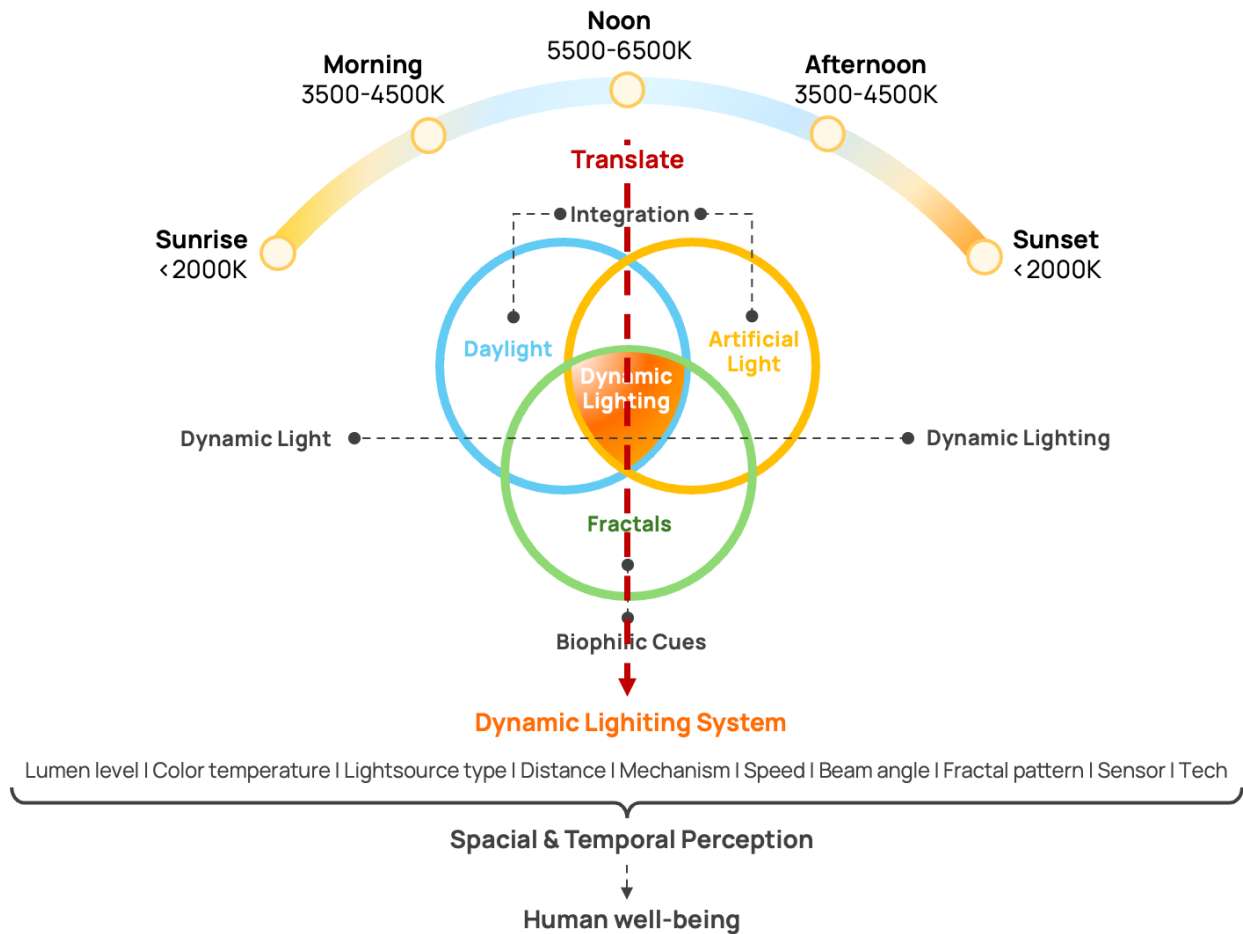
Layered Dynamic Lighting Framework (Daylight, Artificial, Fractal)



