

Natural Rhythms and Temporal Perception - Visualization of Sunlight Patterns with Energy
Monitoring

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ABSTRACT

In his book *Ritual House*, Ralph Knowles states, “The houses we inhabit, the cities surrounding our houses, even the clothes we wear – all are shelters we erect against the elements. But they are also manifestations of ancient rituals, developed in response to nature’s rhythms” (2006). Implicit within this quote is the importance of nature’s rhythms in our lives, particularly those related to the movement of the sun. Many built environments have no connection to the exterior. Those who work in these spaces are disconnected from these natural rhythms and often experience detrimental physiological effects. However, technology has the potential to reintroduce aspects of natural rhythms into built environments.

This research crossed disciplinary boundaries separating architecture, engineering, psychology, and building science during the design of an architectural intervention for an interior workspace known as the Sandbox, at Virginia Tech. The design proposal includes skylights that combine Photovoltaic-integrated glazing with LED lighting to create conditions that stimulate the occupants while connecting inside to out. To reestablish a connection to natural rhythms the BIPV energy monitoring is used during the day to record variations in solar radiation which at night are played back through intensity and color variations of LED lighting. The effect of the LED lighting was compared with the sunlight entering through the skylights using quantitative analysis methods and qualitative visual comparison tools including time lapse photos and videos. The research merges architectural design, lighting technology and BIPV to demonstrate a proof-of-concept for the reintroduction of natural rhythms into built environments.

For Kari
Erna & Andreas
Lisa & Rob

Acknowledgments

The idea for my research project emerged during the class “Light: Performance, Presence, Place” taught by my advisor James Jones which I attended in the spring semester 2016. I became interested in combining science and design through my experiences in class when Professor Jones explored the phenomenon of light by looking at both its physical properties and its applications in architectural design. I want to thank Jim for his helpful guidance in narrowing down my subject and for suggesting literature which formed an architecture theoretical framework for my project in the early phase. I benefited from his constructive suggestions that helped me to improve my research methods and documentation during the implementation. I also want to thank Jim for editing this thesis document pointing out where the language was not explaining my project clearly.

Professor Robert Schubert thankfully provided the photovoltaic module which I used for my sunlight recorder and his support led to the reception of a grant to fund a large part of my research materials. Bob also helped me to develop the setup for the sunlight recorder experiment including the selection of its location at the Virginia Tech Research and Demonstration Facility. I am grateful for Bob’s comments during the committee meetings when he encouraged me to document the limitations and errors of my methods.

I want to thank Professor Georg Reichard for fruitful discussions that developed a context for the project and its potential applications in the real world. Georg shared his knowledge of light sensors and data collection methods with me which helped me to refine my own data collection process. When I presented my first results during a committee meeting Georg constructively questioned my interpretations which led me to develop additional analysis methods which improved the validity of my results.

I owe my knowledge of developing research methods to Professor Elizabeth Grant’s class “Environmental Design Research” which she taught with Kenneth Black. Elizabeth lent me her light meters and provided access to light sensor data from the pyranometer of her roof research setup at Virginia Tech. I could use Elizabeth’s green roof research structure to support the Sandbox model during the sunlight studies. Midway through the project Elizabeth encouraged me to apply to present my project at the ASES Solar 2017 conference. The experiences at the conference helped and motivated me to develop my project further based on the feedback from peers in the field of solar energy.

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List of Abbreviations

BIPV - Building Integrated Photovoltaics
CSV - Comma Separated Values
GPIO - General-Purpose Input/Output
JND - Just Noticeable Difference
LED - Light Emitting Diode
MOSFET - Metal–Oxide–Semiconductor Field-Effect Transistor
PCB - Printed Circuit Board
PWM - Pulse Width Modulation
RGB - Red/Green/Blue additive color model

1. Introduction

1.1	Translation in the design process	2
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1.1 Translation in the design process

Throughout history architects understood themselves as generalists who are involved in all design aspects of a building – architectural design, structural design, building equipment, etc. With the development of ever more sophisticated construction materials and mechanical building equipment, the architects' role as a generalist became a more and more challenging one. The increase in the level of detail which is required when moving from concept design to schematic and construction design in modern construction is significant. Now the knowledge that is required to design all components of a building is often so vast that it requires the collaboration between several people from different professional disciplines. Large architecture offices employ designers trained in various fields including architects, structural engineers, MEP engineers, building scientists, light designers and other specialists. Smaller offices which predominantly employ trained architects often assign sub consultants to perform design tasks that cannot be done in-house. The fast pace in which construction knowledge develops in modern society is amplified by the introduction of construction standards which are regularly updated and thus have become quite extensive and complex. Historically working in the construction environment has required the stakeholders' ability to carefully cull the information which is most relevant to the project from their respective specialization's information pool. Today the magnitude of these information pools has made it more challenging to reduce that pool to a manageable selection of the most relevant information (balance between knowing everything and knowing where to look). Also as the information pool continues to become greater the number of stakeholders in a project tends to increase as well. The ability to master various communication methods and technologies which enable all participants to "translate" between construction (quantitative) knowledge and design (qualitative) knowledge is now an important factor in the process in which the level and quality of communication determines the quality of a project to a great extent.

There are various design tools available for architects and engineers to develop very complex design concepts. Most of these tools are very specifically developed for the design of either formal qualities and compositions (form, proportion, scale, ambience - qualitative) or the design of functional and technical properties (structural integrity, thermal comfort, energy demand, safety - quantitative). Ideally the formal design and the functional design are developed in parallel to better integrate the respective design requirements and create a solution that is both formally and functionally convincing. This means that during the design process there is a need to translate information which is exchanged between qualitative design tools and quantitative design tools used by both architects and engineers. The proportion of architectural design requirements on the one hand and engineering design requirements on the other hand is variable and depends on the size and type of project. In the process of coordination, a common language that explains qualitative as well as quanti-

tative design elements is very helpful. This can for example mean that specific parts of the building are named according to their position, form, function, or other properties in agreement between all parties to maintain orientation when talking about the project in the group. During my work experience as an architectural designer we used such a common language to communicate in our team. The balance between working individually to develop the design on the one hand and working collaboratively in regular workshops to coordinate the design on the other improved all parties understanding of the project and enabled the team to create more convincing design solutions. A common language to translate between qualitative and quantitative design as well as each project member's will to acquire a basic understanding of the others' subjects greatly improve a process of parallel design integrating form and function.

Project Idea

The experiences from my occupation in a collaborative design environment prompted my interest to expand on the interaction of design and technology. I was motivated to select the topic of Building Integrated Photovoltaic (BIPV) for the current thesis research because this field requires the application of concepts addressing the previously mentioned interaction. I studied selected projects that showcased successful and inspiring concepts of integrating PV technology and architectural design. Each case study project distinctly considered the interaction between the PV design and the daylight design as well as artificial light design combining functionality and design.

Akademie Mont-Cenis in Herne, GER
HHS AG, Jourda & Perraudin Architects

The solar glass roof of the Akademie Mont-Cenis filters daylight and provides shade. The cloud pattern arrangement of PV cells is more dense over buildings and less dense over the semi-public spaces. The microclimatic envelope provides an artificial Mediterranean climate for the semi-public spaces.

Solar plant facts:

total roof area: 12,600m²
no. of PV roof modules: 2,905
no. of PV façade modules: 280
output per module: 250-416 Wp
total output: 1MWp
mean insolation: 975 KW/m²a
energy yield: 750,000 KWh/a



Fig. 1.1 Akademie Mont-Cenis in Herne, GER - HHS AG, Jourda & Perraudin (Source: commons.wikimedia.org, Arnold Paul top, Frank Vincentz bottom)

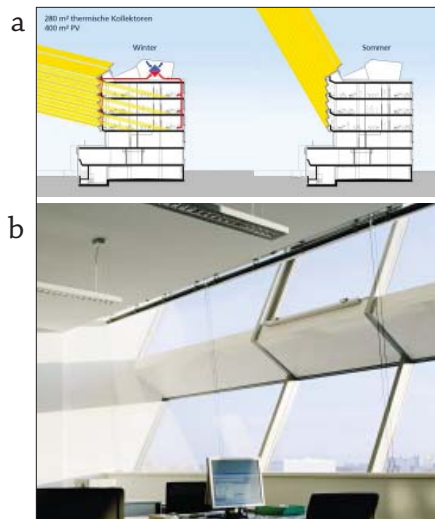


Fig. 1.2 Energy Base in Vienna, AUT
(Source: <http://www.pos-architektur.com>, © POS architekten ZT gmbh, top
© Hertha Hurnaus Photography, bottom)

Energy Base in Vienna, AUT POS architekten

At the Energy Base in Vienna the PV integrated folded south facade blocks direct sunlight during the summertime and allows desired heat gain from sunlight in the winter. In addition to producing electric energy the PV panels become a formative element in the architectural design of the building and act as a shading device.

Solar plant facts:

area of façade modules: 400m²

area of solar thermal panels: 280m²

energy yield: 37,000 KWh/a



Fig. 1.3 Plus-Energy Office High-rise Building in Vienna, AUT
(Source: <http://www.schoeberlpoell.at>,
© Schöberl & Pöll GmbH)

Plus-Energy Office High-rise Building in Vienna, AUT Architect: Kratochwil-Waldbauer-Zeinitzer Building Physics: Schöberl & Pöll GmbH

Solar plant facts:

inclination of roof panels: 15°

energy output of roof panels: 97.8 KWp

energy output of facade panels: 230.6 KWp

total output: 328.4 KWp

energy yield roof: 102,444 KWh/a

energy yield facade: 146,360 KWh/a

energy yield elevator energy recovery: 15.971 KWh/a

The production of the PV integrated roof and façade is monitored to manage the energy balance of the Plus-energy rated building. The brightness of the electric space lighting is automatically adjusted to the sensed present daylight level in the room. To reduce the energy consumption of typical office equipment the building has a 24V grid to replace power adaptors.

I collected additional information about current research and the latest developments in the field of BIPV at the conference “8. Forum Bauwerkintegrierte Photovoltaik” (8th Forum Building-Integrated Photovoltaics) which took place in Germany in March 2016. I developed the idea for this thesis project during the spring semester 2016 inspired by Professor Jones’s class “Light: Performance, Presence, Place” and through conversations with researchers at the Institute for Creativity, Art, and Technology (ICAT). The final assignment for the class was to investigate the temporal dimension of light which led me to a potential application of BIPV for lighting design in buildings - a PV integrated skylight intervention that makes present the passing of time. I had learned about a workspace for ICAT students called the Sandbox when I first visited the Moss Arts Center in 2015. The space is prominently located in the center of the building next to the main corridor as depicted in Fig. 1.4. Visual access from the corridor to the Sandbox is provided through clerestory windows.

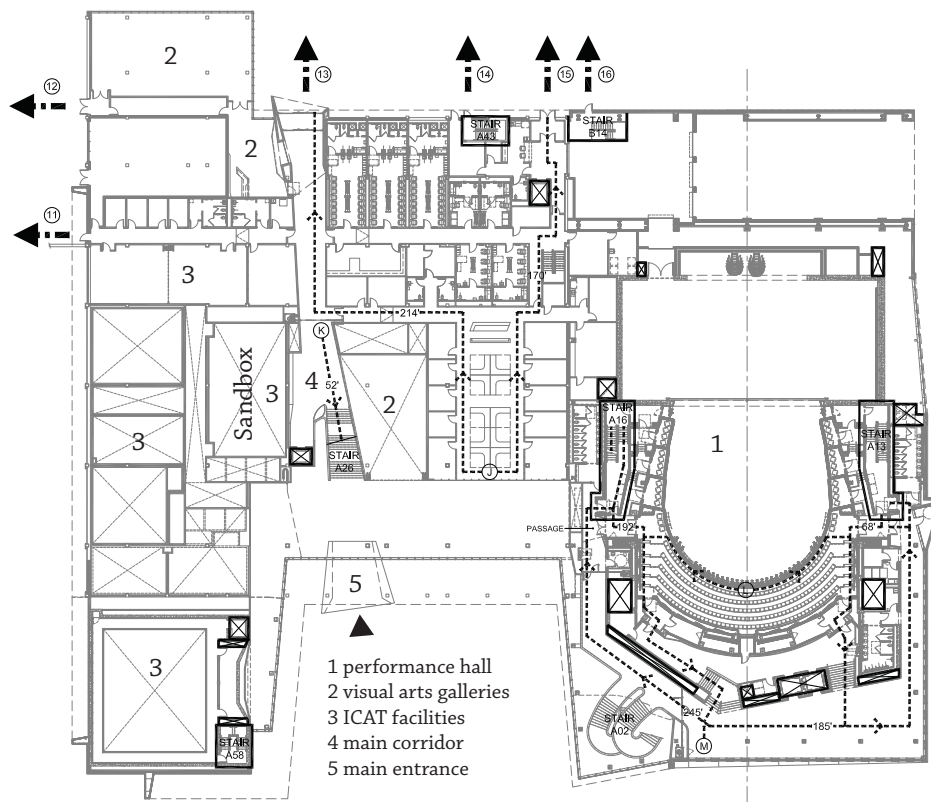


Fig. 1.4 Moss Arts Center facilities: performance hall, visual arts galleries, ICAT facilities
Snøhetta, STV Group Inc. (Source: Moss Arts Center - construction documents)

ICAT describes the Sandbox's function as follows:

"The Sandbox, the room you see here through this second-story window, is a synonym for idea incubator. ICAT teams, composed of students and faculty from across Virginia Tech, meet in the Sandbox, to brainstorm, critique ideas, and roll up their sleeves to start projects. With moveable furniture, dry-erase boards, and a projection array, this comfortable, flexible meeting space encourages collaborative creativity."

(http://www.icat.vt.edu/facilities/living_labs)



Fig. 1.5 View down into Sandbox through second-story windows
(Source: <https://artscenter.vt.edu>)

Considering the properties of the space and its use I determined that the Sandbox is suitable to serve as a case study for the implementation of a PV integrated skylight in the course of my thesis project.



Fig. 1.6 ICAT Maker Camp 2014 - designing and building instruments in the Sandbox
(Source: <https://www.flickr.com/photos/artscenteratvt/14773230511>)

1.2 Problem

I documented the as-built condition of the Sandbox in detail in Chapter 3. In summary, a central feature of the room is its location in the middle of the Moss Arts Center with limited connection to the outside. The following research questions were formulated to address the described problem.

Light is one of the most important factors that need to be considered when designing an architectural space and making a place.

If there is an experienced need to enhance a space's connection to the outside, how can daylight and artificial light design interventions reestablish this connection, make present a sense of time, and contribute to creative stimulation?

Daylight, dynamic by nature, gives presence to the passing of time, yet it is not available at all times. When artificial light is used to substitute in the absence of daylight it most importantly lacks the dynamic temporal character of daylight.

How can artificial light be modified so that it assumes the dynamic nature of daylight?

Making Building-Integrated Photovoltaics integral to the experience of space

Building-Integrated Photovoltaics (BIPV) are defined as photovoltaic materials used to replace conventional building materials in the envelope (roof, façade, skylight glazing, etc.) and thus fulfill an additional function supplementing the primary function of energy production. The conference proceedings of the "8. Forum Bauwerkintegrierte Photovoltaik" give an overview of areas which are currently being addressed by researchers, most of which are related to architectural appearance (shape and color), material test criteria for BIPV components, and cost effectiveness (Ostbayerisches Technologie-Transfer-Institut e.V., 2016).

How can BIPV be used to modify space lighting and thus become integral to the experience of this space?

1.3 Objectives

Examine the phenomenological potential of dynamic lighting

The positive effects of daylight on spaces for working and learning are widely acknowledged and designers have access to comprehensive design strategies for proper daylighting in a space. Although there has been research conducted on potential positive effects of dynamic electric space lighting through variation in intensity and color temperature similar to daylight (De Kort & Smolders, 2010) these are much less recognized and comprehensive. However, research in the mentioned field indicates that a balanced combination of daylight and dynamic artificial light contributes to the physical and psychological well-being of human beings in work and learning environments (Begemann, Van den Beld, & Tenner, 1997).

Even though De Kort's and Smolders' study did not find the desired measurable positive effects related to office workers' performance and health, the participants of the study expressed a higher satisfaction with a dynamic lighting scenario. This points to a perceived positive phenomenological effect of the dynamic lighting condition. I will examine the potential of dynamic lighting as a tangible phenomenon by replacing the pre-set protocol of the mentioned study's dynamic lighting with a protocol generated by natural patterns of variation in solar radiation.

Make present the passing of time using sunlight as a source – representation of daylight patterns

Photovoltaic technology can become integral to users' experiences of a space by making the system visible and tangible through two central design strategies:

- *Introducing Daylight:* Daylight is the source in photovoltaic energy production. The project showcases the relation between daylight and photovoltaics by making visible the interaction between the energy source (sunlight), the energy production system (photovoltaic cells), and the electrical load (dynamic LED lighting).
- *Translating time dependent energy monitoring data to patterns for dynamic electric lighting:* BIPV systems are usually monitored to ensure an optimal energy production performance. But the recorded data of the monitoring systems also contains information about the conditions of the daylight intensity over time. This information is represented in the current project through dynamic light intensity and color patterns for the LED lighting.

Develop design for photovoltaic integrated skylights

The location and size of the skylights were determined using available construction documentation of the Sandbox and are situated between existing air ducts in the ceiling while avoiding extensive relocation work in a potential implementation scenario. The depth of the skylight wells is based on the thickness of the existing ceiling and roof. The skylights are located in proximity to the clerestory windows to create a perceived amplification effect of the small amount of daylight entering the space through the windows from the corridor. The skylight wells are illuminated at night using the dynamic light intensity and color patterns.

Documentation of the design process

The primary audience of this project is the researcher. In the current immersive case study, the design process is documented in an effort to improve our understanding of the qualitative and quantitative interactions for design decisions for photovoltaic integrated skylights. An interdisciplinary thesis committee consisting of faculty with experience in both quantitative and qualitative research supports the researcher in this task. The committee members were selected due to their expertise in three general knowledge domains that I identified as being central to the project's development:

- use **Technology** to quantify a natural phenomenon
- draw on **Phenomenology** to translate quantitative data and make present time passing
- illustrate **Physical Processes** to augment the users' experience and connect inside to out

While the current project is aimed at designers and researchers in the field of lighting design, as well as professionals in the field of building integrated photovoltaics, I also seek to contribute to research on dynamic lighting and its potential to introduce a temporal stimulus to a space.

1.4 Goals

Nonmaterial informational potentials of BIPV

Building Integrated Photovoltaics are defined as PV materials used to replace conventional construction materials such as façade materials, skylight and window glazing, shading installations, or roof materials. They fulfill at least one supplemental function in addition to energy generation. BIPV are implemented in the context of sustainable design, a field that is commonly associated with the character of awareness. Solar cells react to the condition of (sun)light thereby assuming the character to sense solar radiation. The qualitative data inherent in the quantitative measurements taken in the process of PV energy monitoring establishes a potential for nonmaterial informational functions of PV materials supplementary to energy production and physical application as construction material. The idea is to expand the field of BIPV by informational functions which raise the occupants' awareness about exterior light conditions through the PV system itself. In this way, the primary function of energy production is integrated with the occupants' experience of the space.

Potential applications of the project and future development

The project concept lends itself to several applications in buildings with a variety of functions. The design shall be flexible and adaptable to these applications. The current case study addresses a project and meeting space for creative work with limited access to daylight. Daylight and dynamic artificial lighting give presence to the passing of time enriching a creative environment during the day and at night. The artificial lighting component can be used in spaces where it is impossible to provide daylighting or in buildings which are occupied around the clock respectively mostly at night in an extreme case. With that, the research shall contribute ideas and concepts to improve spatial conditions in workplaces, educational facilities, and public spaces without access to daylight due to space or time restrictions.

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(Source: <https://commons.wikimedia.org>)
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Architect: POS architekten
(Source: <http://www.pos-architecture.com>)
- Fig. 1.3 Plus-Energy Office High-rise Building in Vienna, AUT
Architect: Kratochwil-Waldbauer-Zeinitzer
Building Physics: Schöberl & Pöll GmbH
(Source: <http://www.schoeberlpoell.at>)
- Fig. 1.4 Moss Arts Center facilities: performance hall, visual arts galleries, ICAT facilities
Design Architect: Snøhetta, Executive Architect: STV Group Inc.
(Source: Moss Arts Center - construction documents)
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(Source: <https://www.flickr.com/photos/artscenteratvt/14773230511>)
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2. Photovoltaic Technology and Light – Theoretical Framework

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2.1 Generating Electric Energy from Sunlight

Photovoltaic panels convert light energy to electric energy using an effect explained in quantum theory. Jenny Nelson elucidates this in Chapter 1 of her book *The Physics of Solar Cells* (2003, p. 1):

“Light is made up of packets of energy, called photons, whose energy depends only upon the frequency, or colour, of the light. The energy of visible photons is sufficient to excite electrons, bound into solids, up to higher energy levels where they are free to move.”

Nelson explains an extreme effect of this conversion, the *photoelectric effect*, where “... blue or ultraviolet light provides enough energy for electrons to escape completely from the surface of a metal.” (2003, p. 1). The effect is used in light sensors, image sensors, electroscopes and night vision devices. In 1905 Albert Einstein developed his quantum theory of light which explained experimental data on the photoelectric effect (Wikipedia, 2017). The *photovoltaic effect* was discovered in 1839 by Alexandre-Edmond Becquerel. Though related this effect differs from the photoelectric effect. The photovoltaic effect occurs in solar cells which are designed with a spatial asymmetry that causes the excited electrons to be pulled away from the solid they are bound into before they relax and fall back to the lower energy level. This is achieved through separating the excited state from the ground state by an energy gap large enough to maintain the excited electrons at the higher energy level where they are collected. Modern solar cells use semiconductors to create the required energy gap. In a photovoltaic system, radiant energy produces an increase in electronic potential energy resulting in a potential difference between the contacts attached to the thick p-type (positive) semiconductor on the back side and the thin n-type (negative) semiconductor on the front side of the solar cell. Nelson describes the mentioned potential difference (2003, p. 15):

“This light driven charge separation establishes a photovoltage at open circuit, and generates a photocurrent at short circuit. When a load is connected to the external circuit, the cell produces both current and voltage and can do electrical work.”

The design of a PV panel determines its characteristic short circuit current (I_{sc}) and open circuit voltage (V_{oc}) measured at Standard Test Condition (STC) with set values for light spectrum (air mass coefficient 1.5), solar radiation power density ($1000\text{W}/\text{m}^2$), and temperature (25°C). The graph that can be established between these two values determines the panel’s characteristic IV curve.

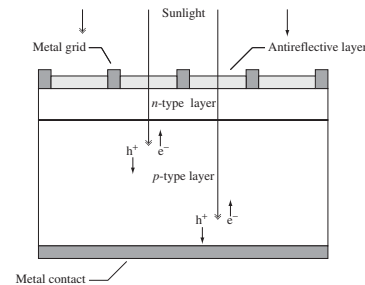


Fig. 2.1 Solar cell schematic (Source: *Handbook of Photovoltaic Science and Engineering*, 2011, p. 83)

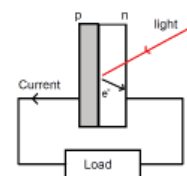


Fig. 2.2 Photovoltaic effect in a solar cell (Source: *The Physics of Solar Cells*, 2003, p. 1)

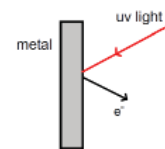


Fig. 2.3 Photoelectric effect (Source: *The Physics of Solar Cells*, 2003, p. 1)

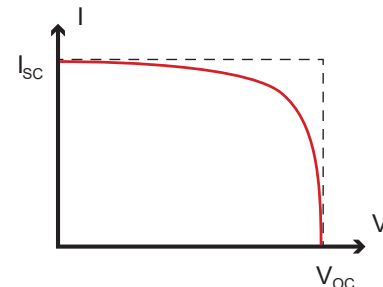


Fig. 2.4 PV panel I-V curve

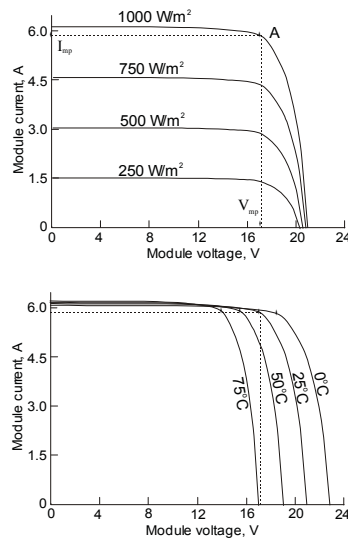


Fig. 2.5 Influence of illumination and temperature on I-V curve
(Source: Study Guide for Photovoltaic System Installers and Sample Examination Questions, 2005, p. 8)

The current values of the IV curve are proportional to the power density of the incident light. The voltage values are less effected by illumination. However, increased temperature reduces the band gap of a semiconductor thus lowering V_{oc} and reducing the solar cell's potential power output. The quality of the light absorbing material (the semiconductor) and the quality of its connection to the external circuit through metal contacts greatly affect the efficiency of the PV panel.

As described in (Nelson, 2003, p. 4), a solar cell “can be considered as a two-terminal device which conducts like a diode in the dark and generates photovoltage when charged by the sun.”

The photovoltage of one cell is too small for consumer loads. The solar cells are thus connected in series forming PV modules which produce a useful voltage. Several modules are usually connected in series to create a string. The voltage in the string increases with the number of modules. Several strings are then connected in parallel forming a PV array. The current in the array increases with the number of strings.

To ensure a maximum power production many modern PV installations use power optimizers. These devices adjust the voltage of two or more panels to the specific value (Maximum Power Point) along the panels' I-V curve that results in the maximum power density which is the product of current and voltage. This process is called Maximum Power Point Tracking (MPPT) and greatly improves the power output of a PV array addressing system imbalances caused by exterior influences such as panel shading. Ideally the power output of a PV array is monitored which allows the operator to detect faulty panels and to determine a cleaning schedule mitigating the negative effect of panel soiling.

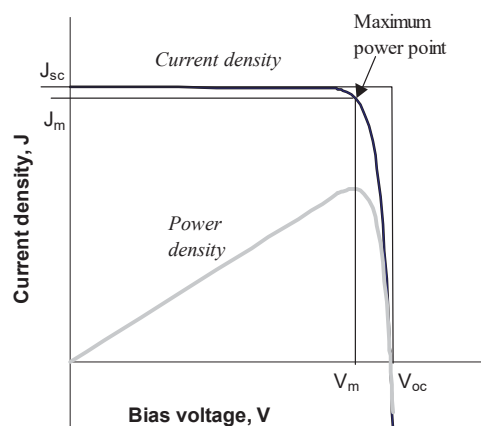


Fig. 2.6 Power optimizing with MPPT
(Source: *The Physics of Solar Cells*, 2003, p. 12)

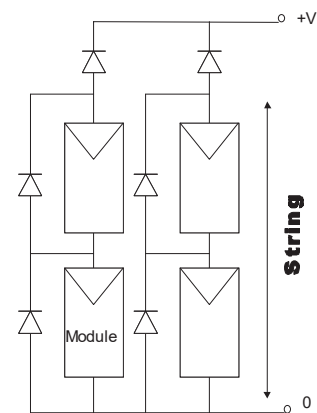


Fig. 2.7 Strings of modules form a PV array
(Source: *The Physics of Solar Cells*, 2003, p. 5)

2.2 Light in Architectural Design

Light and Placemaking

Numerous architects have described the phenomenon of placemaking in architecture. The term placemaking refers to the architect's task to design a space in such a way that the people who occupy it develop a sense of place. There are many factors that need to be considered for the design of a place. One very important factor is light. John Lobell writes in his book *Between Silence and Light* about the work of Louis Kahn: "Kahn used the word Light to mean pure being, as yet without material quality" (2008, p. 64). He then describes the importance of the literal meaning of light in Kahn's description of architecture:

"He observed that material begins where light (using the word in its ordinary sense) stops. ... He said "All of the material world is Light that has spent itself." Light (again using the word in its ordinary sense) is of immense importance to architecture; it is the revealer of architecture." (Lobell, 2008, p. 64)

Light also assigns character to a space. In *Thinking Architecture* Peter Zumthor writes about his observations in a restaurant located in a tourist village and begins with a vivid description of the light in the space:

"The atmosphere of the room seemed dark, even gloomy, until our eyes grew accustomed to the light. The gloom soon gave way to a mood of gentleness. The daylight entering through the tall, rhythmically placed windows lit up certain sections of the room, while other parts which did not benefit from the reflection of the light from the paneling lay withdrawn in half-shadow." (Zumthor, 1999, p. 40)

In *The Eyes of the Skin* Juhani Pallasmaa argues that the character of light in a space influences the individual's imagination: "The imagination and daydreaming are stimulated by dim light and shadow. ... Homogenous bright light paralyses the imagination in the same way that homogenisation of space weakens the experience of being, and wipes away the sense of place" (2005, p. 46). While Pallasmaa does not specifically talk about artificial light, it should be noted that his observation is descriptive of the artificial lighting condition in many current offices and educational workspaces.

The design of a place is influenced by temporal factors. The temporal character of dynamic light clearly shapes our perception of a space. In a philosophical discussion of the factor time in architecture Peter Zumthor refers to the importance of memory in space perception: "... I am convinced that a good building must be capable of absorbing the traces of human life and thus of taking on a specific richness." (1999, p. 24). Steven Holl explains the influence of past experiences on perception in his book *Parallax* using science to illustrate his thinking (2000, p. 14):

“The two fundamental theories of modern physics, general relativity (for the large scale) and quantum mechanics (for the smallest scales), are not yet reconcilable. Science remains essentially mysterious, yet our daily scientific and phenomenal experiences shape our lives; experience sets a new frame from which we interpret what we perceive.”

For Ralph Knowles, it is important to consider natural rhythms in architectural design. In his book *Ritual House* Knowles describes natural rhythms generated by the movement of the sun. Variable light and shadow change the perception of space over time and this variation, induced by natural rhythms, enriches the space and connect it to its setting. Knowles argues that space is dynamic:

“Most people understand architectural space as enclosed by fixed elements such as floors, ceilings, and walls. Yet space can be thought of dynamically as well, defined by passing sensations of sound, smell, and shadow.” (Knowles, 2006, p. 8)

The passing sensation of shadow rests upon the passing sensation of light that gradually changes its direction and intensity based on the movement of the sun. A complex combination of the steady and regular movement of the sun and manifold irregular weather influences such as cloud cover and fog modify the sunlight’s color temperature and create an intensity pattern of solar radiation over time.

The dynamic lighting system proposed in this thesis project echoes a day’s natural solar radiation pattern during the following night and makes present the passing of time in the moment. Furthermore, the echoed light patterns enrich the space at night recalling the traces and memories of a day just gone by.

The measurable and the unmeasurable

Reading the work of architects who are involved in architectural theory I noticed a recurring theme whereby design requires an interplay between the quantitative and the qualitative realm: Louis Kahn (as cited in Lobell, 2008, p. 48) states that “[a] great building, in my opinion, must begin with the unmeasurable, must go through measurable means when it is being designed, and in the end must be unmeasurable”. Peter Zumthor debates a process of iteration between qualitative and quantitative strategies: “The design process is based on a constant interplay of feeling and reason.” (1999, p. 20). For Steven Holl the design process is a transition from the qualitative (unmeasurable) to the quantitative (measurable) realm: “The path of passage in architecture must lead from the abstract to the concrete, the unformed to the formed.” (2000, p. 345). This recurring theme shaped the framework of the current project in so far as I studied the interaction between quantitative and qualitative design methods in the process.

2.3 Daylight, Dynamic lighting and preferences of artificial light

The majority of today's offices, laboratories and classroom spaces are artificially lit with only some consideration of daylight. In their conference paper *Review on visual comfort in office buildings and influence of daylight in productivity* (2008) Michele De Carli, Valeria De Giuli, and Roberto Zecchin discuss the debate of artificial light and its role in the context of the current focus on sustainability in work environments. De Carli et al. (2008, p. 1) state that "[m]any studies have demonstrated that if daylight is the primary source of lighting, there is a great improvement in productivity, performance and well-being in general." Despite the preference for daylight as a light source De Carli et al. argue that it cannot replace artificial light completely because of its variable character and thus present studies in which the effects of different artificial lighting conditions on the human being are investigated.

A study conducted by Begemann et al. showed a preference of variable lighting similar to daylight over a static light condition. The study also found that people prefer high light levels which enable biological stimulation. Begemann et al. refer to the negative effects on health caused by poor lighting as "ill-lighting syndrome" (1997, p. 231).

In 1941 Arie Andries Kruithof published research on combinations of illuminance and color temperature values for lamps which he summarized in the Kruithof curve. Kruithof's curve defined values for illuminance and color temperature that result in pleasant (natural) light and was subsequently used by manufacturers for luminaire design. Kruithof's experiment was later criticized due to insufficient documentation of the methods and the Kruithof curve was largely disproved as discussed in Ian Ashdown's article "*The Kruithof Curve*" (2015). Noguchi and Sakaguchi thus used Kruithof's findings more as an intuitive framework during their experiment on the *Effect of Illuminance and Color Temperature on Lowering of Physiological Activity* (1999, p. 117-123). The researchers sought to investigate light conditions for bedrooms that lower physiological activity looking at different levels of illuminance and color temperature. The findings of the experiment confirm that low color temperature light results in a relaxing atmosphere and high color temperature light causes people to be more alert. Noguchi and Sakaguchi also found that the effects of variable illuminance were less pronounced than the effects of variable color temperature. These findings, among other factors, informed the design of the dynamic lighting protocols in the current thesis project.

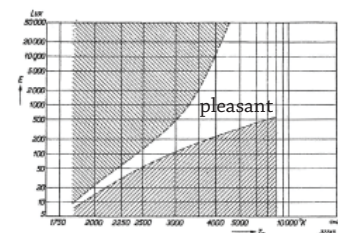


Fig. 2.8 Kruithof curve - pleasant lighting conditions based on illuminance and color temperature (1941), (Source: *All Things Lighting*, 2015)

Myriam Aries's research (2005) shows a clear requirement for sufficient lighting at the work surface that meets visual demands for performing work tasks (reading, drawing, etc.). However, there is also the aspect related to vertical illumination for biological stimulation which requires much higher lighting values.

The comfort at the workplace can be increased by addressing the non-visual demand for “healthy lighting”. Aries’s findings support Begemann et al. (1997) who stated that lighting levels set in standards are lower than the ones occupants prefer. Brightly lit areas in the field of vision (typically windows) address the mentioned non-visual demand for lighting. Given the infeasibility of windows in the project space the current thesis project proposes skylights to meet this demand.

Boyce et al. (2006) studied how direct and/or indirect lighting as well as the option to individually control lighting effect the performance, health and well-being of office workers. According to De Carli et al. the researchers found that a mixture of direct and indirect lighting is more comfortable compared to exclusively direct lighting and that individual control (task lighting) is preferred. The skylights proposed in the current thesis project introduce indirect lighting of the skylight wells to modify the existing direct space lighting. The indirect light of the skylights introduces an additional light scenario where the direct light can be turned off. Lighting from the skylights in combination with task lighting thereby provide a mixture of indirect and direct lighting.

It is widely accepted that daylight has a positive effect on human well-being. As described by De Carli et al. (2008) this is related to its properties for physical and psychological visual comfort (ideal light spectrum resulting in excellent color rendering, flicker-free, dynamic intensity and color temperature) as well as its properties for non-visual comfort through biological stimulation (regulation of basic biological functions, production of hormones, support of circadian rhythms). De Carli et al. (2008, p. 2) draw from Thorington et al. (1971) that “[s]ome researchers have argued that all the physiological processes should work optimally when exposed to daylight, since daylight has been the sole source of illumination for most of the period of humans’ evolution” which according to them indicates that electrical light should be as similar to daylight as possible.

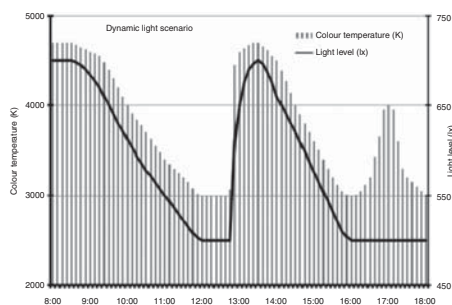


Fig. 2.9 Preset protocol for dynamic lighting field study, (Source: De Kort & Smolders, 2010, p. 346)

The positive effects of dynamic lighting on the human being have been indicated by researchers in different laboratory tests and studies. In their paper *Effects of dynamic lighting on office workers: First results of a field study with monthly alternating settings* Yvonne de Kort & Karin Smolders explain their conduction of a field experiment in order to validate “lighting as a potential environmental feature impacting office workers’ well-being” (2010, pp. 345-360). De Kort & Smolders point to research on physiological and psychological effects of lighting on human beings, specifically effects related to the characteristics of color temperature and illuminance. In order to test potential positive effects of dynamic light on office workers’ performance and well-being the field ex-

periment exposed participants to dynamic lighting which varied over time in color temperature and illuminance based on a pre-set protocol. Two different lighting conditions (dynamic and static) were tested on two different groups in three consecutive measurement periods. De Kort & Smolders report that there were no significant differences in the measures related to performance and health between the dynamic and the static lighting scenarios. However, they were able to find a higher level of satisfaction in general with the dynamic lighting condition while simultaneously there were more complaints about disturbances by reflected light. The fact that despite the reported disturbances the test groups were still more satisfied with the dynamic scenario points to an important result. The dynamic lighting condition raised the perceived comfort to a higher degree than the glare reduced it. This indicates that a small controlled amount of glare is tolerable if the overall lighting condition results in more dynamic (natural) space lighting.

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- Fig. 2.1 Solar cell schematic
(Source: *Handbook of Photovoltaic Science and Engineering*, Jeffery L. Gray, 2011, p. 83) © 2011 John Wiley & Sons
- Fig. 2.2 Photovoltaic effect in a solar cell
(Source: *The Physics of Solar Cells*, Jenny Nelson, 2003, p. 1)
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- Fig. 2.3 Photoelectric effect
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- Fig. 2.5 Influence of illumination and temperature on I-V curve
(Source: Study Guide for Photovoltaic System Installers and Sample Examination Questions, 2005, p. 8)
- Fig. 2.6 Power optimizing with MPPT
(Source: *The Physics of Solar Cells*, 2003, p. 12)
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- Fig. 2.7 Strings of modules form a PV array
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- Fig. 2.8 Kruithof curve - pleasant lighting conditions based on illuminance and color temperature (1941)
(Source: Kruithof, A. A. 1941. "Tubular Luminescence Lamps for General Illumination," Philips Technical Review Vol. VI, No. 3, pp. 65-73.)
(accessed Jan. 21, 2018 from *All Things Lighting*)
- Fig. 2.9 Preset protocol for dynamic lighting field study
(Source: De Kort & Smolders, 2010, p. 346)
- Fig. 2.10 Sculptural PV array at the Universal Forum of Cultures in Barcelona
(Source: <https://commons.wikimedia.org>)

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Fig. 2.10 Sculptural PV array at the Universal Forum of Cultures in Barcelona
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3. Visualization of Sunlight Patterns - Immersive case study design



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3.1 Project Framework

The Sandbox is operated by the Institute for Creativity, Art, and Technology (ICAT) and is located near the entrance lobby of the Center for the Arts which also houses the Cube (an audiovisual research space), exhibition spaces, and a performance theatre. The design of the Center for the Arts was developed based on the winning entry in an international design competition by Snøhetta practice of architecture. After the finalization of the competition the responsible project developers at Virginia Tech asked for an adaptation of Snøhetta's design due to the necessary integration of the project with an existing canteen building located at the proposed project site. The integration of the old structure was necessary to gain the status of a renovation project on the university campus unlocking important state funding for the project. The Center for the Arts' adapted design locates the Sandbox in the old structure of the canteen building. It was decided that the existing roof structure, which consists of prefabricated concrete slabs supported by a system of steel I-beams and columns, should not be replaced. The lighting in the Sandbox thus could not include natural daylight using roof skylights. The space is now solely illuminated by means of artificial light sources. Some ambient indirect daylight is entering the Sandbox from the entrance lobby through clerestory windows located in the wall adjacent to the Art Center's main corridor, but its effect for the space is subdued by the intensity of the artificial light fixtures.

The users of the Sandbox comprise engineers (mostly students in computer sciences), artists and design students, and students in social sciences. The space is designed to provide a multidisciplinary collaborative project workspace. The desks are assigned to individuals or groups for the time of their respective projects. This means that they spend a large part of their time in the Sandbox, often also at night. The absence of daylight and views means that the users are not aware of the exterior conditions, they have no connection to the outside. There is a lack of sense of time in the space which is uniformly lit during both daytime and night time. If zeitgebers such as the change of natural daylight intensity and color temperature are missing in a space it is much more difficult for people to maintain orientation in time. A slight disorientation of this kind can have a detrimental effect on the work and study environment.

Currently the approach to environmental design tends to focus on energy conservation. The proposed project for the Sandbox will take an approach that investigates supplementary alternative solutions to energy conservation which focus on an architectural design intervention. The proposed project enhances the work environment of the space and improves the environmental design as it relates to the lighting of the space. The enhancement shall be achieved with-



Fig. 3.1 ICAT workspace Sandbox
(Source: <https://artscenter.vt.edu>)

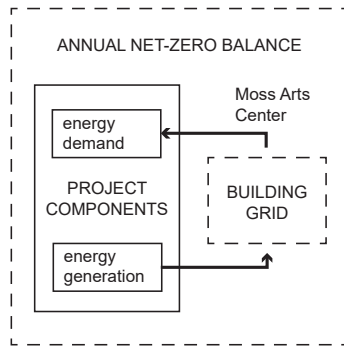


Fig. 3.2 Annual project net-zero balance concept diagram

out raising the environmental footprint of the building which consequently requires that the project components maintain a net-zero energy balance.

3.2 Project Design

Phenomenal experiences of light

The Sandbox is a project work and meeting space and is open to be used day and night throughout the year. The current project aims to raise the lighting quality of the space with design interventions that stimulate creativity. Addressing the reported benefits, skylights introduce natural daylight into the selected space during the hours when it is available. During dark hours, the artificial space lighting is supplemented with dynamic indirect skylight well lighting echoing the solar radiation patterns of the preceding day. Light patterns visually make present the passing of time. The patterns follow natural cycles to address the occupants' reported preference for dynamic lighting. In the light of Zumthor's argument for the importance of memory in space perception, the playback of recorded solar patterns is also meant to invoke memories of the past day's sunlight pattern. Following Holl's line of thought, our phenomenal experience of the sunlight pattern during the day will arouse our interest and shape how we interpret the perception of the dynamic skylight well lighting during the following night.

Nature of architectural design

Architectural design is positioned at the boundary between art and science as well as idea and representation. The methods of representation can be quantitative and/or qualitative requiring the designer to understand the interactions between these methods for informed design decision making. Issues in architectural design are related to context and location, massing and geometry, enclosure, as well as windows and views. The natural variation of the sunlight's properties (intensity, color, angle) creates patterns which can be experienced in spaces with daylight. The experience of such patterns makes present the phe-

nomenon of time passing. In this project, I look at the emerging issues and opportunities of the integration of PV and windows as well as the use of PV to record intensity patterns and use them to give presence to the phenomenon of time perception in an artificially lit space.

I selected the qualitative method of an immersive case study to improve the understanding of the interaction between idea and representation. The research shall include models, simulation, calculation, and documentation of the outcomes (process findings). The following variables inform the research design:

PV integrated skylight

Exogenous	Indigenous
<ul style="list-style-type: none"> • Latitude • Sky conditions • Obstructions • Climate 	<ul style="list-style-type: none"> • Size • Orientation • Geomerty (well index) • Surface properties • PV distribution

Tab. 3.1 PV integrated skylight variables

Sunlight intensity patterns playback

Exogenous (recording)	Indigenous (playback)
<ul style="list-style-type: none"> • Sunlight intensity • Sky conditions (intensity patterns) • Obstructions • Climate 	<ul style="list-style-type: none"> • Translation of patterns • Light color • Arrangement of light fixtures • Energy demand

Tab. 3.2 Sunlight intensity patterns playback variables

Domains of interaction

The variables listed earlier in tables 3.1 and 3.2 inform the design of PV integrated skylights and concepts for playback of sunlight intensity patterns. I consolidated the variables to four larger domains which shaped the Sandbox immersive case study:

- *structure* (integration of design and existing building construction and systems)
- *sunlight* (regular recurrent pattern created by the movement of the sun and modified by irregular patterns created by the weather)
- *time* (dynamic properties of daylight provide a temporal stimulus for the occupants of a space)
- *energy* (potential energy production of PV array and calculated energy demand of the dynamic artificial light system).

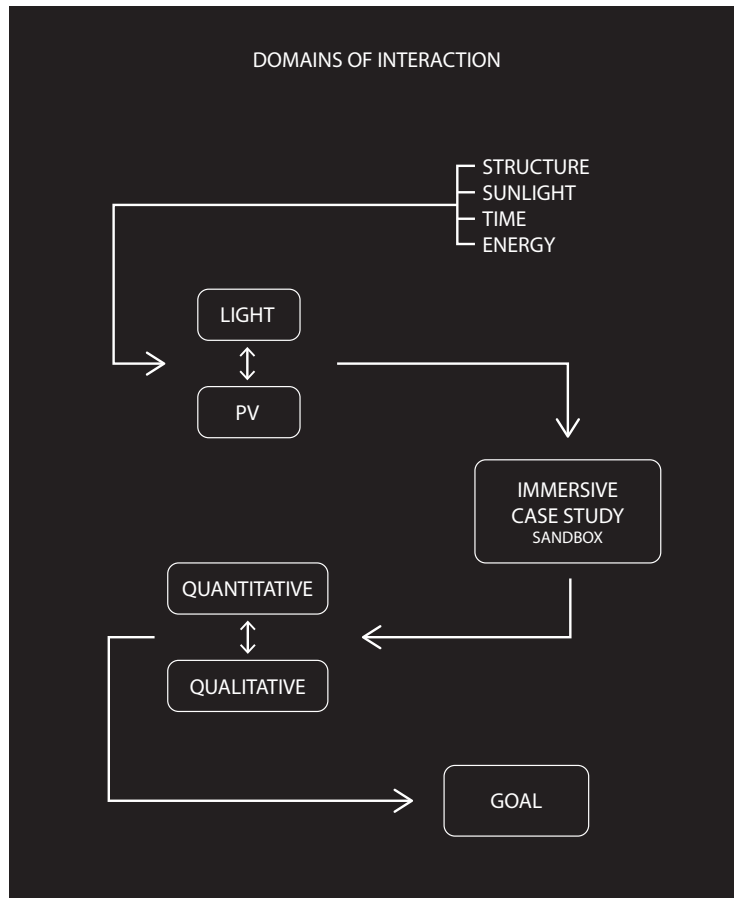


Fig. 3.3 Domains of interaction

Fig. 3.3 identifies the domains of interaction for the current research and how they relate to each other.

To record variations in solar radiation the PV panel assumes the function of a light sensor. This assumption requires a study of the interaction between sunlight and photovoltaic systems to understand the properties of the PV panel and how they compare to a dedicated light sensor. The findings inform the design of the recording and translation process in the immersive case study.

The interaction between quantitative and qualitative methods and design is documented in a journal during the period of the immersive case study to inform the subsequent analysis and evaluation of the process findings.

The documentation and the analysis of the skylight design lead to the goal of the project which is to better understand the design process and the interaction of technology and design.

Fig. 3.4 illustrates the interdependencies between the case study scopes. The two primary objectives of the project are displayed in the center of the diagram. The design aims at improving the light quality of the space without raising the energy demand of the building. The PV integrated skylight introduces dynamic lighting to the space through daylight and dynamic electric light. In this way, the design improves the light quality of the space by responding to the reported preference of occupants for variable lighting over static lighting.

A net-zero balance is established considering the calculated energy consumption of the electric light and the available energy resulting from the skylight size (PV integrated glazing area). The energy demand of the dynamic electric lights is determined by the power that is required to provide enough variation in light intensity for the light effect to be perceivable (threshold, range).

In *Ritual House* Ralph Knowles explains that we are perceiving rhythmic boundaries of space using our senses mentioning several phenomena. One example is a moving shadow that can be sensed by the difference of brightness and temperature. We decide which part of the space we occupy based on our preference for one condition (bright or dark, warm or cool). To make this decision “[w]e must be able to experience the difference for it to make a difference” (Knowles, 2006, p. 9).

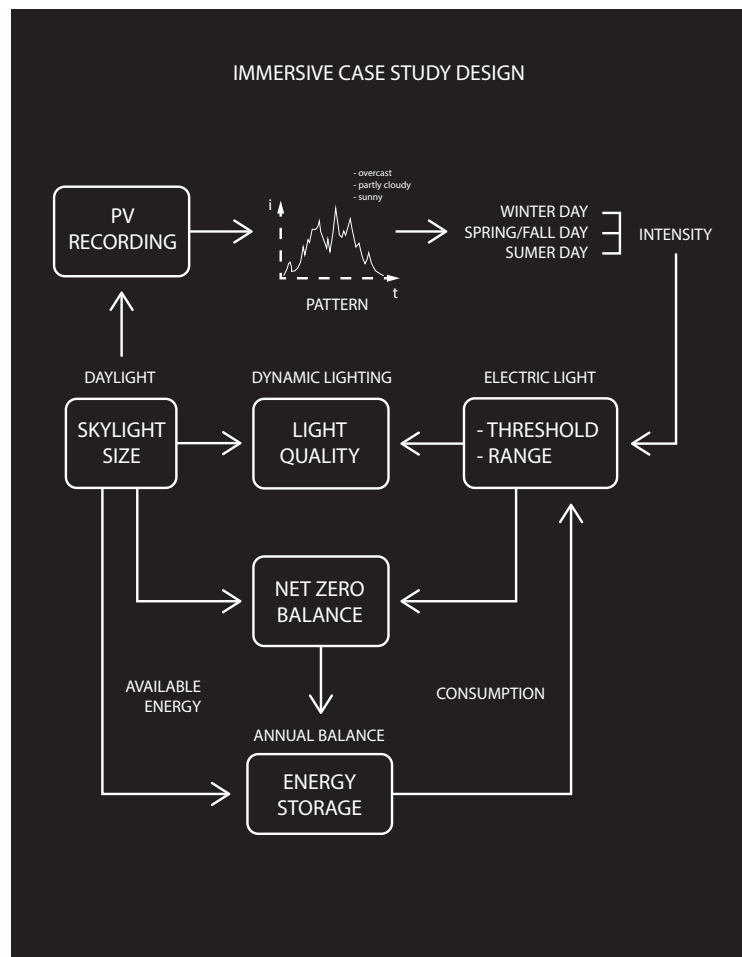


Fig. 3.4 Immersive case study design

In the mid-nineteenth century, the physiologist Ernst Weber investigated the concept of *just-noticeable difference* (JND) in the context of psychophysical research at the time. Weber expanded on determined absolute thresholds for the detectability of stimuli to establish difference thresholds. The research questions are depicted in *The Corsini Encyclopedia of Psychology* (Weiner & Craighead, 2010, p. 887):

“To what extent must the intensity of one physical stimulus differ from the intensity of a second physical stimulus for subjects to distinguish one from the other? What is the smallest increment in stimulus intensity that is detectable?”

Weber found that when comparing two stimuli “we perceive the ratio of the difference to the magnitude of the stimuli” (Weiner & Craighead, 2010, p. 1850). According to Weber’s law the JND increases with the magnitude of the stimulus. Gustav T. Fechner developed a mathematical formula for Weber’s law: $\Delta I/I = k$, where ΔI is the JND, I is the stimulus magnitude, and k is the Weber fraction depending on a particular sense. The Weber fraction is not exactly constant over the full stimulus range, it depends on the stimulus intensity. The *Corsini Encyclopedia of Psychology* provides representative values for Weber fractions including brightness: 0.02-0.05 (p. 1850). The fractions for brightness are used in the evaluation of the skylight’s dynamic lighting impact on the space to confirm that the effect is perceivable.

The electric light consumes energy when the PV array is not producing power and vice versa. Also, the number of daylight hours compared to night hours varies throughout the year which means that the calculated energy demand of the dynamic electric lighting will be different from the energy that has been produced by the PV array on most days. To solve this imbalance the building is used as energy storage whereby the PV array is tied to the electric grid of the building (grid-tied electrical system). The PV power lowers the building’s annual energy demand from the main electric grid balancing the additional annual energy demand of the project’s dynamic electric lighting.

The project’s net-zero balance is managed by monitoring both the PV energy production and the energy consumption of the electric lighting. The PV monitoring data is used to record sunlight intensity patterns which are translated to create lighting protocols that control the dynamic electric lighting. The creation of dynamic light protocols via PV energy monitoring facilitates achieving the net-zero balance because of a strong correlation between the light system’s energy demand and the PV array’s energy production in that the brightness of the electric light is synchronized to the PV array power. The electric light is dimmed based on the information from the energy monitoring system reducing its demand in accordance with the available PV power.

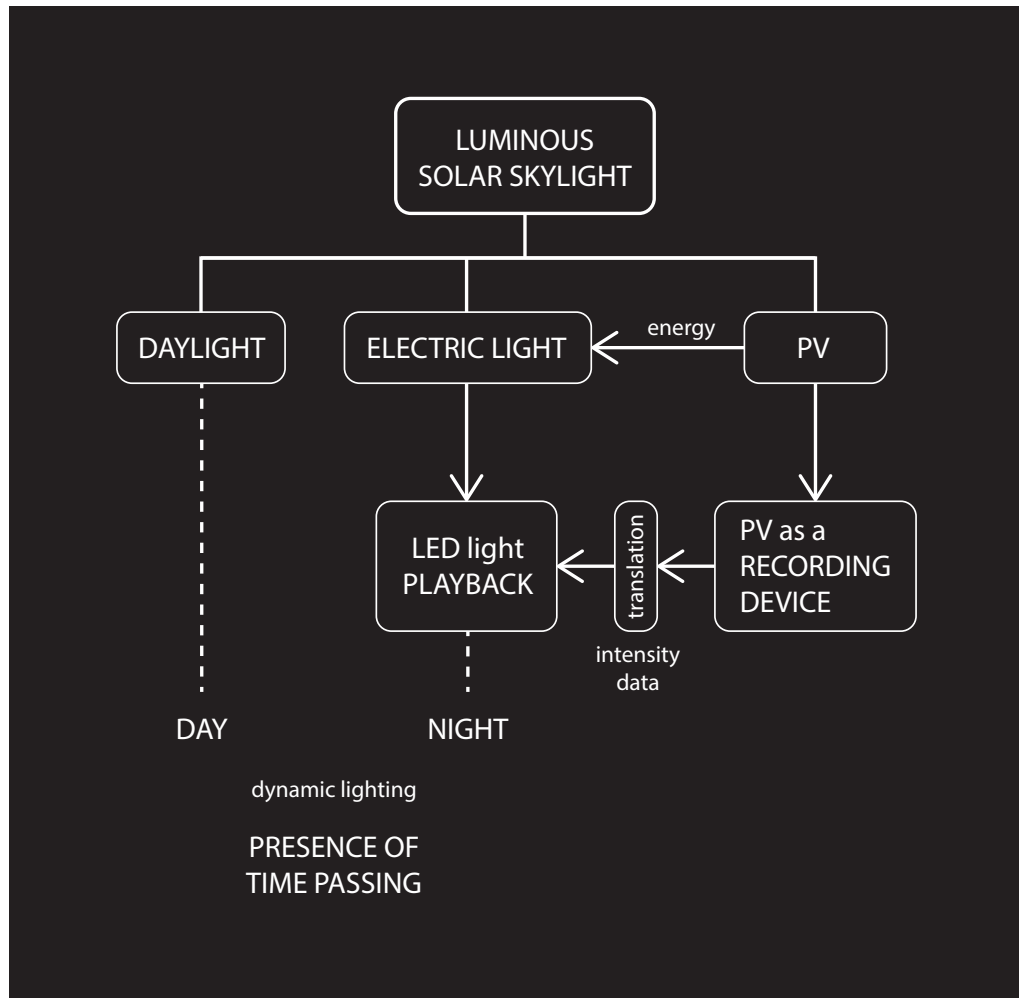


Fig. 3.5 Immersive case study - project components

The label Luminous Solar Skylight refers to a PV integrated skylight which is designed regarding the project conditions of the immersive case study. The project components are represented in Fig. 3.5.

The project purpose is the introduction of dynamic lighting to the Sandbox and give presence to the passing of time through a temporal stimulus. During the day, the natural sunlight, which is dynamic by nature, enters the space through the PV integrated skylight glazing– **DAYLIGHT** (skylight glazing).

At night, dynamic lighting is artificially created with **ELECTRIC LIGHT** fixtures installed in the skylight well. The PV cells integrated in the skylight glazing provide energy for the electric light fixtures and energy monitoring data. The monitoring data represents recorded variations in solar radiation which are translated to natural lighting protocols for dynamic lighting at night.

The immersive case study was structured based on the project timeline in Fig. 3.6 and I assigned the targeted tasks to each project subdomain:

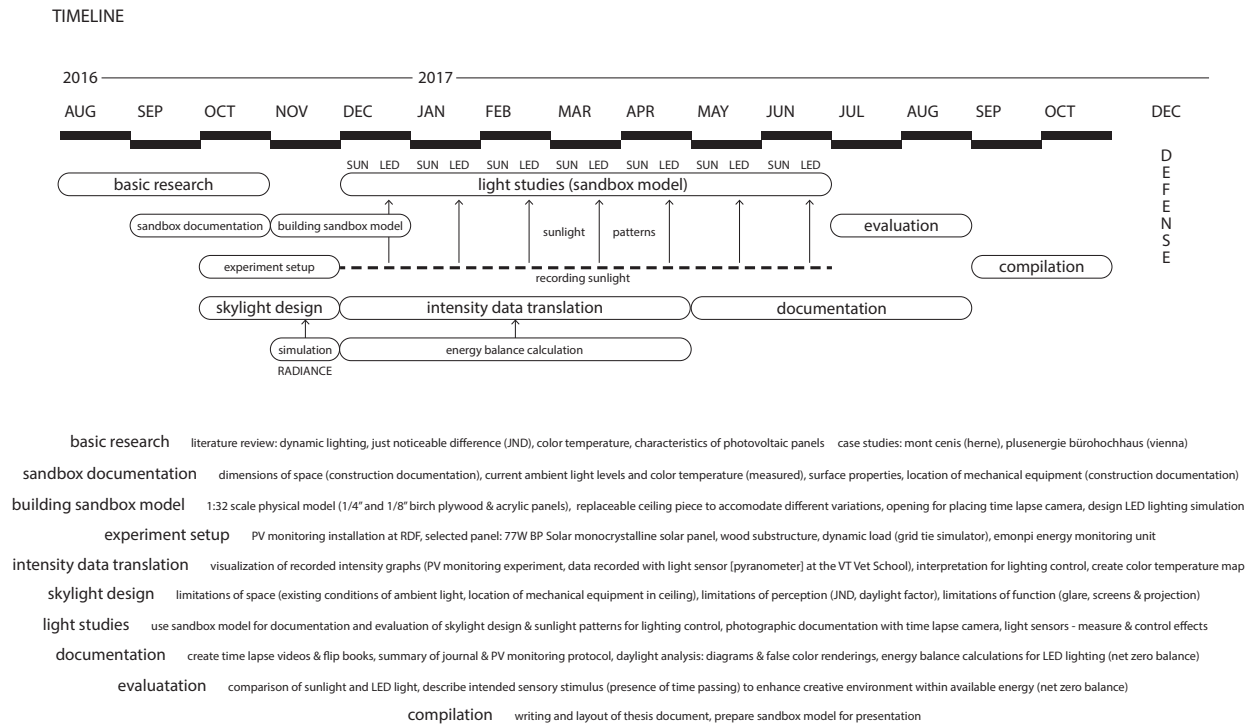


Fig. 3.6 Immersive case study project timeline

Basic research

literature review: dynamic lighting, just noticeable difference (JND), color temperature, characteristics of photovoltaic panels
case studies: mont cenis (herne), plusenergie bürohochhaus (vienna), energy base (vienna)

Sandbox documentaion

dimensions of space (construction documentation), current ambient light levels and color temperature (measured), surface properties, location of mechanical equipment (construction documentation)

Building Sandbox model

1:32 scale physical model (1/4" and 1/8" birch plywood & acrylic panels), replaceable ceiling piece to accomodate different variations, opening for placing time lapse camera, design LED lighting simulation

Experiment setup

PV monitoring installation at RDF, selected panel: 77W BP Solar monocrystalline solar panel, wood substructure, dynamic load (grid tie simulator), emonpi energy monitoring unit

Intensity data translation

visualization of recorded intensity graphs (PV monitoring experiment, data recorded with light sensor [pyranometer] at the VT Vet School), interpretation for lighting control, create color temperature map

Skylight design

limitations of space (existing conditions of ambient light, location of mechanical equipment in ceiling), limitations of perception (JND, daylight factor), limitations of function (glare, screens & projection)

Light studies

use sandbox model for documentation and evaluation of skylight design & sunlight patterns for lighting control, photographic documentation with time lapse camera, light sensors - measure & control effects

Documentation

create time lapse videos & flip books, summary of journal & PV monitoring protocol, daylight analysis: diagrams & false color renderings, energy balance calculations for LED lighting (net zero balance)

Evaluation

comparison of sunlight and LED light, describe intended sensory stimulus (presence of time passing) to enhance creative environment within available energy (net zero balance)

Compilation

writing and layout of thesis document, prepare sandbox model for presentation

3.3 Documentation of the Sandbox

I started my case study research with the documentation process of the existing Sandbox space in the Moss Arts Center at Virginia Tech. To create the framework for the case study project I used several documentation methods identifying the status quo of the project space.

Photographic documentation – qualitative space properties

I used the integrated digital 5-megapixel camera of a Samsung Galaxy Express 3 smartphone to take photographs of both the interior space of the Sandbox and the exterior corridor leading down to the Moss Arts Center's entrance lobby. The Sandbox is visually connected to the corridor via clerestory windows. The camera software allows the manual adjustment of the white balance. I visually compared the color balance of the image on the smartphone screen to the per-

ceived color balance of the real space and adjusted the camera's white balance accordingly. This qualitative adjustment via the researcher's visual perception was done to record and illustrate the impressions of the room as perceived by the occupants.



Fig. 3.7 Clerestory windows – visual access to corridor



Fig. 3.8 Daylight entering the corridor through the main lobby

I took notes of the occupants' personal feedback in a few informal conversations with students who have workspaces in the Sandbox. The space lighting was described as very bright and monotonous. The students also reported a missing connection to the outside. There is some daylight which can be perceived through the clerestory windows, but its intensity is low and has very little impact on the bright space lighting in the space. The neutral white state of the Sandbox had prompted a student art project which was realized during the spring semester of 2014. The participants of the project designed and implemented a geometric pattern in one corner of the room using variations of Virginia Tech's college colors to break the monotony of the space.

The feedback from the students corresponds with my own impression of the Sandbox space. The artificial light is very diffuse and bright which results in a uniform white space. I could only sense the daylight that was visible on the corridor ceiling when I looked directly at the clearstory windows. The Sandbox light ambience was not modified by the daylight.

Construction documentation - quantitative space properties

To document the Sandbox's dimensions and its location in the Moss Arts Center in detail I wanted to refer to accurate plan material. I contacted William H. Sanders, Director of Information Technology Initiatives in the Arts, who had been responsible for the technical equipment coordination during the buildings construction phase. Director Sanders agreed to a meeting in his office where he informed me about an important detail of the project. After the architectural competition, the winning design for the Moss Arts Center had to be adapted to incorporate the structure of an existing canteen facility named Schulz Hall which was located on the Art Center's future construction site. This way important state funding for the renovation of existing campus buildings could be added to the project budget. Director Sanders also provided me with a digital copy of the Moss Arts Center's construction documentation.

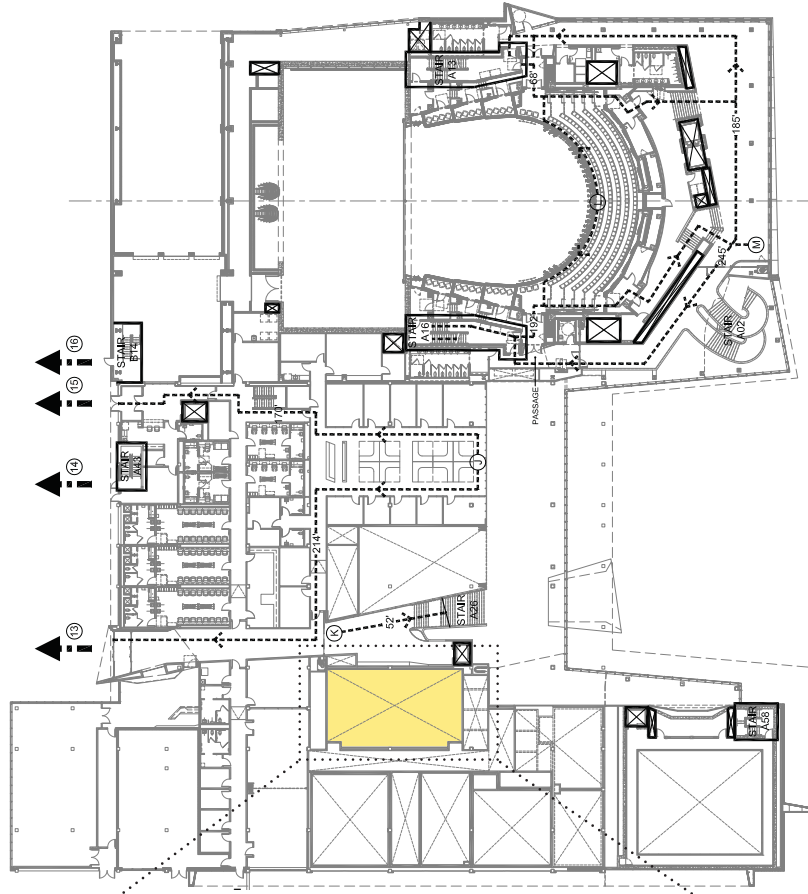


Fig. 3.9 Location of the Sandbox in the Moss Arts Center - Composite Level 02 floorplan
(Source: Moss Arts Center - construction documents)

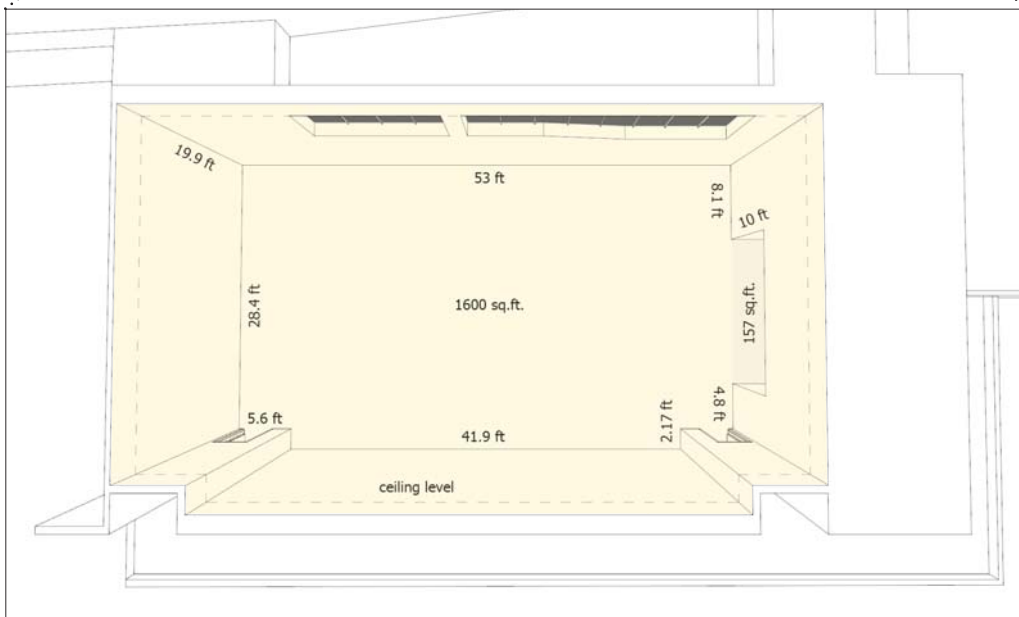


Fig. 3.10 Sandbox physical dimensions

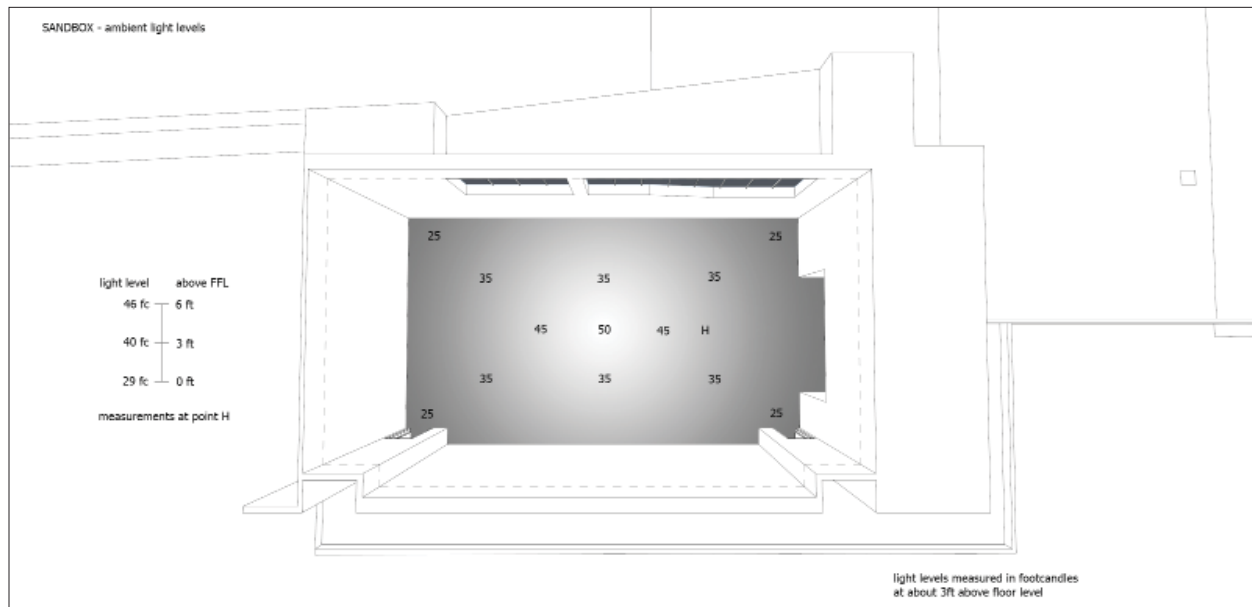


Fig. 3.11 Sandbox ambient light levels

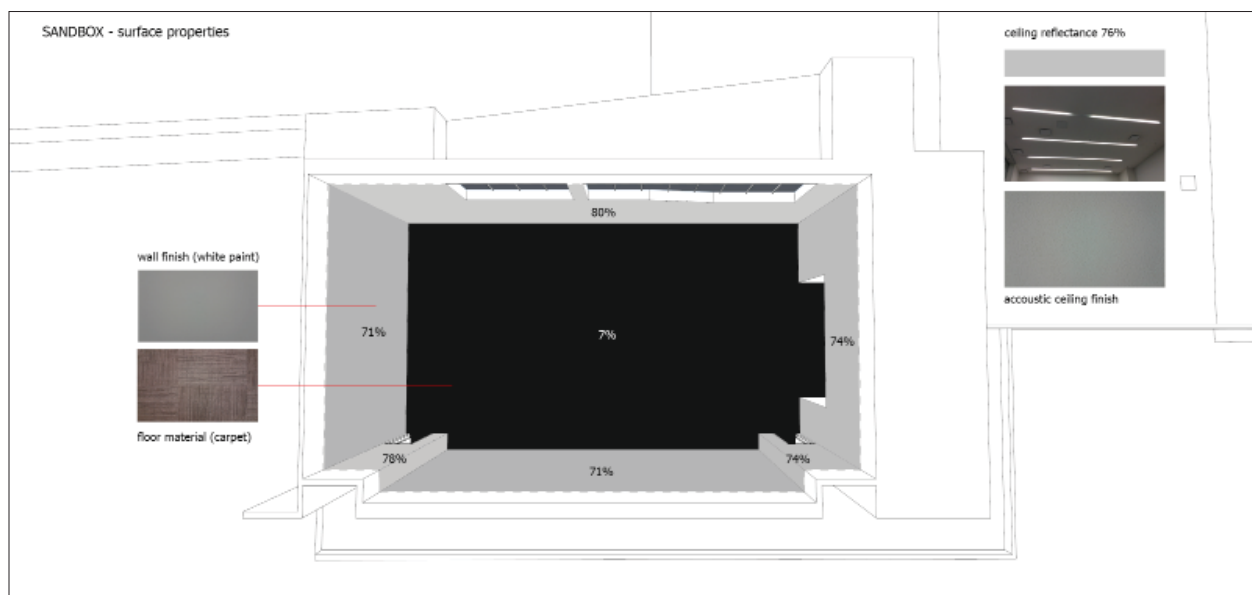


Fig. 3.12 Sandbox surface properties

I measured light levels and approximated surface reflectance levels in the room with Extech LT300 light meters in several spots in the room and mapped the values in di I measured light levels and approximated surface reflectance levels in the room with Extech LT300 light meters in several spots in the room and mapped the values in and . The light levels were measured in foot-candles 3 feet above the floor level. The surface reflectance was estimated by comparing the level of light impinging on the surface (placing light meter in front of the surface facing away from it) to the level of light reflected from the surface (turning the light meter 180° to point it at the surface). I recorded the difference between the two measurements as reflectance in percent.

The reflectance values were verified visually by comparing the surfaces of the room to the fields of a *grey scale & value finder*.



Fig. 3.13 White wall paint finish



Fig. 3.14 Dark grey carpet floor finish

I compared the glossiness of the walls perceived in a photo taken at an acute angle to a sheen guide for interior wall paint. The glossiness of the Sandbox walls most closely resembled the eggshell finish of the sheen guide.



Fig. 3.15 Photographic illustration of wall finish glossiness



Fig. 3.16 Interior wall paint sheen guide

To measure the light color temperature of the room, I utilized the Color Temp Meter smartphone app available for Android devices. The software of the app uses live image data from the smartphone's integrated camera to determine the light color temperature. If the camera is pointed at a white surface the app calculates the color temperature of the light falling on that surface by calculating the deviation of the RGB pixel values from true white. Although this method is not scientifically accurate and limited by the accuracy of the smartphone camera and the proximity of the surface's color to true white. The app is designed to help users to visually select the correct white balance setting on digital smartphone cameras. In the beginning of the case study I assumed that the app's

outputs are accurate enough for the purpose of this research. I took several measurements in different areas of the Sandbox. The Color Temp Meter app indicated a range of light color temperature values between roughly 4000K and 4200K. I thus assumed an average value of 4100K for the light color temperature in the room.

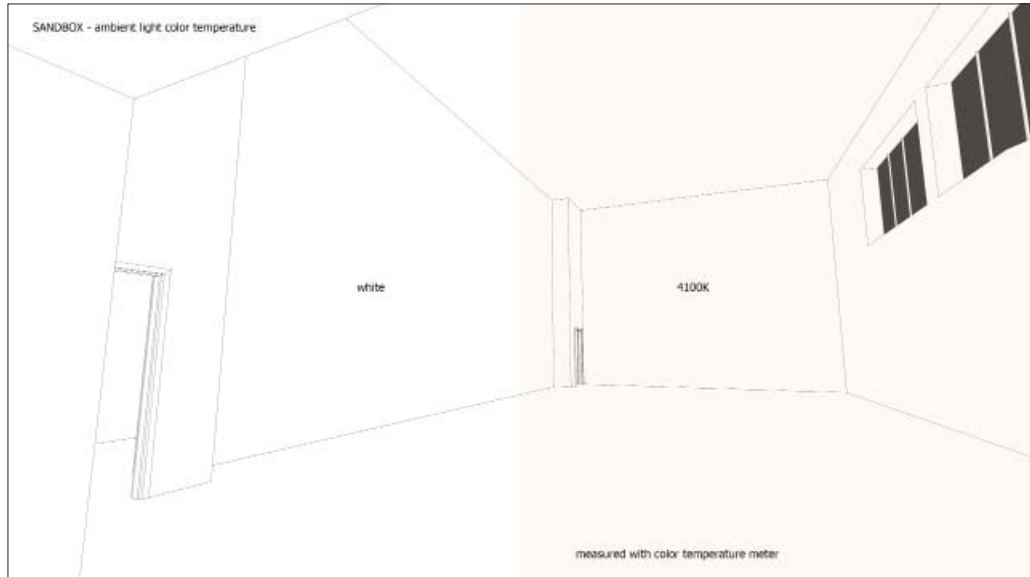


Fig. 3.18 Sandbox ambient light color temperature

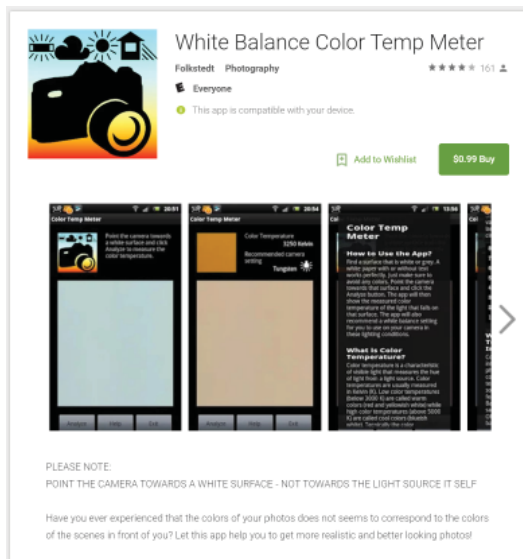


Fig. 3.17 Color Temp Meter app (Source: Google Play store)

I questioned my assumption regarding the app's accuracy later in the process and tested the Color Temp Meter app obtaining quantitative data to corroborate decisions I had made using my own visual judgment. The testing was done by pointing the camera at a computer screen while displaying selected colors in full screen mode. The colors were set to selected color temperatures which were translated to RGB values using the *Blackbody color datafile D58*, a translation schedule for color temperature to RGB created by Mitchell N. Charity. The datafile can be found online (Charity, 2016). I compared the app's indicated color temperature to the color temperature that was displayed on the screen to determine the margin of error. I noted this test method for the Color Temp Meter app in my journal.

I am looking at the chart I found translating color temperature to RGB values. I want to find out if the chart and the color temperature app of my smartphone produce comparable results. To test this, I look at a selected color temperature value and find the RGB value using the chart. I then use Photoshop to display the RGB color on the screen. The color temperature app determines the color temperature of the light by analyzing the color of a true white surface. Assuming the screen's color matches the color of that white surface when illuminated by light with the selected color temperature, the app should display the same value when pointed to the screen.

With a few exceptions, the Color Temp Meter app measurements are quite close to the screen values up to a value of 5500K. The color temperature of the Sandbox lighting was measured between 4000K and 4200K, the measurements of the app are reasonably accurate in this range. The analyzed test values are listed in table 3.3 below.

screen	color temp app	ACCURACY	SANDBOX LIGHTING
1500K	1460K		
2500K	2810K		
3000K	3710K		
3500K	3750K		
4000K	3770K	reasonably close	range of measure- ments
4050K	3850K		
4100K	4180K		
4150K	4340K		
4300K	4470K		
4400K	4480K		
4500K	4480K	very close	
4700K	4600K		
5000K	5240K	reasonably close	
5500K	5250K		
6500K	5600K		
6550K	5930K		
6600K	6250K		
6700K	6400K		
6800K	6490K	inaccurate	
7000K	6490K		
8000K	6490K		
10000K	6490K		
12000K	6490K		

Tab. 3.3 Color Temp Meter app test values 41

I referred to the construction documentation for the specifications of the linear luminaires installed in the Sandbox. The model Stripe STRP31 by Linear Lighting is indicated in the reflected ceiling plans as Type TAG. The building O&M manual specifies Philips F28T5/841/ALTO linear fluorescent lamps for Type TAG luminaires. According to the technical datasheet the fluorescent lamps deliver a color temperature of 4100K. This corresponds with the color temperature measured with the Color Temp Meter app.



Fig. 3.19 STRP31 linear ceiling lamp
(Source: Moss Arts Center - construction documents)

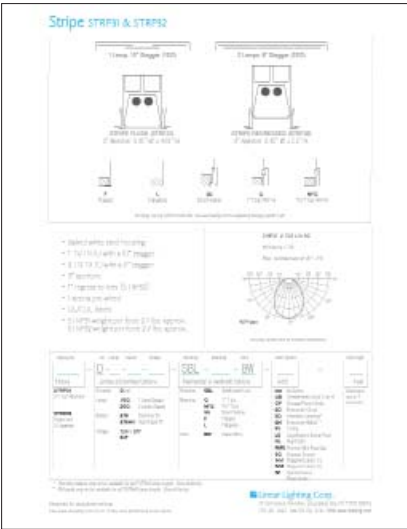


Fig. 3.20 Luminaire specifications
(Source: Moss Arts Center - construction documents)

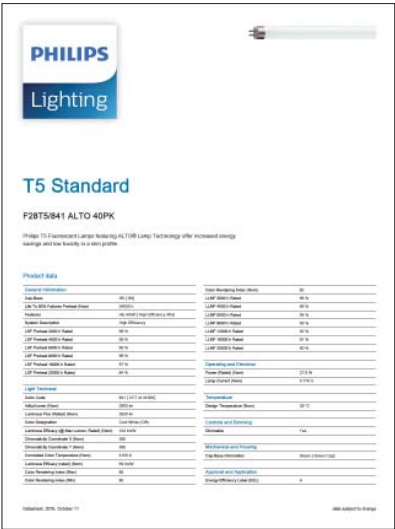


Fig. 3.21 Philips F28T5 datasheet
(Source: Philips Lighting)

Digital 3D model

I used applicable plans and elevations from the digital construction documentation to draw a CAD model of the Sandbox including the adjacent main corridor and the main lobby using the 3D modeling software Rhinoceros. The digital model was useful for the creation of diagrams which illustrated the Sandbox documentation information and to explain the project visually to the thesis committee via rendered images. Rhinoceros includes tools for sunlight studies based on the local sun azimuth and altitude. The daylight simulations from these studies were used to make design decisions in the Luminous Solar Sky-light case study. In this way, the CAD model combined both quantitative and qualitative information for the process of making design decisions.

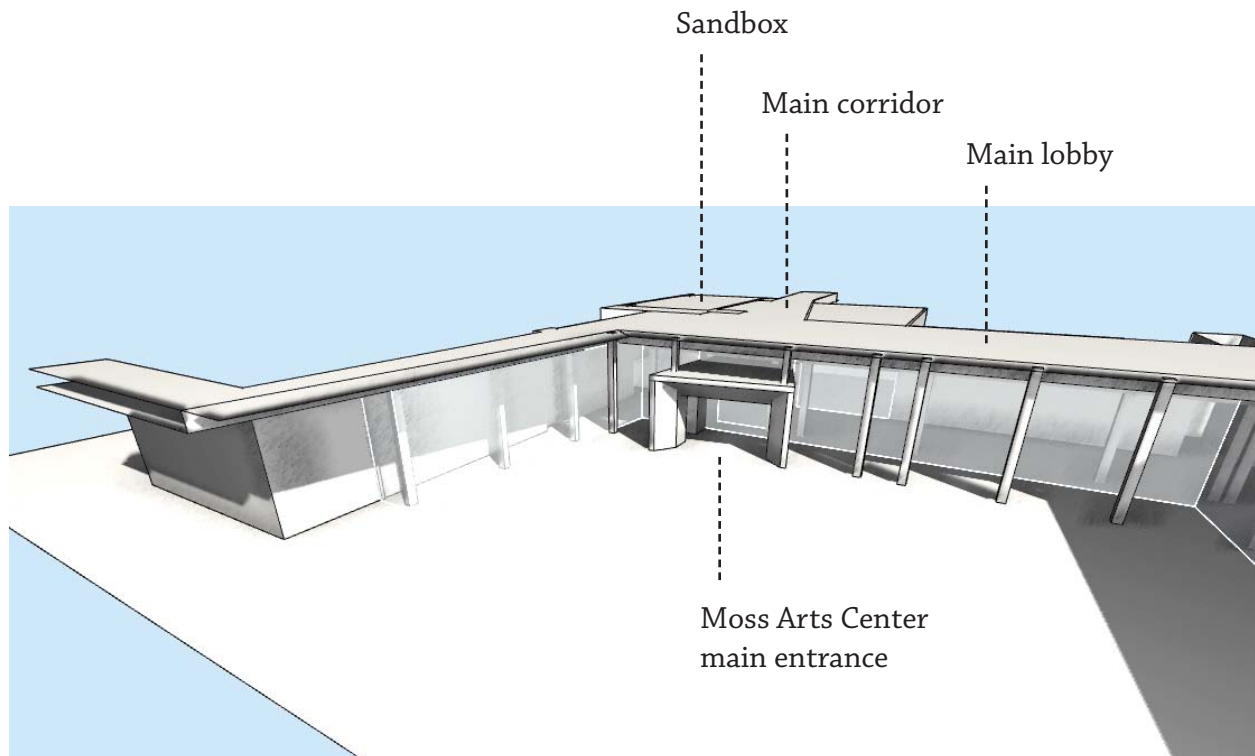


Fig. 3.22 Sandbox context model rendered image

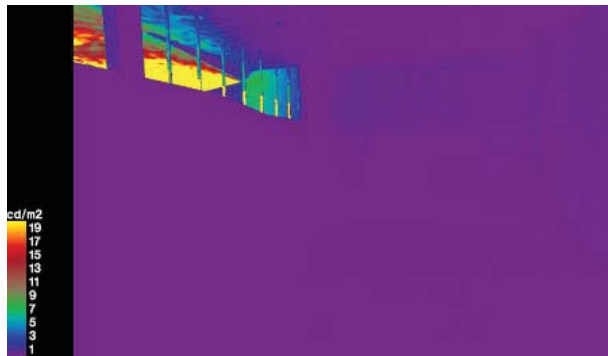


Fig. 3.23 Daylight luminance in as-built condition

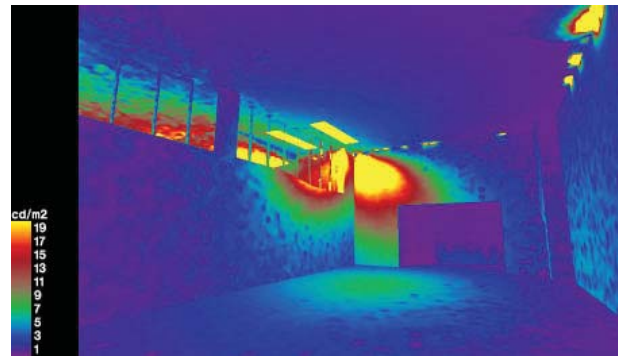


Fig. 3.24 Daylight luminance with skylight

I used the digital model of the Sandbox and the lobby of the Moss Arts Center to calculate the daylight levels with the program DIVA for Rhinoceros. DIVA uses Radiance to render daylighting images of 3-dimensional CAD models. Figures 3.23 and 3.24 show the light levels in the Sandbox considering only daylight. In the as-built condition the daylight was only noticeable in the clerestory windows and did not illuminate the other surfaces. I placed a skylight near the clerestory windows which increased the luminance in that area to 7-19 cd/m^2 .

Design of Skylight location and dimensions

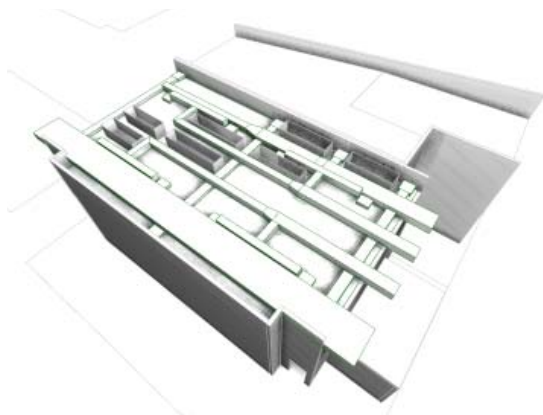


Fig. 3.25 Arrangement of 7 skylights

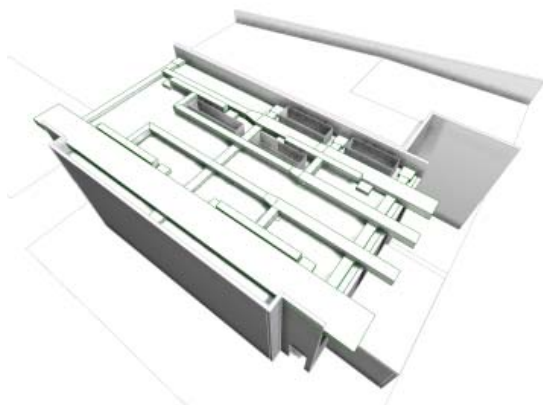


Fig. 3.26 Arrangement of 4 skylights

The Luminous Solar Skylight immersive case study is a speculative project in the way that it includes the installation of glazed PV integrated skylights in an existing ceiling and roof construction. The implementation in the real space was beyond the scope and budget of the thesis project, thus the design had to be evaluated using simulation tools and modeling concepts. Despite the speculative nature of the project's design, the case study was meant to outline a feasible scenario to retrofit the Sandbox with PV integrated skylights.

I modeled the existing mechanical equipment installed above the Sandbox' suspended ceiling based on the mechanical construction documentation. The skylights could now be placed such that a relocation of large air ducts was avoided. I located the skylights near the clerestory windows which allow a small amount of daylight to enter the space from the main corridor. The daylight entering through the skylight thereby amplifies the daylight entering through the clear-story windows. Furthermore, the skylights are placed away from the wall opposing the clerestory windows which is used as a projection surface.

I used the DIVA daylight simulation tools plug-in for Rhinoceros to perform sunlight studies based on the annual sun azimuth and altitude values for Blacksburg's coordinates. I created rendered interior views in a quick first study to find the appropriate number of skylights for the space. The arrangement of 4 skylights appeared to be more suited to the space properties of the Sandbox. I found that the arrangement of 7 skylights overwhelm the space and would be more prone to unpleasant glare.

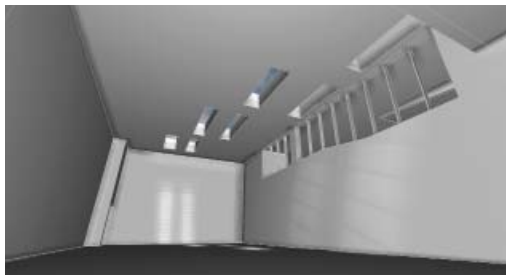


Fig. 3.27 Interior view with 7 skylights

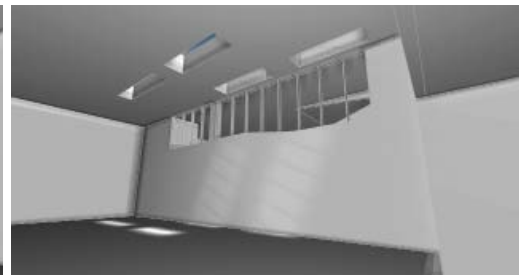


Fig. 3.28 Interior view with 4 skylights

The interior views show that clear skylight glazing produces bright swaths of direct light in the space which would be detrimental to a work environment where computer screens are used. PV integrated glazing mitigates unwanted glare because it blocks a large part of the direct light. Only a small part of the direct light passes through the narrow slits between the PV cells.

I assumed that the glare problem shown in the interior views could be solved this way and modified the glazing in the model by adding an array of PV cells to each skylight. Now I could create two animated sun-light studies, one with clear glazing and another with PV integrated glazing. The animations showed, that the swaths of light were much less pronounced with PV integrated glazing.



Fig. 3.29 clear skylight glazing (rendered frame from animation)



Fig. 3.30 PV integrated skylight glazing (rendered frame from animation)

The documentation of the Sandbox's status quo and the design for the skylights set the framework for the immersive case study in which I investigated the introduction of dynamic lighting to the room. In the construction documentation, the room that is now called Sandbox is referred to as room number 160 "Digital Imaging". The lighting design is based on the requirements for a digital imaging room which could explain the neutral and diffuse lighting condition. After the construction documentation was completed room 160 was renamed and its designated use was changed. The updated function of room 160, now called Sandbox, was defined as project work and meeting space which typically requires a different lighting design than a digital imaging room. The introduction of dynamic light with variable intensity and color is a reaction to the current perceived monotony of the space regarding color and light ambience and aims to improve the work and study environment in the Sandbox.

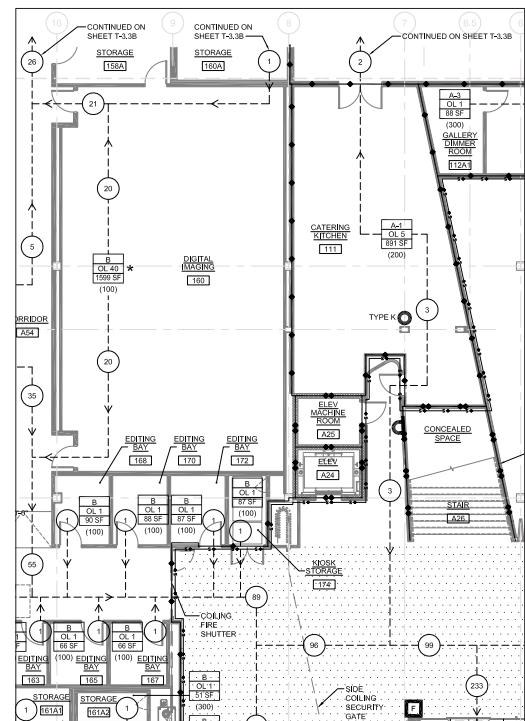
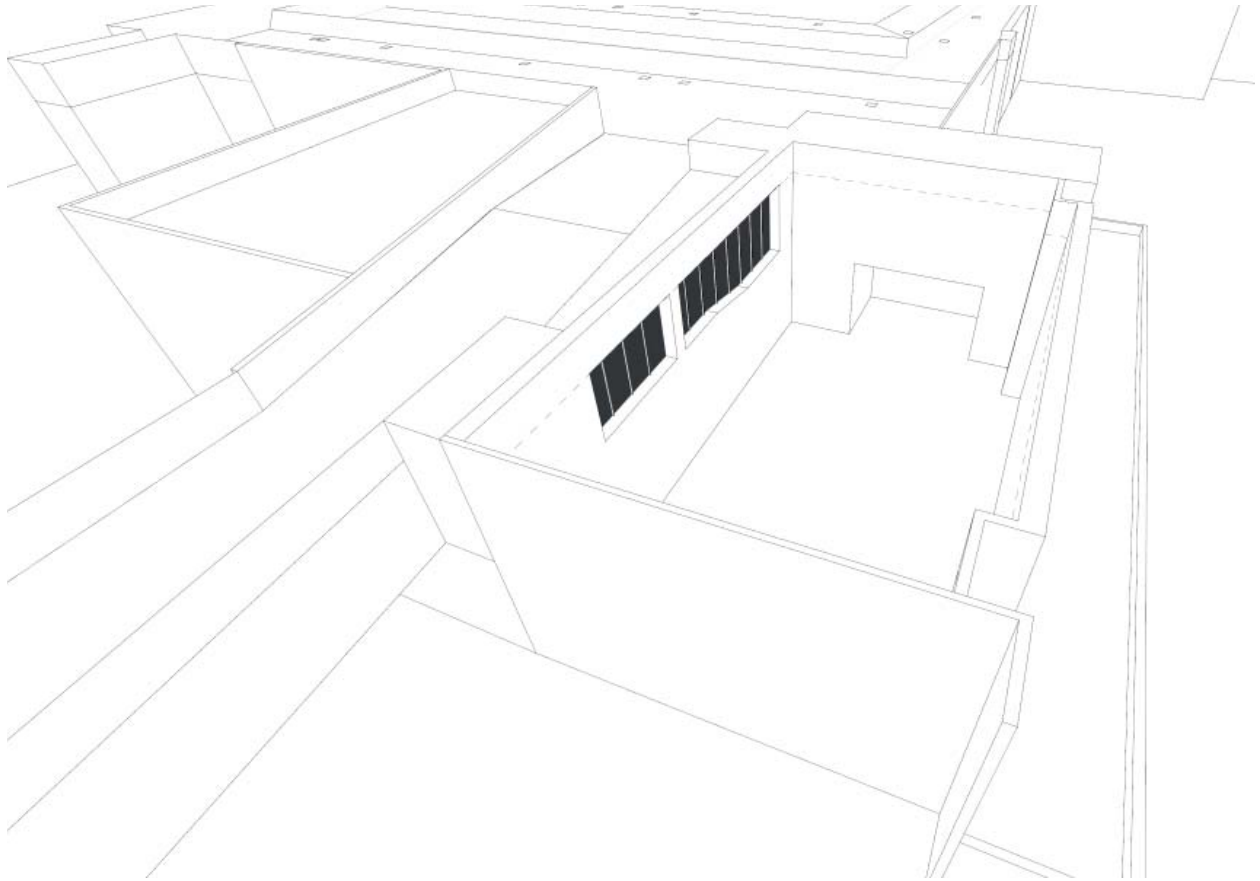


Fig. 3.31 Room 160 "Digital Imaging" as shown in the Moss Arts Center construction documentation, Level 01 – Partial Life Safety Plan



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(Source: <https://artscenter.vt.edu>)
- Fig. 3.9 Location of the Sandbox in the Moss Arts Center
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(Source: Moss Arts Center - construction documents)
- Fig. 3.17 Color Temp Meter app
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Executive Architect: STV group Inc.
(Source: Moss Arts Center - construction documents)
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Design Architect: Snøhetta
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(Source: Moss Arts Center - construction documents)
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4. A Stimulus for Creative Inspiration – Project Implementation



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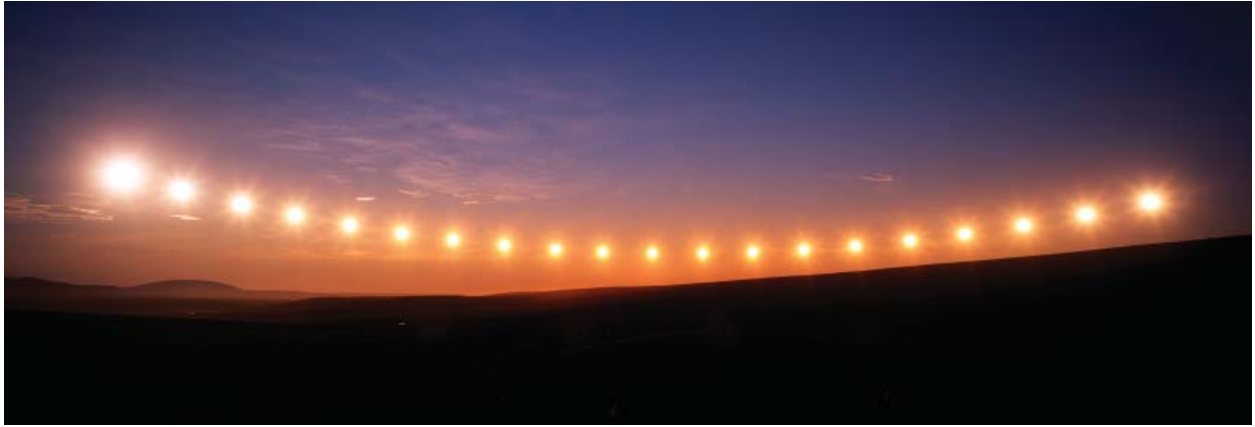


Fig. 4.1 Multiple exposure of midnight sun

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The purpose of the Luminous Solar Skylight is to introduce a temporal stimulus to the Sandbox that facilitates the perception of the passing of time. The design of the lighting feature is aimed at stimulating creative inspiration and connect inside to out thematically. I developed the design procedures and research methods of the current thesis project based on the information I collected during the literature review and the Sandbox documentation process. The goal is to improve the working environment and to address deficiencies associated with a lack of connection to the outdoors which were reported by occupants. The Luminous Solar Skylight project was described in section 3.2. where figure 3.4 delineated the design of the immersive case study while figure 3.5 described the project components. I created a more detailed project diagram introducing sub-projects for the case study which are illustrated in figure 4.1.

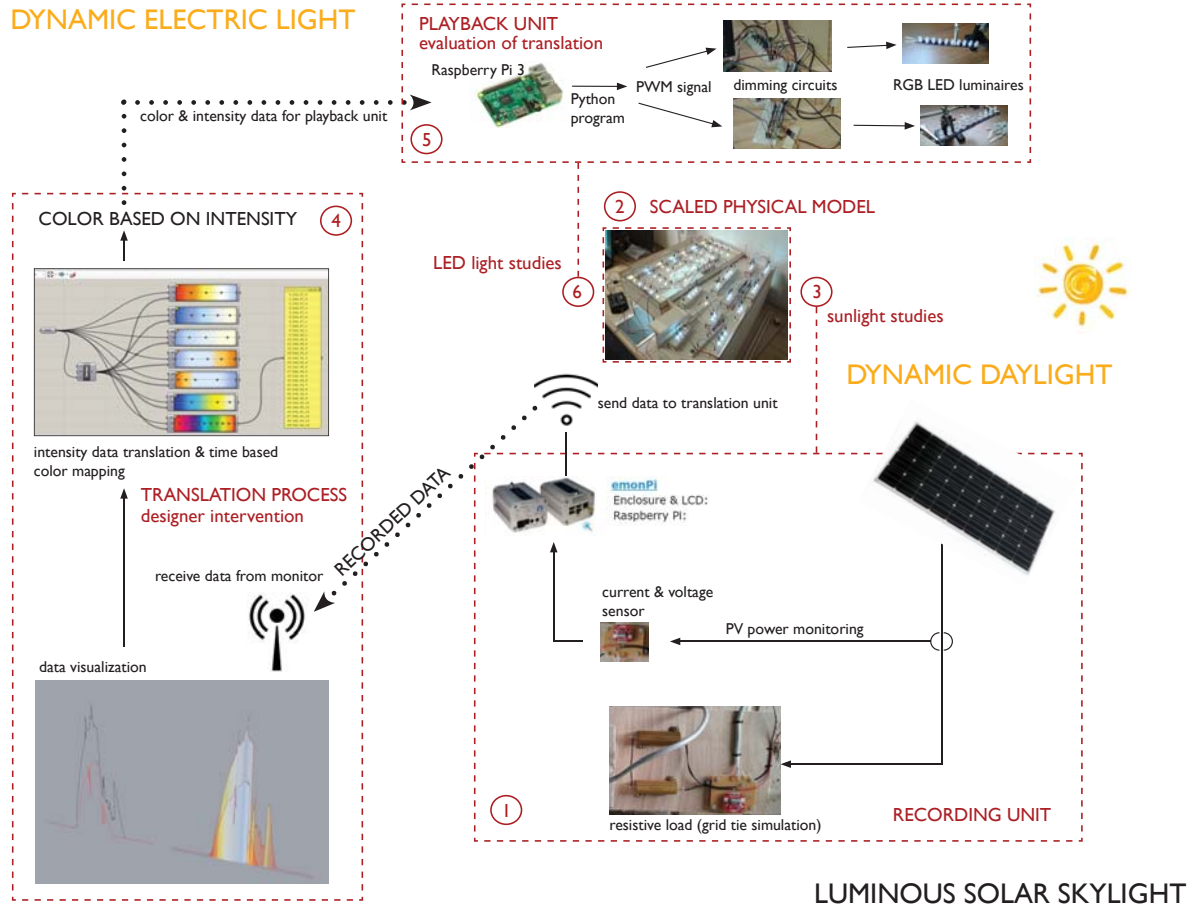


Fig. 4.2 Luminous Solar Skylight - Immersive case study project diagram

The sub-projects are numbered based on the chronological sequence in which they were conducted. The recording unit (1) represents the energy monitoring component (PV recording) of the Luminous Solar Skylight. The recorded data formed the foundation of the project and informed the translation process from insolation sensing to lighting control (4). During the translation process, I created color and intensity data which was used to test the control protocols for the RGB LED lighting. The Luminous Solar Skylight's visual impact in the Sandbox was investigated using a scaled physical model (2) which I built early in the case study project during the Sandbox documentation. Designing and constructing the model helped me to determine which parts of the Moss Arts Center influenced the project and therefore needed to be incorporated in the case study. Once the physical model with the proposed skylights was completed I conducted sunlight studies illustrating the dynamic daylight entering the model (3). Finally, I built the LED luminaires and dimming circuits of the skylight lighting which formed the playback unit (5) and incorporated them into the physical model to conduct the LED light studies (6) illustrating the dynamic electric light. The design procedures and research methods of the sub-projects are described in detail hereafter.

4.1 Sunlight recorder (design-build experiment)

The main purpose of the sunlight recorder was to generate temporal data that can be used to create dynamic lighting protocols controlling the skylight's integrated electric light fixtures. A PV energy monitoring unit recorded variations in solar radiation and logged the data in its internal memory. I collected the data once a week for further use in the project. Simultaneously I collected data from a Pyranometer (Onset S-LIB-M003) and compared it with the PV energy monitoring data. This was done to confirm that the response characteristics of the PV panel were similar to a radiation sensor. The design of the sunlight recorder is illustrated in figure 4.2. The components of the experimental setup are: a PV panel, a deep-cycle battery, a solar charge controller, a power inverter and an energy monitoring unit.

I purchased the EmonPi energy monitoring system which is designed for use in private homes with grid-tied PV systems. The EmonPi is an inexpensive product and comes with the manufacturer's own open source monitoring software Emoncms which allowed modifications for the implementation in the sunlight recorder experiment. At the time, I did not have expertise in the design of electrical circuits and consulted Kaleb Kleine who is a graduate student in

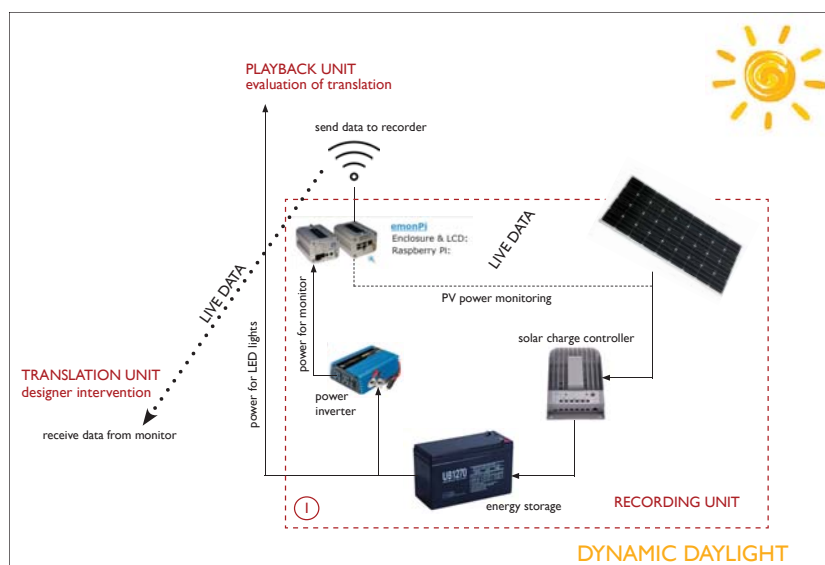


Fig. 4.3 Sunlight recorder - initial design diagram

the electrical engineering department. I discussed the initial sunlight recorder design with Kaleb who advised me that the components needed to be modified if I wanted to ensure that the panel produced power whenever sunlight was present. The problem was that when the battery is fully charged the main load on the panel would disappear. Since a PV panel only produces power if a load is connected the energy monitoring would show drops in the power curve at times when the solar radiation doesn't change. As a result, these drops would skew the recording of solar radiation.