The framework is further developed into a parameter-based dynamic lighting methodology that translates daylight characteristics into controllable indoor lighting strategies. As illustrated in Diagram 5, the system interprets changing daylight conditions throughout the day—including sunrise, morning, noon, afternoon, and sunset color temperature variation—and translates them into responsive indoor lighting conditions through multiple controllable parameters, including lumen level, color temperature, light source type, projection distance, movement mechanism, speed, beam angle, fractal pattern behavior, sensor input, and control technologies. These parameters were informed through AGI32 and DIALux simulations as well as physical prototyping conducted within the lighting laboratory, establishing a framework for simulating temporal daylight progression and spatial lighting variation within window-limited interiors. While environmental sensing systems and automated control mechanisms were not fully implemented within the scope of this research, the framework proposes future integration between environmental sensors, control systems, and adaptive lighting technologies capable of responding to exterior environmental conditions such as solar position, daylight intensity, weather conditions, and time of day. Through this relationship, the framework suggests a responsive relationship between outdoor environmental conditions and indoor lighting behavior. Overall, this phase establishes a layered and parameter-based methodology for translating daylight characteristics into dynamic interior lighting environments that integrate daylight cues, artificial lighting strategies, and fractal-based biophilic effects to support spatial and temporal perception, while also identifying opportunities for future integration with responsive control systems, environmental sensing technologies, and human-centered evaluation methods.

Diagram 5

Layered Dynamic Lighting System Integrating Daylight Cues, Artificial Lighting, and Fractal Light-in-Motion with Environmental Response and Control Parameters



Chapter IV: Discussion, Limitations, and Future Research

Discussion

This study investigates how dynamic lighting can be developed as a layered system for simulating daylight conditions within window-limited interior environments. Through observation, daylight analysis, simulation, and physical prototyping, the research explores how daylight characteristics may be translated into controllable indoor lighting strategies. The discussion is organized in relation to the three research questions concerning design framework, system composition, and evaluation criteria.

Addressing Research Question 1: Design of a Layered Dynamic Lighting Framework

The findings demonstrate that a layered dynamic lighting framework can be developed by translating observable daylight behavior into controllable lighting parameters and coordinated spatial strategies. Through field observation, daylight analysis, AGI32 and DIALux simulations, and physical prototyping, the study identifies key daylight characteristics—including directionality, intensity variation, temporal progression, and patterned shadow behavior—that may be synthesized into artificial lighting conditions.

Rather than replicating daylight geometrically, the framework focuses on reproducing its perceptual and behavioral qualities. The resulting methodology integrates daylight cues, artificial lighting, and fractal light-in-motion to create dynamic interior environments that communicate temporal variation and spatial hierarchy. This suggests that dynamic lighting can be approached as a process of synthesis rather than direct imitation of natural daylight conditions.

Addressing Research Question 2: Layers and Technologies in Dynamic Lighting Systems

The study identifies that an effective dynamic lighting environment is composed of multiple coordinated lighting layers operating simultaneously within the interior environment.

These layers include ambient lighting, directional lighting, and fractal-based pattern projection. Ambient lighting establishes the general overall illumination and baseline visibility of the space, while directional lighting introduces focused daylight-like projection and spatial emphasis. Fractal light-in-motion contributes biophilic shadow variation, patterned projection, and temporal complexity inspired by natural daylight behavior.

The framework is supported through multiple lighting technologies and design methods, including simulation software (AGI32 and DIALux), digital visualization techniques, CNC fabrication, LED lighting systems, adjustable spotlight projection, and physical prototyping. The integration of these components demonstrates that dynamic lighting is not a single fixture type or isolated technology, but rather a coordinated system of spatial, temporal, and perceptual lighting relationships.

The physical prototype further confirms that combining ambient illumination with directional projection and fractal-based modulation creates a more perceptually dynamic spatial experience than conventional static lighting systems. While the current prototype uses simplified lighting mechanisms, the findings suggest that future integration of programmable controls, motorized optics, and environmental sensing technologies may further enhance the adaptability and responsiveness of dynamic lighting environments.

Addressing Research Question 3: Evaluation Criteria for Daylight Simulation

To evaluate the effectiveness of daylight simulation within window-limited interiors, the study establishes three primary perceptual criteria: perceptual clarity, temporal legibility, and spatial impact. Perceptual clarity refers to the readability of light direction, hierarchy, and spatial articulation within the environment. Temporal legibility describes the ability of lighting variation to communicate time-of-day progression through changes in brightness, directionality, and color

temperature. Spatial impact refers to the perceptual richness created through contrast, movement, layered illumination, and patterned projection.

The findings indicate that artificial lighting systems can reproduce several key daylight characteristics, particularly directionality, luminance contrast, color temperature variation, and temporal progression. The integration of fractal light-in-motion further contributes to spatial complexity and perceptual variation by introducing multi-scale shadow behavior and biophilic lighting effects inspired by natural environments.