Kaleb suggested to build a small circuit with a resistive load for the panel to simulate a grid-tied PV system as shown in figure 4.3. Grid-ties are typically used for PV systems when the use of batteries is not feasible and usually include Maximum Power Point Tracking (MPPT) technology. Using MPPT in the sunlight recorder would make the circuit design very complex. Therefore, it was decided that the data should be sufficiently accurate for this experiment

without using MPPT. The resistive load simulates the grid-tie by dissipating the energy produced by the panel ensuring that the power level corresponds to the level of solar radiation. The circuit also allows for measuring current and voltage which are logged by the energy monitoring unit.

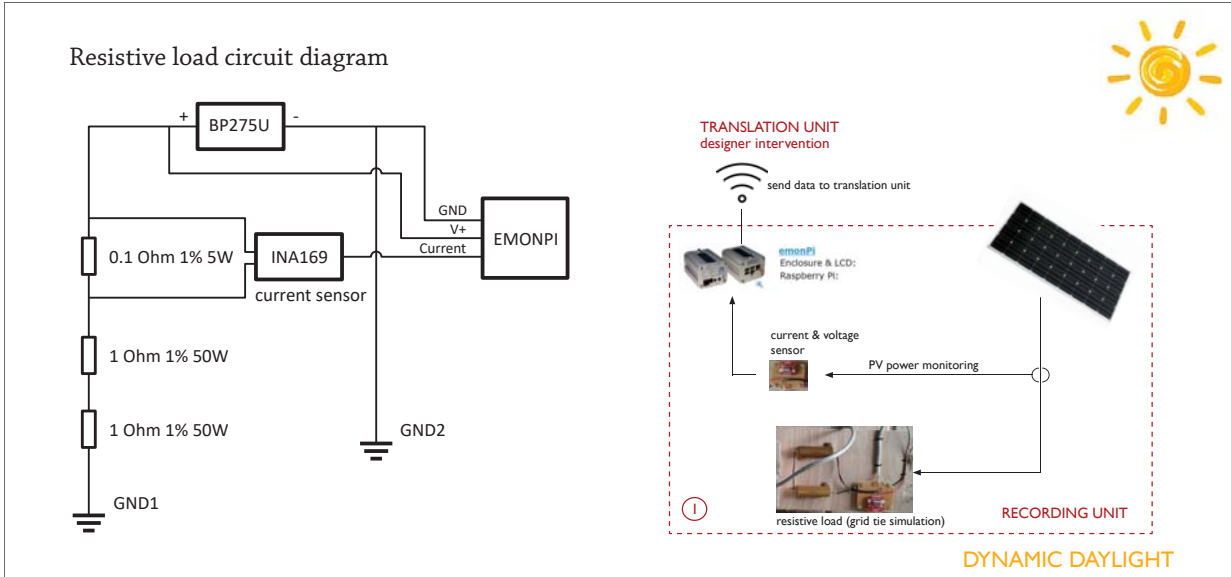


Fig. 4.4 Sunlight recorder - updated design

I presented the design to Professor Robert Schubert to apply for funding through a student initiated grant and to discuss an appropriate location for the sunlight recorder. We selected the CAUS Research and Demonstration Facility (RDF) located just outside of Virginia Tech's main campus. RDF is specifically dedicated to accommodating experiments and offers a straightforward approval process for the implementation of experimental setups. The PV panel could be placed on the roof of the facility's test cell building. The energy monitoring unit was placed in test cell 10 below the panel location.



Fig. 4.5 VT CAUS Research and Demonstration Facility (Source: <https://www.caus.vt.edu/about/research>)



Fig. 4.6 Roof of test cell building at RDF (Source: <https://www.caus.vt.edu/about/research>)

PV panel specifications

Professor Schubert suggested to use one of the two types of PV panels owned by the School of Architecture + Design. I tested three panels (two 77W SBM Solar modules and one 75W BP solar module) using a multimeter and compared the measurements with the specified V_{oc} values. One SBM Solar panel was faulty and removed from the selection. Between the two types I selected the BP275U panel manufactured by BP Solar because the specific I-V curves were available. This information was needed to design the circuit of the sunlight recorder. The specifications of the BP275U module are listed in table 4.1.

BP Solar BP275U	
Rated peak power (P_{max})	75 W
Rated voltage (V_{mp})	17 V
Rated current (I_{mp})	4.45 A
Open circuit voltage (V_{oc})	21.4 V
Short circuit current (I_{sc})	4.75 A

Tab. 4.1 PV module specifications

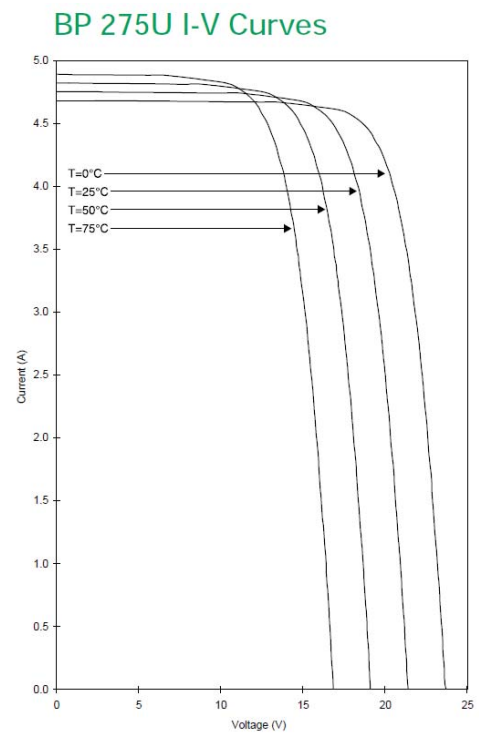


Fig. 4.7 PV module specific I-V curves

Designing and building the recording unit

After selecting the BP275U solar panel for the sunlight recorder I started the design process. First, I measured the physical dimensions of the BP275U. The panel's length and width are 4'6" and 2' respectively. I needed to determine a way to install the sunlight recorder at RDF. There were no mounting structures available to secure the solar panel on the roof of the test cell building hence I needed to construct a substructure for the sunlight recorder.



Fig. 4.8 Pressure treated 2x4 lumber



Fig. 4.9 Wood connector



Fig. 4.10 Foldable support frame



Fig. 4.11 completed adjustable substructure with mounted BP275U

Building the substructure

Due to its location outside, the substructure needed to be weatherproof. In line with this, I considered two material options, galvanized steel and pressure treated timber. I selected the timber option because it was more cost effective and more adaptable to modifications. The tools and materials required to construct the sunlight recorder were sourced from two local hardware stores. I used simple galvanized wood connectors and pressure treated 2x4 lumber which enabled me to build the substructure at home on the terrace using tools at hand. I cut the 2x4 lumber to the size of the actual panel dimensions and then used the panel as a square to arrange the parts before joining them. For easier maintenance, I decided to mount the solar panel at an angle of 35° so that rain would contribute to self cleaning, presumably mitigating soiling. I wanted to transport the substructure and panel in my private car which led me to create a foldable support frame. This way the substructure was adjustable and the solar panel could be set up at the desired angle.

Installing the sunlight recorder

With the completed support frame and the solar panel mounted I could install the sunlight recorder at RDF. I located the recording unit on the roof of the test cell building and placed the monitoring equipment in test cell 10 directly below. The solar panel was mounted at an angle so I needed to orient the recording unit to the South to neither amplify the sensed radiation in the morning nor in the evening and make the recordings comparable to the radiation sensor data. A rotation toward the East would have increased the power production in the morning and decreased the evening power.

Rotating the unit to the West would have result in an opposite effect with lower recorded values in the morning and higher values in the evening. I determined the recording unit's rotation using a smartphone compass showing true north via a GPS bearing toward the geographical location of the North Pole.

Solar panel modules are typically equipped with a junction box which houses cable connectors and bypass-diodes used to mitigate partial shading effects. I connected the photovoltaic cables to the positive and negative connection points in the junction box and ran the cables along a downspout into test cell 10.

To test the cable connections, I measured the open circuit voltage of the module using a multimeter. The actual V_{oc} of 19.7V was slightly lower than the specified 21.4V which was probably due to the module's age. Solar panels degrade over time resulting in adverse effects including lower V_{oc} values. The difference of 1.7V was acceptable for the experimental purpose.

I connected the EmonPi energy monitoring device to the grid-tie simulation circuit and placed them in the test cell. Now I could connect the photovoltaic cables to the resistive load and plug in the EmonPi's power supply unit. Kaleb helped me to start the monitoring process and showed me how to use the Emoncms software. We could start two feeds to log the voltage and the current of the solar panel. As expected the software was easy to use. However, I would have to be careful with the EmonPi's internal clock. The EmonPi automatically restarts after a power loss and synchronizes the clock after the boot process using real time data obtained from the internet through its integrated WIFI feature. The test cell building did not provide internet which would potentially lead to problems



Fig. 4.12 Sunlight recorder on test cell building roof



Fig. 4.13 Non-invasive ballast securement



Fig. 4.14 Photovoltaic cable routing



Fig. 4.15 Solar panel junction box

with the timestamps of the monitoring data. For this reason, I set a weekly schedule to check the time of the internal clock and download the monitored data regularly. When the time was incorrect I took a note for documentation and used my cell phone's hotspot to connect the EmonPi to the internet and thereby synchronizing the internal clock.



Fig. 4.16 Monitoring equipment at test cell 10



Fig. 4.17 Resistive load (simulating grid-tie) and EmonPi energy monitoring unit

PV energy monitoring visualization

I obtained the first data set on December 8th, 2016 and saved the recorded values of current and voltage in an Excel spreadsheet. I created a grasshopper program to visualize the data. The program created a bar for each measuring point and aligned them along the x-axis. The height of the bars was scaled along the y-axis based on the measured current and voltage values. Each bar was assigned a color based on its dimension on the y-axis. The visualization helped me to evaluate if the data from the sunlight recorder would be useable for the translation to color and intensity based lighting protocols. I used a color scheme that

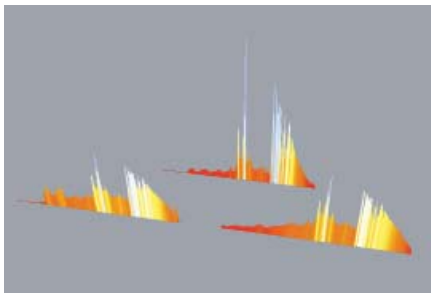


Fig. 4.18 Grasshopper visualization of first data set from December 8th, 2016

assigned warm colors to low values and cool colors to high values approximating the properties of sunlight. During mornings and evenings when low-intensity sunlight has a warm color temperature while the high-intensity sunlight during the day has high color temperature. The color scheme assumed a clear day and neglected the influence of atmospheric conditions like clouds or fog. The visualization showed a great variety of colors where even small variations in the data produced a perceivable difference in color. The data was thus useable to create color gradients for the translation of monitoring data to lighting protocols.

4.2 Scaled model of the Sandbox (architectural design method)

One of the objectives of the immersive case study was to study the dynamics of daylight and electric light in the Sandbox. During the documentation process, I created digital renderings of the daylight entering the Sandbox using DIVA for Rhinoceros. In addition to the quantitative false color images, Radiance also produces very realistic true color renderings of daylit spaces which was useful to illustrate how much daylight could be perceived when the existing electric lighting is turned off. I visually compared the brightness of the space before and after the addition of the skylights.

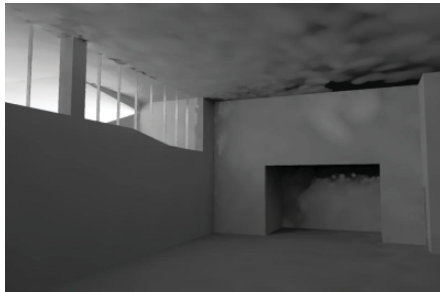


Fig. 4.19 Current daylight situation (no electric space lighting)



Fig. 4.20 Daylight situation with skylights (no electric space lighting)

While single frames could be created relatively quickly it proved to be quite complex to render realistic animations that could represent the movement of the sunlight over the course of a day while showing the impact of changing light color temperature. In addition, I wasn't confident that within the timeline for the thesis I would be able to become proficient using Radiance to simulate the light from the colored LED skylight in a realistic way. Consequently, I needed to find another way to achieve the described objective of studying the dynamic light.

Physical models in architectural design

The making of physical models is a very popular and effective method in architectural design. It allows the designer to quickly observe a physical scaled recreation of a real object or space from different viewpoints and angles, and to evaluate the decisions made in the design process. The scale of the model is selected based on the level of detail required to serve the purpose. Design updates can be incorporated quickly and provide immediate visual feedback. Architectural models are particularly powerful tools to depict the visual effect of sunlight entering through apertures in the building envelope. The characteristic qualities of the architectural models described above work well to create realistic dynamic light studies. The current availability of small high quality digital cameras enables designers to mount cameras inside manageably sized models and take photos or even videos that give an accurate impression of the interior space.

Designing and building the Sandbox model

The previously mentioned qualities of architectural models make them applicable for the study of dynamic light. In the current project, I used a model of the Sandbox to generate time lapse images to illustrate the visual impact of both daylight entering through skylights as well as dynamic LED lighting installed in the skylight wells. I started by adapting the 3-dimensional CAD model that I had created for the documentation of the Sandbox to find an appropriate scale for the physical model. The model had to be large enough for the researcher to easily access the inside of the space through openings in the walls. I selected 3mm birch plywood for the structural components of the model. Birch plywood is sturdy enough to give a sizeable model adequate structural integrity and can tolerate the impact of sunlight and humidity over an extended time period. I purchased 12 x 24 x $\frac{1}{8}$ inch birch plywood boards that would be cut with laser cutters. I built the model in two parts. One part represented the Sandbox and a second part included the corridor that can be seen through the clerestory windows. The model was scaled such that the largest pieces of the model parts would fit on one of the plywood boards. The minimum scale was also based on the size of 5mm LED bulbs which are inexpensive and available with several different light colors including variations of warm and cool white as well as tri-color RGB. 5mm LEDs could easily be installed in the model using plastic holders. I determined that a model scale of 1:32 (1' equals $\frac{3}{8}$ ") best fulfilled the mentioned requirements.

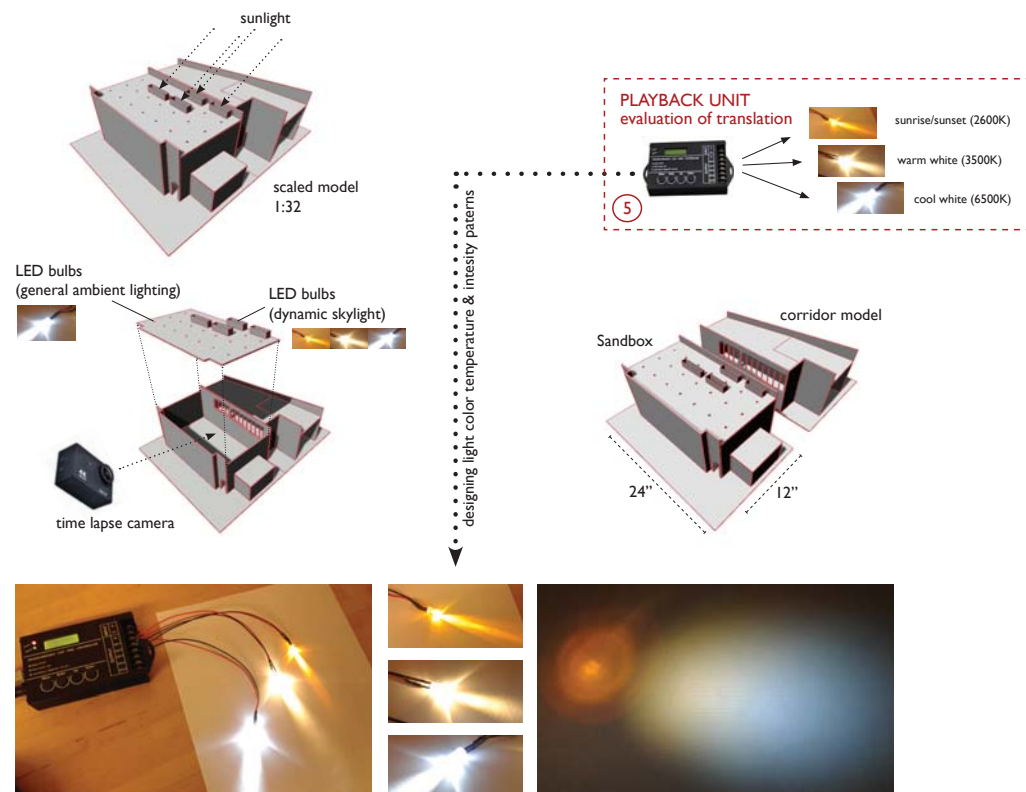


Fig. 4.21 Advanced Design Lab Fall semester 2016 - model concept

After determining the appropriate model scale, I created a new CAD model which was then subdivided into the corresponding parts for the physical model. I drew the parts in 3D while considering the area and thickness of the plywood boards. 2-dimensional outlines of the parts were created to cut the parts using a laser cutter.

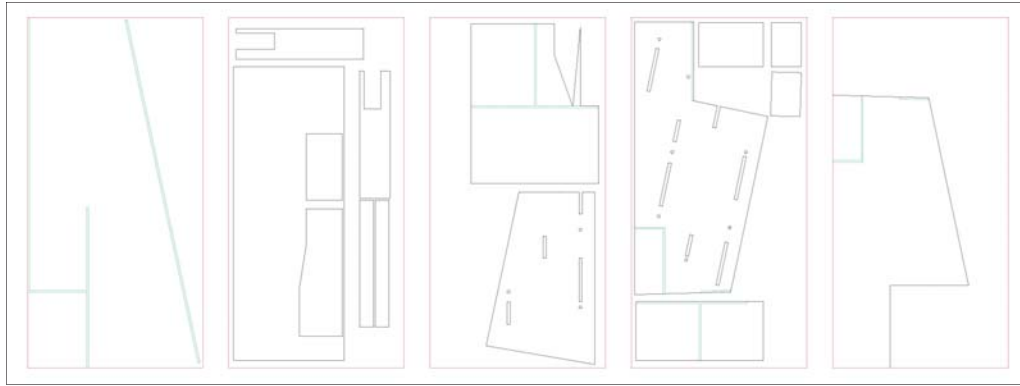


Fig. 4.22 Laser cut lines for model pieces - arranged on 12 x 24 inch plywood boards

I designed the base lighting in the model to closely match the existing light conditions in the Sandbox as documented in chapter 3. To create the required diffuse bright light, I selected 5mm flat top LEDs. Typical 5mm LEDs have a round lens and a beam angle between approximately 20° and 45° . Flat top LEDs have flat lens bodies resulting in a beam angle of about 120° to 140° . The large beam angle was helpful to create a light distribution in the model which resembled the light distribution produced by the existing luminaires in the Sandbox. The available white LEDs had specified color temperatures of 3500K and 6500K. I planned to use the Color Temp Meter app to determine the specific ratio of both color temperatures which provided a color temperature of 4100K which was approximately equal to the existing Sandbox lighting.



Fig. 4.23 5mm LED – round lens



Fig. 4.24 5mm flat top LED – flat lens

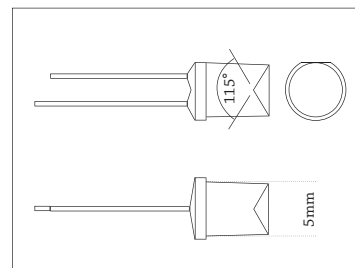


Fig. 4.25 LED dimensions and geometry - flat lens



FLAT TOP 5mm LED	forward voltage	MCD at 20mA	power angle
white	3.2	20000	120-140°
warm white	3.2	15000	120-140°

Fig. 4.26 LED specifications

As listed in figure 4.26, the cool white flat top LEDs had a higher luminous intensity than the warm white LEDs. I estimated that by replacing each line of luminaires in the Sandbox ceiling with a row of 3 flat top LEDs in the ceiling of the model with alternating warm and cool white color I should be able to recreate the existing light condition.

LED Calculator .net

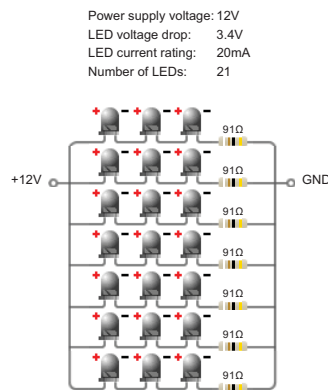


Fig. 4.27 LED circuit design

To test this, I used an online calculation tool (LED Calculator, 2011) to design a circuit powering the 5mm LEDs. I used 5mm flat top LEDs, jumper wires, resistors, breadboards, a programmable LED time controller with PWM dimming capability, and a 12V power supply in the circuit design. Based on the design proposed by the LED calculator, groups of 3 LEDs were connected in series with a 91Ω resistor. Each group needed to be connected to the 12V power supply in parallel resulting in the specified 20mA current for each LED bulb.

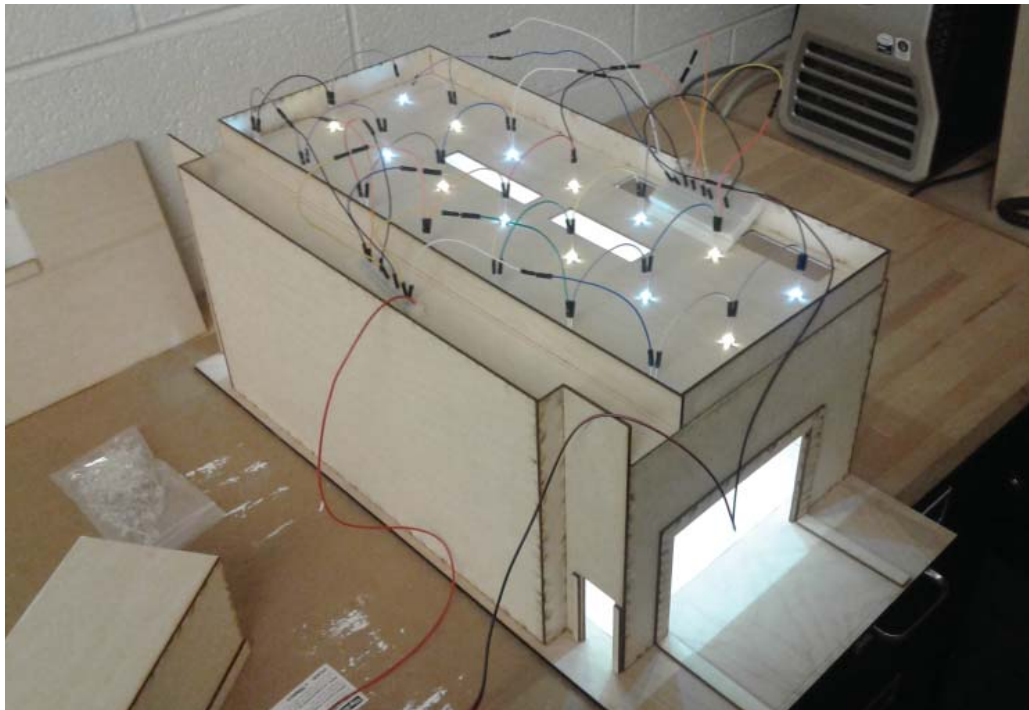


Fig. 4.28 Sandbox model ceiling lighting test

I assembled the pieces of the Sandbox model and painted the ceiling with white acrylic interior paint. I selected an eggshell finish to match the room's observed actual wall specularility. Then I mounted the LEDs into precut holes in the ceiling using plastic holders alternating warm white and cool white LEDs in a regular grid. The LEDs were connected to the resistors and the power supply through jumper wires using a breadboard. This non-permanent connection method is typically used to build prototypes of electrical devices and provides flexibility for changes in the design and test process. I documented the first test of the model lighting with a smartphone camera.



Fig. 4.29 Sandbox model interior lighting test – photo documentation

I used an Extech LT300 light meter to measure the light levels in the model. The light level was significantly lower than the target value which I attributed to the fact that the walls in the model hadn't been painted yet. The light color temperature of 4400K measured in the model was very close to the 4100K measured in the Sandbox. I tested the dimming function of the programmable LED time controller by setting the intensity to several different values and measuring the resulting light levels as well as color temperature in the model. The test values listed in table 4.2 show that the light levels correspond closely with the dimming values and that the color temperature remains constant.

100%	75%	66%	50%	33%	25%	dimming value
31fc	24fc	21fc	16fc	10.7fc	8fc	light level at center
21.7fc	16.5fc	14.5fc	12fc	7.5fc	5.7fc	light level at corner
4450K	4460K	4420K	4430K	4440K	4350K	color temperature

Tab. 4.2 Sandbox model lighting measurements



Fig. 4.30 Extech LT300 light meter



Fig. 4.31 Light meter sensor placed inside the model

The measurements were done to test if the model representation of the existing Sandbox lighting was successful. The light distribution was reminiscent of that in the as-built space. However, the light levels in the model were lower than those in the Sandbox:

- Model
measured light levels: 31 fc in the center, 21.7 fc in the corners
- As-built space
measured light levels: 50 fc in the center, 25 fc in the corners)

I presented the model to Professor Jones to obtain a second opinion on the lighting representation. He commented that the LEDs produced a very successful representation that looks very close to the real space. Raising the light level and slightly lowering the color temperature should further improve the model's resemblance to the real space and make it an appropriate tool for my research. We agreed that painting the walls white will increase the light level and raise the color temperature which was already a little bit too high. However, this could hopefully be mitigated by modifying the LED light grid and replacing cool white bulbs with warm white bulbs.



Fig. 4.32 Finishing interior model walls with acrylic white paint



Fig. 4.33 Sandbox model interior with first white coat of paint

The lighting of the corridor model was designed to represent the existing arrangement of cool white recessed linear ceiling luminaires and warm white recessed circular downlights in the main corridor of the Moss Arts Center. I chose to use warm white 5mm flat top LEDs for the downlights. To simulate the linear luminaires white translucent acrylic strips were backlit using cool white 5mm flat top LEDs. The cut-outs in the model corridor ceiling were based on the locations depicted in the reflected ceiling plans of the Moss Arts Center.



Fig. 4.34 Sandbox model and partial corridor model

I painted the floor in the model corridor with grey acrylic paint to approximate the terrazzo floor finish in the building. The grey value was determined using the Gray Scale & Value Finder. I furnished the clerestory windows of the model with clear acrylic sheets. It was important to include a representation of the glazing because the reflection of the Sandbox ceiling in the windows is a strong feature of the room's visual impression. I wanted to visualize the effect of the skylights' reflected images in the clerestory window glazing in the proposed time lapse studies.



Fig. 4.35 Final coat and clerestory window glazing



Fig. 4.36 Corridor model - gray floor paint



Fig. 4.37 5mm flat top LED downlights (1)



Fig. 4.38 clear acrylic window glazing (2)

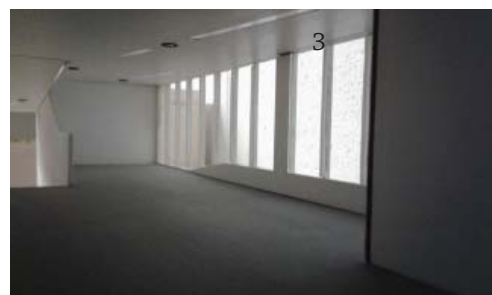


Fig. 4.39 white translucent linear lights (3)

After incorporating the described updates, I asked Professor Elizabeth Grant to look at the model and evaluate its usefulness as a visual representation of the Sandbox. She commented that in her opinion the model was a good research tool for the dynamic lighting studies I intended to conduct. Professor Grant had worked on green roof designs for the Moss Arts Center and had provided me with a copy of the electrical specifications during the Sandbox documentation process.

The dark gray carpet floor finish of the Sandbox absorbs a large part of the incident light. I selected colored cardboard to simulate the floor finish properties in the model. Again, I used the Gray Scale & Value Finder to determine the cardboard color. I had painted all interior walls white and increased the number of warm white LEDs. After mounting the model floor finish, I made photos for documentation and remeasured the light level and color temperature in the model.



Fig. 4.40 Sandbox model interior with grey floor finish
light level 30 fc, color temp. 5100K

The model updates resulted in an even lower light level (30 fc) and a much higher color temperature (5100K). I attributed both effects to the dark floor finish and decided to redesign the model ceiling LED grid and to replace the floor material with a brighter gray color to achieve the required light level and color temperature.

The new layout consisted of 5 LEDs per row adding 12 LED bulbs to the ceiling grid. Figure 4.41 shows that the additional LEDs and the brighter gray floor finish color raised the brightness of the lighting considerably. I conducted another series of measurements which yielded to the results listed in table 4.3.



Fig. 4.41 Updated Sandbox lighting layout
7 rows of 5 LEDs



Fig. 4.42 Sandbox model interior
light level 48 fc, color temp. 5100K

Sandbox	model	
50fc	48fc	center
25fc	33fc	corners
4100K	5100K	color temp.

Tab. 4.3 Sandbox model lighting - 5 LEDs per row

The light level was now very close to that in the as-built space, but the color temperature was still too high. I again modified the color temperature removing several cool white LEDs and replaced them with warm white LEDs. The modification achieved the required color temperature as shown in table 4.4.

Sandbox	model	
50fc	47fc	center
25fc	33fc	corners
4100K	4200K	color temp.

Tab. 4.4 Sandbox model lighting - final design

I visually compared the final model lighting design to the as-built light condition in the Sandbox. Figure 4.42 illustrates that both the light level and the light color temperature in the model were now very close to those in the Sandbox.



Fig. 4.43 Illustrated lighting condition in the Sandbox model (left) and in the as-built space (right)

Next, I needed to evaluate the model lighting in the corridor which had a much smaller impact on the Sandbox lighting condition than the ceiling lighting. However, I still wanted to check if the brightness and color of the corridor light was reasonably close to the as-built condition.

The color temperature of the corridor LED downlights was too warm causing a pronounced yellow tint on the walls. Figure 4.43 illustrates the difference between the light color temperature in the model and the as-built space.

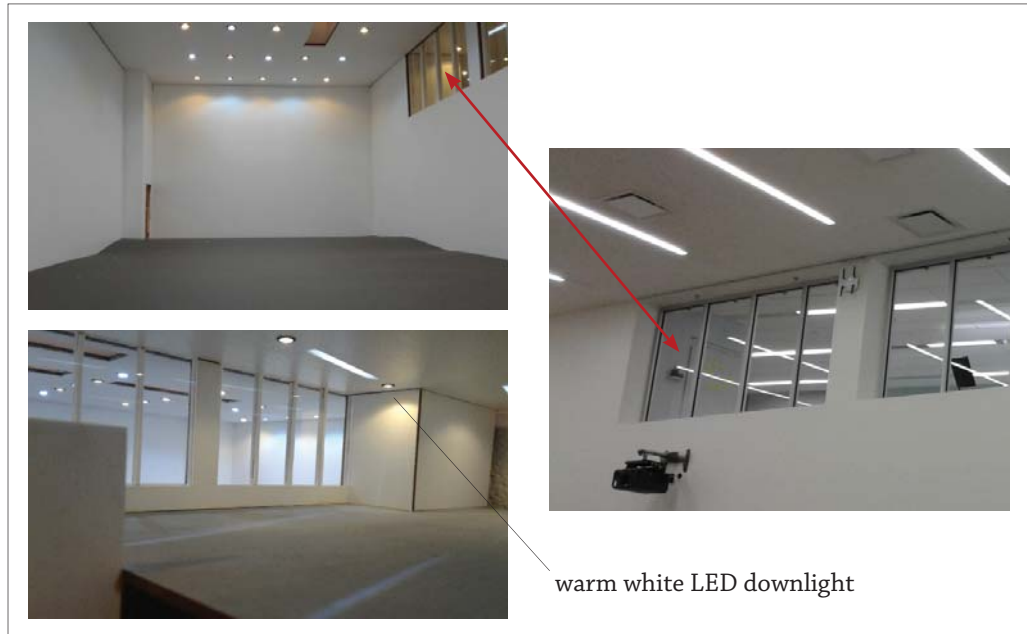


Fig. 4.44 Corridor model light color temperature deviating from as-built condition

I replaced the warm white LED downlights near the walls with cool whites to match the as-built lighting condition in the corridor and evaluated the result by comparing photos of the model and the as-built space in figure 4.44. With this the model now provided a good representation of the Sandbox

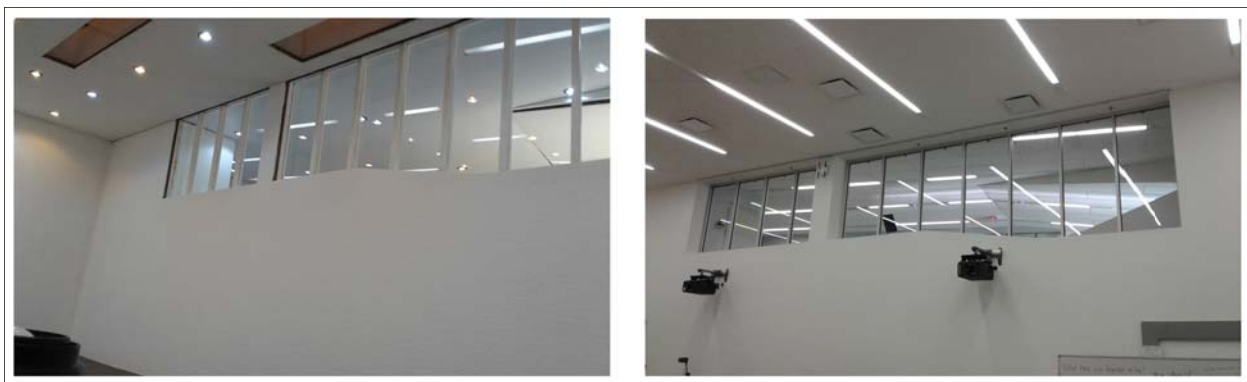


Fig. 4.45 Final lighting condition in the Sandbox model (left) and in the as-built space (right)

The model scale was too small to simulate LED light strips which are typically used for indirect cove lighting like the one I envisioned for the skylight wells. Instead of indirect lighting I chose to use backlit translucent white acrylic panels which provide soft light. The self illumination effect of the model's acrylic skylight wells certainly differed from the effect of reflected indirect light. However, the backlit skylight wells met the design intent delivering soft light that was meant to counteract the direct light of the existing space lighting.



Fig. 4.46 Skylight wells – translucent white acrylic panels



Fig. 4.47 Sandbox model interior - view of skylights

I constructed a housing for the model LED lighting to protect the electrical parts and to avoid daylight illuminating the back side of the acrylic skylight wells. The ceiling of the model with the white LED space lighting became the bottom piece of the housing. I adjusted the height of the vertical side pieces and the skylight well pieces of the housing to match the thickness of the Sandbox's ceiling structure.



Fig. 4.48 Model LED lighting housing

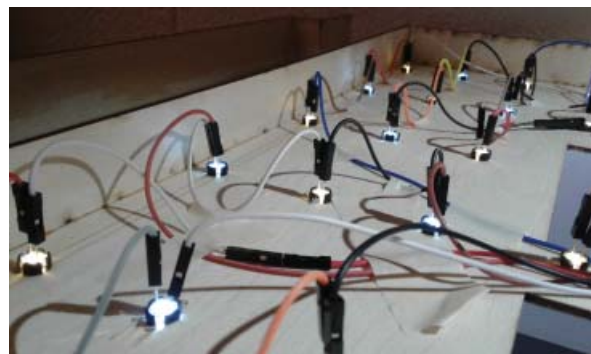


Fig. 4.49 5mm flat top LEDs connected with jumper cables

I closed the housing with a plywood top piece for a final evaluation of the simulated lighting condition and prepared the model for the exterior sunlight studies using masking tape to close gaps between some model pieces and reduce unintended penetration of sunlight.



Fig. 4.50 Completed Sandbox model part with housing top piece

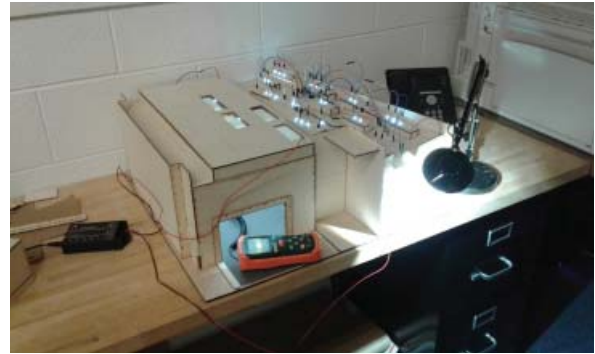


Fig. 4.51 Final lighting condition evaluation simulating the daylight in the corridor with a desk lamp



Fig. 4.52 Simulated daylight in corridor as seen from the Sandbox



Fig. 4.53 Simulated daylight in corridor as seen from the desk lamp position

4.3 Sunlight studies (time lapse photo documentation)

The two parts of the physical model were now ready to be used for the sunlight studies illustrating the natural daylight as it enters the model through the skylights. The Luminous Solar Skylight was designed to introduce dynamic lighting to the Sandbox, hence the dynamic nature of the light needed to be illustrated. Video recordings were the most appropriate way to create the dynamic lighting. A live video of an entire day requires a large amount of memory on a digital camera. The volume of data thus becomes very difficult to manage, especially if the videos are recorded with high resolution. It is very difficult to comparatively evaluate several hours of video information. Consequently, I do not use recording of live videos for the reasons described above. During the design process architects often use scaled models of proposed buildings. I used the concept of scaling for the sunlight studies. In addition to physical scaling (using a model of the Sandbox) I decided to scale the temporal dimension of the studies by replacing real time videos with time lapse videos which required a smaller frame rate and used less memory storage. Another advantage was that the time lapse videos could be created from photo sequences using digital photo cameras and video editing software.

Sunlight study setup

When setting up the study I first needed to determine an appropriate location for the model. This was done considering the requirements as listed below.

I needed access to electricity for the model lighting and the digital camera. I still had to determine the specific camera model for the recording. I wanted to record the effect of the sunlight in a neutral setting, therefore the model had to be set up in such a way that it wouldn't be shaded by adjacent trees or structures. Finally, it was desirable to place the model as close to the sunlight recorder as possible. I had installed the sunlight recorder next to Professor Elizabeth Grant's experimental setup for her research on green roofs which was also located on the roof of the RDF test cell building. In consultation with Professor Grant I determined that I would use one of her experimental structures for positioning my model since it provided a flat elevated surface near the PV panel of the sunlight recorder. There were no trees or buildings close by that would shade the model during the recording process and I had access to power through an extension cable connected to the wall outlet in the test cell 10 below.



Fig. 4.54 Test cell building at RDF

Recording of time lapse photos

I chose to use a GoPro Hero 4 silver action camera to record the images for the sunlight studies. The Hero 4 camera has an internal clock and can be set to record time lapse videos and photos. The maximum specified time interval for the time lapse photo function was 60 seconds which corresponded to the data logging frequency of the sunlight recorder's energy monitoring unit. Another important camera feature was its preinstalled protune software which allowed for fixed settings for white balance, color profile, and ISO limit. The fixed white balance was particularly important to ensure that the change of the sunlight color wouldn't be compensated by the automatic white balance adjustment most digital cameras use by default. By using fixed settings, I could increase the comparability between the sunlight study photos and the photos I planned to take of the model's skylight LED lighting.



Fig. 4.55 GoPro Hero 4 silver action camera

The GoPro Hero 4 camera has a compact design which made it easy to place inside the model. However, the available tripods were too large and bulky to be used in the sunlight studies. I decided to build a custom-made camera stand using leftover plywood from the Sandbox model. The height of the stand was adjusted so that the center of the camera lens was roughly at eye level in the model scale (1"3/4) simulating the perspective of a standing person.



Fig. 4.56 Plywood camera stand

There were several GoPro Hero 4 cameras available for take-out from Innovation Space, a service that provided multimedia equipment to students for the purpose of their studies. I obtained one of the cameras for testing and familiarized myself with its operation using the manufacturer's manual which was available online.



Fig. 4.57 Center of camera lens adjusted to eye level

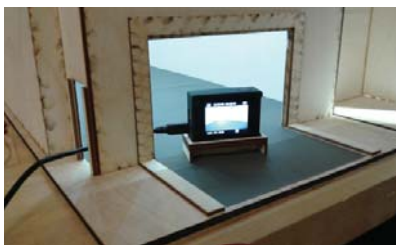


Fig. 4.58 Marked camera position in model



Fig. 4.59 Camera rotated toward the clerestory windows (more dynamic perspective)

The next step was to calibrate the camera and select appropriate settings in protune to produce photographic representations of the model interior that are visually as close to the as-built condition as possible regarding brightness and color. The protune settings which were tested are listed in table 4.5. The test photos shown in figure 4.59 were taken to select the white balance settings such that the color of the photos would match the condition in the Sandbox.

	available presets							
white balance	native	auto	3000K	4000K	4800K	5500K	6000K	6500K
ISO limit	100		200		400		800	

Tab. 4.5 GoPro camera settings - protune presets



Fig. 4.60 Camera white balance test photos

The 4000K white balance setting was very close to the light color temperatures of 4100K and 4200K that I had measured in the as-built space and inside the model respectively. The test photos shown in figure 4.60 were taken with a fixed white balance of 4000K while changing the ISO limit to evaluate the impact on the image brightness.



Fig. 4.61 Camera ISO limit test photos

Changing the maximum ISO limit setting did not affect the color or brightness visually which led me to use the camera preset (ISO 800).

It was important to orient the model correctly to the cardinal direction of the Sandbox in the Moss Arts Center. As a result, the sunlight entering the model through the skylights would result in a realistic visual representation of the proposed skylights in the as-built space. This in turn would enable me to observe potential glare problems caused by direct sunlight and update the skylight design accordingly. I created a top view of the test cell building to determine the orientation of Professor grant's experimental structure using Google Maps. Then I imported the image in a CAD drawing to determine the rotation angle for the model in relation to the structure. In the end, I made an angled paper guide that I used to achieve the correct model orientation on site.



Fig. 4.62 Top view of test cell building

- 1 experimental structure
- 2 Sandbox model

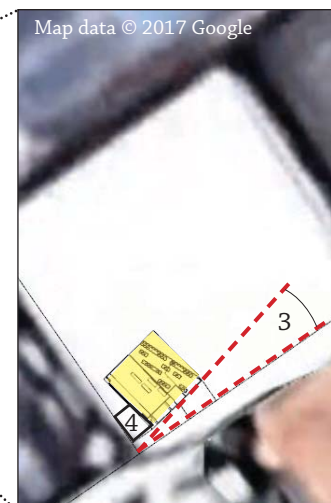


Fig. 4.63 Model orientation

- 3 rotation angle
- 4 angled paper guide

Recording sunlight study 1

I selected February 24th as the date for the first sunlight study while considering the local weather forecast because the model wasn't waterproof. I went to RDF the day before the recording to prepare the roof for the model by placing concrete pavers that would weigh down the model (wind securement) and to ensure that the extension cable was properly connected and live.

I started sunlight study 1 in the morning of February 24th before sunrise by placing the model on the designated structure and orienting it using the angled paper guide. I set the GoPro Hero 4 camera to take time lapse photos at 60 second intervals with 4000K fixed white balance. Next, I turned on the white interior model LED lighting and placed the stand with the camera on the position which I had marked in the model. The marks were necessary to reproduce the camera angle and position for the future sunlight studies. I arranged the recording process in a way that it did not need to be supervised during the day. After sunset, I returned to stop the recording and disassemble the model setup.



Fig. 4.64 Model location on green roof experiment structure



Fig. 4.65 Using angled paper guide to achieve correct model rotation in relation to structure



Fig. 4.66 Concrete paver ballast serves as wind securement



Fig. 4.67 Sunlight study location close to sunlight recorder

- 1 sunlight recorder
- 2 Sandbox model

Analyzing the time lapse photo sequence

I transferred all recorded images to my laptop computer for analysis. I selected specific photos between 6:36 in the morning and 6:45 in the evening using Windows Explorer's large icon view feature to display the photos in an array on the screen. Due to the 60 second time lapse interval, each photo represents one minute in real time. Figure 4.67 shows an extract of the array.

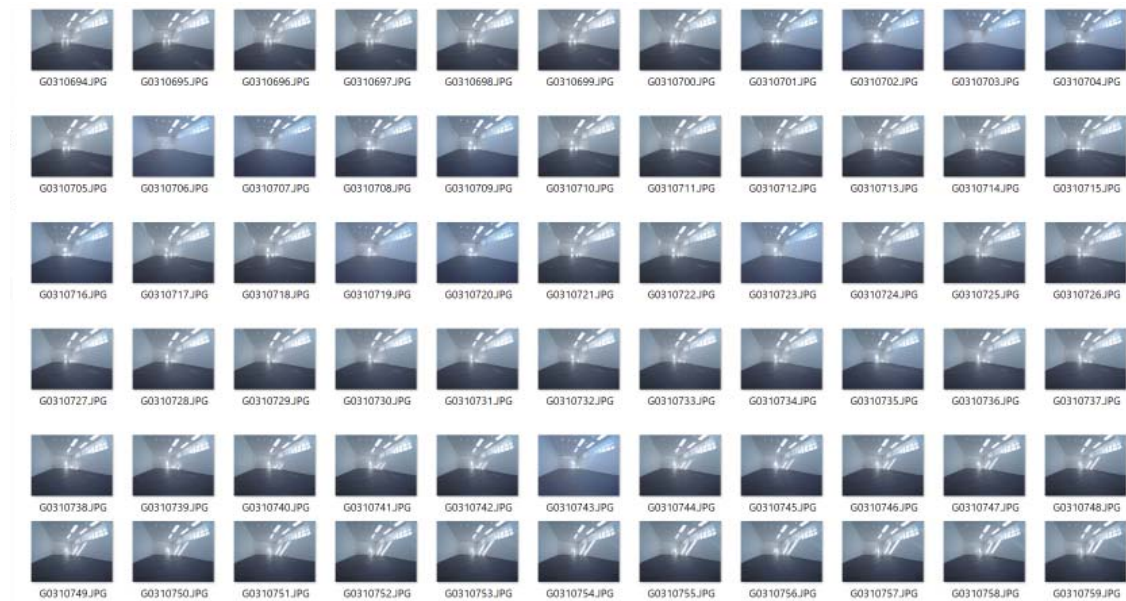


Fig. 4.68 Extract of photo array – Sunlight study 1

The photo array showed several images with a low illumination level and a slight blue color tone. I interpreted this to be the effect of moving clouds that cast their shadows on the model for brief periods of time (between 1 and 4 minutes). I compared the times for these photos with the times of low power output from the PV panel. The correlation between the times of lower illumination and the times of lower power provided corroboration for the cloud shadow effect. After analyzing the photo array, I created time lapse videos from the photo sequence in Adobe Premiere to dynamically analyze the visual data.

I used clear acrylic panels for the glazing of the model's skylights and did not simulate the PV cells during the first sunlight study. As expected the study revealed that the clear skylight glazing caused problems. Following this, I printed a grid of dark blue rectangles on transparent film for color laser printers and then cut out rectangles that I adhered to the clear acrylic skylight pieces to simulate PV integrated glazing during a second sunlight study.



Fig. 4.69 Visible glare at skylight due to bright sunlight

Sunlight study 2 – recording and analysis

A second sunlight study on March 2nd was conducted to investigate the mitigation of glare through PV integrated glazing. For this the GoPro Hero 4 camera that I had obtained from Innovation Space did not have the latest software installed and had a reduced selection of white balance settings. I did not have time to exchange the camera and therefore decided to conduct the study with the automatic white balance setting because the available presets of 3000K and 5500K were not close enough to the model lighting color temperature of 4200K. A potentially inaccurate representation of the color would not prevent me from evaluating the effectiveness of the glare mitigation strategy using PV integrated glazing. I started the second sunlight study at 6:06 in the morning and stopped the recording at 6:44 in the evening.

Using Windows Explorer, I visually analyzed the recorded photos using the photo array display method. I dynamically analyzed the time lapse video created from the image sequence using Adobe Premiere. The photos and the video revealed that the skylights were still causing glare. During periods with bright sunlight the skylights appeared as bright white patches and the PV cells in the glazing could not be identified. I attributed this to the fact that the modeled PV cells weren't completely opaque and thus didn't sufficiently block the sunlight.

To mitigate this, I replaced the modeled grid of PV cells with a new grid with opaque representations of PV cells. I achieved this by cutting the grid out of dark blue pulp-dyed color paper (Canson Mi-Teintes #140 Indigo Blue) using a laser cutter and adhered the new PV cell layers to the clear acrylic skylight glazing panels. The model was now ready for the third sunlight study.



Fig. 4.70 color paper PV cell grid

Sunlight study 3

Due to changing weather conditions it was much more difficult to determine an appropriate day for the third sunlight study. After several unsuccessful attempts, I was finally able to conduct the third sunlight study with the new PV cells on April 26th. I started the study at 6:13 in the morning and stopped recording at 8:38 in the evening.



Fig. 4.71 potential glare on the work surface

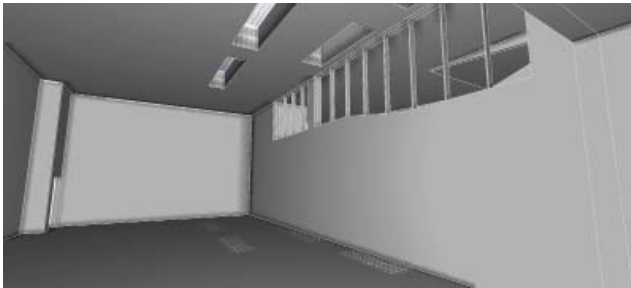


Fig. 4.72 Rhinoceros rendering illustrating a pronounced glare reduction through PV integrated skylight glazing

Again, I conducted a visual analysis using a photo array and a time lapse video. The glare problem from the skylights was solved by the color paper PV cell grids. The PV cells in the glazing could now be identified during periods with bright sunlight. However, the new PV cells did not alleviate the problem of bright specs of direct sunlight moving across the room during the day.

The Rhinoceros renderings of the direct daylight showed very pronounced blurring of the PV cell grid which helped mitigate glare. This was not observed in the model photos which points to an exaggerated light scattering effect in the rendered images.

The findings described above suggest the need for future research with PV integrated glazing to study the scattering of light by the grid of the PV cells while improving our understanding of glare mitigation through PV integrated glazing.

I observed one more issue that was addressed through the current case study project. The daylight from the adjacent corridor was more intense than what I observed in the as-built space in the Moss Arts Center. As a result, I decided to conduct a fourth study on June 21st to record the longest day of the year.

Sunlight study 4

The photos for the fourth sunlight study were taken on June 21st between 5:35 in the morning and 9:10 in the evening. In the photo array and the time lapse video I could observe that the daylight level in the model of the corridor was now much closer to the daylight level in the as-built space. This is illustrated in figures 4.72, 4.73, and 4.74.

I now had sunlight studies of a winter day (closer to the shortest day), two days in the spring (close to equinox), and a summer day (on the longest day of the year). This provided recorded sunlight patterns with various durations that could be used during the data translation process which is explained in detail in the next sub-chapter.



Fig. 4.73 Sunlight study 3



Fig. 4.74 Sunlight study 4

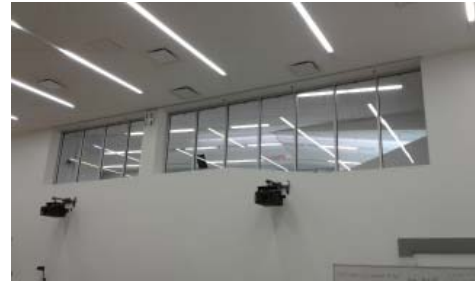


Fig. 4.75 Corridor daylight condition

4.4 Data translation (color concept research)

In the translation process of the project insolation sensing is translated to lighting control protocols for dynamic space lighting. I started the development of translation concepts early in the immersive case study project. The data translation exploration was a continuous process that extended almost to the end of the thesis project. I developed several concepts to translate the data from the sunlight recorder to dynamic lighting protocols. The concepts for color variation were tested using the RGB LED lighting which I built to represent the indirect lighting of the skylight wells. I used the visual feedback from the tests to modify the color concepts and create new schemes. Finally, I selected the translation concepts which best matched the visual impact of the sunlight observed in the sunlight studies. I used the selected translation concepts to create time lapse photo sequences and study the dynamic LED lighting.

Colored intensity graphs

To begin the color intensity visualization the power levels of the PV panel recordings were plotted over time as 2 dimensional diagrams. A Grasshopper script was written to create a vertical line for each data point. The length and color of the line was determined by the power level recorded for the respective data point.

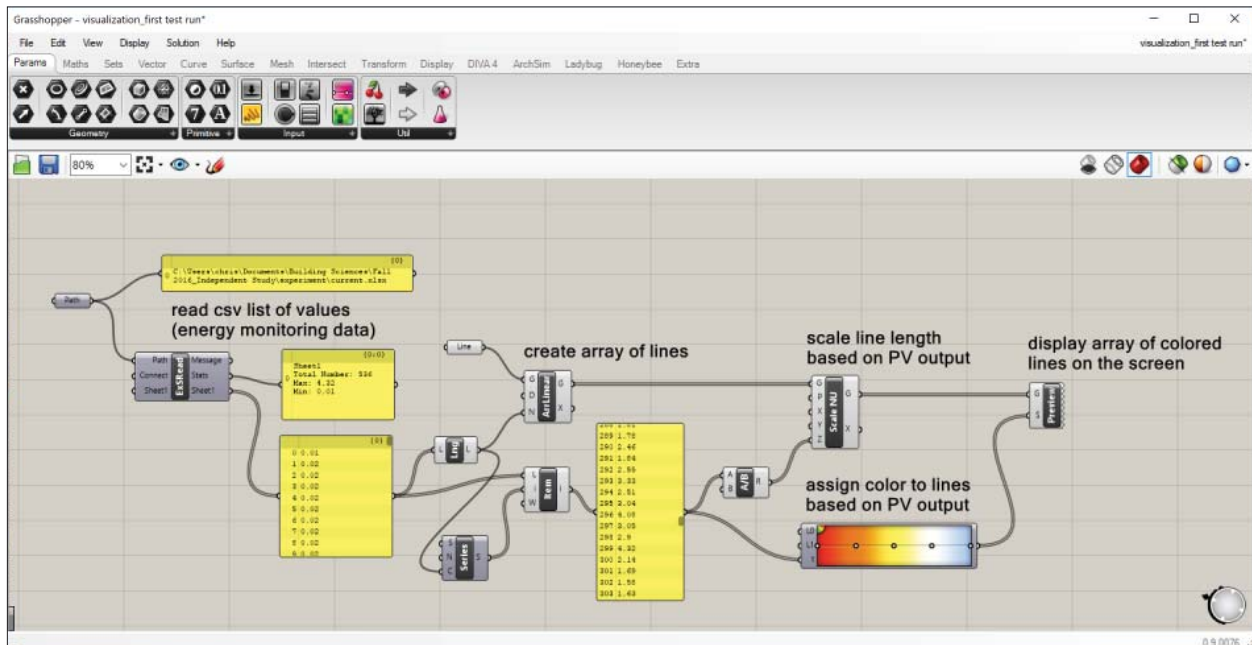


Fig. 4.76 Grasshopper script assigning color based on PV output respectively solar radiation

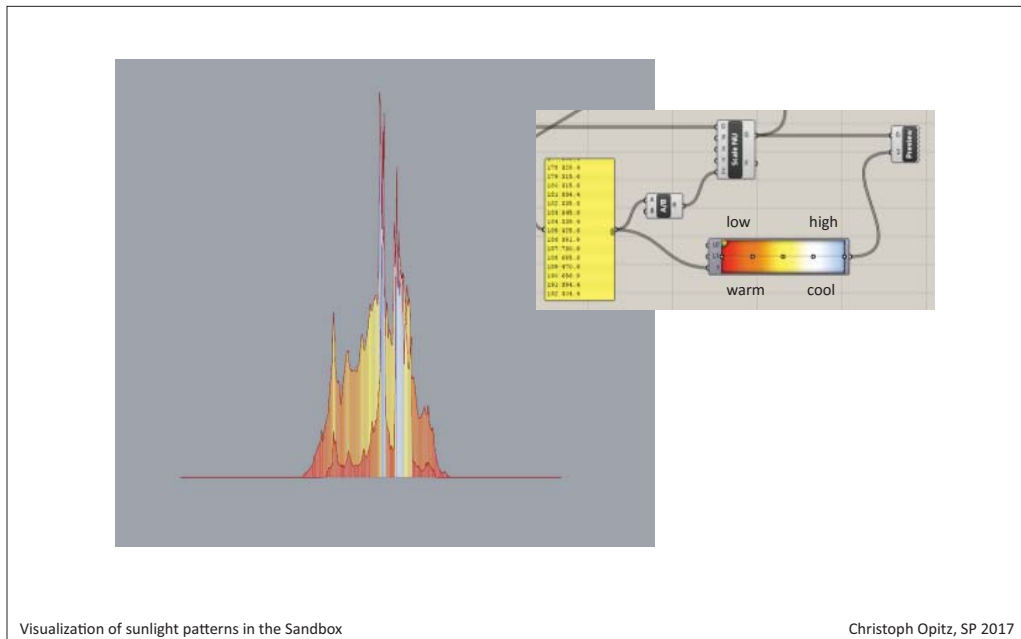


Fig. 4.77 Proposed PV energy monitoring visualization - Spring semester 2017

Figure 4.76 illustrates the proposed visualization of energy monitoring data graphs with Grasshopper. I applied the same process to the light sensor pyrometric data assigning color based on solar radiation for a visual comparison as depicted in figure 4.79. The light sensor data was obtained from a pyranometer (Onset S-LIB-M003) installed on the roof of the Virginia-Maryland Regional College of Veterinary Medicine located 1.15km northeast of RDF.

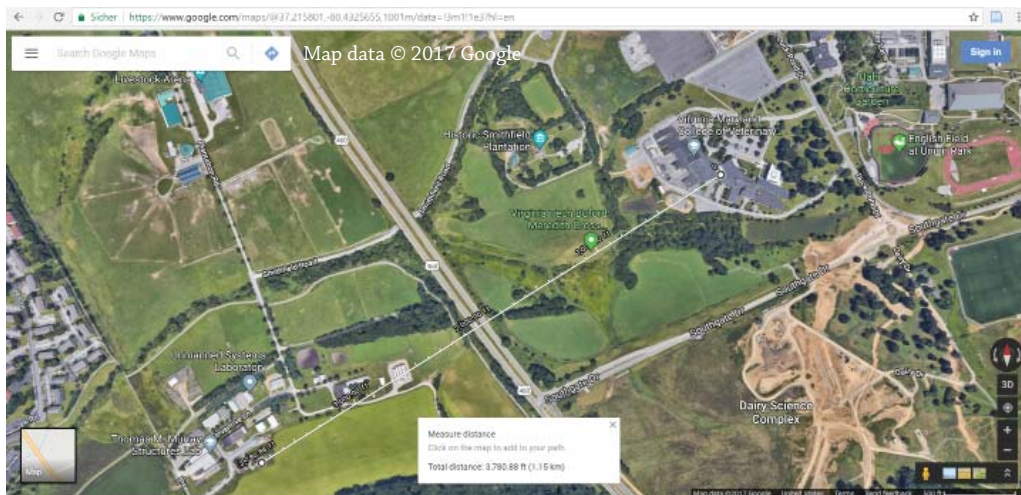


Fig. 4.78 Location of sunlight recorder at RDF in relation to the light sensor (pyranometer) at Virginia-Maryland College of Veterinary Medicine (Vet Med)



Fig. 4.79 Light sensor (Onset S-LIB-M003 pyranometer) installed at the weather station on the Vet Med roof

The initial color visualization approach followed a sunlight color scheme where low light (power) levels have a low color temperature and high light (power) levels have a high color temperature. Figure 4.79 compares the output of the PV panel with the radiation sensed by the pyranometer as single line graphs on the left. The visualization on the right shows the comparison of the color patterns based on the colors assigned by the Grasshopper script according to the sunlight color scheme described above.

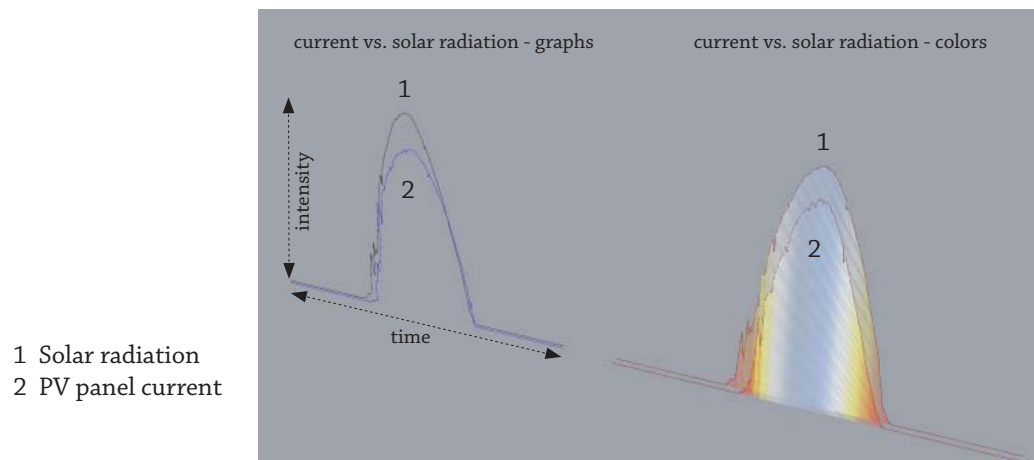


Fig. 4.80 Current vs. solar radiation (PV panel vs. pyranometer)

The PV panel of the Luminous Solar Skylight project had two functions. First, it was meant to produce energy for the dynamic electric lighting and second it served as a recording device for solar radiation. The latter required that the response characteristics of the PV panel corresponded that of the light sensor. I studied the data from several consecutive days visually looking at graphic visualizations of the recorded current, voltage, and wattage values. The characteristics of the graphs varied widely between the days depending on the weather

conditions and sky cover. The form of the graphs generated from the sunlight data corresponded to the form of the curves generated with the data measured by the pyranometer.

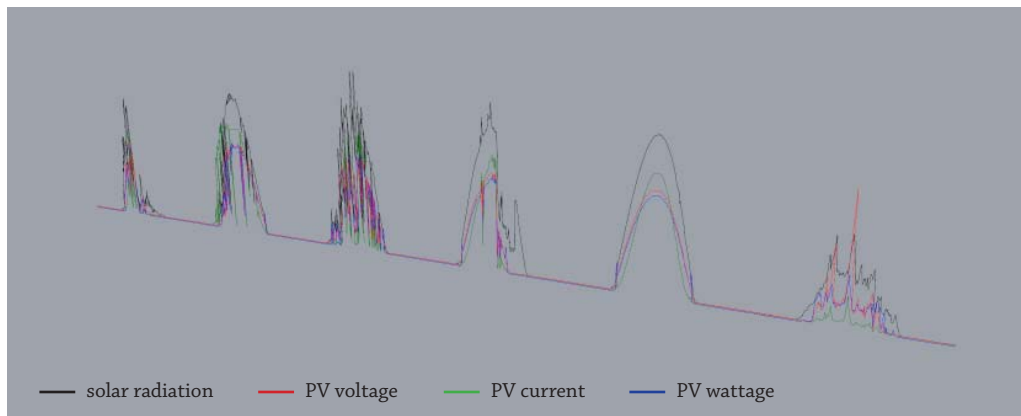


Fig. 4.81 Comparing the form of the curves - PV panel data: voltage , current, wattage vs. pyranometer data: solar radiation

In addition to the relation between the two data sets I wanted to examine if the color gradient translation of the PV panel values and light sensor values produced similar results. The graphs arranged in figure 4.81 below show that the color distribution from the two data sets are similar.

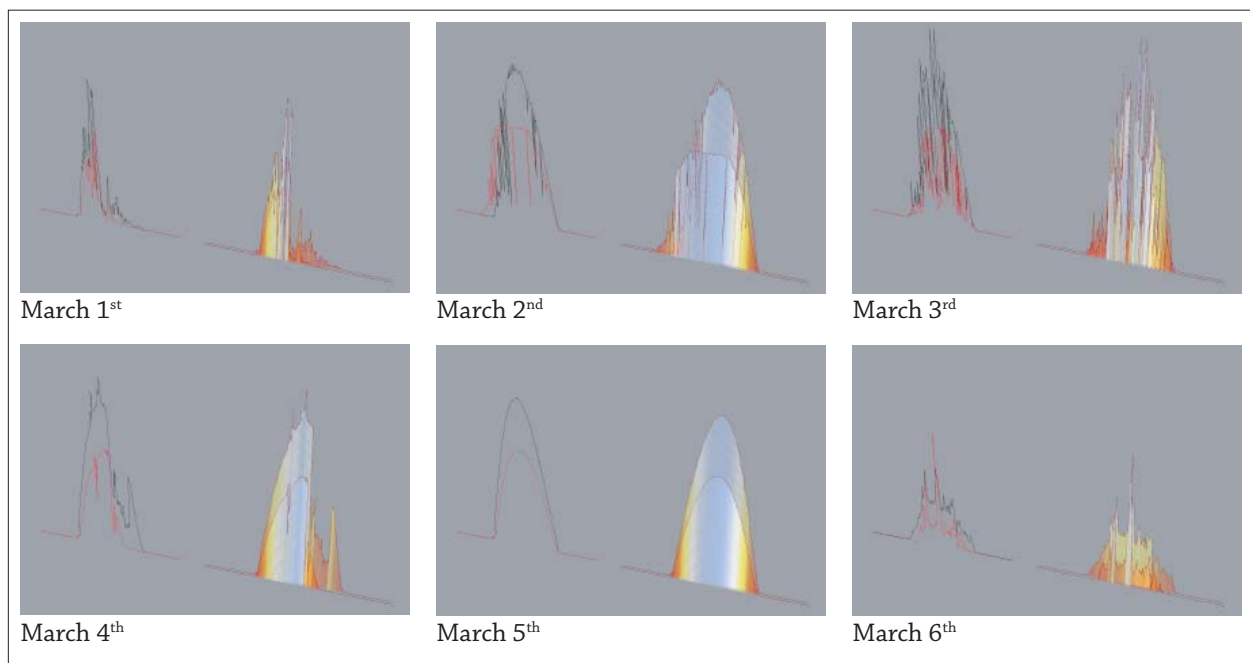


Fig. 4.82 Comparing color distribution from two datasets - Grasshopper color assignment script visualizations

Sky color study

To analytically determine the range of sky colors I created a series of photographs depicting various levels of brightness and colors depending on the time of day and weather conditions. Figure 4.83 illustrates shades of red, orange, yellow, purple, blue, and gray that were used to generate a color palette.

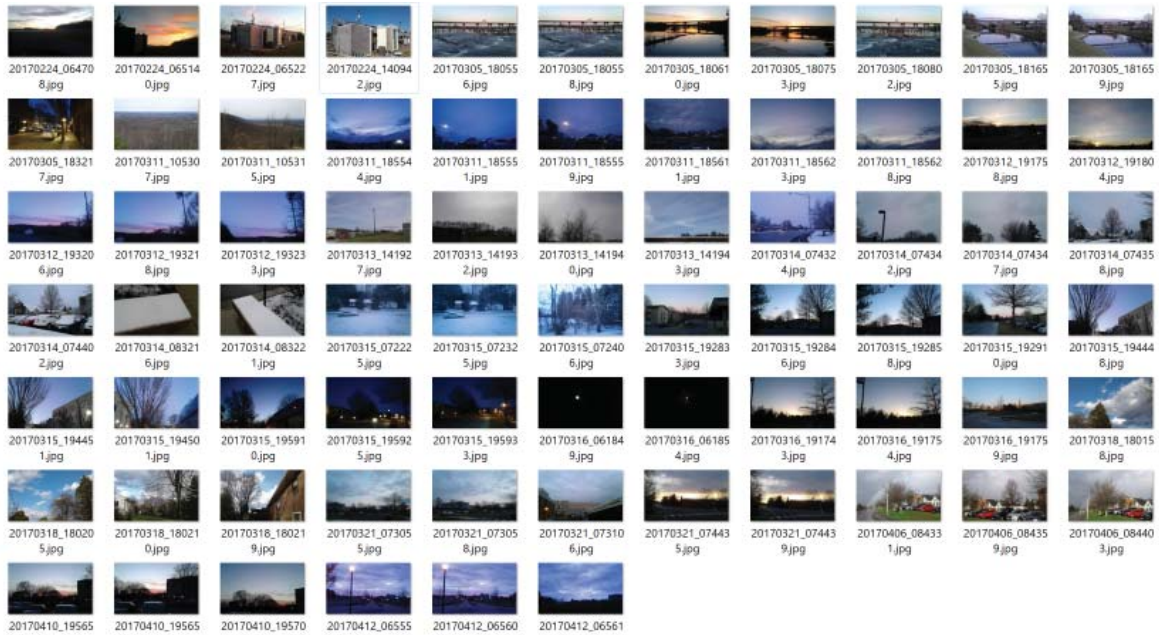


Fig. 4.83 Sky color photo study

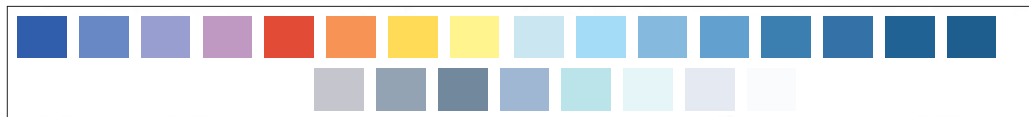


Fig. 4.84 Sky color palette for gradient design

Translation of color temperature to RGB

Black-body objects such as lamp filaments start to glow when they reach a certain temperature and emit light with a specific color. The color of the emitted light changes with the temperature of the filament. The color temperature of a light source is a numeric value that relates its light color to the temperature of a black-body emitting light with that same color. Color temperature is specified in degrees of Kelvin. Light with low color temperatures appears in shades of red and light with high color temperatures appears in shades of blue. This is the opposite of our cultural association with color where blue is cold and red is warm. Light sources that behave like black-bodies are called incandescent radiators and have a continuous light spectrum. Fluorescent lamps or LEDs do not have

a continuous light spectrum and render colors differently than incandescent light sources. This is explained in the website Lowel EDU:

"Light sources that are not incandescent radiators have what is referred to as a "Correlated Color Temperature" (CCT). It's connotations to any part of the color temperature chart are strictly visually based. Lights with a correlated color temperature do not have an equal radiation at all wavelengths in their spectrum. As a result, they can have disproportionate levels (both high & low) when rendering certain colors. These light sources are measured in their ability to accurately render all colors of their spectrum, in a scale is called the Color Rendering Index (CRI). Incandescent radiators have a CRI of 100 (the max.)" (Lowel Light, 2010)

Color temperature, CCT and CRI are used to describe and compare light sources.

The predominantly used color model for digital image processing and multicolor light sources is RGB (red, green, blue) which follows an additive mixing process. Mitchell Charity created a colorized datafile translating color temperature to RGB values for the visualization on a screen while considering chromaticity (hue and saturation) but ignoring brightness. In addition to the sky color palette the colorized datafile informed the design of color gradients for the data translation process. I used selected colors to find RGB values for the color of sunlight referring to color temperatures commonly specified for different times of day and weather conditions (sunrise/sunset, overcast sky, clear sky, etc.).



Fig. 4.85 Colorized datafile translating color temperature to RGB values created by Mitchell Charity

Mitchell Charity converted the colors of the black body spectrum for the use in the sRGB color space as described on his website:

"The black body spectrum was mapped to the CIE XYZ color space for integration using the CIE 1964 10-deg color matching functions. The XYZ to RGB conversion was done with sRGB's primaries and gamma correction, and a D65 whitepoint. A blackbody color tool hack was used to create a colored datafile, and a plain text one." (Charity, 2016)

The display of color temperature on the screen is limited by the screen's range of intensities. Charity outlines the limitations as follows:

"These values show color chromaticity (hue and saturation), but ignore brightness. Blackbody power output increases greatly with temperature, so also showing intensity is problematic." (Charity, 2016)

Figure 4.85 illustrates the problem described above.

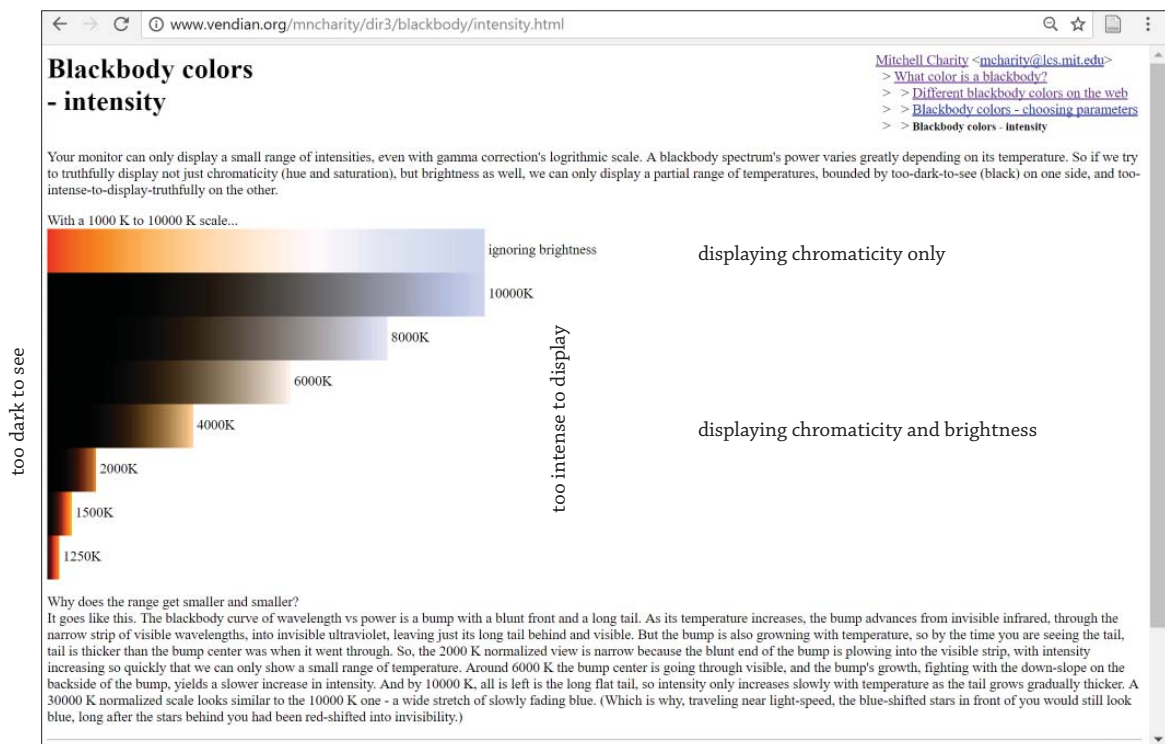


Fig. 4.86 Limitations of displaying color temperature on a computer screen

Despite the described limitations I was able to use the information from the colored datafile to display color temperature on the screen of my laptop during the process of testing the *Color Temp Meter* app which I discussed ear-

lier in section 3.3. The app's determined color temperatures did not exactly match the color temperatures displayed on the screen as RGB colors, but they were reasonably close. The method was accurate enough to measure the light color temperature in the Sandbox and confirm the specified light color of the installed linear ceiling lights. I considered the color chromaticity values from the colorized datafile to be abstracted representations of selected daylight color temperatures which I could use to create sky color gradients.

Two-dimensional color gradients

The proposed approach to color visualization was to determine the color of the light from the Luminous Solar Skylight's integrated RGB LED lighting based on two factors. One factor was the power level of the PV system which is proportional to the solar radiation. The other factor was the time of day where the brightness of the LED lighting would vary with solar radiation and the LED lighting color would gradually change with the time of the day. The daylight studies had revealed that the color changes very quickly in relation to the brightness of the sky any time the shadow of a cloud moved across the model. Consequently, I wanted the color of the LED lighting to reproduce these quick changes in addition to a gradual change of color based on the time of day.

I created a few different applications to create two-dimensional color gradients using the Python programming language. In the first program, I used linear interpolation to create a square color gradient from 4 different colors. I superimposed a recorded graph from the sunlight recorder over the color gradient. The result was visually pleasing, but I did not have enough control over the algorithm to create a complex color gradient that would change the LED color quickly when the daylight intensity dropped.

- 1 red, yellow, green, blue
- 2 dark orange, bright orange, dark purple, bright purple
- 3 superimposed graph

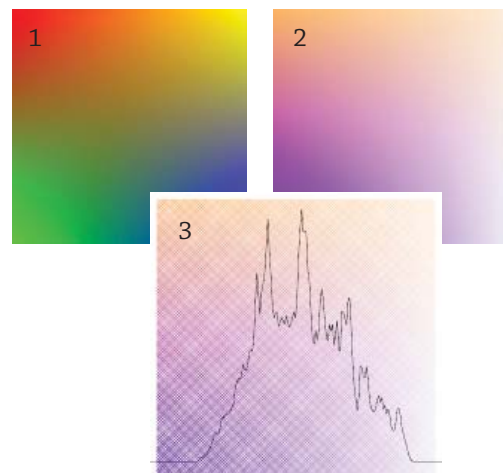


Fig. 4.87 Square color gradients

The second program combined a grid of square color gradients to create a multicolor gradient map. Figure 1.87 shows that the complexity of the gradient was improved and that the light color would change both with time (on the x-axis) and with daylight intensity (on the y-axis).

Using more saturated colors resulted in a patchy gradient map which can be observed in the image to the right in figure 1.87. The program required me to

define the RGB values for a grid of color points. Increasing the resolution of the color point grid resulted in too many RGB values for me to define manually.

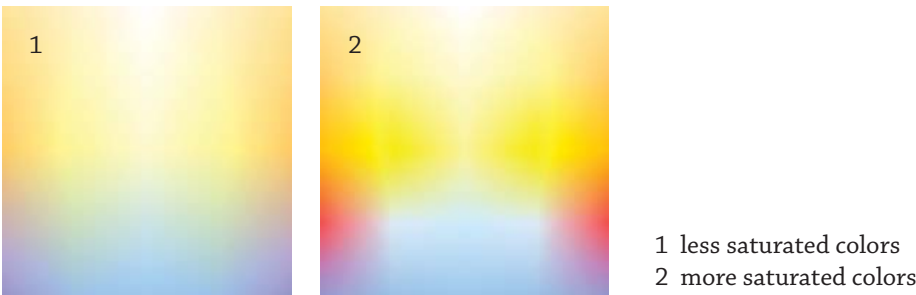


Fig. 4.88 Multicolor gradient maps

The third program interpolated colors between two linear gradients which could be created quickly with a modified version of the Grasshopper color assignment script. I arranged several rectangular gradient interpolation strips next to each other to create new color gradient maps. The generation of interpolation strips is illustrated in figure 1.88. Figure 1.89 shows 4 color gradient maps which are combinations of interpolation strips based on the sky color palette.

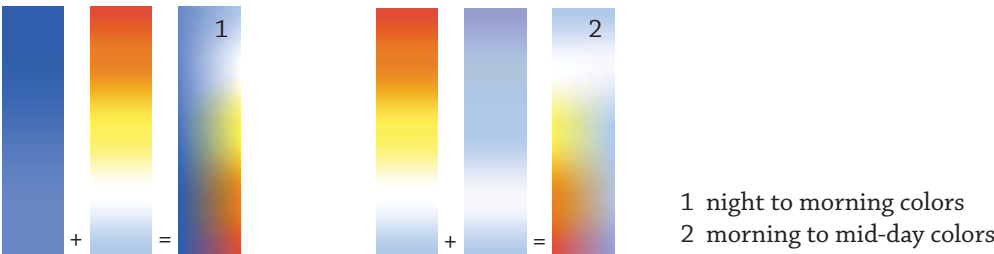


Fig. 4.89 Creation of interpolation strips

The color for the lighting from the protocols could now be determined by retrieving the RGB pixel values from the background image at the x and y positions defined by the graphs. The color protocols of the two-dimensional gradient maps were designed to reflect the gradual color change of sunlight over the course of a day.

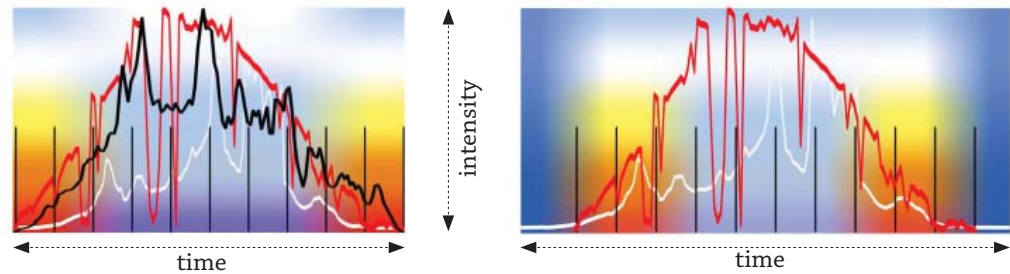


Fig. 4.90 Color gradient maps with overlaid energy monitoring graphs

Linear color gradients

The translation approach described above dealt with the representation of variable light intensity and color over time. I wanted to look at another dynamic property of daylight namely sunlight direction. As the sun moves across the sky the direction of the light rays constantly change. During the sunlight studies I observed bright light patches like shown in figure 4.70 which moved across the room.

To include a feature of spatial movement in the Luminous Solar Skylight I created multiple RGB channels for the lighting protocol so that I could create multiple zones for the lighting as illustrated in figure 4.91. The intensity and color could now be set differently for each channel which would provide a simulated spatial movement for the lighting. For the four skylights a color highlight (for example by setting a more saturated color) was created that moved across the ceiling over time from one skylight to the adjacent one and so forth. Instead of the complex two-dimensional color gradients (color changes with time and PV output) described earlier I used selected one-dimensional linear color gradients (color changes with PV output) for the multi-channel light protocols. Now the color changed with the PV output while the factor of time was represented with the spatial movement of the color highlight. I modified the Grasshopper color assignment script as displayed in figure 4.90 and used it to create a series of CSV color files to assign colors based on PV power values from the sunlight recorder.

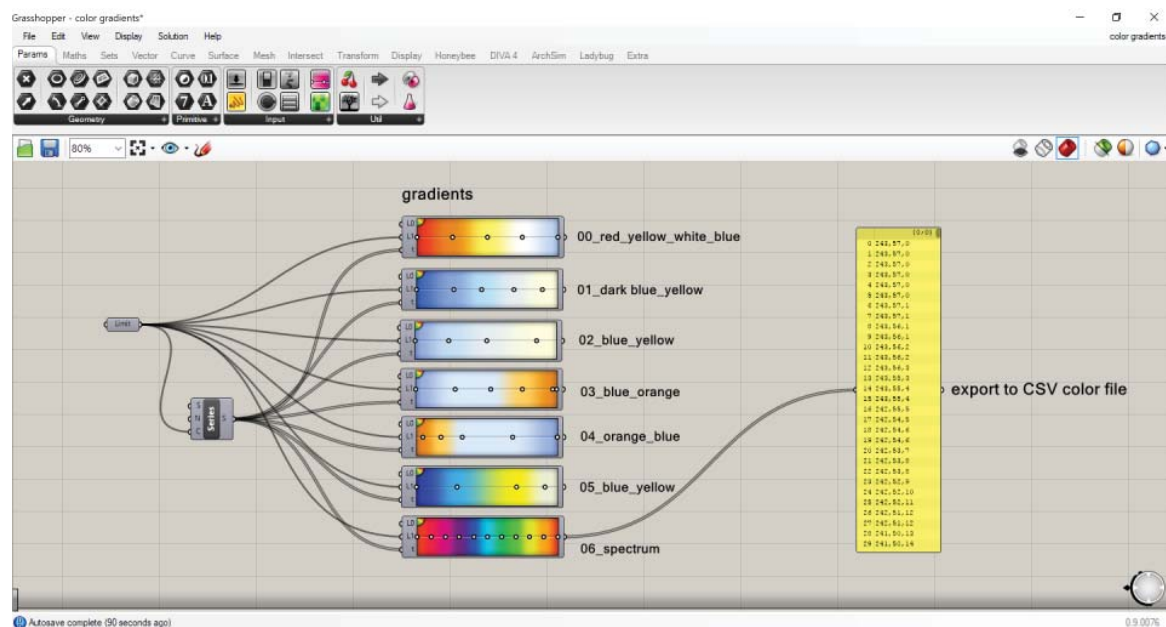


Fig. 4.91 Grasshopper color gradient generation script



Lighting zones
(RGB LED channels 1-6)

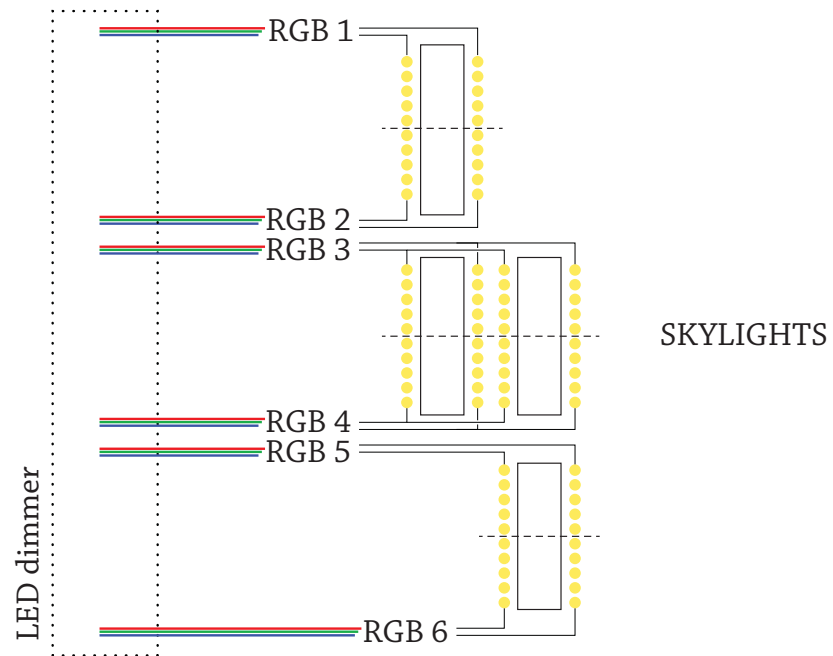


Fig. 4.92 Lighting zones - RGB LED channels 1-6

4.5 Multicolor LED lighting (iterative prototyping process)

I have documented the dynamic daylight studies of the Luminous Solar Sky-light in chapter 4.3. The observations I made with the help of the time lapse photo sequences led to design updates mitigating glare and informed the development of color gradients for the translation of PV energy monitoring data to lighting protocols. Next, I needed to prepare the skylights for the Sandbox model to study the performance of the LED. I chose to use 5mm tri-color LEDs for the model lighting. Tri-color LEDs have separate LEDs for red, green, and blue in one light bulb and thus are called RGB LEDs. The two types of RGB LEDs are common anode LEDs with one positive and three negative contacts and common cathode LEDs with one negative and three positive contacts. The three internal LEDs can be dimmed independently to change the amounts of red, green, and blue light enabling them to display any color from the RGB color model. With this I could display selected colors from the gradients I developed for the dynamic lighting protocols.

Because the internal LEDs can be seen separately when looking at a clear RGB light source while diffuse RGB LEDs have a translucent lens to mix the colors, I selected the diffuse RGB LEDs for their more even color distribution.



Fig. 4.93 Diffuse 5mm RGB LEDs



Fig. 4.94 Additive mixing - RGB color model

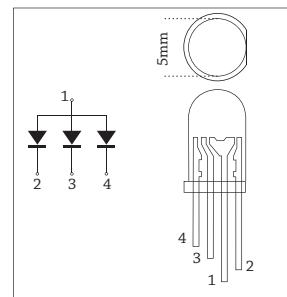


Fig. 4.95 Common anode RGB LED sections & circuit diagram

LED dimming

Displaying colors with RGB LEDs required dimming the separate internal LEDs. However, the dimming of LEDs is not straight forward. Incandescent lamps are dimmed by reducing the voltage in the circuit. The dimming effect of LEDs using voltage reduction is not linear and the LED turns off abruptly when the voltage drops under the minimum voltage required to power it. The predominant dimming strategy for RGB LED lighting is pulse width modulation (PWM). The dimming effect is achieved by modifying how long the LED is turned on during a specified duty cycle. Potential eye-strain or fatigue can be

mitigated by setting a high frequency for the duty cycle preventing perceivable flicker. The concept of PWM dimming is illustrated in Figure 4.95.

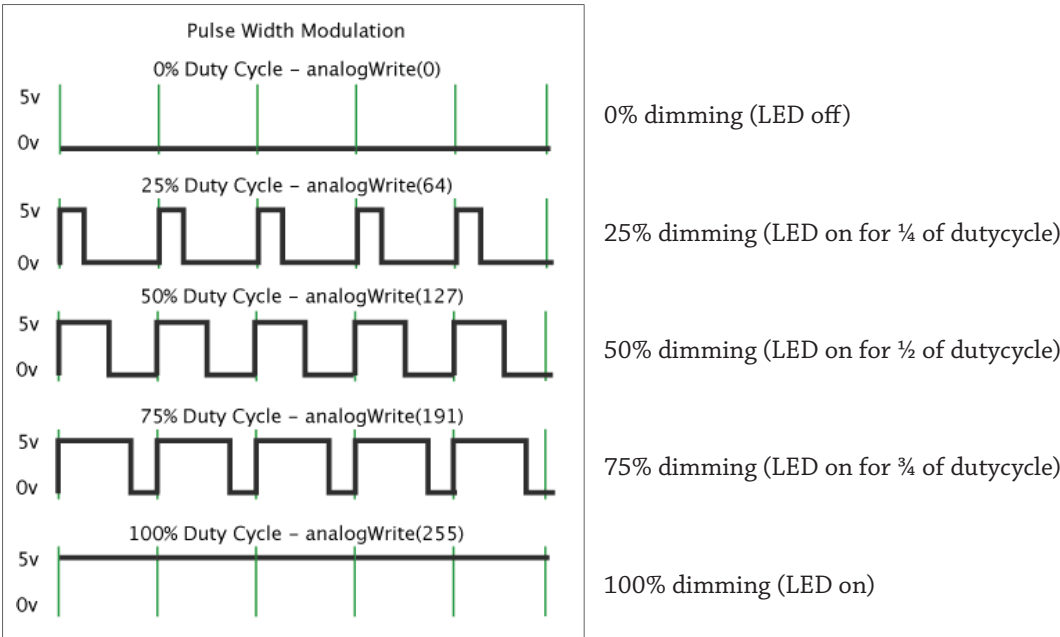


Fig. 4.96 LED dimming with pulse width modulation

Building a test circuit

For building the test circuit I acquired a Raspberry Pi 3 single board computer to control the model RGB LED lighting. The Raspberry Pi 3 has 40 General-purpose input/output (GPIO) pins which I used to transmit the PWM signal and dim the RGB LEDs. First, I built a test circuit using a prototyping breadboard, resistors, jumper wires, and RGB LEDs and connected it to the Raspberry Pi's GPIO pins. Then I created the dimming signal with a Python program using the PIGPIO library which includes a software PWM generator.



Fig. 4.97 Raspberry Pi 3 single board computer

Pin	Function	Pin	Function
1	5V PWR	2	5V PWR
3	GPIO2 (SDA1, I2C)	4	5V PWR
5	GPIO3 (SCL1, I2C)	6	GND
7	GPIO4 (GPIO CLK)	8	(UART_TXD0) GPIO14
9	GND	10	(UART_RXD0) GPIO15
11	GPIO17 (GPIO GEN0)	12	GPIO GEN1 GPIO16
13	GPIO27 (GPIO GEN2)	14	GND
15	GPIO22 (GPIO GEN3)	16	GPIO CLM1 GPIO23
17	5V PWR	18	(GPIO GEN5) GPIO24
19	GPIO10 (SPI0_MOSI)	20	GND
21	GPIO9 (SPI0_MISO)	22	GPIO GEN6 GPIO25
23	GPIO11 (SPI0_CLK)	24	(SPI_CEO_N) GPIO8
25	GND	26	(SPI_CEO_N) GPIO7
27	ID_SD (I2C EEPROM)	28	ID_SC (I2C EEPROM)
29	GPIO5	30	GND
31	GPIO6	32	GPIO12
33	GPIO13	34	GND
35	GPIO19	36	GPIO14
37	GPIO24	38	GPIO20
39	GND	40	GPIO21

Fig. 4.98 Raspberry Pi 3 GPIO pin layout

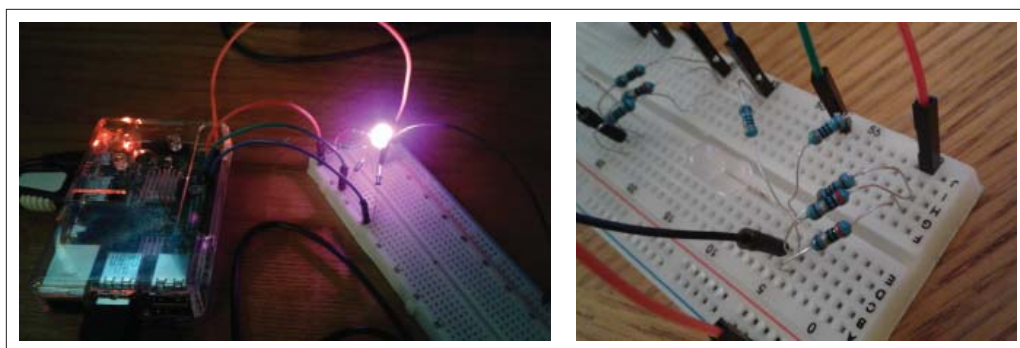


Fig. 4.99 RGB LED test circuit

The Python program in figure 4.99 set the brightness of three color channels to specified levels by sending PWM signals to three GPIO pins. Setting the red, green, and blue channels to 255 (LED turned on during 100% of the duty cycle) should cause a connected RGB LED to display bright white light.

```

LED white balance.py - C:/Users/chris/Documents/Building Sciences/00_Thesis Document/4_...
File Edit Format Run Options Window Help

import csv
import os
import pigpio
import time

pi = pigpio.pi()

def setcolor(channel,rgb):      1

    pins = [[14,15,18],[17,27,22],[23,24,25],[5,6,13],[12,19,26],[16,20,21]]

    pi.set_PWM_dutycycle(pins[channel][0], rgb[0])
    pi.set_PWM_dutycycle(pins[channel][1], rgb[1])      2
    pi.set_PWM_dutycycle(pins[channel][2], rgb[2])

color = [255,255,255]      3
setcolor(0, color)      4
|
stop = input('enter to stop')

setcolor(0, [0,0,0])

pi.stop()
Ln: 21 Col: 0

```

Fig. 4.100 RGB LED PWM test program

- | | |
|--------------------------------------|------------------------------|
| 1 PWM signal generation definition | 3 define RGB values |
| 2 turn on PWM for specific GPIO pins | 4 send RGB color information |

I tested one RGB LED with equal resistor values and with brightness set to maximum for each color channel and observed a strong green tint. Looking at the LED's datasheet revealed the reason for the tint. As shown in figure 4.100 the maximum luminous intensity of the RGB LEDs' separate internal diodes

at equal current flows (20mA) is not the same. The luminous intensity of the green LED is higher than the red LED, but the human eye is more sensitive to green light than to red light which explains the green tint. This means that each color channel required a different resistor value to control the current flow so that the luminous intensity of the internal diodes was equal. This way the light color could be displayed accurately according to a selected RGB color.



5mm diffused (If = 20mA)	Wavelength	Luminous intensity	Forward voltage	Viewing angle
White	6000-9000K	2000-3000mcd	3.0-3.2 V	120°
Red	620-625nm	1000-2000mcd	2.0-2.2V	120°
Green	515-525nm	4000-5000mcd	3.0-3.2V	120°
Blue	450-455nm	5000-7000mcd	3.0-3.2V	120°
Yellow	588-592nm	1000-2000mcd	2.0-2.2V	120°
Orange	602-610nm	1000-2000mcd	2.0-2.2V	120°

Fig. 4.101 5mm diffused LED datasheet (the values in lines 2-4 are applicable for the RGB LEDs red, green, and blue colors)

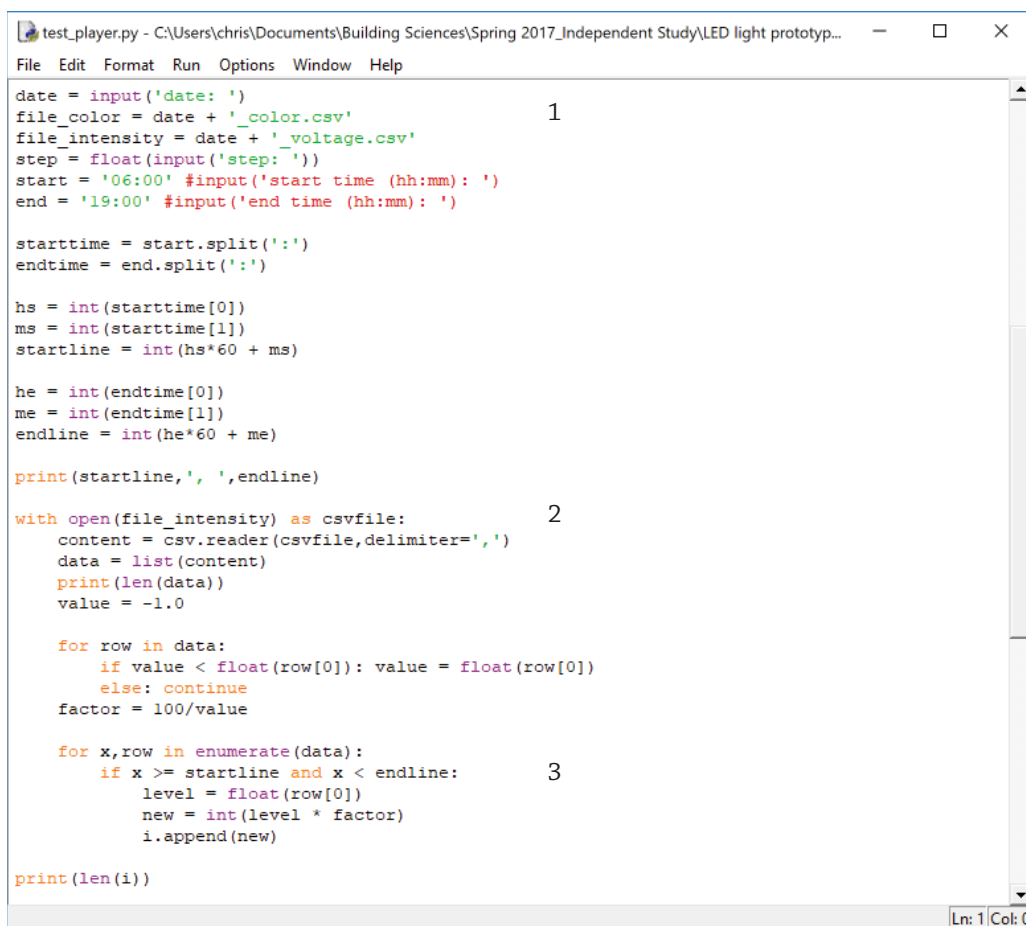
Designing and building skylight integrated RGB LED luminaires for the Sandbox model

Because I did not have experience with the design of electrical circuits I consulted a graduate student from Electrical Engineering department to help me. Kaleb Kleine assisted me on several occasions during the design and building of the RGB LED luminaires for the Sandbox model.

When designing the LED luminaires, I estimated that I needed between 60 and 80 LEDs, but the GPIO pins can't handle the amount of electric current required to power several LEDs at once. There were two options which I considered to build a dimming circuit. The PWM signal generated by the Raspberry Pi computer could be used to switch MOSFET transistors and hereby dim the LEDs. A more sophisticated option was to use a dedicated LED microcontroller such as the TLC5940. I needed six RGB channels for the model lighting. Each RGB channel was divided into three separate color channels. The dimming circuit thus had to control 18 separate PWM signals. LEDs are usually connected in series so that several LEDs can be controlled with the same signal. RGB LEDs which share either the cathode or the anode can only be connected in parallel within electrical circuits. Unfortunately, material imperfections and irregular-

ities in the manufacturing process of RGB LEDs lead to an uneven current distribution in such circuits. Kaleb advised to limit the number of LEDs connected in parallel to five per PWM channel to control potential uneven current distribution. The maximum current of 5 LEDs also would not exceed the current rating of a the TLC5940's channels.

Before continuing the design of the luminaire for the model two more tests were performed with one RGB LED to improve my understanding of the Python programming language and the PIGPIO PWM signal generator. First, I added a fading function to the PWM program to be able to play back lighting protocols which change the LEDs color and intensity over time. Next, I amended the program with a function that read the energy monitoring data from a CSV file which then could be used to control the light color and intensity. excerpts from the PWM program code are shown in Figures 4.101 and 4.102.



```
test_player.py - C:\Users\chris\Documents\Building Sciences\Spring 2017_Independent Study\LED light prototyp...
File Edit Format Run Options Window Help

date = input('date: ')
file_color = date + '_color.csv'
file_intensity = date + '_voltage.csv'
step = float(input('step: '))
start = '06:00' #input('start time (hh:mm): ')
end = '19:00' #input('end time (hh:mm): ')

starttime = start.split(':')
endtime = end.split(':')

hs = int(starttime[0])
ms = int(starttime[1])
startline = int(hs*60 + ms)

he = int(endtime[0])
me = int(endtime[1])
endline = int(he*60 + me)

print(startline, ' ', endline)

with open(file_intensity) as csvfile:
    content = csv.reader(csvfile, delimiter=',')
    data = list(content)
    print(len(data))
    value = -1.0

    for row in data:
        if value < float(row[0]): value = float(row[0])
        else: continue
    factor = 100/value

    for x, row in enumerate(data):
        if x >= startline and x < endline:
            level = float(row[0])
            new = int(level * factor)
            i.append(new)

print(len(i))
```

Ln: 1 Col: 0

Fig. 4.102 PWM test player program code - read data

- 1 define data source files
- 2 read PV monitoring data
- 3 create list of intensity values for every minute

```

test_player.py - C:\Users\chris\Documents\Building Sciences\Spring 2017_Independent Study\LED light prototyp...
File Edit Format Run Options Window Help

    for x,row in enumerate(data):
        if x >= startline and x < endline:
            level = float(row[0])
            new = int(level * factor)
            i.append(new)

print(len(i))

with open(file_color) as csvfile:
    content = csv.reader(csvfile,delimiter=',')
    data = list(content)
    print(len(data))

    for x,row in enumerate(data):
        if x >= startline and x < endline:
            rgb.append(row)

print(len(rgb))

for x,row in enumerate(rgb):
    3 color1 = [int(int(row[0])*i[x]/100),int(int(row[1])*i[x]/100),int(int(row[2])*i[x]/100)]
    color2 = [row[0], row[1], row[2]]
    bright = int(i[x]*2.55)
    setcolor(1, color1)
    setcolor(2, color2)
    setbright(17, bright)
    setbright(22, bright)
    time.sleep(step)

    4

setcolor(1, [0,0,0])
setcolor(2, [0,0,0])
setbright(17, 0)
setbright(22, 0)

pi.stop()

```

Ln: 1 Col: 0

Fig. 4.103 PWM test player program code - lighting protocol playback

- 1 read color gradient data
- 2 create list of RGB color values for every minute
- 3 color1: dynamic color, dynamic brightness / color2: dynamic color, static brightness
- 4 fading function - change RGB color over time

To test the controlling of multiple RGB channels with the Python program simultaneously I added two RGB LEDs to the test circuit. I also used the new test circuit to calibrate the LEDs and find correct resistor values for accurate color rendering through visual observation. To do this I displayed colors on my laptop screen and set the PWM channels to the RGB values of the displayed color and compared the LED's color to the color on the screen. I used a sheet of white paper to display the LED's light color on a larger surface facilitating the visual comparison of several colors listed in table 4.6. Figures 4.103 and 4.104 illustrate the calibration process.

Primary colors	red	green	blue
Mixed colors (100%/100%)	magenta	yellow	cyan
Mixed colors (100%/50%)	violet	orange	turquoise
	dark pink	light green	light blue

Tab. 4.6 RGB LED calibration colors



Fig. 4.104 Calibrating magenta (above) and cyan (below)



Fig. 4.105 Inaccurate color rendering with too much red (left) and accurate color rendering (right)

There was no Python library available to control the TLC5940 at the time, though I did find a C++ library for this purpose. It is possible to include C++ libraries in Python, but since I was not a very experienced code writer the incorporation of the TLC5940 library would have taken me too much time. I decided to use the transistor based dimming concept for the design of the RGB LED luminaire control which could be achieved using Python's PIGPIO PWM generator.

A metal–oxide–semiconductor field-effect transistor (MOSFET) is an electronic component whose conductivity changes with the applied voltage and is, among others, used to switch electronic signals. In the test circuit shown in figure 4.105

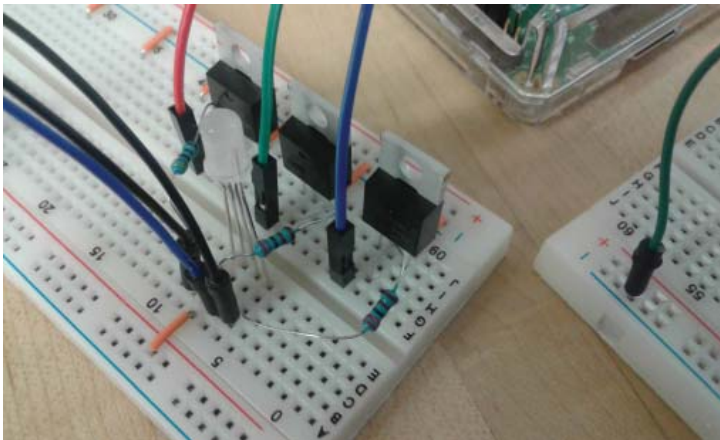


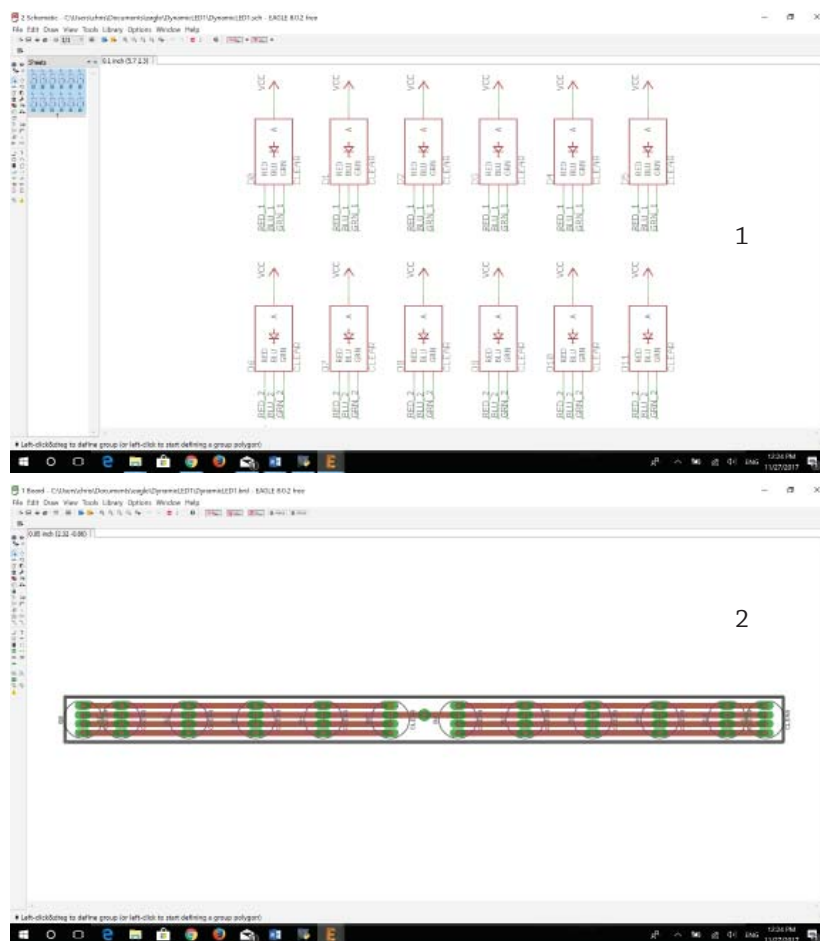
Fig. 4.106 MOSFET transistor dimming test circuit with RGB LED

the PWM signal generated by the Raspberry Pi computer was used to switch the LED circuit. The disconnection of the PWM switching signal from the LED power circuit enabled the Raspberry Pi to dim LED circuits with very high current values that its GPIO pins otherwise couldn't have handled.