However, the evaluation conducted in this study is based primarily on simulation analysis, visual comparison, and design synthesis rather than empirical human-subject testing. As a result, the findings demonstrate design performance and conceptual effectiveness rather than directly measured physiological or psychological user responses.

Limitations

This study contains several limitations related to technical implementation, spatial scope, and evaluation methodology.

First, the physical prototype utilizes a simplified lighting mechanism without advanced optical systems such as motorized lenses, automated movement systems, or programmable projection technologies. Consequently, the fractal lighting behavior remains relatively controlled and does not fully replicate the continuous variability of natural daylight movement.

Second, the framework does not incorporate fully integrated environmental sensing systems or real-time adaptive control technologies. Although the study proposes future relationships between outdoor environmental conditions and indoor lighting response, the prototype system does not dynamically respond to solar position, daylight intensity, weather conditions, or sky variation in real time.

Third, the study is conducted within a single controlled spatial condition using a south-facing daylight simulation scenario. Variations in window orientation, aperture geometry, room proportion, and architectural context are therefore not comprehensively evaluated. Since daylight behavior changes significantly according to orientation and environmental conditions, these variations remain outside the scope of the current investigation.

Additionally, the exploration of fractal lighting conditions is limited to a relatively small range of pattern types and projection behaviors. Variations in fractal density, motion speed, projection scale, and contrast were explored conceptually but not systematically evaluated across multiple environmental conditions.

Finally, the study does not include human-subject testing or Institutional Review Board (IRB)-based perceptual evaluation. Therefore, conclusions regarding visual comfort, mood, temporal awareness, and user well-being remain interpretive and based on design evaluation rather than empirical human-response data.

Future Research and Development

Future research should expand this work through both technological development and human-centered evaluation.

One important direction is the development of adaptive lighting systems integrating motorized optics, programmable projection mechanisms, and adjustable lighting components capable of simulating changing daylight behavior in real time. These systems may allow greater variation in projection scale, movement, beam direction, and temporal transition, more closely approximating the dynamic qualities of natural daylight.

Future systems may also integrate environmental sensing technologies capable of connecting indoor lighting behavior to outdoor environmental conditions. Through the use of

daylight sensors, solar tracking systems, weather data, and environmental inputs, lighting parameters such as color temperature, lumen output, movement speed, and projection behavior could dynamically respond to changing daylight conditions throughout the day.

Further studies should investigate how the proposed framework performs under different architectural conditions, including variations in window orientation, aperture geometry, spatial scale, and room configuration. Expanding the framework into healthcare environments, educational facilities, workplace interiors, and retrofit conditions may further evaluate its adaptability across different spatial typologies.

Human-centered evaluation should also be incorporated into future research. This may include empirical studies measuring perceptual clarity, spatial perception, visual comfort, temporal awareness, mood, and well-being under different dynamic lighting conditions. Comparative studies involving multiple lighting configurations and user-response testing would help validate the perceptual effectiveness of the proposed framework.

Finally, future implementation would benefit from interdisciplinary collaboration among lighting designers, manufacturers, control system engineers, software developers, and building automation specialists to develop integrated dynamic lighting systems capable of architectural-scale application.

Conclusion

This thesis develops and demonstrates a layered dynamic lighting framework that integrates daylight cues, artificial lighting, and fractal light-in-motion to simulate the spatial and temporal qualities of daylight within window-limited interior environments.

Through a design-based methodology combining observation, daylight analysis, simulation, physical prototyping, and spatial implementation, the study establishes a process for

translating natural daylight behavior into controllable indoor lighting parameters. The findings demonstrate that artificial lighting systems can reproduce several important daylight characteristics, including directionality, temporal variation, luminance hierarchy, and color temperature progression. Furthermore, the integration of fractal light-in-motion introduces additional spatial complexity, perceptual richness, and biophilic variation that more closely reflects natural daylight behavior.

The primary contribution of this research is the definition of dynamic lighting as a coordinated, layered, and parameter-based environmental system rather than a static lighting condition or isolated technological feature. The proposed framework establishes a methodology connecting daylight behavior, lighting technologies, and perceptual spatial experience within interior environments.

Although the study is limited by the absence of fully adaptive control systems and human-subject evaluation, it establishes a foundation for future research integrating environmental sensing technologies, responsive lighting systems, and empirical perceptual testing. As such, the research contributes to both academic investigation and design practice by positioning lighting as an active spatial and temporal medium capable of enhancing environmental experience in spaces with limited access to natural daylight.

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