The new dimming circuit was now suitable to control the RGB LED luminaires, but I still needed to prepare the dimming control software. I used the PWM test program as a base for a new playback program. Next, I generated a list of RGB values from the sunlight recorder's energy monitoring data of a selected day and saved it in a CSV file. The power of the PV panel was continuously recorded once a minute thus a 24h color pattern consisted of 1440 RGB values. The playback program read the CSV file and sent PWM signals based on the contained RGB values to three GPIO pins to visualize the color pattern over time. The program's time lapse interval was adjustable to achieve different playback speeds. I modified the test player program for the use with the MOSFET dimming circuit to create an LED player program which could dim multiple RGB LEDs.

The first step of the design of the RGB LED luminaires was to define the number of LEDs I would need for each of skylights. I placed several RGB LEDs next to one of the model's skylights with different spacings and determined that a row of 10 LEDs should provide an even lighting for the skylight wells. I thus could create two circuits with five LEDs each which was the maximum number Kaleb

had proposed for parallel connection. The four skylights weren't exactly equal in size, but the difference was small enough to use the same luminaire design for all of them which simplified the design. I needed to install two linear RGB LED luminaires for each skylight placed next to the skylight well's long faces. Seen from inside the model, the luminaires would be located behind the white translucent acrylic panels to achieve back-lit skylight wells. I needed eight luminaires with a total of 80 RGB LEDs based on this design. Kaleb suggested to use Autodesk's dedicated PCB design software Eagle and design a printed circuit board (PCB) to connect the luminaire's 10 RGB LEDs. Eagle was easy enough to use for me to draw a simple PCB after a short tutorial. Figure BB illustrates the PCB design of the RGB LED luminaire.



1 Schematic circuit design
2 PCB board design

Fig. 4.107 Schematic and PCB board design for two circuits of 5 RGB LEDs

Kaleb helped me to fix a bug before sending the design to an online PCB ordering service called OSH Park. The service catered to designers of electrical prototypes who needed only a few copies of the same PCB. I ordered 9 copies of my PCB design and received them two weeks later.



Fig. 4.108 RGB LED luminaire placed behind skylight well



Fig. 4.109 Back-lit white translucent acrylic skylight well

For a first test, I plugged 5 RGB LEDs in one of the PCBs and put it next to a skylight. Then I connected the PCB to the dimming circuit and set the Python program to display magenta.



Fig. 4.110 Using plywood piece as a reflector



Fig. 4.111 Interior view of partially illuminated skylight

The first test revealed that the translucent acrylic panels absorbed a considerable amount of the RGB LEDs' light. The individual LEDs were noticeable which resulted in an uneven light distribution.

I asked Professor Jones to look at the playback of a color pattern using the test PCB and showed him the visual effect of the back-lit skylight well. He found the color pattern very successful. As far as the reduction in brightness through the translucent acrylic pieces is concerned Professor Jones agreed that times with potentially lower variation in brightness could be mitigated by increasing the color saturation which would lead to a more pronounced variation in light color. The uneven light distribution could be solved by placing the luminaire a little farther away from the acrylic panel.

Next, I repeated the color calibration with new resistor values based on the connection of RGB LEDs in parallel. As expected the luminous intensities of

the internal red, green, and blue LEDs varied which resulted in color variations between the LEDs. I tested all RGB LEDs by plugging them in a breadboard and set the color to white. I compared the light color of five LEDs at a time and sorted them based on the red or blue tint I observed. This way I wanted to avoid placing two LEDs with a very different color representation next to each other on a PCB.

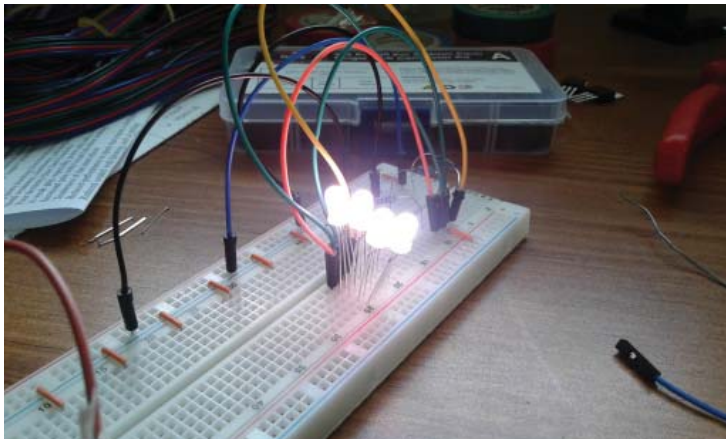


Fig. 4.112 Sorting RGB LEDs with white color calibration circuit

I now could start to build the RGB LED luminaires. The MOSFET dimming circuit could only be used with common anode RGB LEDs. I purchased 100 diffuse 5mm RGB LEDs and soldered them to the PCBs.



Fig. 4.113 Soldering RGB LEDs to PCBs



Fig. 4.114 2 circuits of 5 LEDs in parallel per PCB



Fig. 4.115 Completed RGB LED luminaire with 10 LEDs

The next step was to design and build supports for the completed luminaires to mount them in the model. For each support, I used plywood and a laser cutter to make a rectangular panel which would serve as a reflector and hold two l-shaped support pieces with slits to insert the luminaire.

- 1 reflector
- 2 support piece

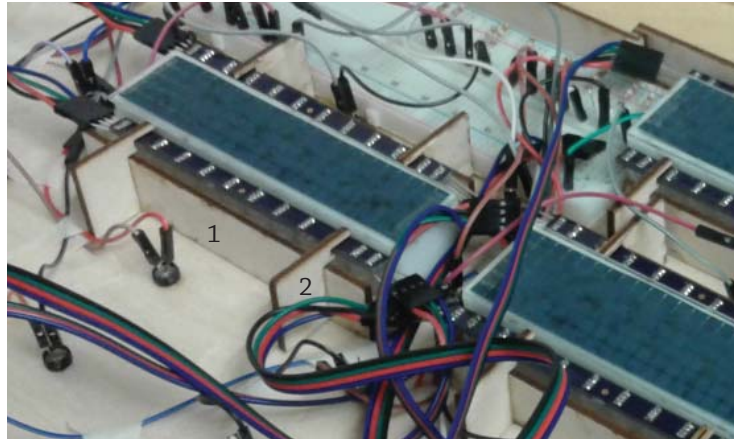


Fig. 4.116 Plywood luminaire support

I mounted the eight luminaires in the model using the plywood supports and made RGB power cables with customized lengths to connect them to breadboards with resistor circuits. As described in chapter 4.4, I wanted to create six separate channels for the model lighting. Figure 4.116 illustrates the determined resistor values for the LEDs and how the luminaires were connected to the resistor circuits and then to the dimming circuits.

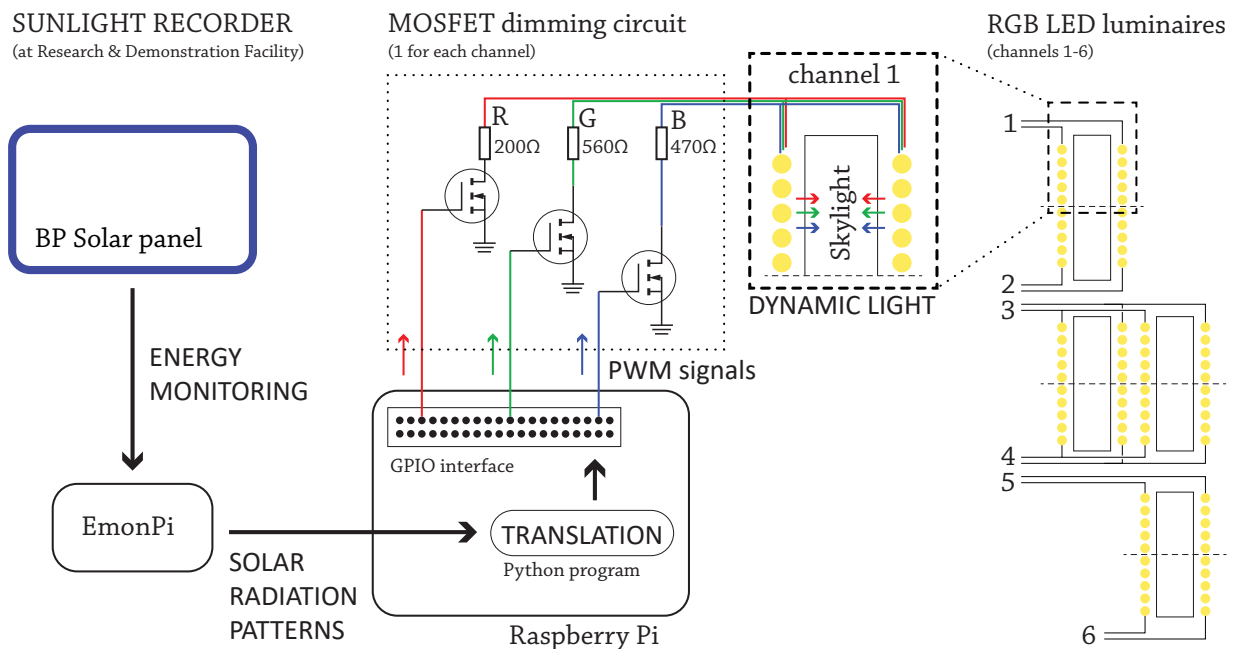


Fig. 4.117 Multicolor LED lighting diagram

I used two breadboards to build 18 MOSFET dimming circuits to control the three colors of each of the six RGB light channels and connected them to the Raspberry Pi's GPIO pins. I connected the resistor circuits to the dimming circuits using additional RGB power cables and completed the Sandbox RGB LED skylight well lighting by sealing gaps in the model to eliminate undesired exterior light that was visible inside the model.

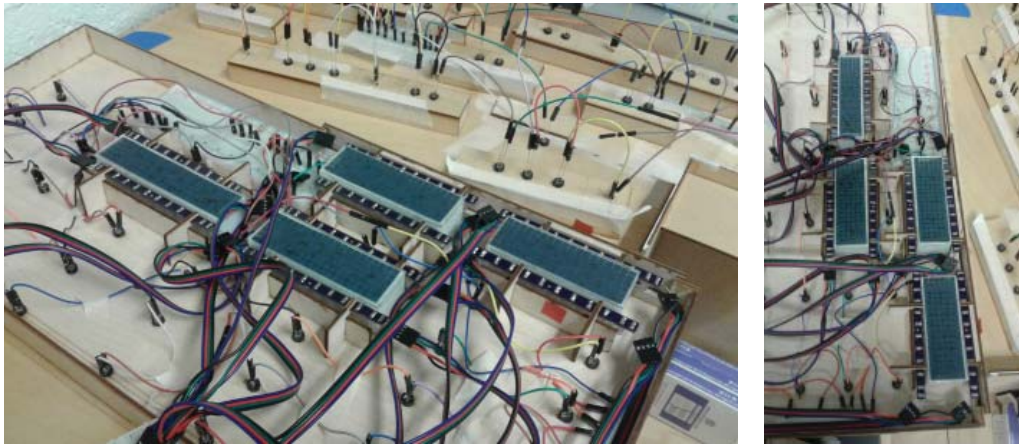


Fig. 4.118 RGB LED luminaires placed along skylight wells

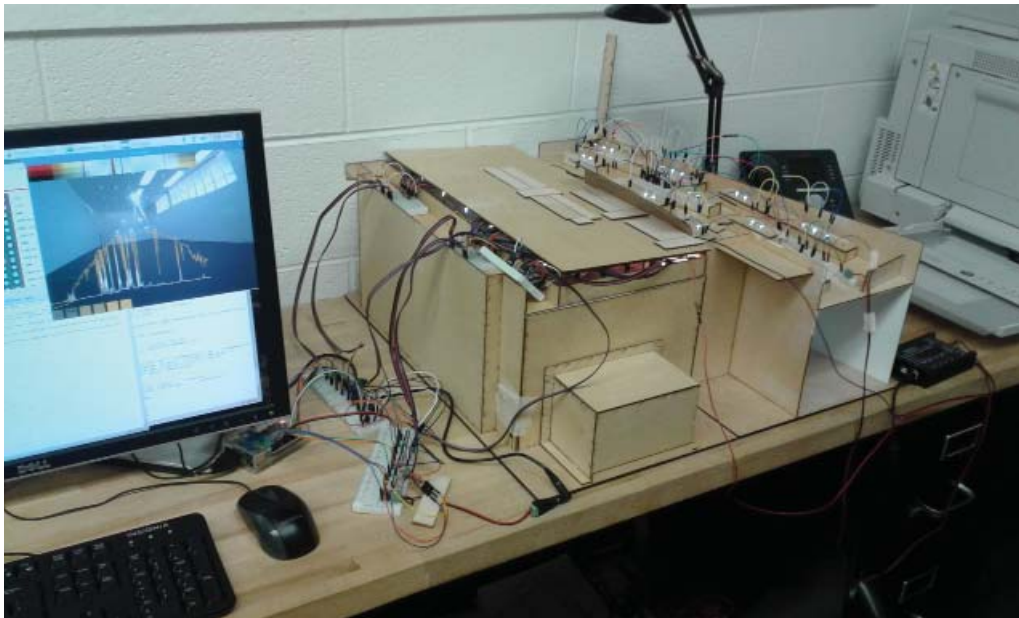


Fig. 4.119 Completed model for the playback of color and intensity patterns via skylight well lighting

4.6 LED light studies (time lapse photo documentation)

I wanted to create time lapse photo studies of the color and intensity patterns displayed by the model's RGB LED skylight well lighting so that I could visually compare the effects of dynamic daylight and dynamic electric light in the Sandbox model. To ensure that the results were comparable I used the GoPro Hero 4 camera I had used for the sunlight studies, applied the same camera settings, and placed it at the same viewpoint in the model. The observations made through the selected method of representation were used to provide a proof-of-concept for the reintroduction of natural rhythms into the built environment.

Creating the LED player dimming control software

I had already written programs for several lighting test purposes with functions I could reuse to create a playback software visualizing dynamic electric lighting. In addition to these I needed new functions to display visual information on screen via a customized user interface (UI). I wanted to draw the graph of the PV power values live on screen while playing the dynamic light patterns. This way I could determine if drops of the PV power coincided with color and intensity changes in the lighting. I found it helpful to display the time of day during the playback. Finally, I decided that the UI should be graphically appealing so that it could eventually become a visual interface for the occupants of the Sandbox and enable them to observe the anticipated correlation between the PV recording data and the visual impact of the LED lighting. In this way, the translation process would be visually illustrated. I noted a list of desired software functions in my journal:

- *Features needed for player: display images, draw polylines, display text, get key events*
- *Structure: Initialize (read data to memory), Resize array based on length of day/night (update data in memory), Play Loop: Get color function (determine color from data), nested Interpolation Loop: Interpolate color function (determine color for display), Screen background function (background images, background color, text), Display update function (update graph, text, color), LED control function (update and send RGB values to GPIO pins)*

Considering these requirements, I found a library for Python called Pygame. The Pygame library is designed to create games in the Python programming language and provides several useful functions to display graphics on screen. The library also includes functions to draw pixels on the screen.

The first test program's playback displayed a color bar set to the light color, the graph of PV power, and the time of day in front of a background image. The PV power values were translated to RGB values using a linear color gradient to determine the light color. A color bar located at the bottom of the window

displayed the current light color. The PV power graph was drawn live during the playback and its color was also set to the current light color. I selected a photo from the sunlight studies for the background image to incorporate the mood of the Sandbox space.

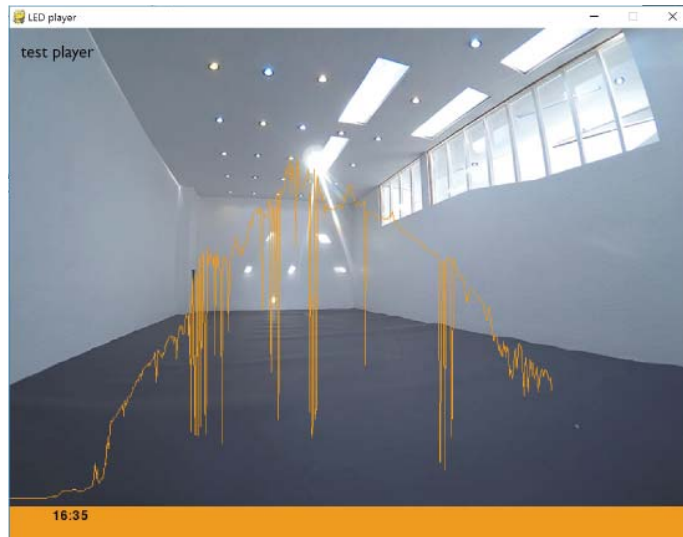


Fig. 4.120 Screenshot of an LED player test program playback sequence

I used the LED player to test the control of RGB LEDs using PWM and to develop the UI for the Luminous Solar Skylight. For now, the program could be paused and stopped by pressing “p” or “q” on the keyboard. Using the Python programming platform facilitated the development of the LED control software. I could easily transfer programs between my laptop computer running of Windows 10 and the Raspberry Pi running on the Linux based operating system Raspbian without having to update the code. I defined potential playback scenarios for the LED control software which are listed below.

- Live mode (for rooms without access to daylight) – represents the current exterior daylight condition
- Night mode (for the Luminous Solar Skylight) – playback of the preceding day’s sunlight pattern
- Mixed mode (live mode in addition to daylight) – amplifying daylight on days with low light intensity

During the testing of the RGB LED luminaires I observed how the various developed color gradients translated to perceivable visual effects of the lighting. Some gradients were too faint and I concluded that using more saturated colors for a more abstract representation of the daylight would be beneficial.

I introduced a spatial dynamic factor to the model LED lighting with the help of a new feature for the LED player. The update for the LED player program included the addition of six separate RGB channels to control the LED luminaires and a function to mix colors. The mixing function enabled the program to shift the color of the channels over time to display the movement of a color accent across the channels. I added a screen representation of the channel colors drawing colored rectangles and bars to the UI. The rectangles showed the current light color and the color bar was established over time illustrating the gradual change of color. Figure 4.120 illustrates the updated UI of the LED player. I used the added screen color representations to further develop the programs LED light control functions and to evaluate several color gradients I had developed earlier during the project and transferred the code of the LED player to the Raspberry Pi. Finally, I added the Pygame function `clock.tick()` which is used to control the framerate of a program. With this I could make sure that the playback was running at a chosen speed matching the GoPro camera's selected time lapse photo recording framerate for the LED light studies.

```

"""main program"""
for x, row in enumerate(rgb):
    keycheck()

    acc_lev = ((x*10)//lenday)
    if acc_lev > 9: acc_lev = 9
    acc_rev = (acc_lev-9)*(-1);

    channel = [[],[],[],[],[],[]]
    r = int(row[0]); g = int(row[1]); b = int(row[2])
    base_light = (i[x],i[x],i[x])

    for c in range(6):
        2 channel[c] = mix_color(base_light,row,accent[c][acc_rev],accent[c][acc_lev])

    y = 550 - i[x]; y2 = 550 - pixeldata[x]
    m += 1
    if m>59: m = 0; h += 1
    t = str(h).zfill(2) + ':' + str(m).zfill(2)
    pointlist.append((x,y)); pointlist2.append((x,y2))

    for c in range(6):
        rc = int(channel[c][0]); gc = int(channel[c][1]); bc = int(channel[c][2])
        3 pygame.draw.rect(screen, (rc,gc,bc), ((0+(50*c)),560,40,40), 0)
        pygame.draw.rect(screen, (rc,gc,bc), (x,(c*10),1,10), 0)

    #screen.fill((r,g,b))
    pygame.draw.lines(screen, (r,g,b), False, pointlist, 1)
    pygame.draw.lines(screen, (255,255,255), False, pointlist2, 1)
    text_display(t, 15)
    pygame.display.update()
    4 clock.tick(10)

time.sleep(3)
pygame.quit()

```

Fig. 4.121 LED player user interface main program code

- | | |
|-------------------------------------|---|
| 1 create moving color highlight | 2 assign colors to channels |
| 3 draw channel color bars and boxes | 4 update display at specified framerate |

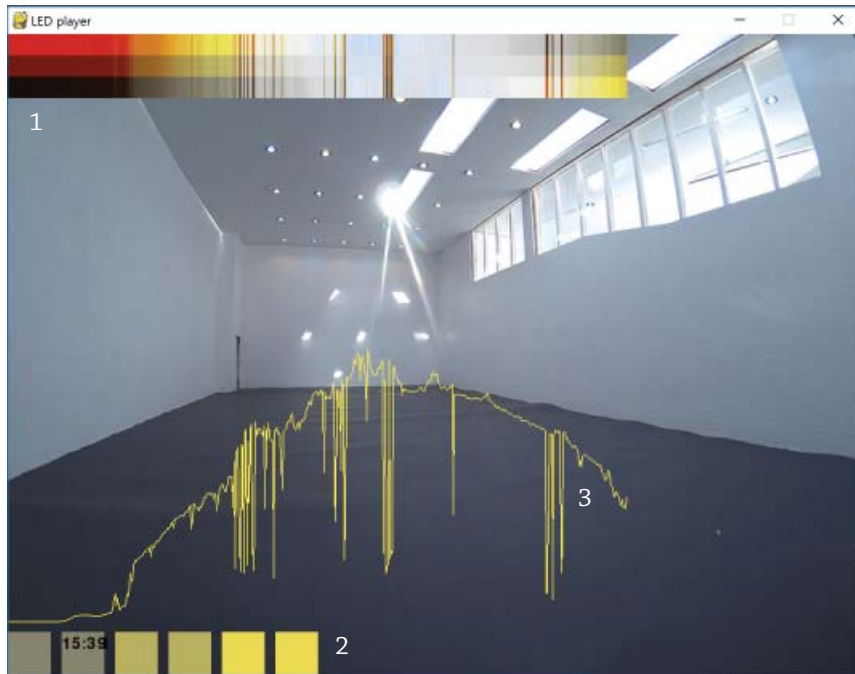


Fig. 4.122 LED player with added functions displaying variable channel colors over time

- 1 channel color bars - display color change over time
- 2 channel color boxes - display current colors of channels 1-6
- 3 colored graph - visualize PV monitoring data

Evaluating color gradients

Figure 4.121 shows a selection of color gradients that I wanted to use for the sunlight studies based on the observations I made looking at the colors as they were represented by the LED player's UI and the LED luminaires in the model. The colors on the screen are represented ignoring the effect of self-illumination thus low light intensities were rendered as very dark sometimes almost black colors. This does not represent the appearance of LEDs with low illumination accurately. However, the screen representation provided information regarding the color pattern over time whereas the model light color could only be observed and evaluated in the moment. I therefore looked at the color representation on the screen and in the model simultaneously to evaluate the gradients.

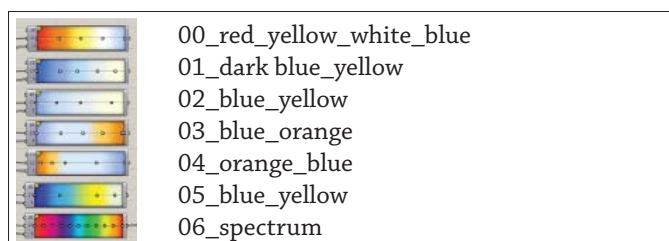


Fig. 4.123 Selected color gradients for LED playback program

Gradient color screen representation with LED player user interface

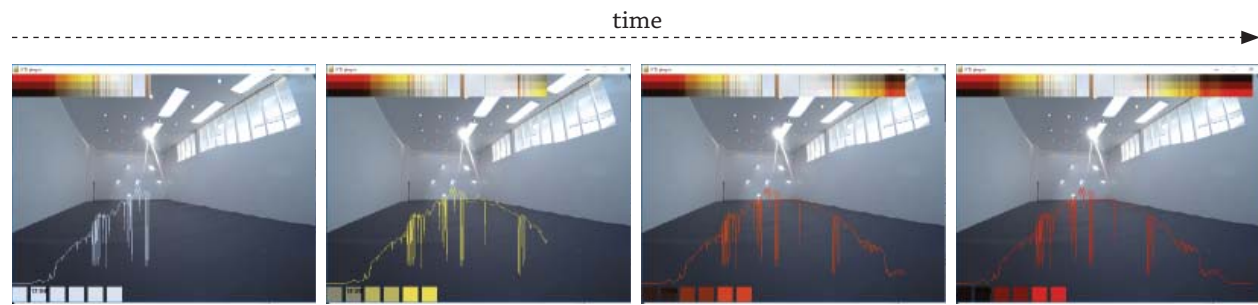


Fig. 4.124 Color study - gradient 00_red_yellow_white_blue

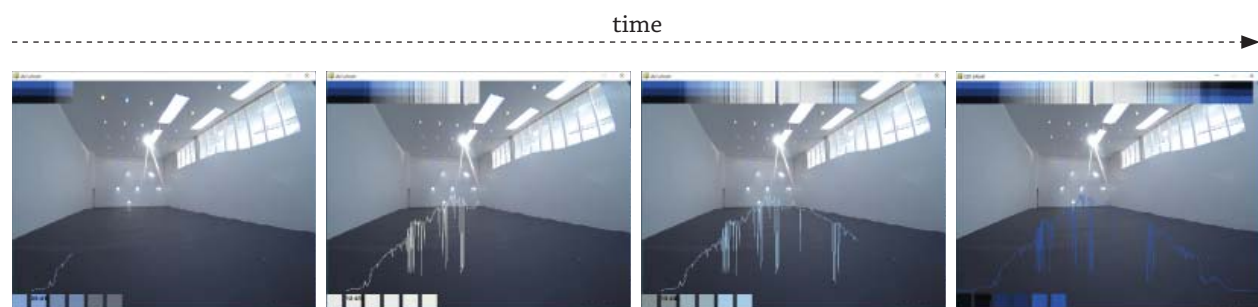


Fig. 4.125 Color study - gradient 01_dark blue_yellow



Fig. 4.126 Color study - gradient 02_blue_yellow

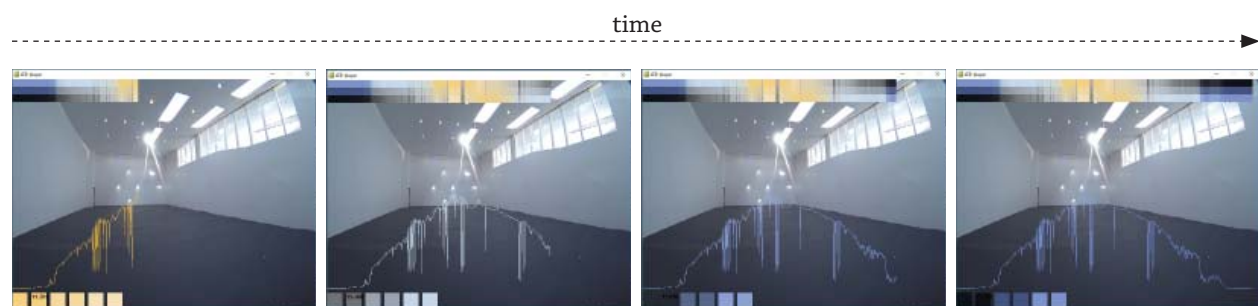


Fig. 4.127 Color study - gradient 03_blue_orange



Fig. 4.128 Color study - gradient 04_orange_blue

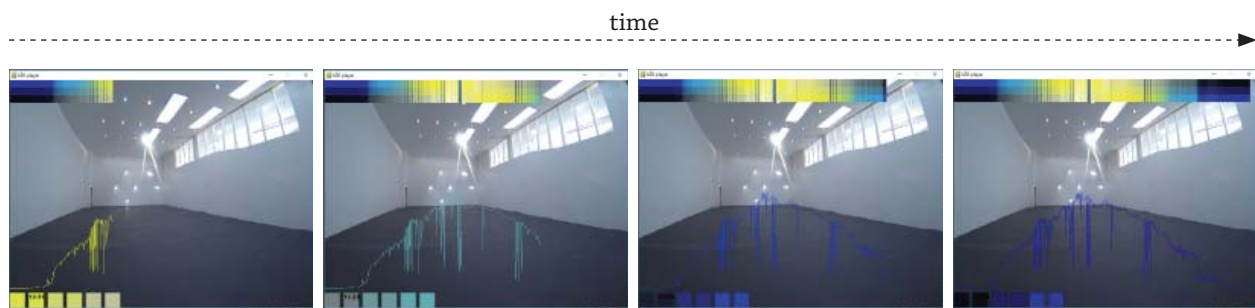


Fig. 4.129 Color study - gradient 05_blue_yellow

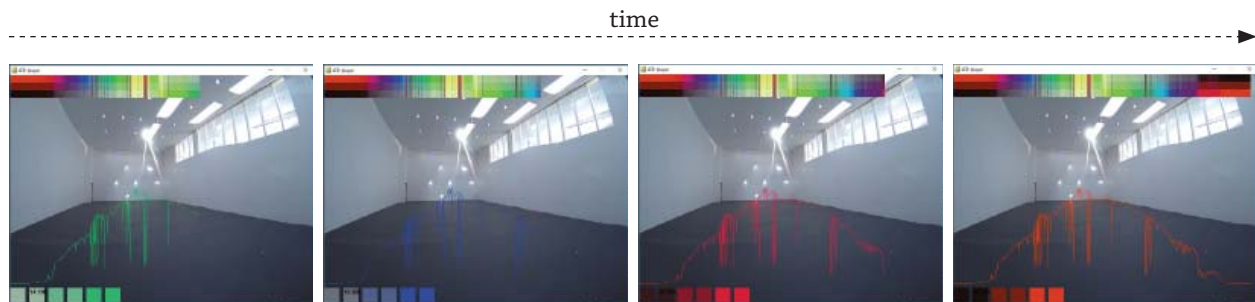


Fig. 4.130 Color study - gradient 06_spectrum

Recording LED light studies

During the gradient evaluation, I noticed that the gradients with more saturated colors looked better in the model. Less saturated colors appeared to be more subdued. I selected the gradients 00_red_yellow_white_blue, 02_blue_yellow, 05_blue_yellow, and 06_spectrum to record comparative LED light time lapse photo studies using the monitoring data from February 24th, the date of

sunlight study 1. The selection included one gradient with warm colors in the morning (gradient 00), one gradient with less saturated colors (gradient 02), one gradient with cool colors in the morning (gradient 05), and one gradient with many different colors (gradient 06). I added three seconds of cyan color to the beginning and to the end of the color protocol to give me time to set up the GoPro camera, start the recording, close the model, and start the playback program. I discarded the photos with cyan lighting later. That way the number of photos in the LED light study was equal to the number of photos in the sunlight study.

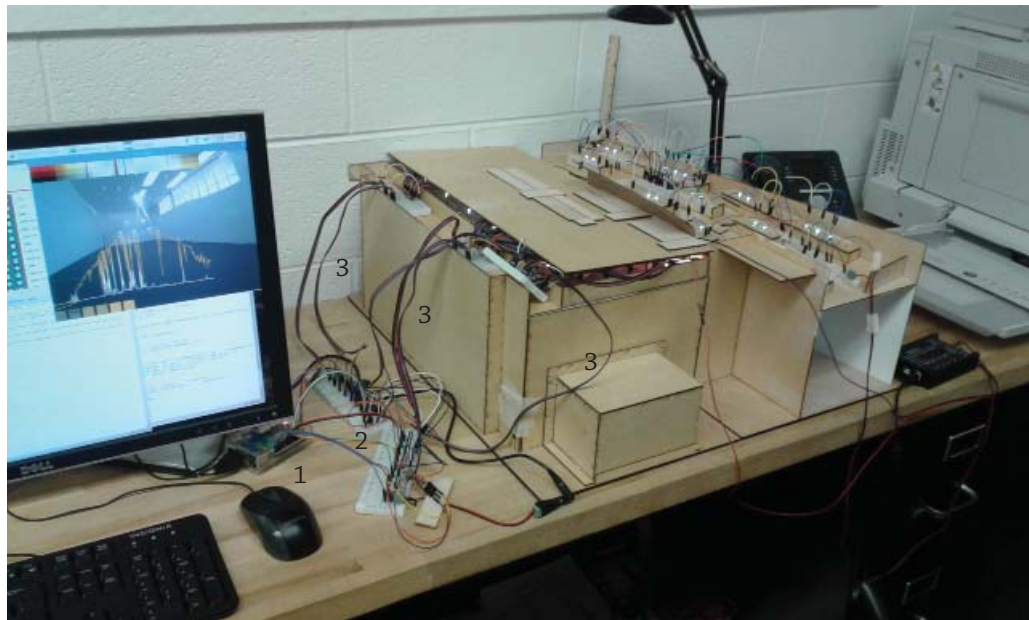


Fig. 4.131 Model setup for LED light studies – office light blocked from entering the model through skylights (night-time simulation)

1 Raspberry Pi 3 2 MOSFET dimming circuits 3 RGB power cables

Analyzing the time lapse photo sequence

The playback frame rate was matched with the camera's time lapse interval. During the sunlight studies, the camera was set to take a picture once a minute in coordination with the logging intervals of the energy monitoring. The recording process of the LED light studies could be accelerated by setting the framerate of the LED player and the camera time lapse interval to one second. I recorded one full day in approximately 15 minutes, but each photo still represented one minute in real time. Again, I transferred all recorded images to my

laptop computer for a thorough analysis and used Windows Explorer's large icon view feature to display the photos in an array on the screen. Figure 4.130 shows an extract of the array.



Fig. 4.132 Extract of photo array – LED light study (gradient 05)

As intended variations in PV power intensity resulted in variable color and brightness of the skylight well LED lighting. The result of the translation process could be visualized by comparing identical extracts from the sunlight study and LED light study photo arrays. Using gradient 05 for the playback caused the LED light to change from warm to cool colors when the PV power dropped. A similar effect occurred during the sunlight studies when the intensity of the daylight decreased accompanied by an increase in color temperature. The described relation is depicted in figure 4.131.

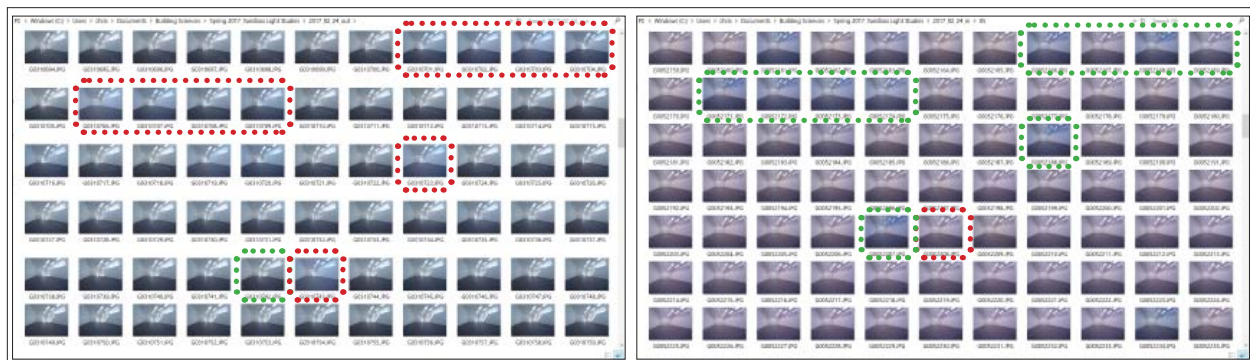


Fig. 4.133 Extracts of photo arrays – sunlight study (left) & LED light study (right)

The photo arrays were very helpful for the evaluation of the translation process, but they produced static representations and thus couldn't illustrate the anticipated dynamic representation of daylight through electric lighting. I had created videos during the sunlight studies using the image sequence function included in Adobe Premiere to visualize the temporal properties of daylight. I now used the same method and created LED light study videos. It seemed to be useful to take advantage of digital video editing capabilities and render the synchronized videos of a sunlight study and the corresponding LED light study side by side on the screen as depicted in figure 4.132. This way I could assess the temporal patterns of both the daylight and the LED light simultaneously and determine if the translation process was successful.

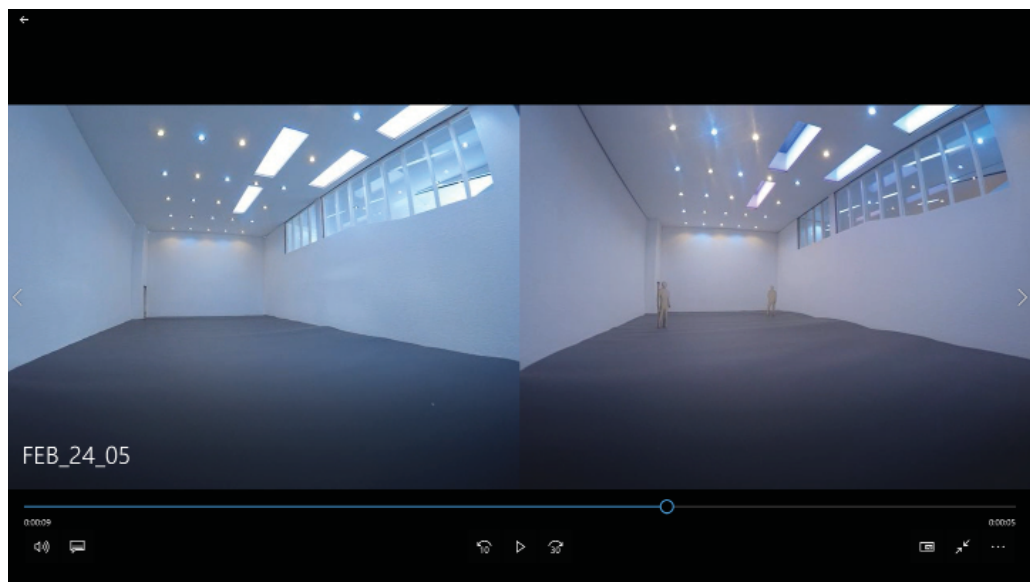


Fig. 4.134 Comparative time lapse video study – sunlight (left) & LED light (right)

The visual effect of the dynamic electric light generated with gradient 05_blue_yellow corresponded best to the skylights' natural daylight. I thus recorded LED light studies for the remaining three sunlight study days in March, April, and June using gradient 05.

4.7 Summary of the immersive case study process

In the immersive case study, I conducted several sub-projects to investigate steps for the implementation of PV integrated skylights with dynamic electric lighting in a project workspace of ICAT called Sandbox. The concept of the project was based on a missing connection to the outside reported by the occupants. I first documented the as-built condition of the Sandbox to provide a basis for the project design. The documentation was followed by the process of designing and building a sunlight recorder and a scaled model of the Sandbox. The sunlight recorder consisted of a 75W BP Solar PV module, a resistive load circuit, and a data logging device. I used the sunlight recorder to sense solar radiation by logging the voltage and current levels of the PV panel over time. I developed the dynamic light patterns by translating sensed insolation to LED lighting control protocols using logged current and voltage levels of the PV panel and several color gradients composed of colors of the sky and blackbody colors. The scaled model of the Sandbox was the primary tool for the research during the immersive case study. I used it to illustrate the influence of the sunlight which was entering the model through the skylights as well as the dynamic light patterns of the skylight integrated LED lights. This was done by recording time lapse photo sequences with a digital GoPro Hero 4 camera which I positioned inside the Sandbox model. I then used the photo sequences to conduct a qualitative and a quantitative evaluation. For the qualitative evaluation I used digital video editing software to create time lapse videos from the images of the photo sequences. I developed programs to conduct a quantitative RGB pixel value analysis determining the pixel color and brightness variation in each photo sequence. I compared the results from my visual observation of the time lapse videos and the results of the pixel variation analysis to confirm that the dynamic LED lighting reproduced the natural rhythm of the sunlight entering the model through the skylights. The results are summarized in the beginning of chapter 5 followed by a detailed discussion of the comparative evaluation.

The process of the immersive case study allowed me to investigate several aspects of the design and implementation of PV integrated skylights. I examined the natural rhythm of the sun cycle and the temporal properties of sunlight. I also looked at translation concepts and technical solutions for the creation of control protocols for the dynamic LED lighting of the Sandbox model. The documentation of the process steps in a journal was helpful as a reference of the findings during the immersive case study. Furthermore, the immersive case study method enabled me to learn in the process while exploring concepts for the representation of a natural phenomenon with technology.

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(Source: <https://www.caus.vt.edu/about/research>)
- Fig. 4.6 Roof of test cell building at RDF
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- Fig. 4.85 Colorized datafile translating color temperature to RGB values
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5. Presence and Place – Comparative Evaluation of Results

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5.1 Summary of results

To verify that a BIPV panel can be considered a recorder of variations in solar radiation I obtained PV power values from a 75W BP Solar PV panel mounted on a timber substructure, and processed with an EmonPi energy monitoring device. I compared time series plots for the PV power values with that of the solar radiation levels of a pyranometer. As expected, different weather conditions strongly influenced the appearance of the plots. The comparison showed a very close relation between the PV current and voltage levels on the one hand and the radiation levels on the other.

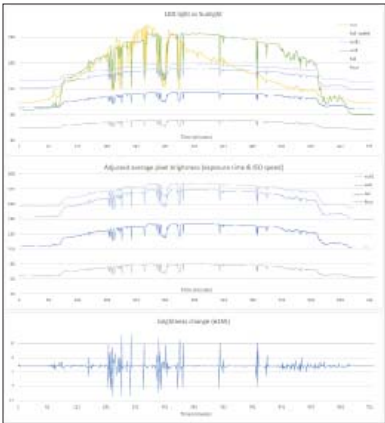


Fig. 5.1 Graph comparisons

I constructed a scaled model of the project space and conducted sunlight and LED light studies using sequences of time-lapse photos to illustrate dynamic light patterns. The quantitative evaluation of the sunlight and LED light patterns was carried out by a RGB value analysis of selected pixels in the photos. The analysis compared the RGB values from pixels of the selected area in each photo with the values of the same pixels in the following photo in the sequence and saved all values as a list of “pixel variations”. These variations indicated magnitudes of difference as numeric quantities for color or brightness as explained in table 5.1. Additionally an average pixel brightness was calculated for each photo as explained in table 5.2. The list values were then plotted as a graph. There were three important findings:

- The fluctuation of the PV power was highly related to the fluctuation of the sunlight.
- The magnitude of the LED lighting pixel color variation was only slightly lower than the magnitude of the pixel variation caused by the sunlight.
- The pixel brightness variation due to dynamic sunlight was much larger than for the dynamic LED lighting patterns.

Formula: pixel variation = current pixel RGB values - previous pixel RGB values
range of RGB values: 0-255 (for red, green, and blue)
Maximum pixel variation: 3 x 255 = 765 (0,0,0 to 255,255,255 - black to white or vice versa)

Tab. 5.1 Computing pixel variations

Formula:	$\text{average pixel brightness} = \frac{\sum \text{pixel GRAY values}}{\text{number of pixels}}$
range of pixel GRAY values:	0.5-242.75 (gamma corrected luminance value weighted for color)
Color weighting factors (adjusting for color cone response):	red = 0.212655, green = 0.715158, blue = 0.072187
Maximum average pixel brightness variation:	242.75 - 0.5 = 242.25 (black to white or vice versa)

Tab. 5.2 Computing average pixel brightness

For the qualitative evaluation, I created time lapse videos from recorded time-lapse photo sequences. The videos of the LED light recording and the sunlight recording were played simultaneously on a computer screen side by side. The eye of the researcher was used as a measuring instrument for a visual comparison. The visual evaluation revealed a close relation between the time-based fluctuation of the daylight and the LED light which can also be observed quantitatively in the plotted graphs. The visual comparison of different color patterns showed that the visual effect of a sky color scheme (cool colors for low PV power and warm colors for high PV power) was similar to the effect of direct sunlight entering through the skylight. The visual effect of a sunlight color scheme (warm colors for low PV power and cool colors for high PV power) which is meant to simulate the light colors during sunrise and sunset was dissimilar to the direct sunlight which entered through the skylights. The observed disparity might be a result of the skylight design. Apparently, the vertical dimension of the skylights was large enough so that the direct component of low morning and evening sunlight was entirely caught in the wells. This reduced the impact of the direct sunlight and raised the impact of the diffuse light from the portion of the sky above the skylights. The color temperature of the sky's diffuse light is higher (cooler) in the mornings than during the day resembling the sky color theme rather than the sunlight color scheme.

The project's goal was to make present the passing of time and improve the sense of place in the Sandbox. I used qualitative methods to determine if the proposed intervention achieved this goal. I then referred to quantitative methods to examine the observations made during the qualitative evaluation. The limitations, errors and the qualitative evaluation methods of the project are discussed in detail hereafter followed by a description of the functionality of the pixel analysis and the quantitative evaluation of the generated results.

5.2 Limitations and errors

There were three main sources of error which affected the immersive case study project. The first was related to the data logging process and the second was related to the digital action camera specifications. The third source of error was associated with the design of the resistive load circuit of the sunlight recorder which for safety reasons set maximum limits for voltage and current accepted from the PV panel.

Data logging errors

The first source of error was from the collection and monitoring of the PV energy data during the recordings of the sunlight experiment. The sunlight recorder consisted of a 75W BP Solar module, a custom built resistive load circuit, and an EmonPi energy monitoring unit. This was located on the roof of the test cell building at the Research and Demonstration Facility (RDF). The automatic update of the EmonPi's internal clock was not functional because there was no internet connection available at the test cell building. There were a few power failures during the recording period (December 2016 to June 2017) leading to data being logged with incorrect time stamps for a few short time periods. On two occasions, the logging process did not start again automatically after a power loss causing a loss of data.

I obtained data from a pyranometer (Onset S-LIB-M003) from Professor Elizabeth Grant's research setup on the roof of the Virginia-Maryland Regional College of Veterinary Medicine. The HOBO data loggers used for the weather station were equipped with photovoltaic panels and batteries which ensured continuous logging. The weather station was located 1.15 km northeast of the sunlight recorder at RDF which led to small discrepancies between the datasets caused by different cloud shadow patterns. As shown in figure 5.4, the mismatch was not very pronounced which allowed me to synchronize the sunlight recorder's data with incorrect time stamps with the pyranometer data.



Fig. 5.2 Weather station on the roof of Vet Med



Fig. 5.3 Distance between Vet Med (1) and RDF (2)

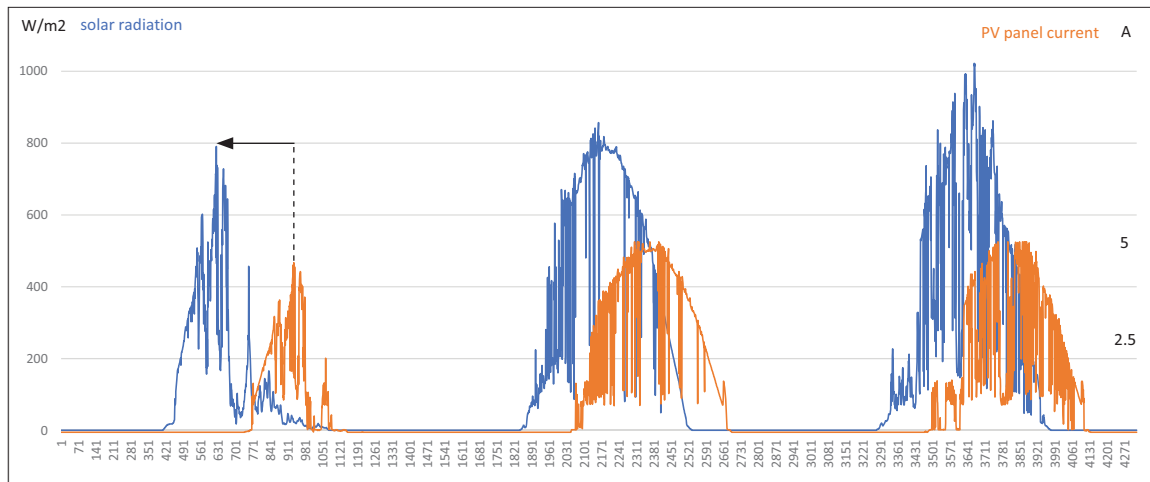


Fig. 5.4 Synchronizing sunlight recorder data (PV panel current) with pyranometer data (solar radiation)

Limitations of the GoPro Hero 4 digital action camera

A small digital action camera was available from the university to record time-lapse photo sequences for sunlight and LED light studies. The small size of the GoPro Hero 4 silver camera was beneficial because it had to be positioned inside the scaled model of the Sandbox. The photo sequences were used for comparative studies to demonstrate a proof-of-concept for the introduction of natural rhythms into the Sandbox. The software of the GoPro Hero 4 camera included a tool called protune which allows for several fixed presets. The GoPro cameras from the university came with the different versions of protune. Thus, when using different cameras, I could not use the exact same settings for recording individual photo sequences. For all sunlight studies but one I could set the white balance to a fixed value of 4000K which perfectly matched the color temperature of the electric base lighting in the Sandbox model. Instead of a fixed value, the ISO speed could only be set to a maximum value. Some of the cameras used allowed the maximum value to 100 which resulted in a constant ISO speed for all photos in the sequence. Other cameras could only be set to a maximum ISO speed greater than 100 leading to different values for individual photos in the same sequence. Furthermore, the GoPro Hero 4 has a fixed focal ratio of $f/2.8$. The exposure time cannot be set as a fixed value and is automatically adjusted by the camera based on the brightness of the scene.

I analyzed the EXIF metadata of the photo sequences for February 24th, March 2nd, April 26th, and June 26th. The ISO speeds and exposure times for the most and least bright photos in the same sequence are shown in figure 5.5. Figure 5.6 shows how the passing of a cloud shadow affected the ISO speed and exposure time of the photos.

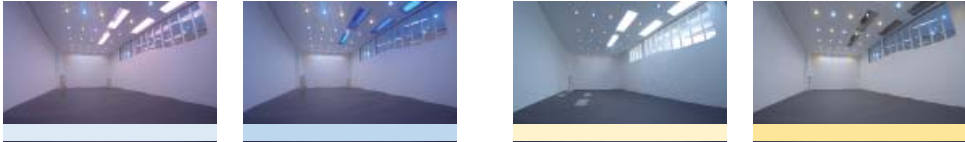
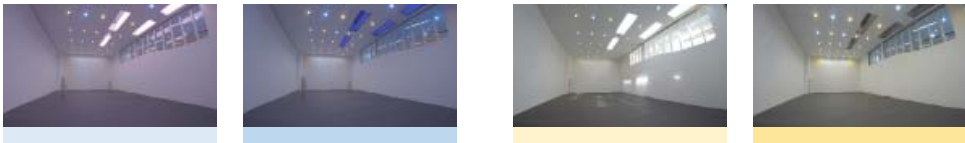
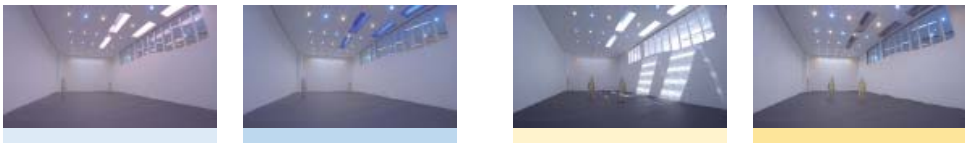
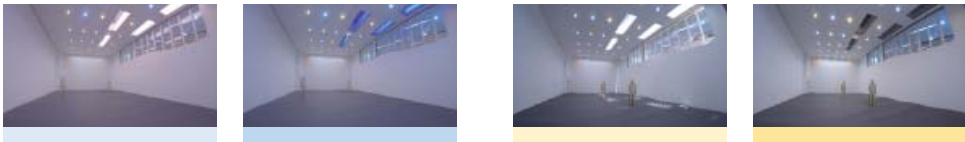
Camera Details	Instance 1a		Instance 1b	Instance 2a	Instance 2b	Date
	LED			SUNLIGHT		
Exposure time	1/15 sec	1/15 sec		1/95 sec	1/17 sec	
ISO speed	124	145		100	100	
Exposure bias	0 step	0 step		0 step	0 step	
f-stop			f/2.8			FEB 24 high-low
						
	LED			SUNLIGHT		
Exposure time	1/30 sec	1/30 sec		1/66 sec	1/16 sec	
ISO speed	139	161		100	100	
Exposure bias	-1 step	-1 step		0 step	0 step	
f-stop			f/2.8			MAR 02 high-low
						
	LED			SUNLIGHT		
Exposure time	1/15 sec	1/15 sec		1/60 sec	1/30 sec	
ISO speed	100	118		116	180	
Exposure bias	-0.5 step	-0.5 step		0 step	0 step	
f-stop			f/2.8			APR 26 high-low
						
	LED			SUNLIGHT		
Exposure time	1/15 sec	1/15 sec		1/60 sec	1/30 sec	
ISO speed	105	118		281	215	
Exposure bias	-0.5 step	-0.5 step		0 step	0 step	
f-stop			f/2.8			JUN 21 high-low
						

Fig. 5.5 EXIF metadata - varying camera settings: maximum and minimum ISO speed/exposure time

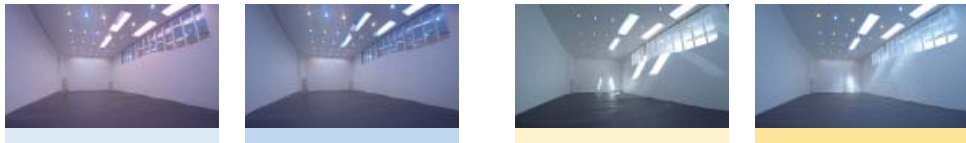
Camera Details	Instance 1a	Instance 1b	Instance 2a	Instance 2b	Date	
	LED		SUNLIGHT			
Exposure time	1/15 sec	1/15 sec	1/166 sec	1/57 sec		
ISO speed	128	129	100	100		
Exposure bias	0 step	0 step	0 step	0 step		
f-stop	f/2.8		f/2.8		FEB 24 cloud shadow	
						

Fig. 5.6 EXIF metadata - Impact of passing cloud shadows on ISO speed/exposure time

As illustrated in figures 5.5 and 5.6 the exposure time and ISO speed values varied sometimes greatly between individual photos of the same sequence. The purpose of the studies was to investigate the effect of dynamic light quantitatively and qualitatively. Both exposure time and ISO speed affect the image brightness counteracting the impact of dynamic light. Therefore, I had to adjust the results to compensate for variable exposure times and ISO speeds.

Resistive load circuit maximum voltage and current levels

The grid-tie simulation circuit consisted of a resistive load and electric power measuring components. It was designed with maximum limits for voltage and current levels to prevent overcharging and failure of the circuit. The maximum power of the resistive load was lower than the maximum power of the BP Solar module which probably contributed to the decreased values measured with the sunlight recorder under high solar radiation. Another decreasing factor which could not monitor is the temperature of the PV cells. The high solar radiation levels on June 21st probably further decreased the power of the PV panel. This observation is depicted in figure 5.7.

The described effect could only be observed at solar radiation levels above 800 W/m². The maximum measured solar radiation did not dramatically exceed this value on three of the four sunlight study recording days. Therefore, the effect of the decreased power only had to be factored in for the sunlight study recorded on June 21st.

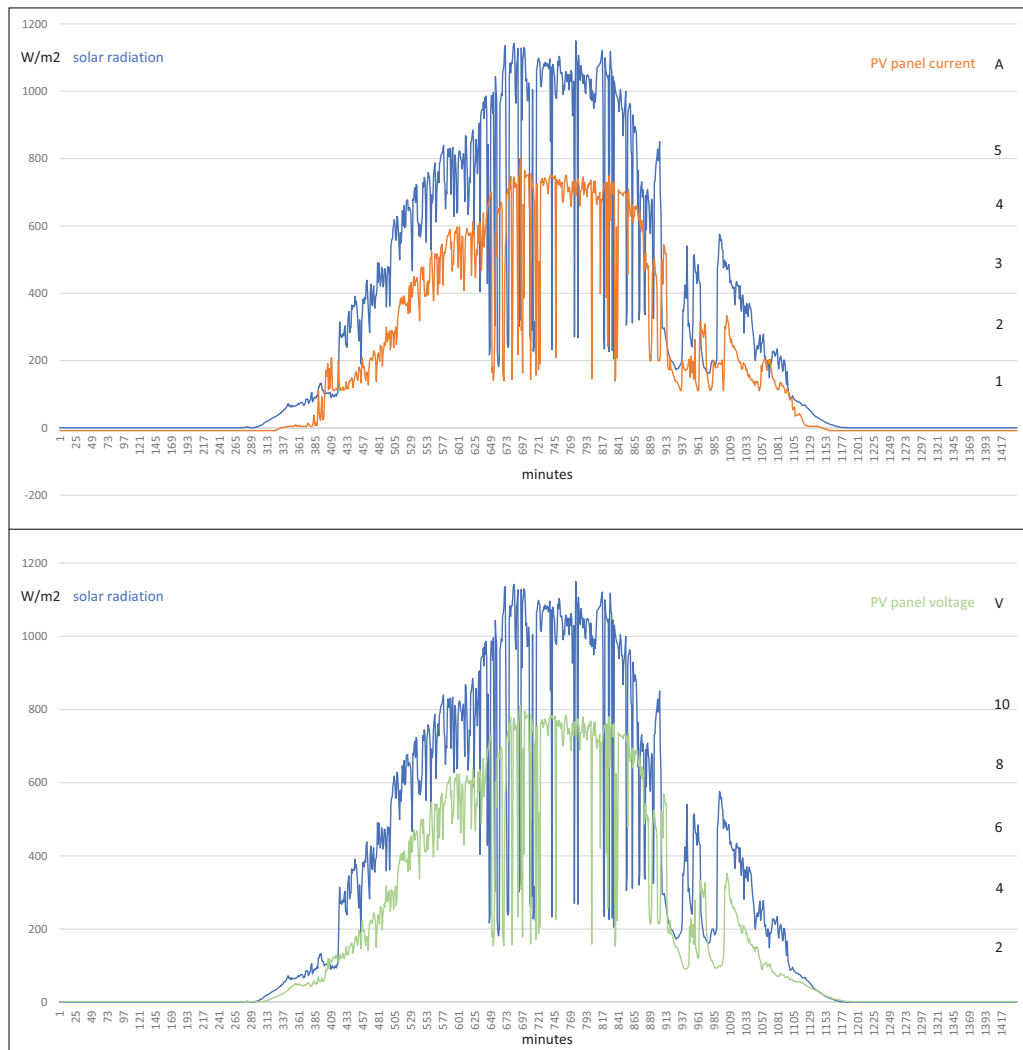


Fig. 5.7 Synchronized energy monitoring data from June 21st – PV panel power recorded 20% below the potential power according to solar radiation

5.3 Qualitative evaluation of results

For the qualitative evaluation I created photo sequences for the sunlight- and LED light studies using a GoPro digital action camera. As mentioned in section 4.6, the static photo arrays were not helpful for evaluating the dynamic representation of daylight and its presence in the space. I thus used the photos to create time-lapse videos. The playback of two videos side by side on the computer screen enabled me to visually compare the temporal variations in brightness and color for a qualitative evaluation of the effectiveness of translating energy monitoring data to light control protocols. This also helped with the design of the LED light control protocols. A fast playback speed made it possible to observe gradual changes in brightness and color that would have been too slow for a comparative evaluation. The qualitative visual evaluation raised new questions which suggested quantitative evaluation methods. The most important question to be answered quantitatively would be if the magnitudes of the visual impact of the sunlight and the LED light on the room were comparable. During the qualitative evaluation, I was mostly interested in the temporal relation between the variations in sunlight and the LED light brightness and color.

Sunrise and sunset

The videos showed that the duration and rate of change (fade) in brightness between of sunrise and sunset was accurately reproduced. However, the timings of the changes were offset by a few minutes. This made sense because the LED lighting protocol was based on energy monitoring data, not illumination. A PV panel starts to produce energy only after the insolation intensity becomes great enough to overcome the internal electrical resistance. This caused the LED light to fade in several minutes after the beginning of the sunrise. The LED light faded out earlier than the beginning of the sunset.

Short-time fluctuations in brightness

During periods of high atmospheric turbidity, the moving shadows of clouds through the skylights in the model caused brief drops in brightness. Simultaneously, the color temperature of the light increased. The LED lighting protocol varied the brightness and color based on the recorded energy levels and the selected color gradient. When compared to the gradual changes described above, I observed a close temporal relation between the short-time fluctuations in brightness of the sunlight and the LED light. However, a slight offset in time was still noticeable. Due to the limitation of the experimental setup which prevented me from using live energy monitoring data, these small offsets might have been caused by inaccuracies during the synchronization of time-dependent PV energy levels and the sunlight study photo sequences.

Selecting color gradients

The intention was not to mimic or replace daylight with artificial light rather to create an abstract representation of the same with dynamic LED lighting. Even though not identical, the abstract representation of daylight was still meant to reproduce the change of mood in the room over time. During the viewing of the sunlight study videos I noticed an interesting effect of the skylights. Contrary to the general association of warm colors with sunrise and sunset I observed a cool daylight color in the model during morning and evening hours. This was probably a result of the filtering effect of the skylights which prevented low angle direct sunlight from entering the room thus elevating the influence of the blue color of diffuse skylight.

I created two time-lapse videos from the studies conducted on February 24th using a warm color gradient and a cool color gradient and compared them to the sunlight study time lapse video. In this way I intended to confirm that a cool LED light color scheme would reproduce the mood of the sunlight over time. The screenshots shown in figures 5.8 and 5.9 illustrate that this was in fact the case. During the warm color scheme, the LED light color became “warmer” with decreased brightness while the cool color scheme resulted in a cool LED light color when the brightness dropped. The cool color scheme’s LED light colors resembled the daylight color temperature during periods with lower insolation respectively lower PV output.

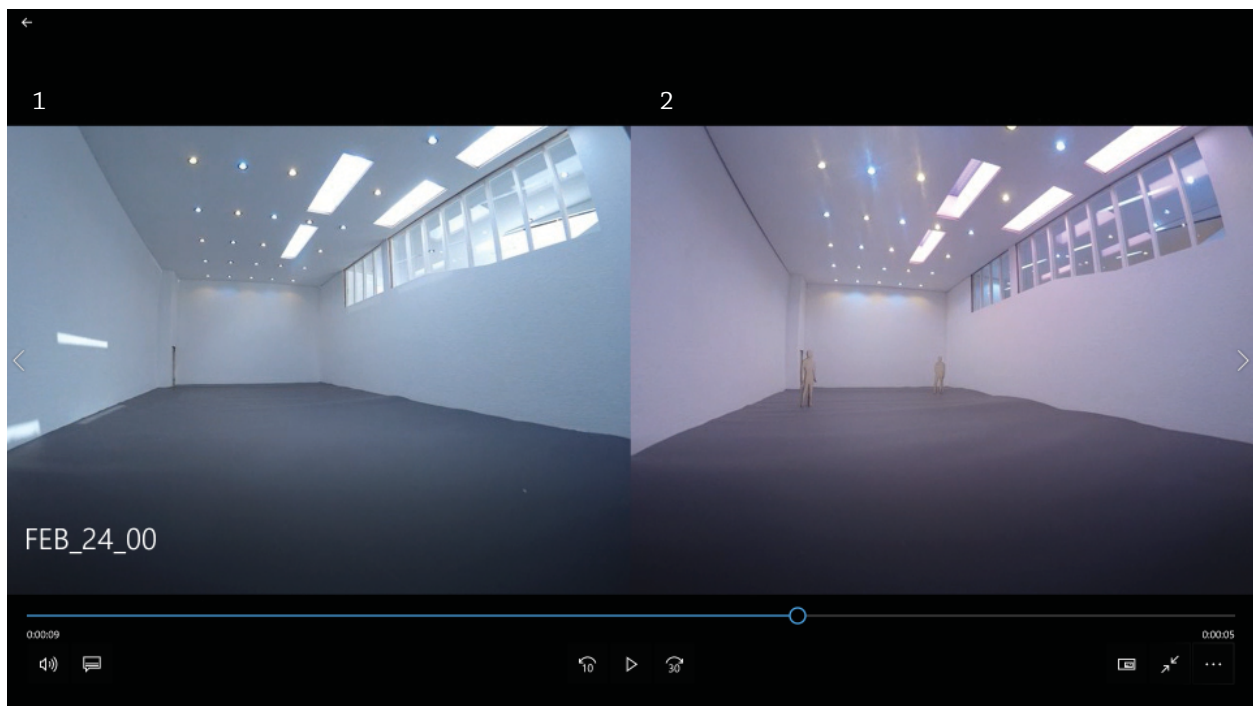


Fig. 5.8 Sunlight study video – cool image color (1), LED light study – warm color scheme and image color (2)

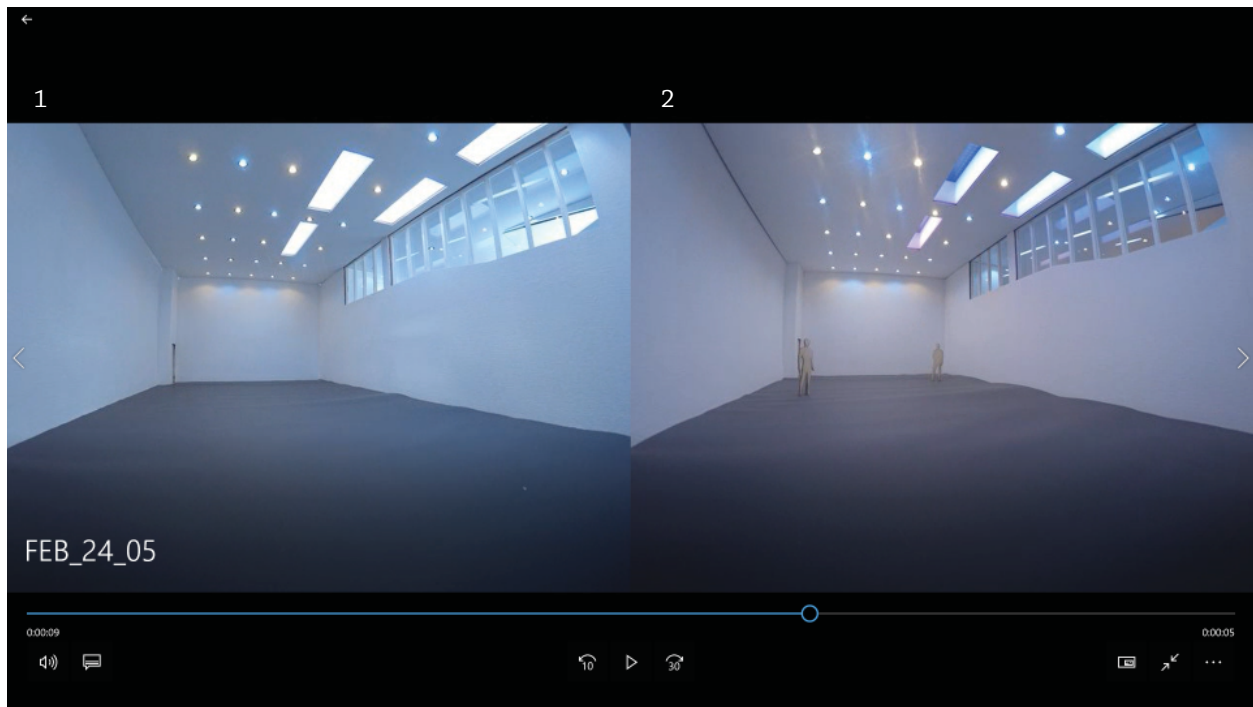


Fig. 5.9 Sunlight study video – cool image color (1), LED light study – cool color scheme and image color (2)

I thus used the cool color scheme to create time-lapse videos from the studies conducted on the remaining days (March 2nd, April 26th, and June 21st). The observations regarding the reproduction of the gradual change of brightness during sunrise and sunset and short-time fluctuations described earlier could also be made in the newly created videos. The comparison of the various dynamic light patterns of the recording days showed that frequent fluctuations in brightness made it easier to visually confirm temporal relations between the sunlight- and LED light in the time lapse videos.

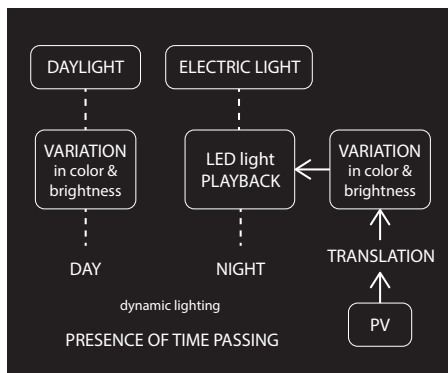


Fig. 5.10 Reintroduce temporal stimulus

The natural variation in brightness and color from daylight over time can best be observed actively when time is “sped up” (scaled). In real time, these variations are perceived passively representing the passing of time. I consider this indicator function to be beneficial for the comfort of an occupant in a space. It could be argued that if the variation in brightness and color from the LED light was comparable to dynamic sunlight, such a system could reintroduce a temporal stimulus and make present the passing of time.

The time-lapse videos can be viewed online using the links listed on page xxx. I now wanted to examine in more detail using quantitative methods the relations between the sunlight and LED light as documented with the videos.

5.4 Quantitative evaluation of results

For the quantitative evaluation I developed two analysis programs in the Python programming language to investigate the impact of dynamic light during the sunlight- and LED light studies using the time-lapse photo sequences. I applied the quantitative evaluation methods described in the following section along with the qualitative evaluation methods discussed in section 5.3.

Pixel color variation over time

Every image contained an equal number of pixels each with RGB color information as recorded by the sensor of the GoPro Hero 4 camera. As previously discussed, some of the camera settings were fixed and others were monitored to enable a meaningful comparison later in the process. The recorded RGB values specify the color of the individual pixels. The assumption was that during the light studies the changes in light intensity, light color, or both, would be detectable by analyzing pixel color values and could be visualized by plotting them over time. I created a Python program that performed an automated RGB value analysis of selected pixels in each image of a photo sequence. The RGB values of the pixels were compared with the values of the same pixels in the successive photo, saved as a list of “pixel color variations” over time, thus indicating the magnitudes of the difference in color. When comparing the pixel color variations of the sunlight study photos with the LED light study photos this enabled me to evaluate if the translation of energy monitoring data to lighting protocols successfully reproduced the sunlight patterns.

Pixel color analysis program functions:

```
for file in os.listdir('.'):
    if file.endswith('.JPG'):
        name = './' + file
        imagelist.append(name)

for f in range(stop):
    print(counter)
    difdata = []
    pixeldif.append([])
    folder,newname,ext = imagelist[f].split('.')
    current_file = newname[1:] + '.' + ext
    im2 = misc.imread(current_file)
    if f == 0: im1 = im2
```

create list of image files

read image data
to array variables
(im1 & im2)

calculate the absolute difference of the numeric RGB values between two consecutive photos for selected pixels - formula explained in table 5.1
(x 2600 to 3600, y 1100 to 1600, step 10)

```
for x in range(2600,3600,10):
    for y in range(1100,1600,10):
        rdif = abs(int(im1[y][x][0]) - int(im2[y][x][0])); rimp += rdif
        gdif = abs(int(im1[y][x][1]) - int(im2[y][x][1])); gimp += gdif
        bdif = abs(int(im1[y][x][2]) - int(im2[y][x][2])); bimp += bdif

total = rimp + gimp + bimp
update = float(total)/float(5000)
difdata.extend((update,rimp,gimp,bimp))
pixeldif[f] = (difdata)
im1 = im2; counter -= 1
```

create variable of analysis values
(pixeldif)

```
with open(NewFilename, 'w+') as csvfile:
    row = []
    newcontent = csv.writer(csvfile,delimiter=',')
    for row in pixeldif:
        newcontent.writerow(row)
```

write pixeldif
data to csv file
(1 line per image)

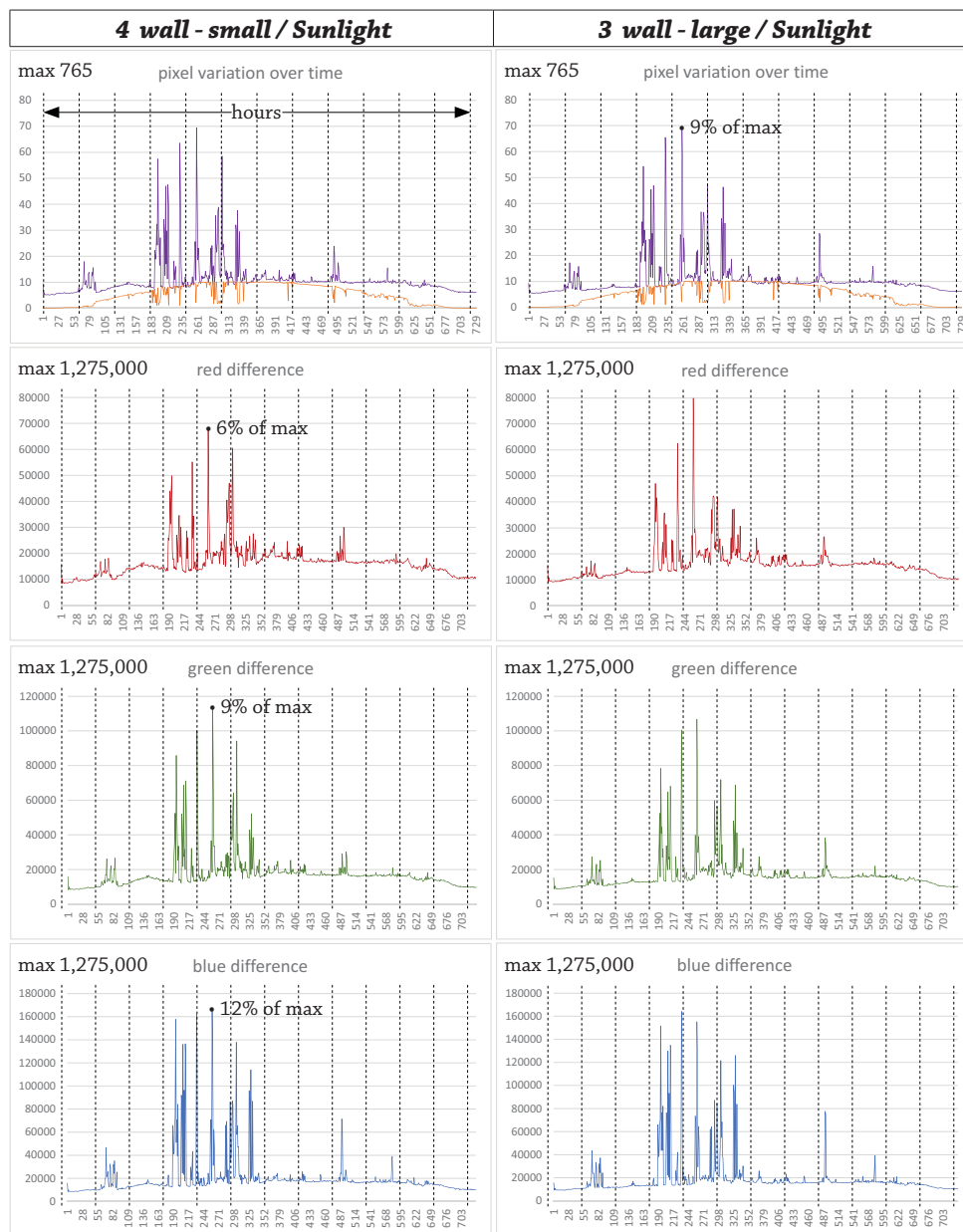
I used the pixel color analysis program to create graphs based on the photo sequences I recorded during the sunlight and LED light studies on February 24th, March 2nd, April 26th, and June 21st. For a better understanding of the program output I defined several pixel selections in different areas of the image and with different sizes. The analyzed areas are illustrated in figure 5.11.



- 1 floor - large
- 2 floor - small
- 3 wall - large
- 4 wall - small
- 5 wall1 - large
- 6 wall1 - small

Fig. 5.11 Analysis areas for color analysis (5000 pixels each)

The analysis program added all absolute pixel variation values of an image. A higher pixel variation was thus caused by both declining and increasing RGB values. The variations in PV power are a function of variable solar radiation, in other words they reflect dynamic sunlight patterns. Sunlight patterns are also inherent in daylight entering through skylights. Indeed, the graphs indeed showed a close temporal relation of high pixel color variation values (evidently caused by variable daylight from the skylights) with pronounced changes of measured PV power. Looking at separate color values revealed that the pixel color variation was most pronounced in the blue portion of the color spectrum. I did not observe a remarkable difference between the results from the small and the large pixel analysis areas.



GRAPH COLORS

orange:
PV voltage
(on y-axis)

purple:
Pixel variation
(on y-axis)
RGB (average of
5000 pixel values)

max value:
3 colors x 255=765
(black to white)

red, green, blue:
Pixel variation
(on y-axis)
per color (sum of
5000 pixel values)
max value:
5000 pixels x 255=
1,275,000
(black to white)



3 wall - large
4 wall - small

Fig. 5.12 February 24th – sunlight study graphs

I compared the LED light of two selected color gradients to determine if the difference in color schemes could be detected by looking at the RGB color components. The pixel color variation of the gradient 05 (blue colors for low PV power, yellow colors for high PV power) was higher in the red spectrum whereas the pixel color variation of the color gradient 00 (red & yellow colors for low PV power, blue colors for high PV power) was higher in the blue spectrum. This was expected because the largest variations in PV power production and thus LED light color occur during times of maximum PV power when sharp drops in power due to clouds cause intense drops of yellow colors (red and green spectrum) for the former respectively blue colors for the latter.

GRAPH COLORS

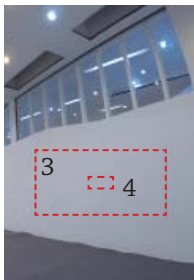
orange:
PV voltage
(on y-axis)

purple:
Pixel variation
(on y-axis)
RGB (average of
5000 pixel values)

max value:
3 colors x 255=765
(black to white)

red, green, blue:
Pixel variation
(on y-axis)
per color (sum of
5000 pixel values)

max value:
5000 pixels x 255=
1,275,000
(black to white)



3 wall - large
4 wall - small

132

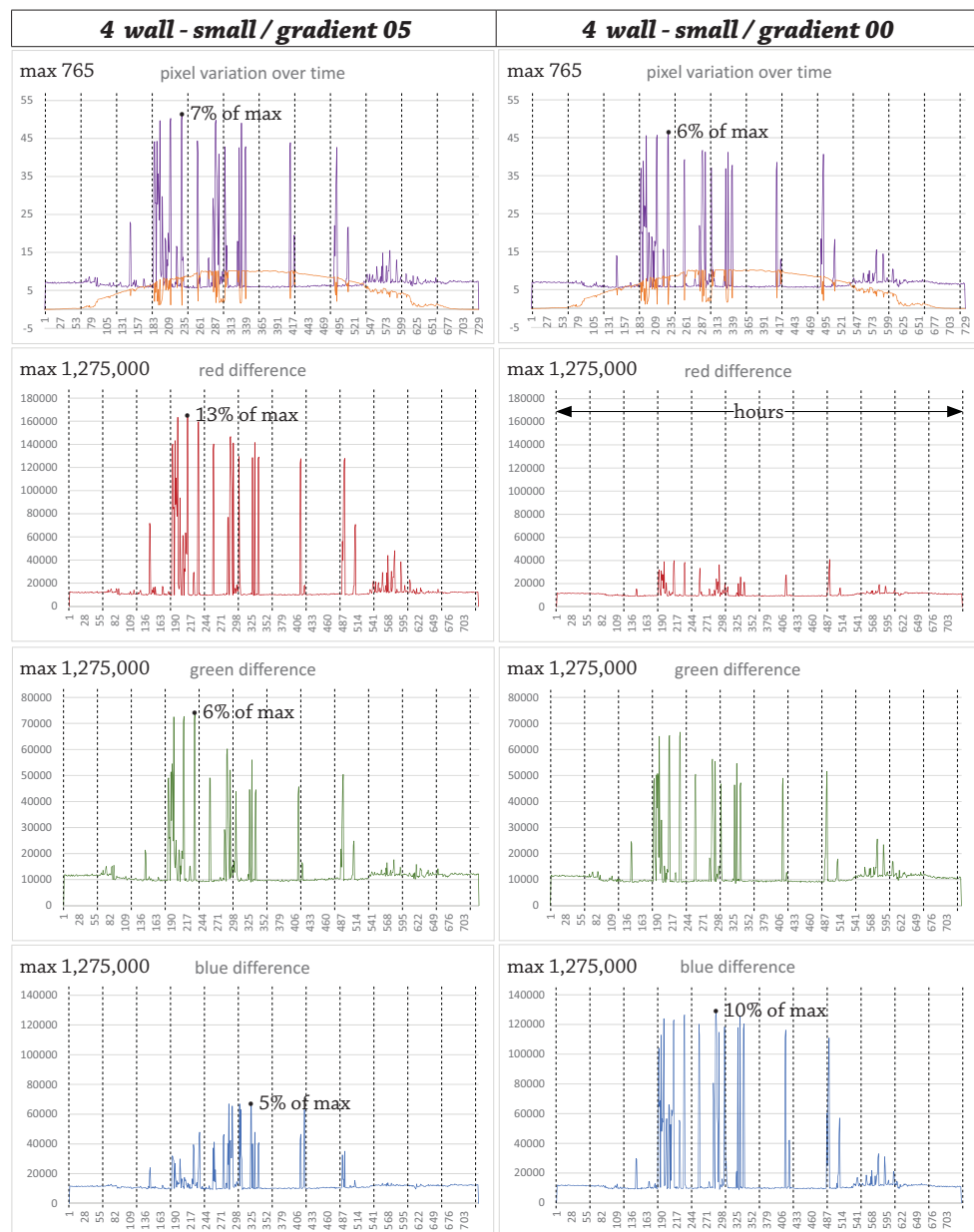


Fig. 5.13 February 24th – LED light study graphs

Figure 5.14 shows a comparison of pixel color variations generated from the photo sequences of a sunlight study recorded on February 24th and the corresponding LED light study. Unlike the pixel color variation of the sunlight, that of the cool color LED light scheme was most pronounced in the red color spectrum. Interestingly, the pixel color variation of the warm color LED light scheme in figure 5.13 was most pronounced in the blue color spectrum similar to the sunlight. This is contrary to visual observations during the qualitative evaluation where the cool color LED light scheme visually resembled the sunlight more closely. The mentioned disparity between the qualitative and quantitative results led me to revisit the question of color schemes and analyze the data again using a pixel brightness analysis program.

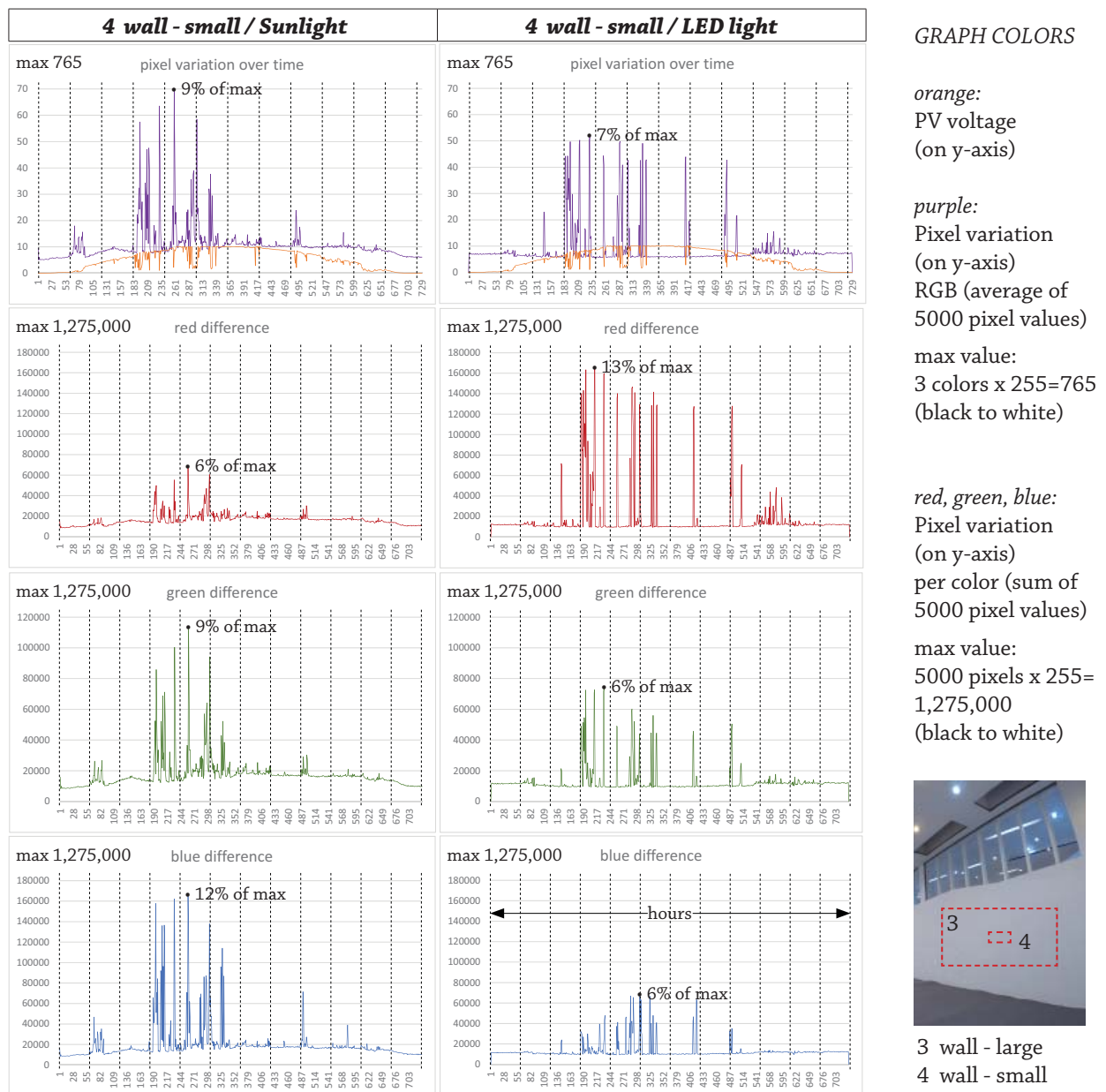


Fig. 5.14 February 24th – sunlight & LED light study graphs

GRAPH COLORS

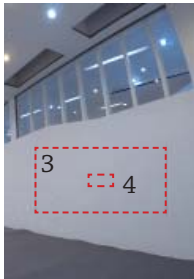
orange:
PV voltage
(on y-axis)

purple:
Pixel variation
(on y-axis)
RGB (average of
5000 pixel values)

max value:
3 colors x 255=765
(black to white)

red, green, blue:
Pixel variation
(on y-axis)
per color (sum of
5000 pixel values)

max value:
5000 pixels x 255=
1,275,000
(black to white)



3 wall - large
4 wall - small

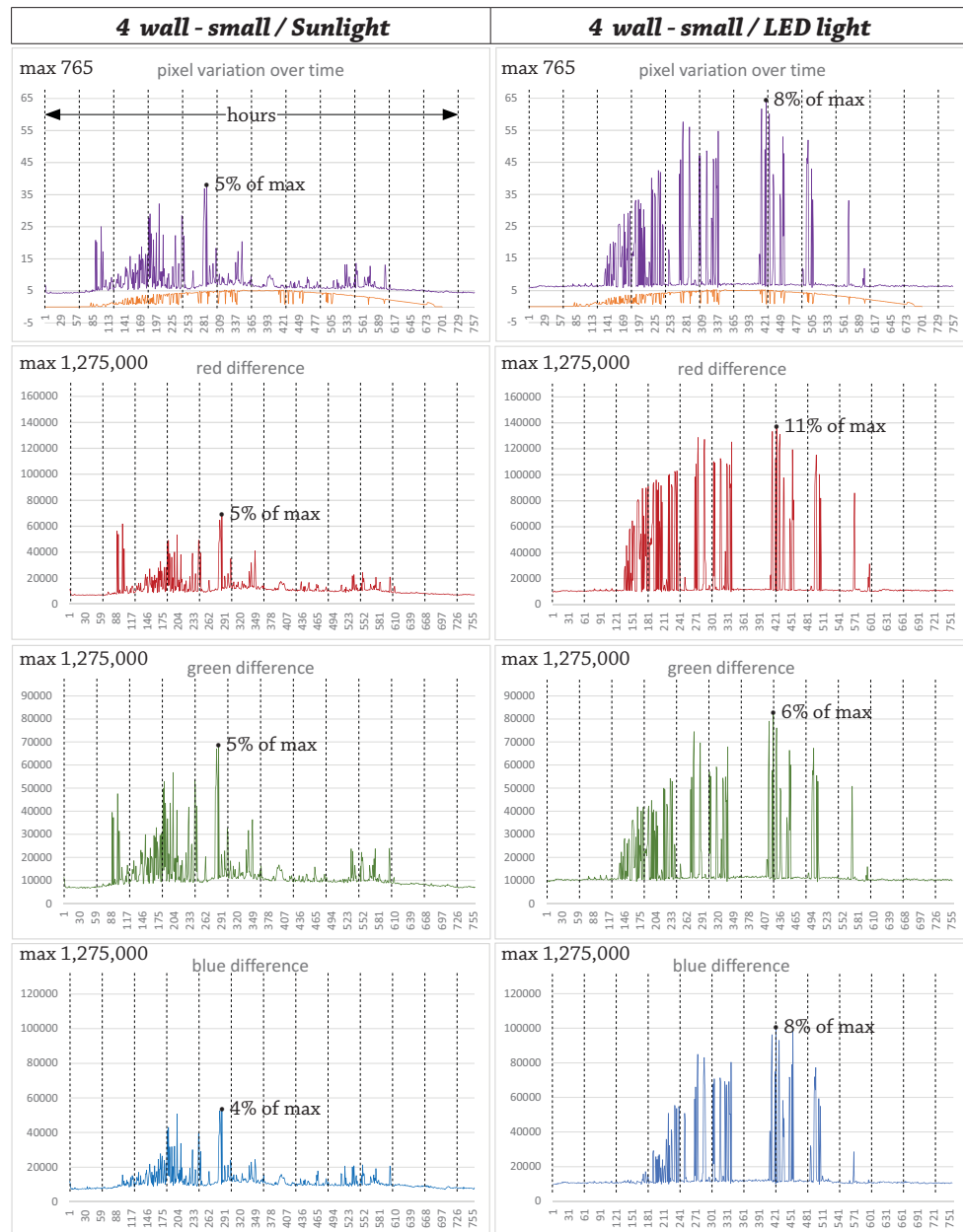
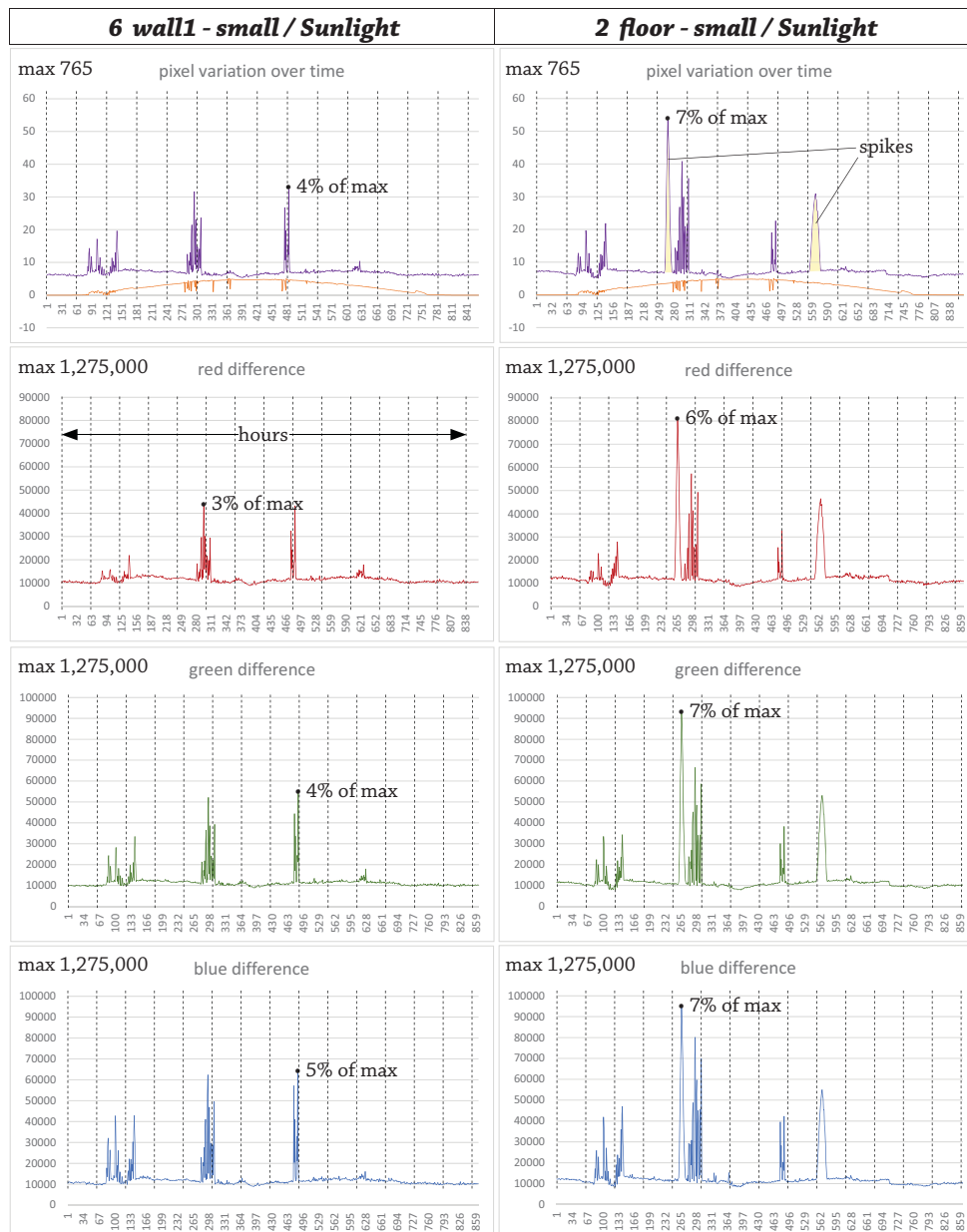


Fig. 5.15 March 2nd – sunlight & LED light study graphs

The temporal fluctuation of the PV power levels from March 2nd in figure 5.15 is less similar to the temporal fluctuation of the sunlight graphs than it was in figure 5.14. The LED light pattern mostly resembles the sunlight pattern, but there were some peaks around minutes 421 and 505 which were higher than the ones due to sunlight. Despite the mentioned disparities, the LED light pattern still provided a temporal stimulus reminiscent of daylight. To determine if the findings described above could be reproduced with multiple sunlight patterns caused by various weather conditions I created graphs illustrating pixel color variation over time for the remaining two days on which I conducted sunlight studies. The results were comparable, but led to new interesting observations which are described in the following.

On April 26th, the pixel color variation graph created using the small “floor” analysis area for the photos showed two unusual spikes at minute 265 and at minute 562. These two spikes could not be observed in the graphs created using the small “wall 1” analysis area. I referred to the respective time-lapse photo sequences and reviewed several photos at the times of the spikes and found that these spikes were caused by swaths of direct sunlight that moved across the analysis area. The area “wall 1” was never affected by direct sunlight and therefore the spikes didn’t show up. Since the representation of direct sunlight was not in the scope of this project I looked at the influence of direct light during the subsequent pixel variation analyses and chose analysis areas that were not affected by direct light.



GRAPH COLORS

orange:
PV voltage
(on y-axis)

purple:
Pixel variation
(on y-axis)
RGB (average of
5000 pixel values)

max value:
3 colors x 255=765
(black to white)

red, green, blue:
Pixel variation
(on y-axis)
per color (sum of
5000 pixel values)
max value:
5000 pixels x 255=
1,275,000
(black to white)



2 floor - large
6 wall1 - small

Fig. 5.16 April 26th – Sunlight study graphs

GRAPH COLORS

orange:
PV voltage
(on y-axis)

purple:
Pixel variation
(on y-axis)
RGB (average of
5000 pixel values)

max value:
3 colors x 255=765
(black to white)

red, green, blue:
Pixel variation
(on y-axis)
per color (sum of
5000 pixel values)

max value:
5000 pixels x 255=
1,275,000
(black to white)



5 wall1 - large
6 wall1 - small

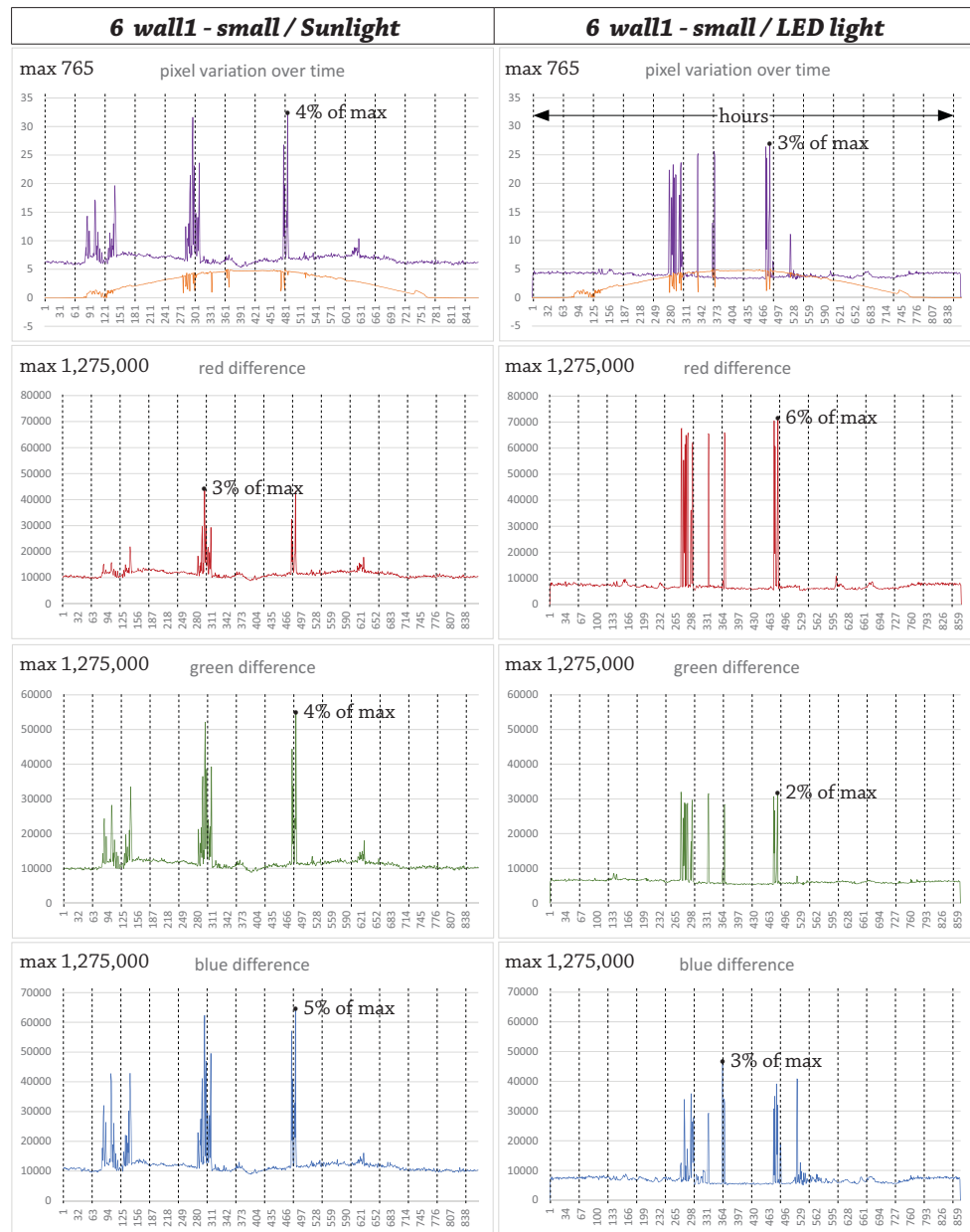


Fig. 5.17 April 26th – sunlight & LED light study graphs

I visually compared the sunlight pattern illustrated by the graph of the small analysis area "wall 1" with the pattern of the LED light graph.

The sunlight study on April 26th showed a pronounced pixel color variation in the morning from minute 63 to 156 that was not observed during the LED light study. I looked at the comparative time lapse video of that day and found that the gradual increase in brightness in the morning was not reproduced by the skylight. This was probably caused by a feature of the playback program which maintains a minimum brightness of the LEDs apparently subduing the LED light pattern variations.

The graphs on the right in Figure 5.18 were created using the large analysis area “wall” illustrating the effect of direct daylight. The wide spikes from minute 316 to 351 and from minute 421 to 526 were not observed in the graphs on the left which were created using the small analysis area “wall 1”. For comparison with the LED light I selected the graph from area “wall1” which was not influenced by direct light. The results are shown in figure 5.19.

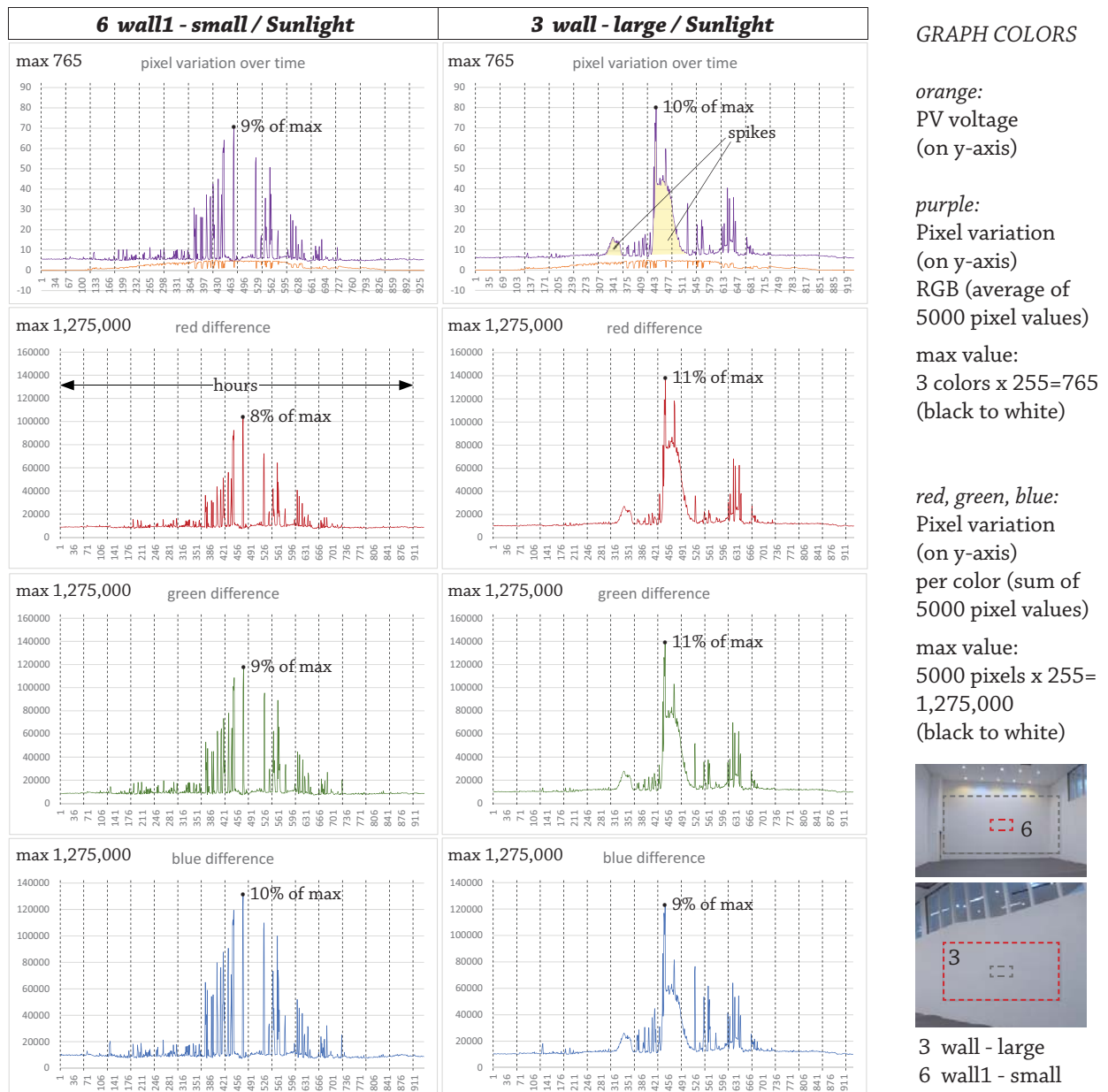


Fig. 5.18 June 21st – Sunlight study graphs

GRAPH COLORS

orange:
PV voltage
(on y-axis)

purple:
Pixel variation
(on y-axis)
RGB (average of
5000 pixel values)

max value:
3 colors x 255=765
(black to white)

red, green, blue:
Pixel variation
(on y-axis)
per color (sum of
5000 pixel values)

max value:
5000 pixels x 255=
1,275,000
(black to white)



5 wall1 - large
6 wall1 - small

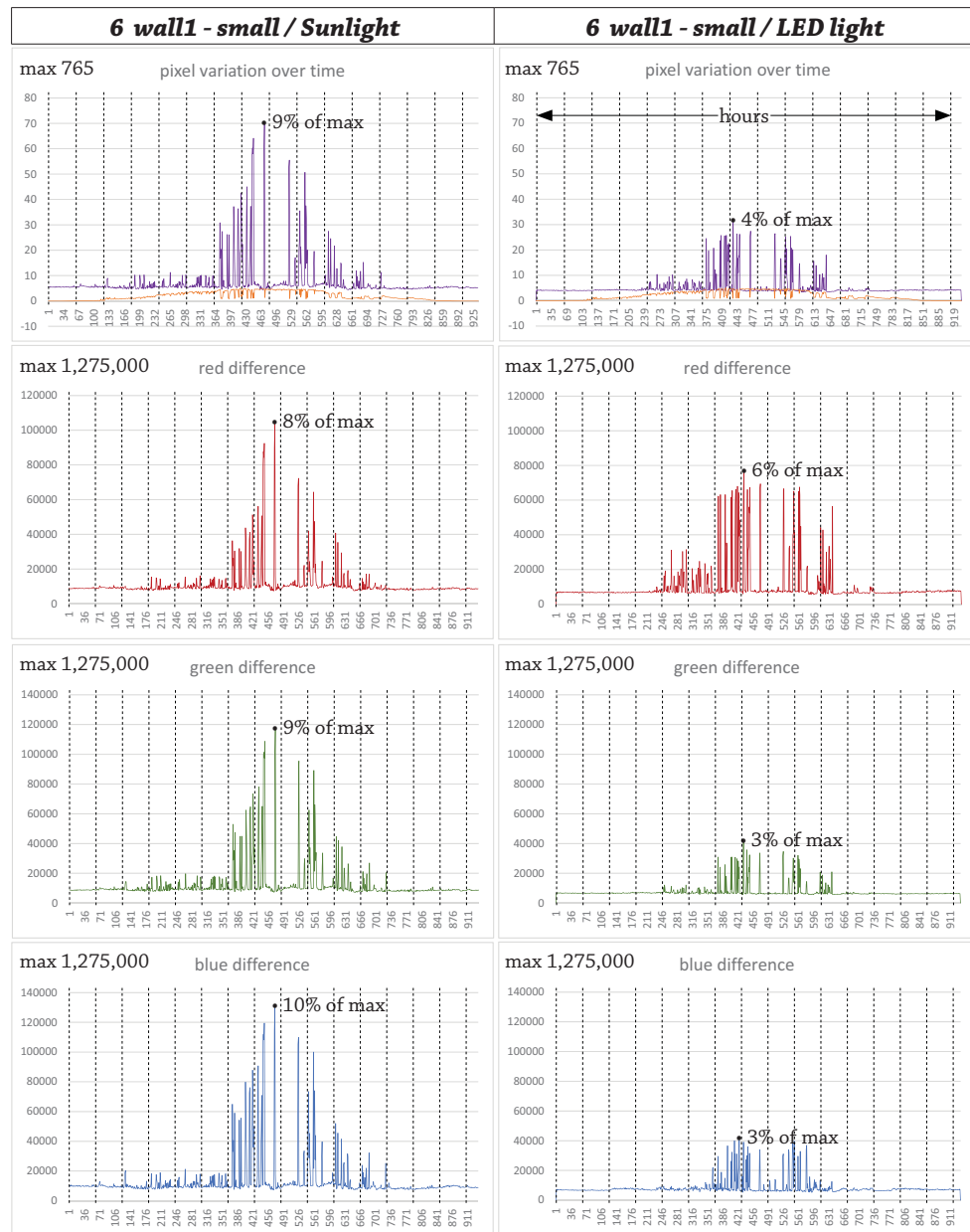


Fig. 5.19 June 21st – Sunlight & LED light study graphs

The comparison of the results from the sunlight and LED light study from June 21st showed much lower magnitudes of the LED light pixel variation spikes. I attributed this to the high daylight intensity of a typical clear summer day which could not be reproduced by the skylight well LED lighting and to the limitation of the sunlight recorder. As described earlier the energy monitoring unit logged power values that were below the maximum possible PV power based on the solar radiation measured on June 21st.

As mentioned a prime goal of the dynamic LED light was to introduce a natural pattern to the Sandbox which makes present the passing of time. I considered the observed close temporal relation of the light patterns to be very important for this purpose. A less accurate representation regarding the magnitudes of changes was acceptable and could later be mitigated by the playback program. The problem of the playback program which subdues the variation during periods of low sunlight intensity could also be solved by modifying the program code. The lower brightness of the dynamic LED light compared to the dynamic daylight was beneficial. While bright daylight caused potential disturbances in the work and study environment this had to be mitigated by the shading effect of the PV integrated skylight glazing. This was not an issue for the dynamic LED lighting because it could be fully controlled with the playback program. The dynamic LED lighting was designed to be subtle so that the occupants wouldn't find it distracting. I quantified the visual effect of the dynamic LED lighting with an automated RGB value analysis program. The evaluation of the resulting pixel color variation over time showed that the higher variation in color from the LED lights could compensate for less pronounced changes in brightness as compared to daylight. I modified the analysis program to quantify pixel brightness variations so that I could assess the effect of the dynamic LED light.

Pixel brightness variation over time

RGB values primarily describe the pixel color, but they also contain information on brightness based on color dependent luminance. Camera sensors record luminance linearly, but the human eye does not detect luminance in this way (see figure 5.20). Digitally recorded images are gamma encoded to mitigate this.

“Compared to a camera, we are much more sensitive to changes in dark tones than we are to similar changes in bright tones. There's a biological reason for this peculiarity: it enables our vision to operate over a broader range of luminance. Otherwise the typical range in brightness we encounter outdoors would be too overwhelming.” (McHugh, 2018)

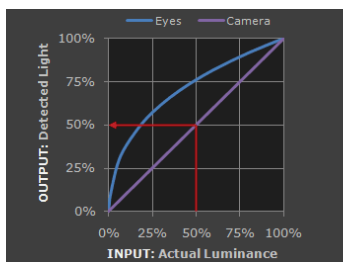


Fig. 5.20 Detected and actual luminance: Eyes vs Camera
(Source: www.cambridgeincolour.com)

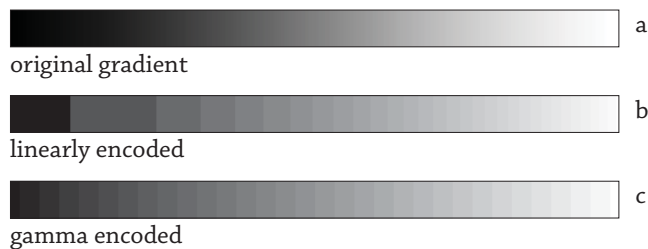


Fig. 5.21 Gradient encoding - linear vs gamma
The representation of dark tones is improved.
(Source: www.cambridgeincolour.com)

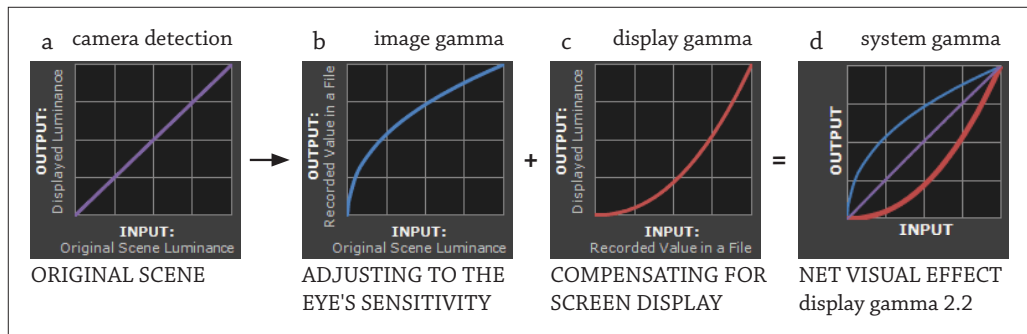


Fig. 5.22 Gamma correction - sequence of operational steps (Source: www.cambridgeincolour.com)

Figure 5.22 shows the gamma correction operations in the process of recording and displaying images. I needed to add gamma correction functions to the pixel analysis program to correctly determine the original luminance of the scene.

Human perception of luminance also differs based on color. The eye is least sensitive to the blue color spectrum, considerably more sensitive to the red spectrum and most sensitive to the green spectrum. Figure 5.23 illustrates the response curves for the color cones of the eye.

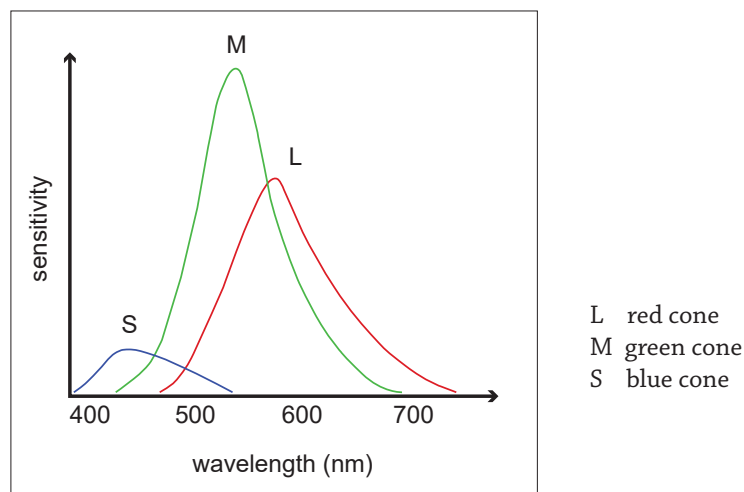


Fig. 5.23 Color cone response curves

I used available luminance weighting factors for the sRGB color space to develop a pixel brightness analysis function based on human perception. The final pixel brightness analysis program determined the average brightness of the same pixel selection in two consecutive images of a photo sequence and calculated the change in brightness between these images.

Pixel brightness analysis program functions:

Jive Dadson created gamma conversion and gray value calculation definitions for the sRGB color space in the C++ programming language and published them on stackoverflow.com (Dadson, 2017). I translated Dadson's code to Python 3 to be used in the brightness analysis program.

```
rY = 0.212655; gY = 0.715158; bY = 0.072187                                color weighting factors

"""definitions"""

def inv_gam_sRGB(ic):
    """inverse gamma function"""
    c = ic/255.0
    if c <= 0.04045:
        return (c/12.92)
    else:
        return pow(((c+0.055)/(1.055)),2.4)
    convert to original scene luminance

def gam_sRGB(v):
    """gamma function"""
    if v <= 0.0031308:
        v *= 12.92
    else:
        v = 1.005 * pow(v,1.0/2.4)-0.055
    return (v*255+0.5)
    adjust to the eye's sensitivity

def gray(r,g,b):
    """GRAY VALUE - brightness"""
    return gam_sRGB(rY*inv_gam_sRGB(r) + gY*inv_gam_sRGB(g) + bY*inv_gam_sRGB(b))
    calculate gamma corrected luminance - pixel brightness
    color weighted (top), not color weighted (bottom)

def value(r,g,b):
    """RGB VALUE - brightness not weighted"""
    return gam_sRGB((inv_gam_sRGB(r) + inv_gam_sRGB(g) + inv_gam_sRGB(b))/3)

for file in os.listdir('.'):
    if file.endswith('.JPG'):
        name = './' + file
        imagelist.append(name)
    create list of image files

for f in range(stop):
    print(counter)
    difdata = []
    bright.append([])
    folder,newname,ext = imagelist[f].split('.')
    current_file = newname[1:] + '.' + ext
    im1 = misc.imread(current_file)
    read image data to
    array variable (im1)
```

```

                                calculate pixel brightness (v:weighted, u:not weighted)
                                analysis area: x(0-4000, step 50), y(0-3000, step 50)
for x in range(0,4000,50):
    for y in range(0,3000,50):
        v = gray(int(iml[y][x][0]),int(iml[y][x][1]),int(iml[y][x][2]))
        u = value(int(iml[y][x][0]),int(iml[y][x][1]),int(iml[y][x][2]))
        vc.append(v); uc.append(u)

                                current image (vc, uc)
                                previous image (vp, up)
if f == 0:
    vp = vc
    up = uc

                                calculate pixel brightness variation - 2 consecutive photos
                                (bdif_sum, bldif_sum)
for p in range(4800):
    dif = (vc[p] - vp[p]); bdif_sum += dif
    difl = (uc[p] - up[p]); bldif_sum += difl
    b_sum += vc[p]
    bl_sum += uc[p]

                                calculate pixel brightness
                                (b_sum, bl_sum)

                                calculate image brightness (average pixel brightness)
                                (b_average, bl_average)
b_average = b_sum / 4800; bl_average = bl_sum / 4800
bdif_average = bdif_sum / 4800; bldif_average = bldif_sum / 4800

calculate image brightness variation (average pixel brightness variation) - 2 consecutive photos
                                (bdif_average, bldif_average)

The method for the average pixel brightness calculation has been explained in table 5.2.

                                create variable of analysis values
                                (bright)
difdata.extend((b_average,bdif_average,b_sum,bdif_sum,contrast,
                                bl_average,bldif_average,bl_sum,bldif_sum,contrastl))
bright[f] = (difdata)
vp = vc; up = uc; counter -= 1

saveas = raw_input('filename: ')
NewFilename = './' + saveas

                                write analysis values to csv file
                                (1 line per image)
with open(NewFilename, 'w+') as csvfile:
    row = []
    newcontent = csv.writer(csvfile,delimiter=',')
    for row in bright:
        newcontent.writerow(row)

```

I used the pixel brightness analysis program to create additional graphs based on the photo sequences I recorded during the sunlight and LED light studies on February 24th, March 2nd, April 26th, and June 21st. The analysis areas for the evaluation are shown in figure 5.24. I first analyzed the pixel brightness variations caused by dynamic daylight during the sunlight studies. Figure 5.25 shows the graphs of average pixel brightness values for different analysis areas.

Location and size of pixel analysis areas:



Fig. 5.24 Analysis areas for brightness analysis (5000 pixels each)

Sunlight study - February 24th

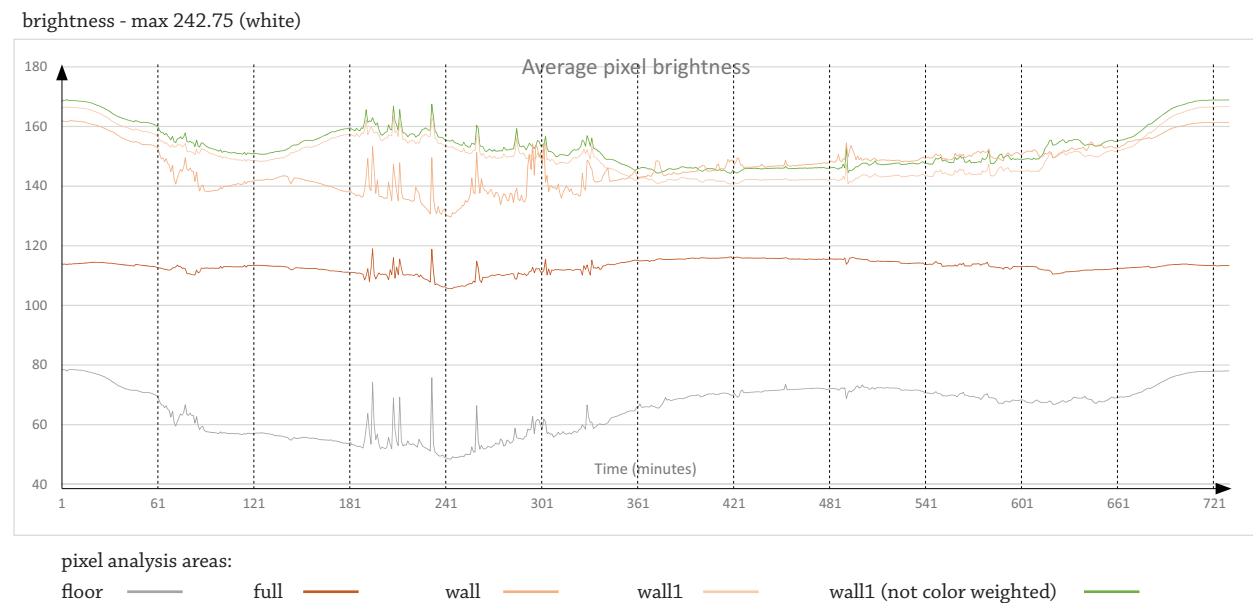


Fig. 5.25 Average pixel brightness graphs created from sunlight study time-lapse photos taken on February 24th

As expected, the graphs from analysis area *wall1* in figure 5.25 show that the color weighted pixel brightness differed from the non-weighted pixel brightness. I used color weighted average pixel brightness values for the evaluation of image brightness based on human perception (color cone response).

As mentioned earlier, the GoPro Hero 4 camera recorded the time-lapse photos with a fixed focal ratio and a constant white balance value. The exposure time and the ISO speed values were automatically adjusted based on the brightness of the scene which affected the image brightness and dampened the amplitude of both dynamic sunlight and dynamic LED light. I created a program that extracted the EXIF metadata from each photo sequence and saved the array with exposure time and ISO speed values in CSV files. The arrays could then be used to adjust the pixel brightness values with the analysis program to compensate for the variable exposure time and ISO speed camera setting. The adjusted graphs are depicted in figure 5.26 below. The multiplication with exposure time and ISO speed adjustment factors led to brightness values above the maximum value 242.75 (the result of the analysis program for a completely white image). This was expected because the purpose of variable exposure time and ISO speed is to avoid overexposure. The adjusted brightness values above 242.75 ignore camera/eye adaptation and thus represent hypothetical numbers which I used to quantify changes of brightness in the model for the comparison of sunlight and LED light.

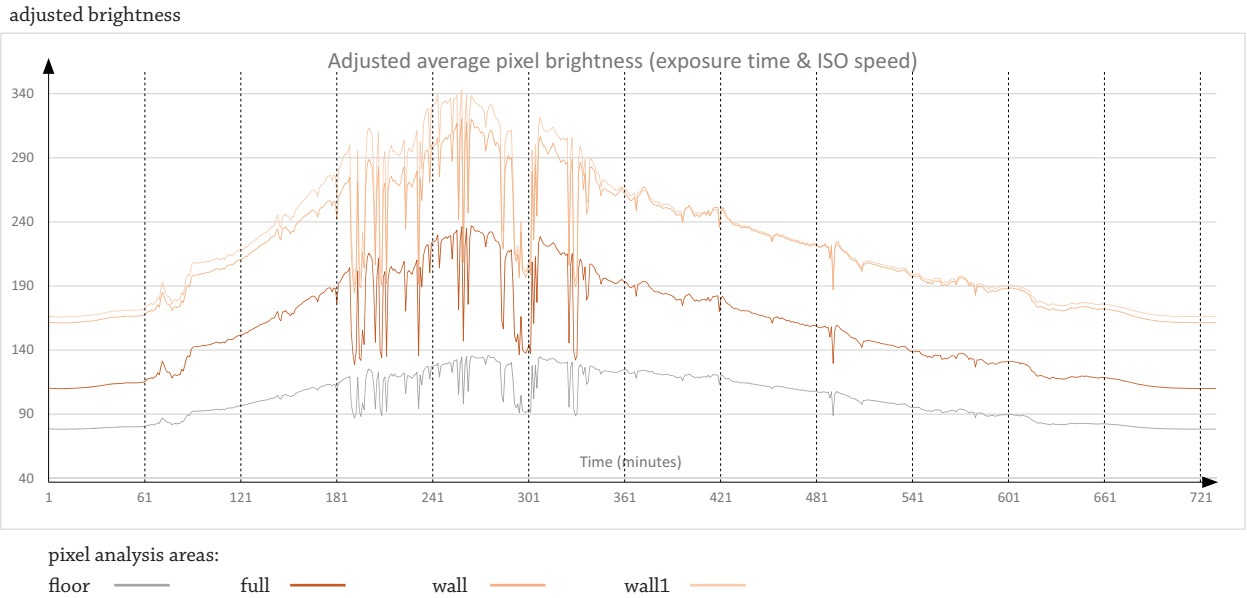


Fig. 5.26 Adjustment for variable exposure time and ISO speed visualizing the brightness change of the scene

In figure 5.24 I introduced a new pixel analysis selection called *full* to the program. This function selects 4800 pixels spread in a regular grid over the entire pixel range. From this the average brightness change of an image was recorded. As expected, these values are lower than the average pixel brightness of *wall* and *wall1* (bright wall color) and higher than the average pixel brightness of *floor* (dark floor color).

Figure 5.27 illustrates the brightness change over time with positive values (brightness increase) and negative values (brightness decrease). The amplitude diagram illustrated the rhythm of the brightness change and facilitated the comparison of different events during a recording day. I regarded each spike as an event with a distinct brightness change magnitude and direction.

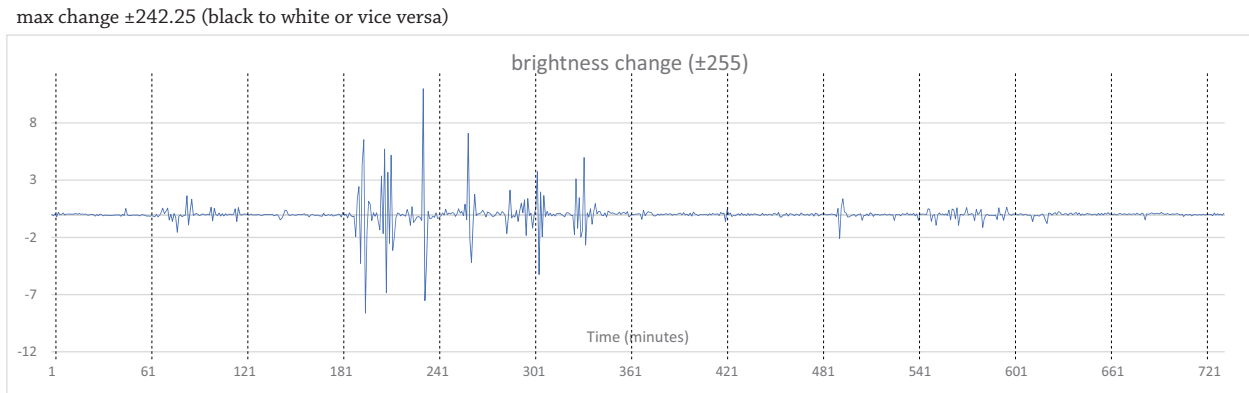


Fig. 5.27 Brightness change plotted as amplitude diagram (from sunlight study on February 24th)

LED Light study - February 24th

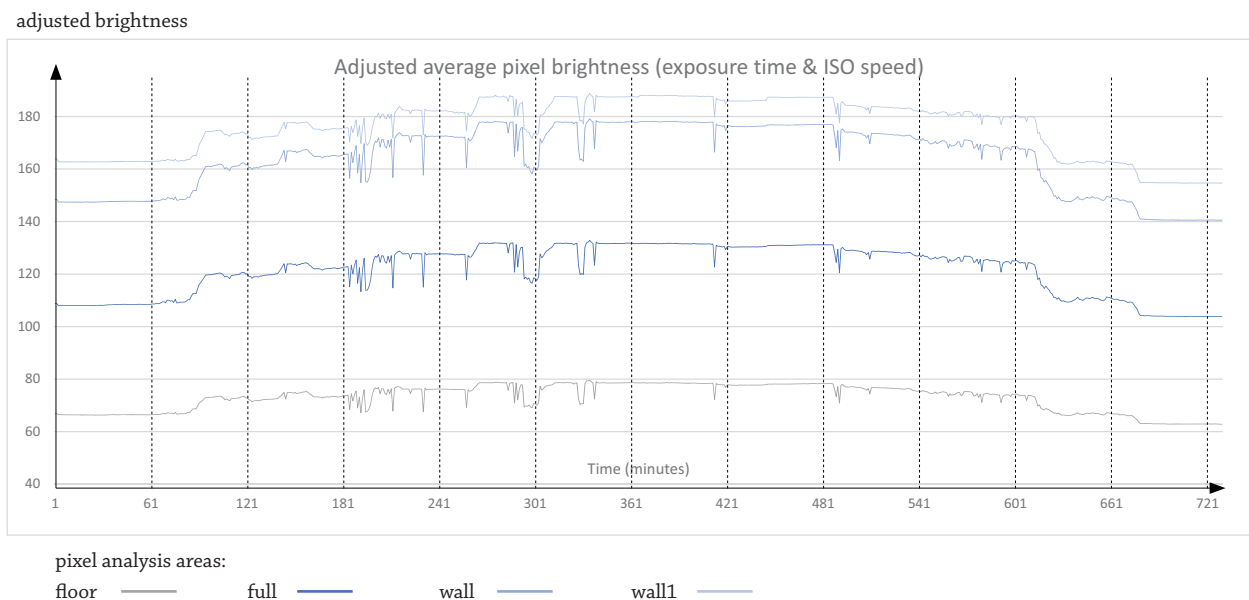


Fig. 5.28 Average pixel brightness graphs created from LED light study time-lapse photos taken on February 24th

The graphs in figure 5.28 were created based on data from the LED light study conducted on February 24th using the *00_red_yellow_white_blue* linear color gradient for the translation of PV energy monitoring data to lighting protocols.

As expected the LED light graphs differed from the sunlight graphs because the RGB LED luminaires provide light with lower intensity and more saturated colors than the sun. Rather than mimicking daylight, the LED lighting was designed to provide an abstract reproduction of dynamic sunlight patterns. I compared the average pixel brightness variations based on dynamic sunlight and on dynamic LED light to determine if this objective had been achieved by the Sandbox model's RGB LED skylight well lighting. A visualization of the comparison is depicted in figure 5.29.

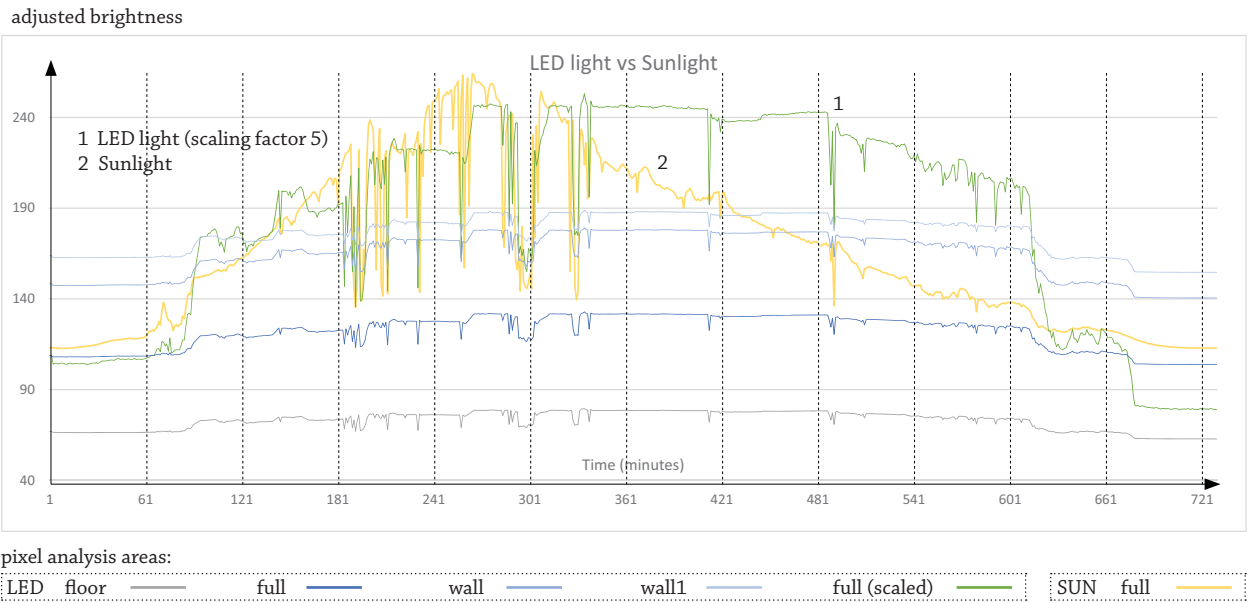


Fig. 5.29 Average pixel brightness graph comparison - LED light study and sunlight study on February 24th

I selected the LED light graph created with the pixel analysis selection *full* and scaled it by multiplying all values by 5 for better comparison with the sunlight graph. As with the pixel color analysis, the pixel brightness analysis also revealed a close temporal relation between the LED light and the sunlight. Both graphs showed an increase in brightness during the first four hours. During the following five hours, the sunlight graph showed a consistent gradual brightness decline whereas the LED light graph depicted a smaller decline until the brightness of the scene dropped suddenly after minute 601.

The scene brightness of the sunlight study was a result of two components: a diffuse component (skylight) and direct component (sunlight entering through the model's skylights). Likewise, the brightness of the LED light was a result of those two components: a diffuse component (diffuse solar radiation) and a direct component (beam radiation) absorbed by the PV panel. The rates of increase respectively decrease in brightness during the sunlight study and the LED light study thus should have been very similar. I compared the LED light

graph to the PV energy monitoring graph to determine how closely the variation in solar radiation had been translated to a variation in brightness during the LED light study.

I scaled the PV energy curve to match the pixel brightness variation values so that I could compare slopes of the curves. Just like in figure 5.29 the graphs in figure 5.30 show a close temporal relation, but there is also a general relation between the PV energy graph and the LED light study brightness graph. The overall shapes of the graphs in figure 5.30 are more similar than in figure 5.29.

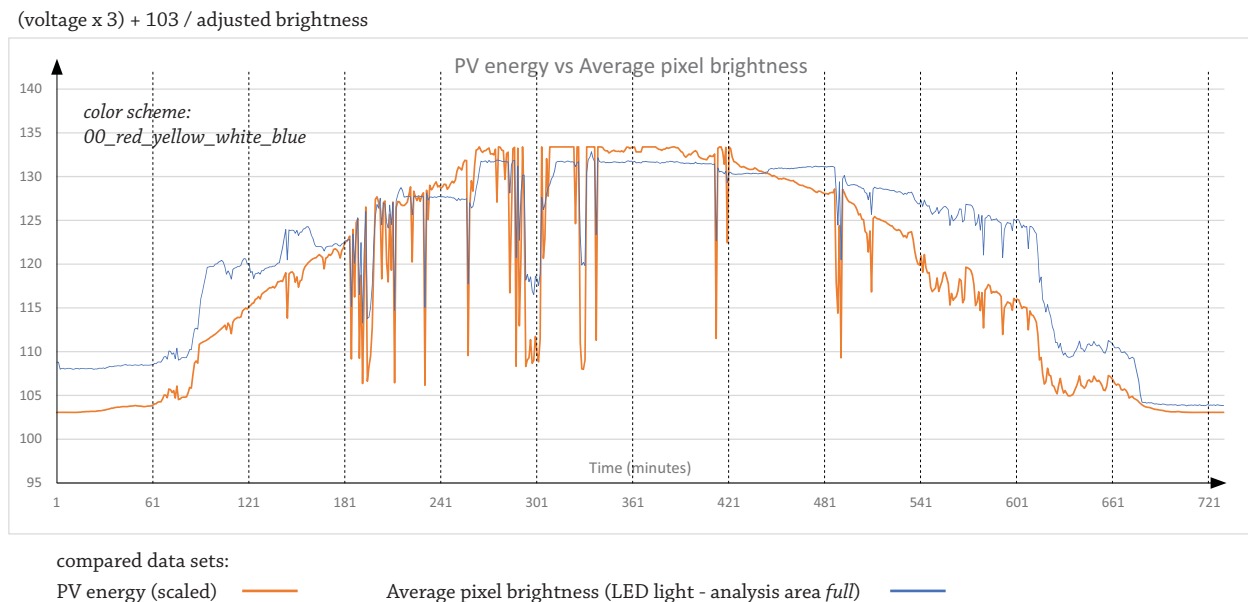


Fig. 5.30 Graph comparison - LED light study and PV energy monitoring on February 24th

The different pattern of the sunlight graph in figure 5.29 could be explained by the influence of the skylights on the direct sunlight entering the Sandbox model. The brightness of direct daylight gradually changed with increasing and decreasing sun angles because, depending on the sun angle, a larger or smaller portion of the direct light was absorbed in the skylight well.

In summary, the LED lighting reproduced the change of solar radiation intensity including fluctuations due to moving clouds over time, but it did not exactly emulate the rate of change in the room brightness when compared to the daylight entering through the skylights in the sunlight study.

During the qualitative evaluation, I found that the “cool” color scheme 05_blue_yellow reproduced the visual effect of the dynamic daylight from the skylights better than the “warm” color scheme 00_red_yellow_white_blue. I wanted to determine if this qualitative observation could be corroborated with quantitative

data. I recorded a study using the PV energy data from February 24th and the color scheme 05_blue_yellow and analyzed the pixel brightness variation in the photo sequence (figure 5.31).

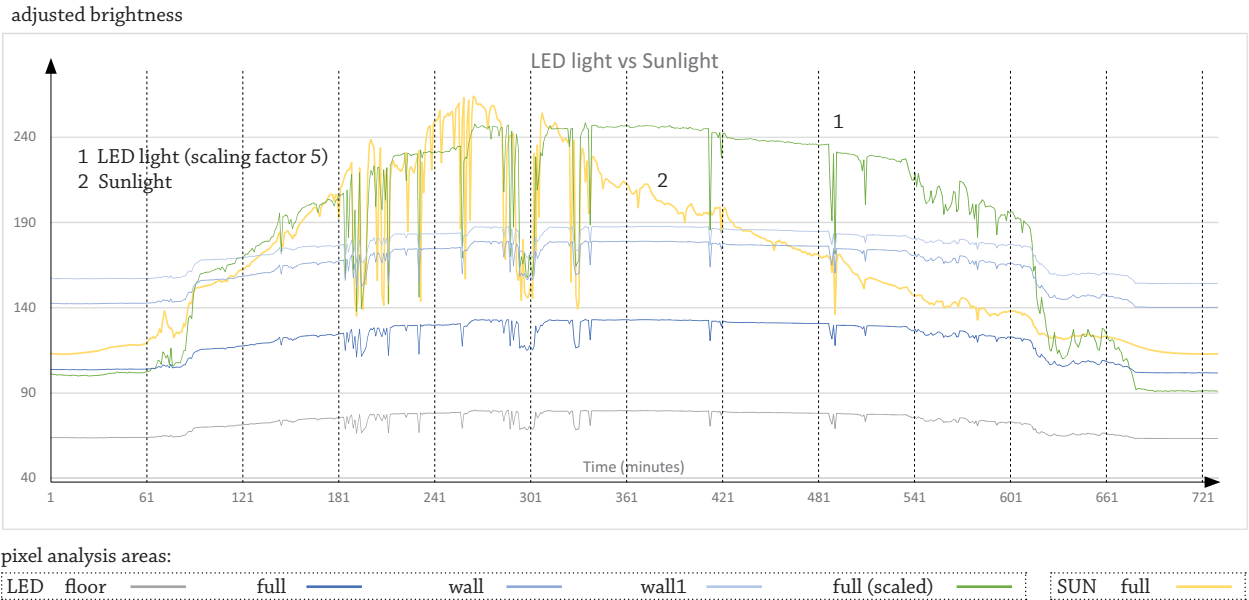
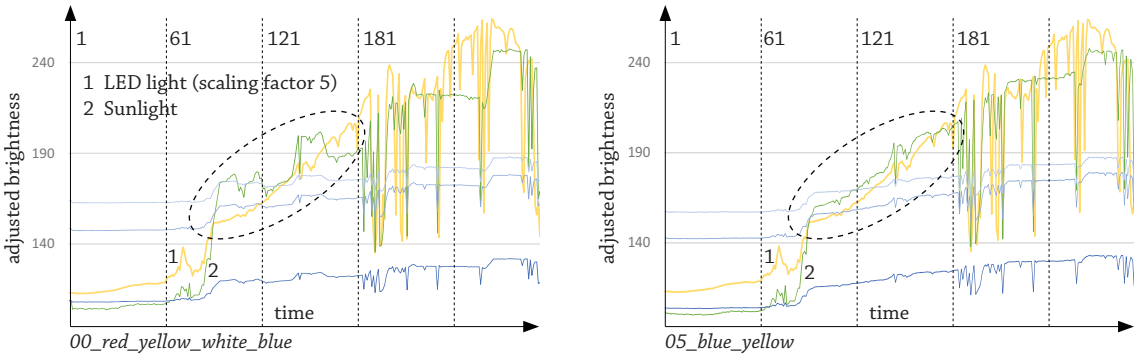


Fig. 5.31 Average pixel brightness graph comparison - LED light study and sunlight study conducted on February 24th using color scheme 05_blue_yellow

Pixel brightness is a function of RGB color values. Thus the pixel brightness variations of two LED light studies of the same day (February 24th) with two color schemes (00_red_yellow_white_blue & 05_blue_yellow) should be different even though they are based on the same PV energy data. The comparison of the LED light graphs with the sunlight graph in figure 5.32 shows that the pixel brightness variations were not the same for the two color schemes. I marked the areas in the morning hours between minutes 61 and 181 where the pixel brightness variation of the color scheme 05 was more similar to the sunlight.



148 Fig. 5.32 Average pixel brightness color scheme 00 (left) and color scheme 05 (right) vs. sunlight graph

Figure 5.33 illustrates the translation of PV energy monitoring data from February 24th to LED lighting protocols using the color scheme 05_blue_yellow. Again, there was a close temporal relation between the graphs. The shape of the LED light graph in figure 5.33 during fluctuations (marked areas) was more similar to the the PV energy graph than in figure 5.30. Also, the general graph shapes were more similar as illustrated in figure 5.34. The relation between solar radiation sensed by the PV panel and the pixel brightness variation was closer for the cool color scheme 05 than for the warm color scheme 00.

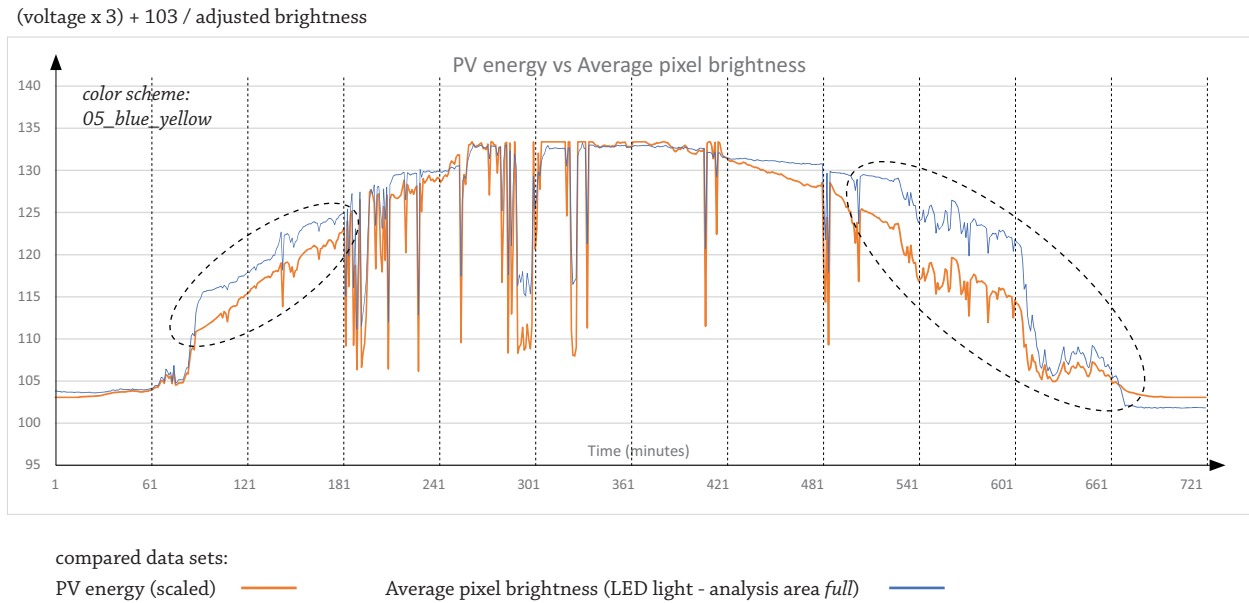


Fig. 5.33 Graph comparison - LED light study and PV energy monitoring on February 24th

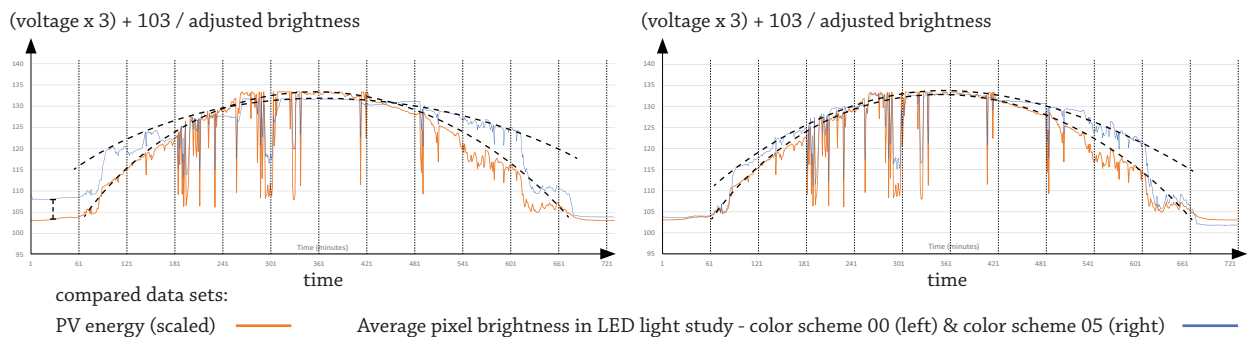


Fig. 5.34 Average pixel brightness of two LED light color schemes vs. PV energy levels - comparing graph shapes

The results from the graph comparisons in figures 5.32 and 5.34 were in line with my observation during the qualitative evaluation. The cool color scheme 05 represented the sunlight more closely than the warm color scheme 00, both qualitatively (visual observation) and quantitatively (pixel brightness analysis).

For visual comparison, I scaled selected graphs to match their vertical extent. I multiplied the LED light graph to match the sunlight in the LED light vs Sunlight diagrams (figure 5.29 and 5.31) and I multiplied the PV energy graph to match the LED light graph in the PV energy vs Average pixel brightness diagrams (figure 5.30 and 5.33). I noted that the impact of the sunlight on the scene brightness was five times stronger than the impact from the LED light, and that the amplitude of the LED light variation was three times higher than the PV energy variation in relative terms. I analyzed the photo sequences of the remaining recording days to determine if the observations in the studies from February 24th could be reproduced. Due to time limitations I recorded only one LED light study each for March 2nd, April 26th, and June 21st using the color scheme 05_blue_yellow and ignoring the color scheme 00_red_yellow_white_blue.

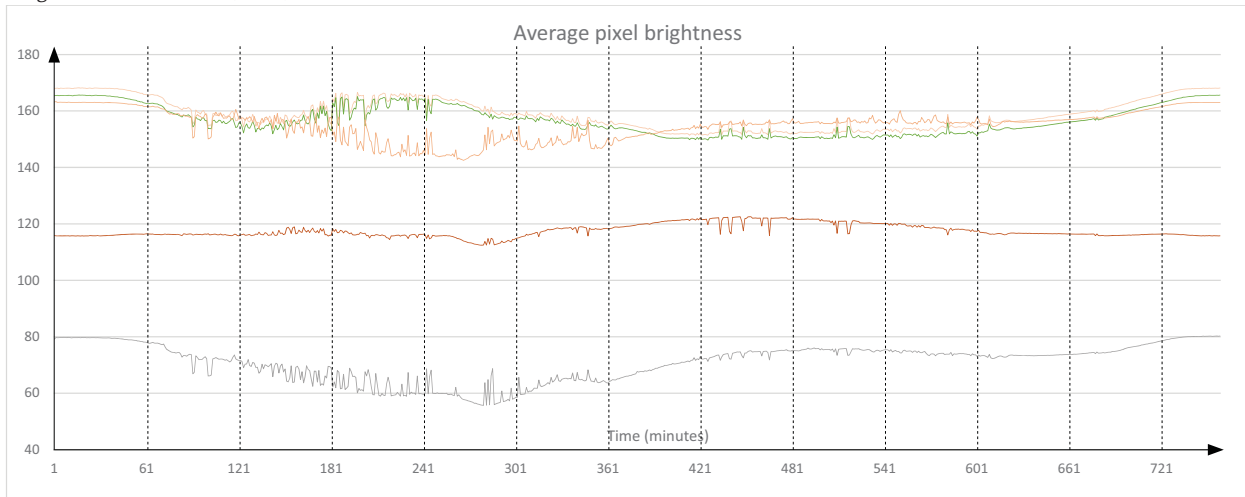
Sunlight and LED light studies - March 2nd

As illustrated in table 5.3, the recorded weather data on March 2nd was much more volatile than on February 24th. Both the wind speed and the cloud cover were higher on March 2nd. This resulted in a higher frequency of brightness changes due to moving cloud shadows as depicted in figures 5.35 and 5.36.

February 24 th		March 2 nd	
WIND (MPH)		WIND (MPH)	
HIGHEST WIND SPEED	12	HIGHEST WIND SPEED	120
HIGHEST WIND DIRECTION	S (180)	HIGHEST WIND DIRECTION	NW (300)
HIGHEST GUST SPEED	17	HIGHEST GUST SPEED	31
HIGHEST GUST DIRECTION	S (190)	HIGHEST GUST DIRECTION	W (280)
AVERAGE WIND SPEED	3.6	AVERAGE WIND SPEED	12.3
SKY COVER		SKY COVER	
AVERAGE SKY COVER	0.1	AVERAGE SKY COVER	0.5
WEATHER CONDITIONS		WEATHER CONDITIONS	
THE FOLLOWING WEATHER WAS RECORDED YESTERDAY: FOG		THE FOLLOWING WEATHER WAS RECORDED YESTERDAY: LIGHT SNOW	

Tab. 5.3 Climate reports from National Weather Service for Blacksburg, VA

brightness - max 242.75 (white)

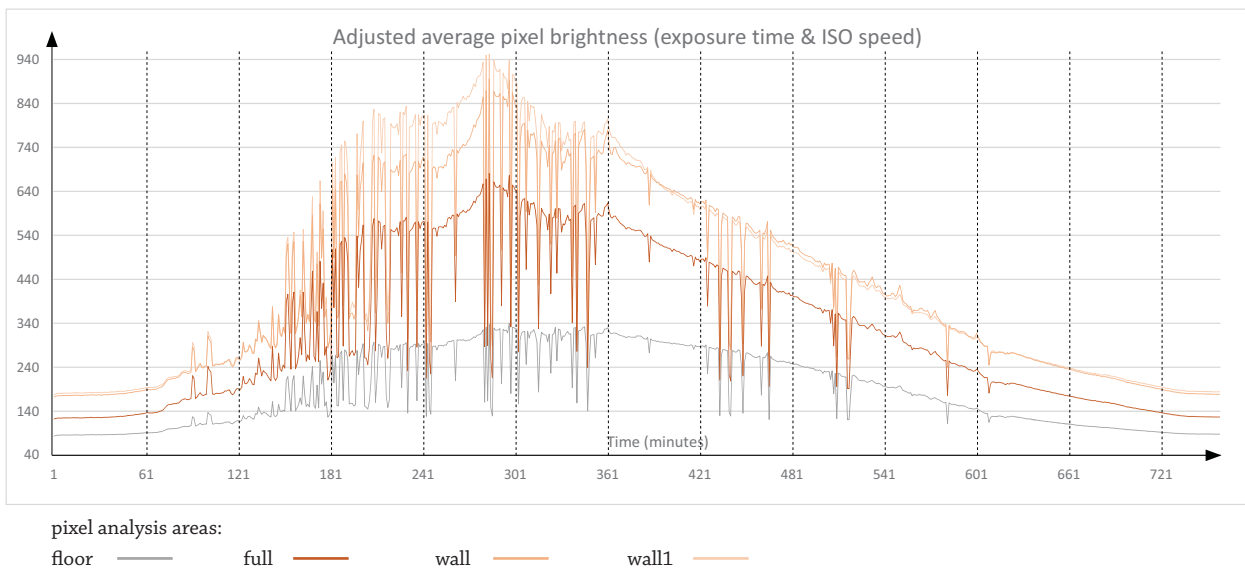


pixel analysis areas:

floor — full — wall — wall1 — wall1 (not color weighted) —

Fig. 5.35 Average pixel brightness graphs created from sunlight study time-lapse photos taken on March 2nd

adjusted brightness



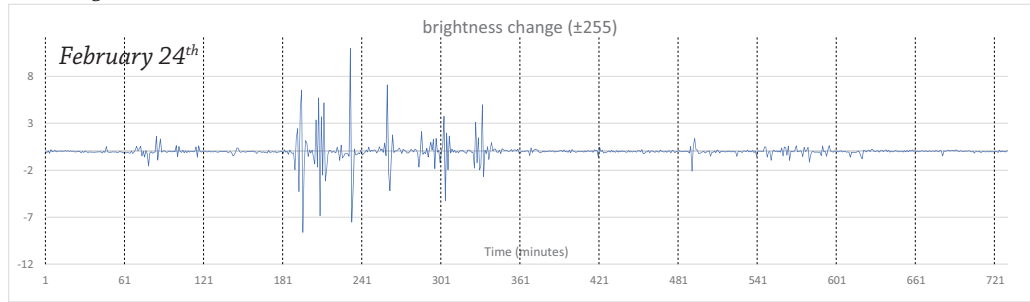
pixel analysis areas:

floor — full — wall — wall1 —

Fig. 5.36 Adjusted average pixel brightness graphs from sunlight study time-lapse photos taken on March 2nd

The frequent drops in brightness between minutes 150 and 240 respectively minutes 280 and 360 were likely caused by shadows of clouds that were scattered by the strong wind and swiftly moved across the sky.

max change ± 242.25 (black to white or vice versa)



max change ± 242.25 (black to white or vice versa)

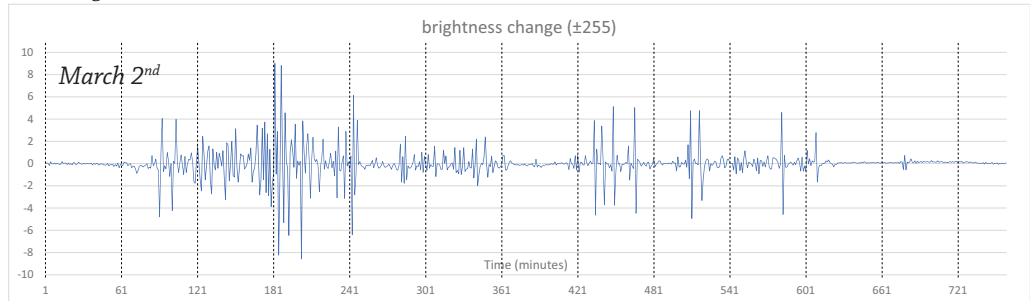
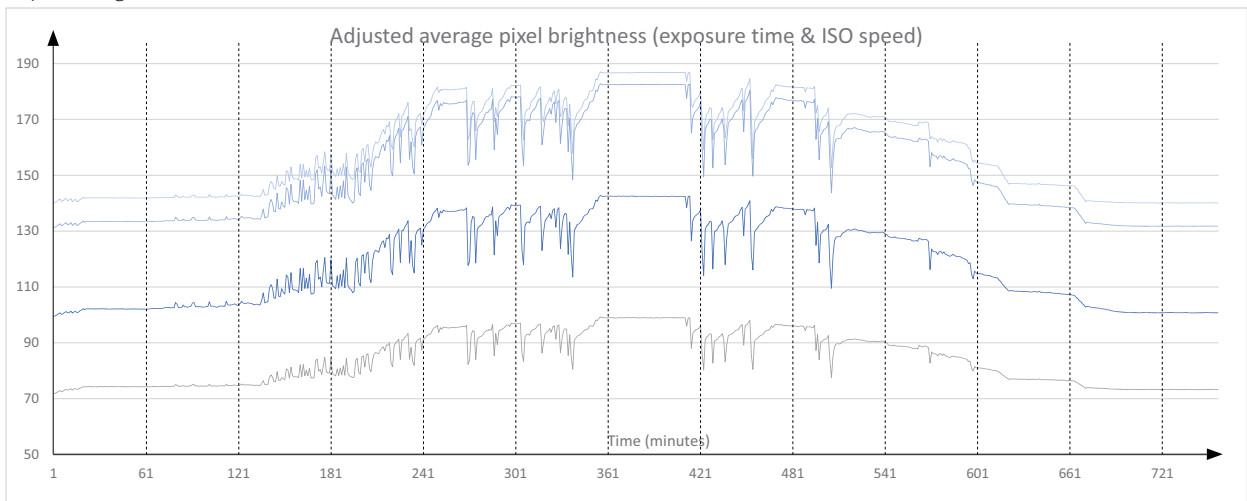


Fig. 5.37 Comparison of brightness change diagrams from two sunlight studies

I compared the brightness change graphs from February 24th and March 2nd in figure 5.37. As expected, the latter showed a much higher frequency of brightness changes. The volatility of the weather could also be observed in the graphs of the LED light study from March 2nd (figure 5.38 and 5.39).

adjusted brightness



pixel analysis areas:

LED floor — full — wall — wall1 —

Fig. 5.38 Adjusted average pixel brightness - LED light study on March 2nd using color scheme 05_blue_yellow

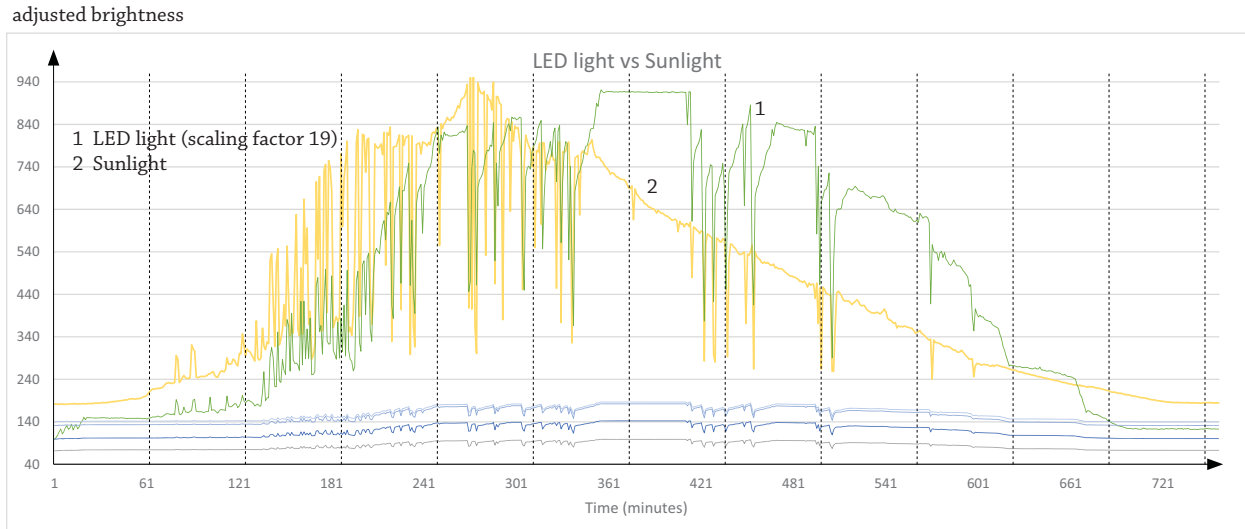


Fig. 5.39 Average pixel brightness graph comparison - LED light study and sunlight study conducted on March 2nd using color scheme 05_blue_yellow

Again, the LED lighting reproduced the change in solar radiation intensity over time and the temporal rhythm of short light fluctuations quite well, but not the consistent gradual brightness decline in the room shown by the sunlight graph. However, I found unexpected chamfers in the graph of the LED light study that did not match the pattern from the sunlight graph. I looked at the camera metadata to determine what caused the curve deformations. Looking at the ISO speed values revealed a lag in ISO speed adjustment that did not occur during the recording of the LED light study on February 24th. Figure 5.40 illustrates that the chamfers in figures 5.38 and 5.39 were caused by the ISO speed adjustment of the GoPro camera.

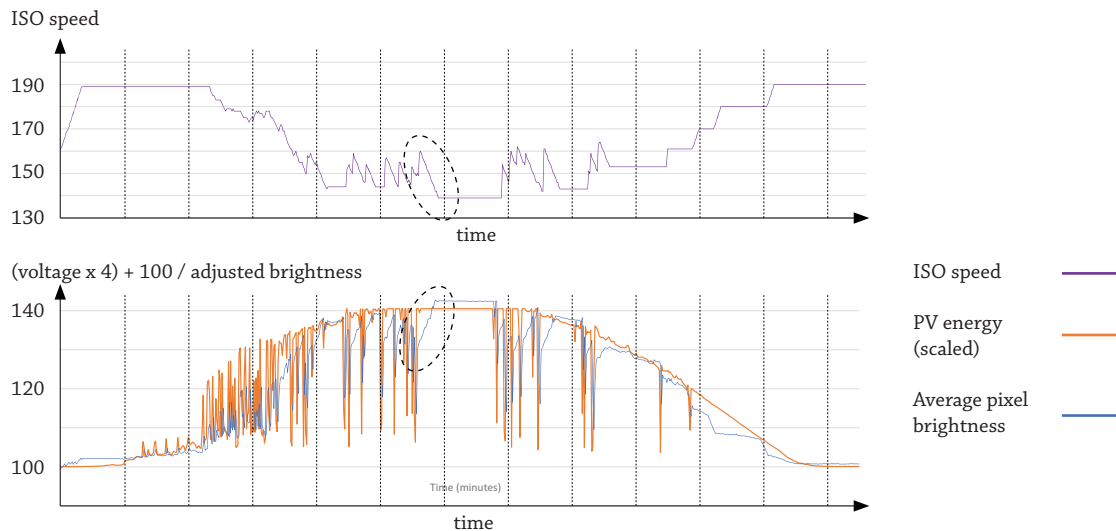


Fig. 5.40 GoPro camera ISO speed adjustment lag during LED light study on March 2nd

Even though the LED light graph was influenced by the lag in ISO speed adjustment the overall shape of the graph still closely followed the PV energy levels. I thus decided that the results of the LED light study were acceptable for comparison with the studies of the other recording days.

On March 2nd the sunlight's impact on the scene brightness was 19 times stronger than the LED lighting's impact and the amplitude of the LED light variation was four times higher than the PV energy variation.

Sunlight study - April 26th

The sunlight study from April 26th illustrated how direct swaths of light can create unnatural peaks in the pixel brightness graph. The graph of the analysis area *wall* shows a pronounced increase in pixel brightness between the minutes 361 and 421 (marked area) that is not present in the other graphs in figures 5.41 and 5.42. I looked at the photo sequence and confirmed that a swath of direct sunlight moved across the wall analysis area while not affecting the areas *wall 1* and *floor* as illustrated in figure 5.44.

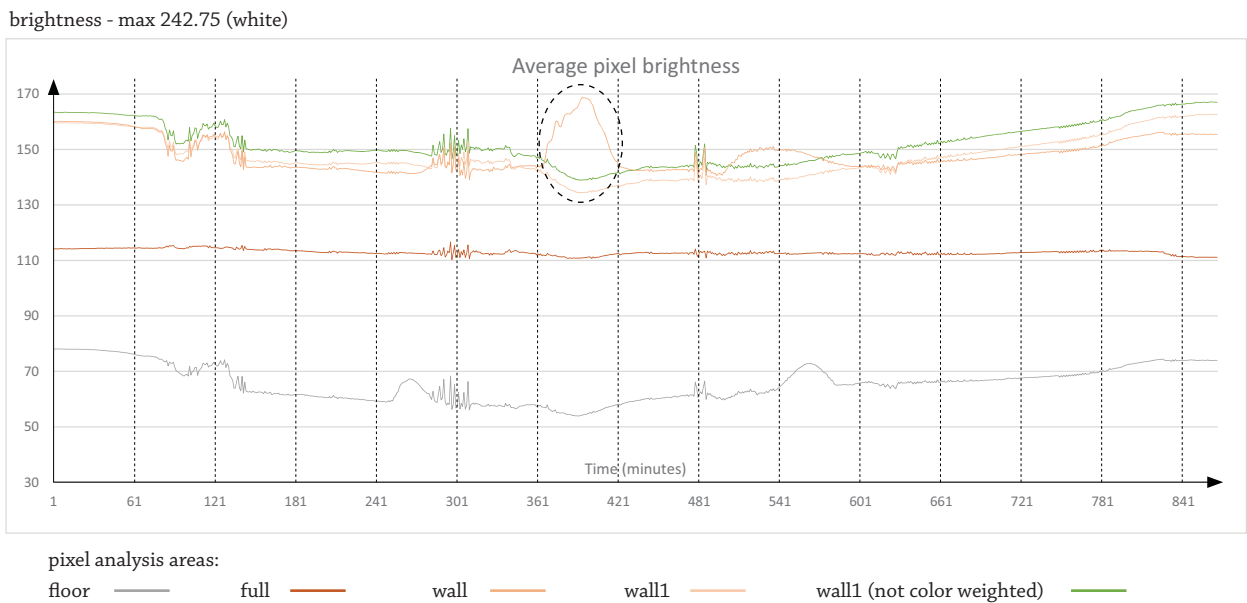


Fig. 5.41 Average pixel brightness graphs created from sunlight study time-lapse photos taken on April 26th

adjusted brightness

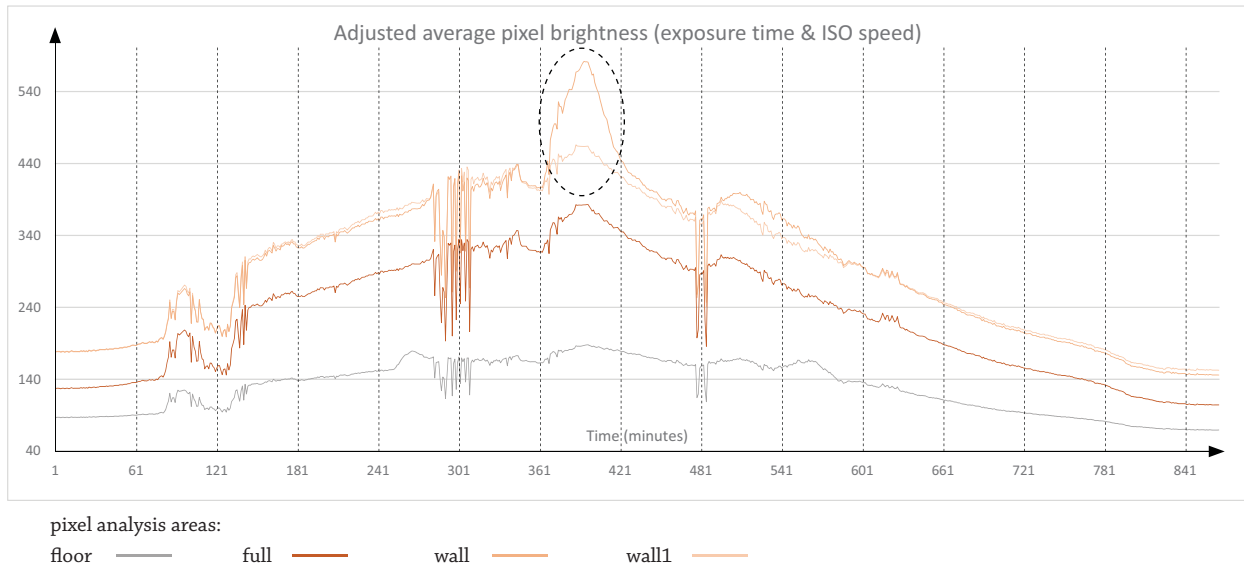


Fig. 5.42 Adjusted average pixel brightness graphs from sunlight study time-lapse photos taken on March 2nd

max change ± 242.25 (black to white or vice versa)

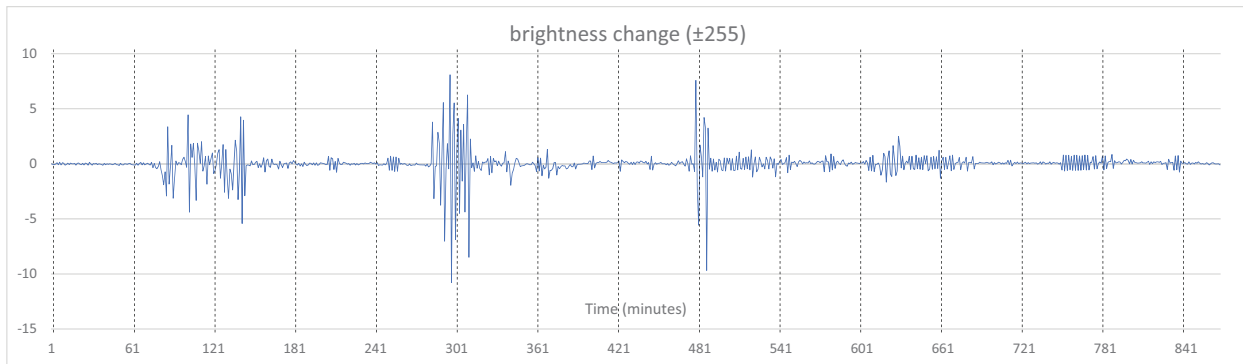
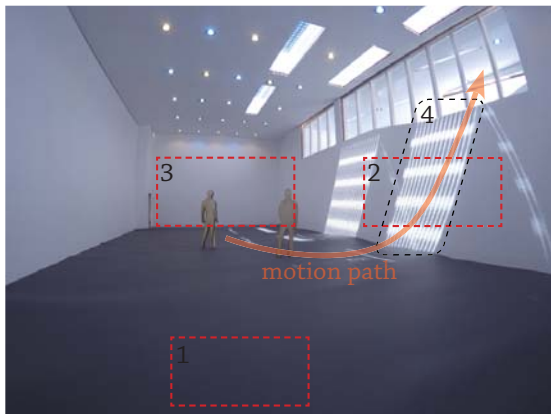


Fig. 5.43 Brightness change plotted as amplitude diagram (from sunlight study on March 2nd)



- 1 floor
- 2 wall
- 3 wall1
- 4 direct sunlight

The direct daylight moved across the room following approximately the path illustrated on the left thus not affecting the analysis areas *wall1* and *floor*.

Fig. 5.44 Direct sunlight moving across analysis area wall

Since the LED lighting could not recreate the effect of direct sunlight I disregarded the graphs from the analysis area *wall* and used the graphs from the analysis area *wall1* when comparing sunlight and LED light during the following evaluation.

LED Light study - April 26th

The sunlight study from April 26th illustrated how direct swaths of light can create unnatural peaks in the pixel brightness graph. The graph of the analysis area *wall* shows a pronounced increase in pixel brightness between the minutes 361 and 421 (marked area) that is not present in the other graphs in figures 5.41 and 5.42. I looked at the photo sequence and confirmed that a swath of direct sunlight moved across the wall analysis area while not affecting the areas *wall 1* and *floor* as illustrated in figure 5.44.

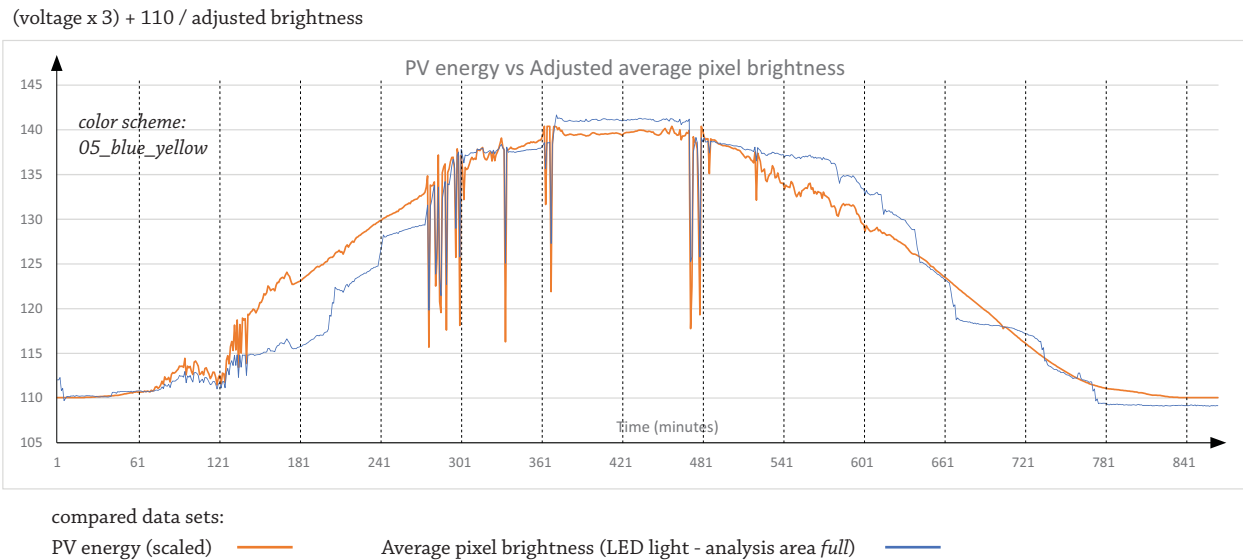


Fig. 5.45 Graph comparison - LED light study and PV energy monitoring on April 26th

As previously, there was a close temporal relation between the LED light graph and the PV energy graph. However, I noticed that the influence of the camera ISO speed adjustment lag which was less pronounced than on March 2nd. I scaled the PV energy graph shown in figure 5.45 by multiplying the PV energy levels by a factor of 3 for comparison. Figure 5.45 shows that the PV power rose earlier than the average pixel brightness between the minutes 121 and 270, and it also dropped quicker later in the day between the minutes 500 and 630. For this time, the national weather service recorded low values for average wind speed (2 mph) and an average sky cover of 0.4 along with heavy fog.

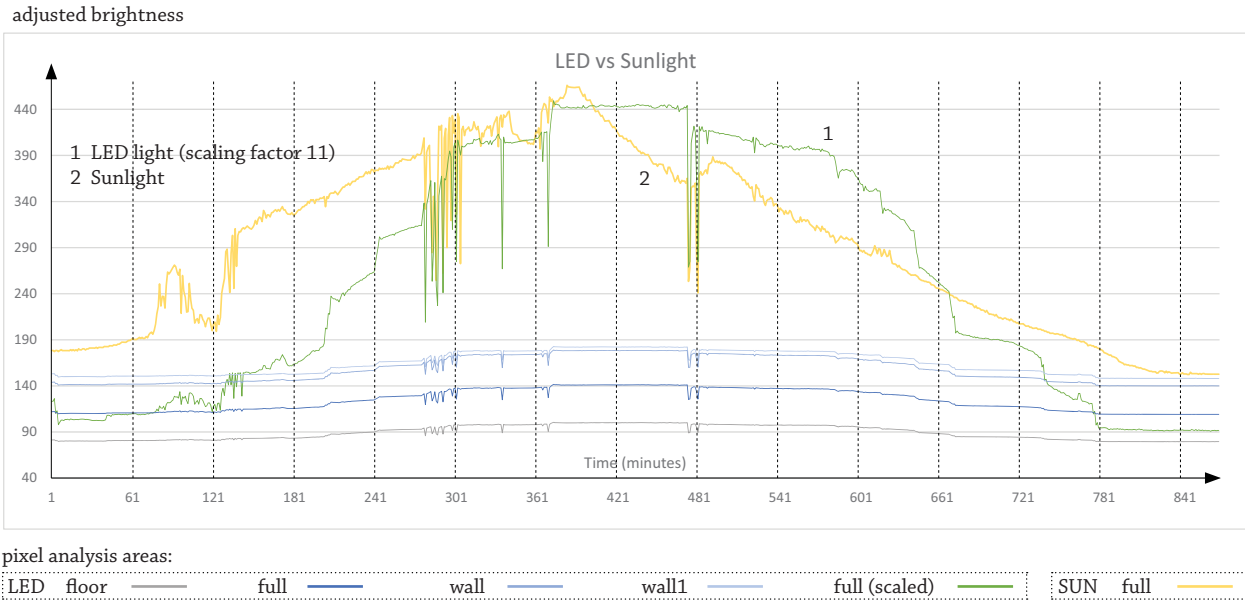


Fig. 5.46 Average pixel brightness graph comparison - LED light study and sunlight study conducted on April 26th using color scheme 05_blue_yellow

In this study, the sunlight's impact on the scene brightness was 11 times stronger than the LED lighting. Figure 5.46 shows that the pixel brightness based on the sunlight rose earlier than that for the LED light. This could have been related to the heavy fog since the PV energy levels during diffuse light conditions are reduced more compared to clear conditions than the brightness of daylight is. The weather on April 26th was much less volatile than on March 2nd as indicated by the low recorded average wind speed.

The diagrams in figure 5.47 illustrate that in the study conducted on April 26th the highest pixel brightness values of both the sunlight graph and the LED light graph occurred at nearly the same time around minute 390.

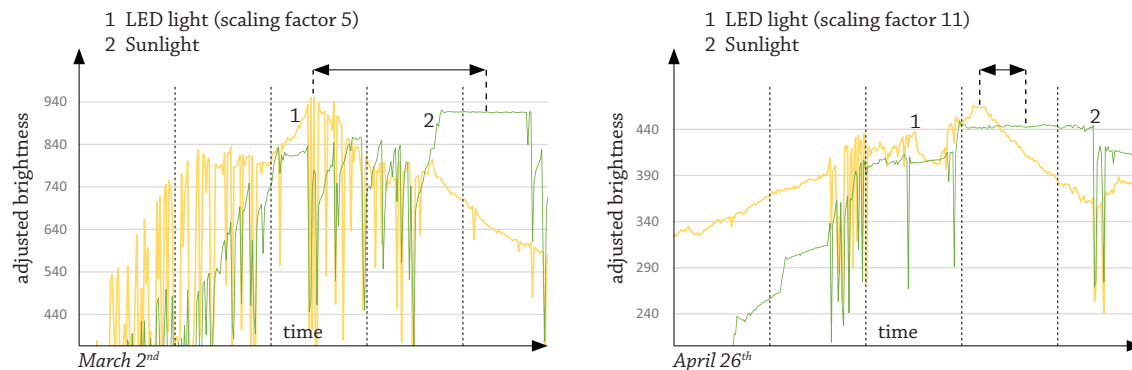


Fig. 5.47 Temporal offset of graph peaks, March 2nd (left) and April 26th (right)

The quantitative data was not helpful in explaining the smaller temporal offset on April 26th. The difference might have been caused by the modifying effect of the skylights which is dependent on the angle of the sunlight. The sun angles on April 26th were different than on March 2nd thus the skylights modified the sunlight entering the room differently.

Finally, I analyzed the data recorded on June 21st to determine if the results would be consistent. For this I expected there to be an even closer relation between the graph peaks.

Sunlight study - June 21st

The graphs of the sunlight study conducted on June 21st showed that the average pixel brightness was rising and falling throughout the day with the highest variation occurring between minutes 361 and 450 as well as between minutes 520 and 650. The pixel brightness measured in the analysis area wall showed a sharp increase between minutes 450 and 520 which was caused by direct sunlight. As expected, I found that both peaks of the general graph shapes (sunlight and LED light) were shortly past the middle of the day around minute 470.



Fig. 5.48 Average pixel brightness graphs created from sunlight study time-lapse photos taken on June 21st

adjusted brightness

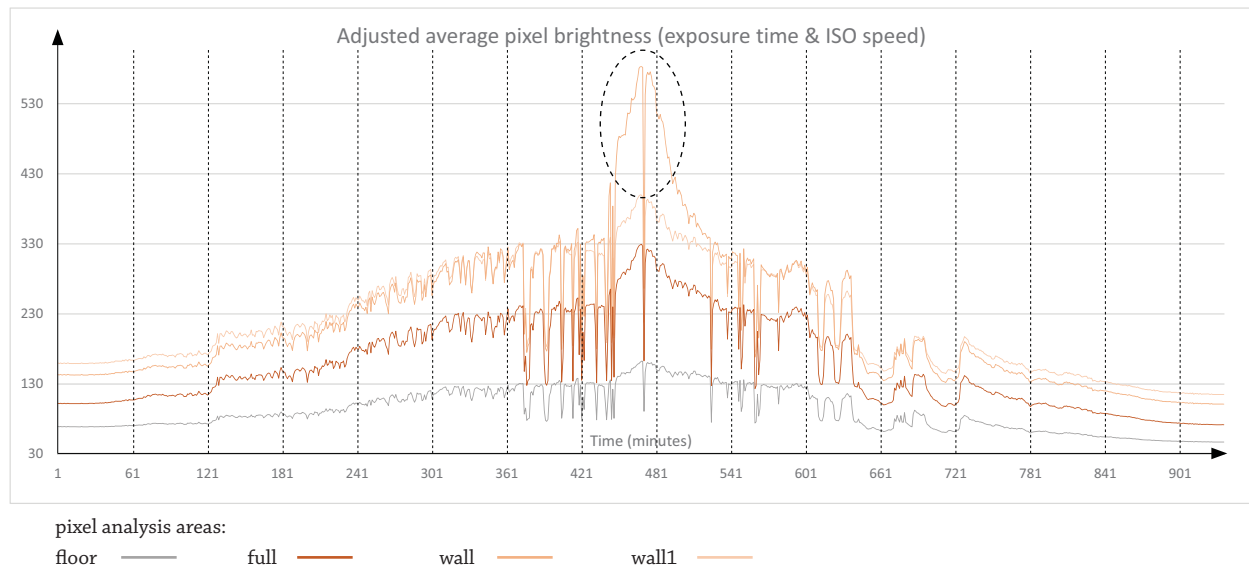


Fig. 5.49 Adjusted average pixel brightness graphs from sunlight study time-lapse photos taken on June 21st

max change ± 242.25 (black to white or vice versa)

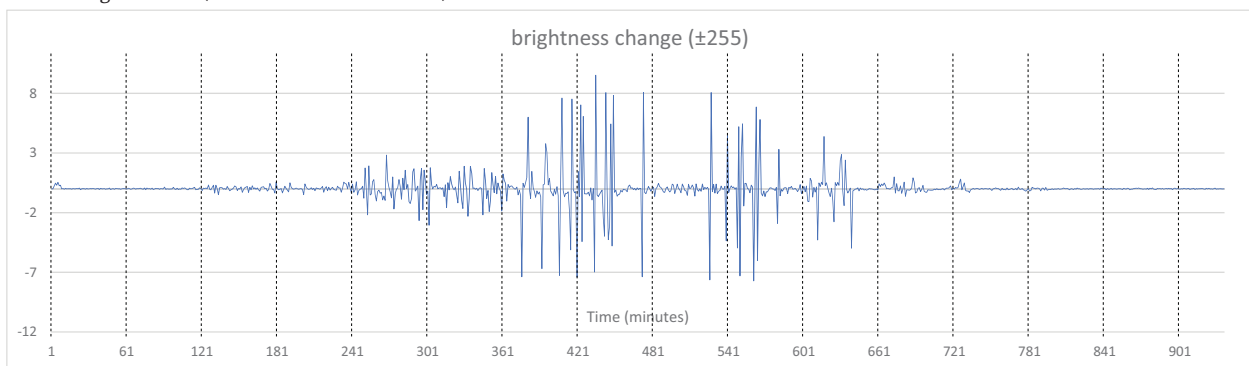
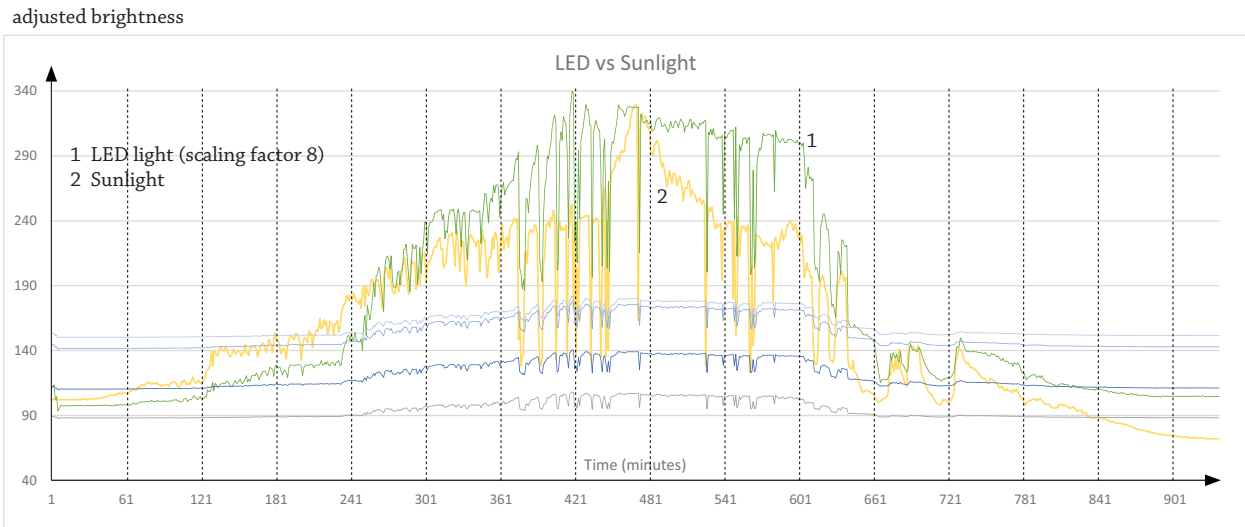


Fig. 5.50 Brightness change plotted as amplitude diagram (from sunlight study on June 21st)

LED Light study - June 21st

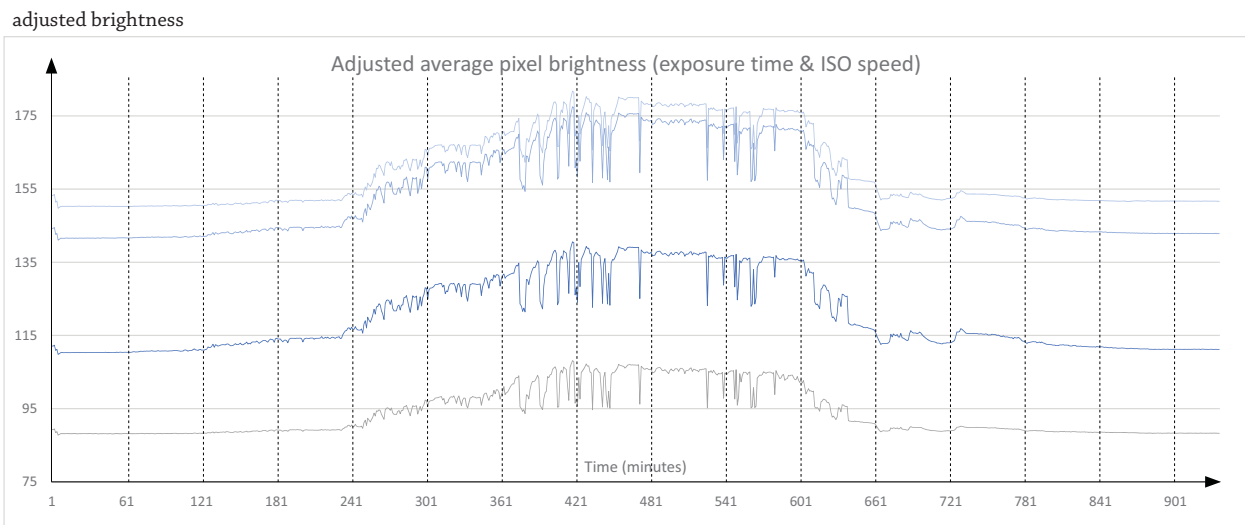
Similar to the sunlight graphs, the LED light graphs showed that the pixel brightness rose and dropped throughout the day. As observed in the previous studies there was a close temporal relation for the fluctuations. The general rates of increase and decrease were more similar on June 21st than on the other recording days. The mentioned variations in average pixel brightness between minutes 240 and 661 are also indicated in the pixel brightness change values shown in figure 5.50.



pixel analysis areas:

LED floor full wall wall1 full (scaled) SUN full

Fig. 5.51 Average pixel brightness graph comparison - LED light study and sunlight study conducted on June 21st using color scheme 05_blue_yellow



pixel analysis areas:

LED floor full wall wall1

Fig. 5.52 Adjusted average pixel brightness - LED light study on June 21st using color scheme 05_blue_yellow

In this study, the sunlight's impact on the scene brightness was 8 times greater than the LED lighting impact. I revisited the other studies to note the mentioned sunlight impact factors. I expected the impact factor to continuously rise between February and June because of brighter sunlight and the gradual increase of the solar elevation angle which allows more daylight into the build-

ing. However, the numbers in table 5.4 show that the impact of the sunlight on the scene brightness increased from 5 to 19 between February and March while gradually decreasing back down to 8 in June.

Date	Sunlight impact factor
February 24 th	5
March 2 nd	19
April 26 th	11
June 21 st	8

Tab. 5.4 Impact of sunlight on scene brightness

Again, I looked at the photo sequences to find the reason for the decline of the sunlight impact factor. As mentioned earlier I modified the skylight and the corridor model after the sunlight studies on February 24th, March 2nd, and April 26th to reduce the glare from the skylights and to achieve the correct amount of daylight present in the corridor. In doing this I unintentionally rendered the sunlight impact factors unusable for a direct comparison because they were based on different conditions. Nevertheless, I selected photos from each sunlight study at times with daylight entering at approximately the same angle. I visually compared the photos and verified that the sunlight impact factors were related to the scene brightness. The photos in figure 5.53 show that the scene on March 2nd is brighter than on February 24th and that the brightness decreased on April 26th (due to the shading effect of the PV cells in the skylights) and on June 21st (due to the reduced daylight in the corridor).

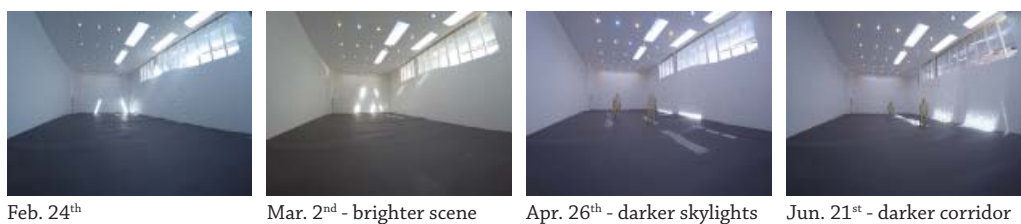


Fig. 5.53 Sunlight studies - scene brightness comparison

The vertical extent of the adjusted pixel brightness graph was three times larger than that of the the PV energy graph. I therefore scaled the latter by multiplying the voltage values by a factor of 3 for comparison in figure 5.54.

(voltage x 3) + 110 / adjusted brightness

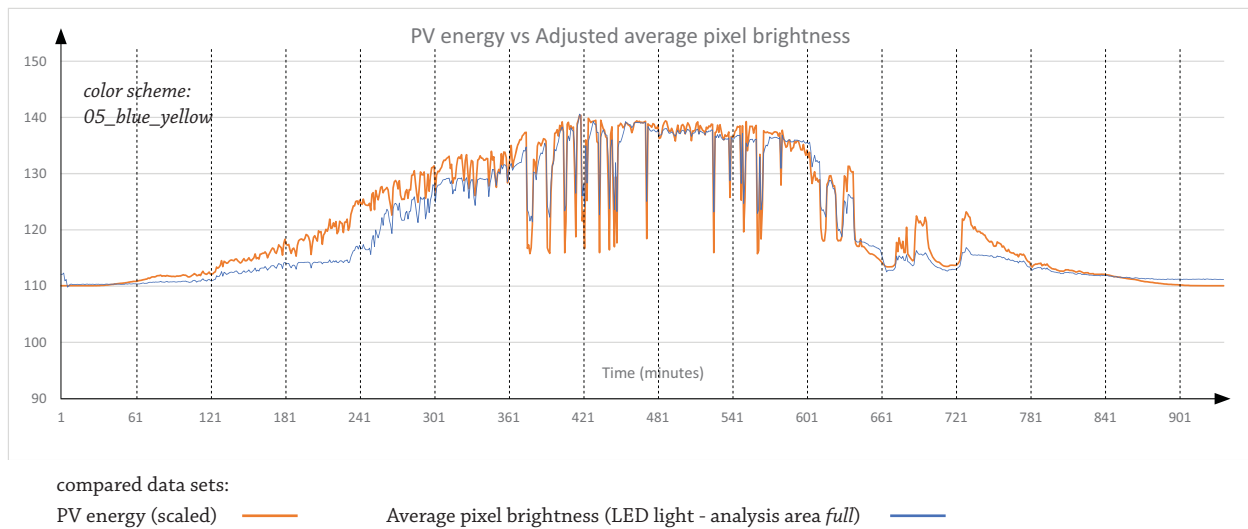


Fig. 5.54 Graph comparison - LED light study and PV energy monitoring on June 21st

Except for the morning hours (minutes 121 to 301) the blue LED light graph followed the orange PV energy graph quite closely. As depicted in figure 5.54, the LED lighting reproduced the variation in solar radiation very well.

Conclusion

As expected the dynamic LED light was not able to mimic daylight. However, this was not the intention of the project. The idea was to introduce a representation of sunlight patterns which make present the passing of time. The results showed that the LED light could create lighting conditions with varying in brightness and color over time in a way sunlight does. The LED lighting reproduced short fluctuations of the sunlight brightness and color caused by moving cloud shadows accurately.


The dynamic LED lighting could not reproduce the effect of patches of direct sunlight which move across the room at certain times of the day. I also observed that the gradual brightness fall-off of the sunlight during the afternoon was different than that of the LED lighting. This could be explained by the fact that the PV panel was oriented to the South while the skylights were oriented northwest-southeast.

5.5 Project net-zero balance


As mentioned in section 3.2, the design aimed at improving the light quality of the space without raising the energy demand of the building. To establish the net-zero balance I first calculated the energy consumption of the model's electric ceiling lights (5mm flat top LEDs) and the RGB LED skylight well lighting (5mm diffuse RGB LEDs).

Model lighting

CEILING LIGHTS

5mm flat top LEDs (warm & cool white)	0.064 W	
11 circuits with 3 LEDs (in series)		
Ceiling lights power	2.64 W	

RGB LIGHTING FOR SKYLIGHTS

RGB LED luminaire		
10 x 5mm diffuse RGB LED (in parallel)	1.012 W	
8 luminaires: RGB skylight well lighting power	8.096 W	

Tab. 5.5 Model lighting power

Due to model scale constraints, I located the RGB LEDs behind white acrylic skylight well panels with a measured transparency of 36 percent to simulate a wall washing light effect. Unlike the white flat top LEDs used for the model ceiling the common anode RGB LEDs cannot be connected in series. I had connected 3 flat top LEDs in series so that the ceiling light's efficiency (luminous intensity per watt) was 3 times greater than the RGB LED light's efficiency.

White-translucent acrylic panels	0.357664	transparency measured with light meter
Reduced efficiency (serial vs parallel circuit)	0.33	3 LEDs in series = 3x greater efficiency

Tab. 5.6 Model lighting power reduction factors

I then calculated the adjusted power of the RGB LED skylight well lighting based on the acrylic panel's transparency and its reduced luminous intensity per watt.

Calculated power for wall washing LEDs (adjusted RGB skylight well lighting power)	0.96 W	= 8.069W x 0.357664 x 0.33
---	---------------	----------------------------

Tab. 5.7 Adjusted RGB skylight well lighting power


Finally, I calculated a RGB skylight well lighting power factor relating the adjusted skylight LED power to the ceiling LED power.

RGB skylight well lighting power factor (in relation to ceiling lights power)	0.361956	= 0.96W / 2.64W
---	-----------------	-----------------

Tab. 5.7 RGB skylight well lighting power factor

Next, I calculated the power of the existing ceiling lights in the Sandbox and multiplied it with the power factor established above. This way I estimated the power of the dynamic electric lights required to provide the same variation in light intensity in relation to the base lighting as in the model lighting.

Sandbox lighting

CEILING LIGHTS		
Linear Lighting - Stripe STRP31 4 x Philips F28T5/841/ALTO (28W)	112 W	
7 rows - 3 luminaires each		
Ceiling lights power	2352 W	
Calculated Skylight well lighting power	851 W	
(ceiling lights power x RGB skylight well lighting power factor)		

Tab. 5.8 Sandbox Skylight well lighting power factor

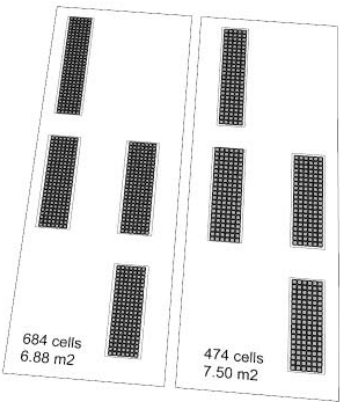
The brightness of the skylight well lighting is dimmed based on recorded PV power over time. The energy demand of the LED lighting is reduced linearly with the dimming factor and thus follows the available PV power over time.

I calculated the hourly potential PV power production of two PV integrated skylight glazing variations based on the factors skylight size (PV integrated glazing area), PV cell size, and number of cells. The simulations were conducted using the ArchSIM PV simulation plug-in for Grasshopper. This program uses 3D geometry from a Rhinoceros model (panel size and orientation) and weather data from EPW weather files to calculate the potential PV energy production over a specified time (figure 5.55).

PV POWER SIMULATION

based on epw weather file for Blacksburg, VA

variation 1		
Max peak power (May 22nd)	1468.39	W
Min peak power (Nov 24th)	125.5671	W
Calculated average peak power	796.9787	W
variation 2		
Max peak power (May 22nd)	1602.021	W
Min peak power (Nov 24th)	136.9943	W
Calculated average peak power	869.5075	W



variation 1	variation 2
PV glazing 684 cells (10x10cm)	PV glazing 474 cells (15x15cm)

Tab. 5.9 PV integrated skylight glazing power

The calculated average peak power of variation 2 is greater than the calculated skylight well lighting power. The surplus energy produced in the summer balances the energy deficit in the winter achieving a slightly positive annual energy balance.

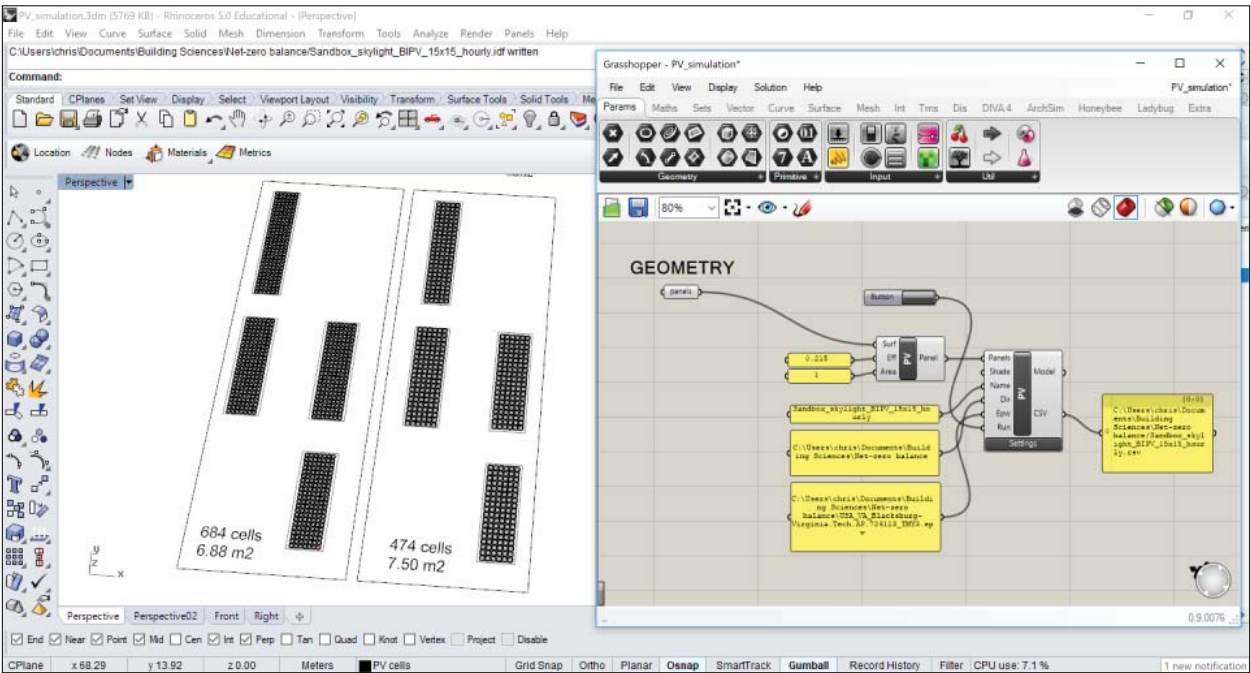


Fig. 5.55 Screenshot of PV glazing model variations and ArchSIM PV simulation tool

5.6 Discussion

The quantification of variations in brightness over time and comparing the influence of sunlight with the impact of the LED skylight well lighting helped me to assess my concepts which translated energy monitoring data to lighting protocols. The findings of the quantitative evaluation process were also helpful to better understand the observations I made during the qualitative evaluation of the sunlight- and LED light studies. The features of daylight are a result of very complex processes. Its color and brightness are dependent on the angle at which sunlight enters the atmosphere and are often further modified by clouds or fog. The translation of PV energy monitoring data to dynamic lighting protocols thus reproducing the dynamic properties of daylight required a careful consideration of different color gradients in combination with the recorded variations in solar radiation. This way the lighting protocols varied in brightness and color like daylight does. However, the LED light of the Sandbox model was not powerful enough to match the intensity of daylight. I found that the LED light's lower variation in brightness could be mitigated by a higher variation in color. This could be achieved by increasing the color saturation of the LED lights. I selected a sky color theme that visually matched the color of the daylight in the sunlight time-lapse videos. The result was a fairly abstract reproduction of dynamic daylight which as I thought, added to the mood of the room.

It was interesting to see that the results obtained with the selected qualitative and quantitative evaluation methods sometimes coincided thus corroborating certain assumptions. The assessment of the intended temporal correlation between the sunlight's and the LED light's variation in brightness and color over time for example was done by means of both quantitative and qualitative methods. At other times, the qualitative and quantitative results complemented each other when certain observations could only be made either qualitatively or quantitatively. I used qualitative criteria to select a color scheme for the lighting protocols because the quantitative results were not helpful for this task. However, the quantitative results show some evidence that the selection was correct as discussed on page 148 and page 149. The quantitative data of the brightness change calculations was helpful to look at the question of perception from a psychophysical perspective. As mentioned in section 3.2, the Weber fractions for the just-noticeable difference (JND) for brightness are specified in the range of 0.02 to 0.05 or 2-5%. The values of the short fluctuations in brightness during the LED light studies were shown in the graphs in section 5.4. The average pixel brightness of the photos from the LED light studies was approximately 120 and the pixel brightness change ranged between 2 and 10 or 1.7-8.3% of the average. The brightness change values fell almost entirely in the range of the JND for brightness.

The current findings of the study are based on a limited number of recording days. Additional recordings of sunlight and corresponding LED lighting pat-

terns are required to further verify the observed relation between the PV power levels and the readings of the pyranometer.

Continued research and field test

This project's results are based on the numeric analysis of RGB pixel values and the visual evaluation of time lapse photos and videos. A scaled model of the studied space and a small action camera were used to capture images visualizing the effect of sunlight entering the space as well as LED lighting patterns based on the recorded variations in solar radiation. In collaboration with ICAT I have proposed a long-term study in the Sandbox to improve our understanding of the effect of these natural patterns in real time. In a field test dynamic RGB LED wall washing lighting installed in a selected section of the space are used to play back dynamic lighting protocols based on real time PV energy monitoring data. Brightness and color of the light are set according to interpreted power values of a PV panel located outside close to the Sandbox. The users of the space are asked to provide feedback on the perceived effect of the dynamic lighting in the space. I hope to find that the dynamic lighting will reintroduce a natural rhythm in the Sandbox and give presence to the passing of time.

Potential applications of energy monitoring based dynamic lighting protocols

During my work on the immersive case study I identified potential application scenarios for the project. The ideal scenario for the project's application is the combination of sunlight through a skylight (day mode) with dynamic LED lighting (night mode). On overcast days with low daylight the LED lighting could be used to complement the sunlight. In spaces with very little or no access to daylight there are additional applications for the project. The PV power monitoring and LED components could be used to introduce dynamic lighting to the space thereby reintroducing natural rhythms and stimulating the circadian rhythm of the users during the day. This thesis project focused on applications with a combination of daylight and artificial light. The design of applications for rooms without access to daylight delineates a scope for a potential follow-up project which would, among others, require further research on biological lighting.

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Fig. 5.3 Distance between Vet Med (1) and RDF (2)
(Map source: maps.google.com)

Fig. 5.20 Detected and actual luminance: Eyes vs Camera
(Source: www.cambridgeincolour.com)
author: Sean McHugh

Fig. 5.21 Gradient encoding - linear vs gamma The representation of dark tones is improved.
(Source: www.cambridgeincolour.com)
author: Sean McHugh

Fig. 5.22 Gamma correction - sequence of operational steps
(Source: www.cambridgeincolour.com)
author: Sean McHugh

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6. Potential Applications and Contributions

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6.1 Theory – Phenomena and Perception

Making present the passing of time relative to sun dynamics

Historically, the sun has been used to measure and structure time. The sun cycle is an accurate visual indicator of time that can be consulted with simple equipment and some elementary knowledge. Early examples of solar timekeeping include sundials, which have been used to tell time for several thousand years. Another example is described in guides for telling the time without a clock. You can get an estimate of how much time is left until the sun sets by counting the number of fingers you can fit between the sun and the horizon (Newquist, 2000).

Though the movement of the sun is not easily perceived in the moment, it can be tracked with simple methods. Architects use carefully placed openings in their buildings to create moving beams of sunlight in a room, thus making present the passing of time both in the short term (throughout the day) and in the long term (throughout the year). In the Roman Pantheon, both the daily sun cycle and the annual sun cycle are represented. At noon, the daily cycle causes the beam to align with the entrance which points to the North. Historical research suggests that the Pantheon was designed to represent a sundial (Hannah & Magli, 2011). The researchers investigated the significance of the varying positions of the beam of sunlight entering through the oculus throughout the year. Hannah & Magli refer to an event on April 21st, the day on which, according to legends, Rome was founded. On this day the beam of sunlight from the oculus fully illuminates the entrance. According to Hannah & Magli, this points to a conscious design with the sun: “If we suppose, as seems likely, that the emperor was celebrating this precise day there, then his entrance “together with the sun” would have been a symbolic link between the people and the Gods” (p. 11).

The design strategies discussed above make present the passing of time through the movement of the sun. In my research, I investigated how time passing could be made present through the dynamics of sunlight intensity. I recorded levels of solar radiation by means of monitoring current and voltage of a PV panel and represented this with dynamic LED light thus introducing a temporal stimulus for the occupants.

Representing dynamic sunlight intensity:

SOLAR RADIATION → BIPV → LED LIGHT → PERCEPTION

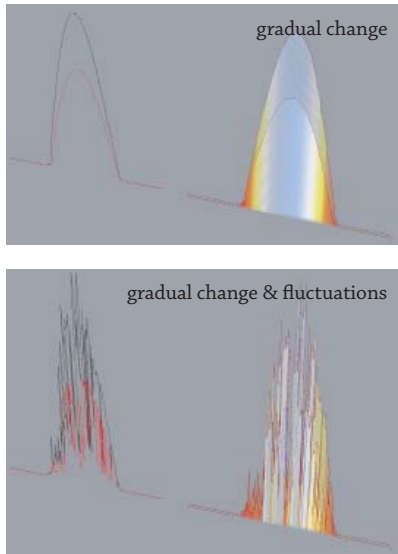


Fig. 6.1 Dynamics of solar radiation

Naturally, the solar radiation gradually increased from the sunrise until noon and decreased during the afternoon until the sun set in the evening. In addition to this gradual change I also observed short fluctuations of solar radiation caused by cloud shadows that moved across the PV panel. Hence there were two different overlapping dynamics of the solar radiation levels during a recording day. One was a gradual change related to the daily cycle of the sun and the other was a series of short fluctuations caused by variable local weather conditions such as moving cloud shadows. There is a third dynamic of seasonal changes concerning the relation between the length of the days and the length of the nights. Except on the equinoxes, the recorded patterns of sunlight of a day would be either stretched or compressed for the playback during the following night.

The Corsini Encyclopedia of Psychology explains the concept of just-noticeable difference (JND) and provides representative values for the JND for brightness (2010, p. 1850). I used these values to investigate whether the variations in brightness produced by the LED light would be perceivable. I found that the magnitude of the analyzed pixel brightness variation during the LED light studies was in the range of JND for brightness. However, JND is most meaningful for a simultaneous comparison of two stimuli. It is much more difficult to perceive a gradual change of brightness since the eye adapts to light intensity, subduing the change. Even though we do not perceive the variation of brightness in sunlight in the moment we still perceive a variation over time. This is where our memory of past conditions seems to come into play.

In my studies I found that the magnitude of difference of sunlight during the day was greater than that which could be achieved with the LED light. To compensate for this lack of brightness variation, I used a greater variation in color of the LED light. The increased color variation helped to reproduce the dynamics of the daylight entering through the skylights. Simultaneous to a decline in brightness, moving cloud shadows also caused an increase of color temperature. To achieve this with dynamic LED light, I designed a gradient with cool colors (high color temperatures) for the translation of insolation sensing to lighting control protocols.

Just noticeable difference

WEBER FRACTIONS

brightness

0.02 – 0.05 (2-5%)

AVERAGE PIXEL BRIGHTNESS

LED light studies

120

PIXEL BRIGHTNESS CHANGE

LED light studies

2-10 = 1.7-8.3% of average pixel brightness

Fig. 6.2 Comparing pixel brightness change to JND for brightness

Reintroducing the primordial connection to the sun cycle

Both the daily and seasonal cycles of the sun have influenced our cultures and rituals for millenia. Surviving ancient architecture, the recorded traditions of ancient civilizations, and physically, our own circadian rhythm all indicate our connection to the cycles of the sun. In his book *Ritual House*, Ralph Knowles emphasized the importance of our connections to the natural world proposing a design in response to seasonal and daily cycles (2006).

The importance of daylight in building design for the visual and physical comfort is widely accepted today. In this project I reproduced the natural rhythm of variable solar radiation to reconnect the Sandbox with the exterior. The project reacted to the current disconnection of the Sandbox from the outside which, according to the occupants, led to discomfort. One of the qualities of daylight is its variation in brightness, color, and angle during the day which enables people to stay oriented in time. During the day, the PV-integrated skylight provided sunlight, which is dynamic by nature. At night, LED lighting provided dynamic electric light. The LED light was controlled with lighting protocols based on insolation sensing and thereby assumed the dynamic quality of daylight. Through this system, the project provided a visual stimulus that supported the occupants' orientation in time.

Blurring the boundary between quantitative and qualitative

Steven Holl suggests that we have artificially separated quantitative and qualitative. In reaction to this he designs projects in which technology and science reveal the nature of things, as he did in his design for the Cranbrook Institute of Science (Steven Holl Architects, 2018). Holl used refracting glass to show the spectrum of sunlight on the walls and reveal one of the dimensions of light, namely color. When I worked as an architectural designer in Vienna, I experienced the separation of the quantitative and the qualitative during design meetings with our consultants. However, the permeability of the boundary varied depending on the consultant's compatibility with our design philosophy and vice versa. In my experience, the projects where the team crossed the borders between quantitative and qualitative design led to more integrated and wholistic solutions. I enjoyed crossing these borders and working on integrated project designs.

In this project I aimed to blur the boundary between the quantitative and the qualitative by using research and design methods from both the world of engineering and the world of architecture to address technological questions as well as questions of perception that arose during the process. Blurring the boundary enabled me to be open to and explore different concepts for the representation of a natural phenomenon through technology. I combined representation and the physical world to explore natural variations in solar radiation through the observation of interactions between a model and the real world. I also combined intuition and reason during the reproduction of these natural variations using visually assessed color concepts to translate measured quantitative data. I recorded sensed insolation levels utilizing the relation between irradiance and electric current in the photovoltaic effect.

Future opportunities

The potential of this project lies in the exploration of a natural phenomenon with technology. As described above, variations in solar radiation were sensed utilizing the photovoltaic effect. I used PV and LED technology to reveal the dynamic character of sunlight through lighting control protocols which varied the brightness and color of the interior LED lighting. The applications of Building Integrated Photovoltaics (BIPV) were expanded by adding qualitative features that are currently lost or ignored. These qualitative features were used to represent the light sensing properties of solar cells in the space thus enabling the occupants to experience and relate to PV technology. Energy monitoring of large PV arrays can give the building skin sensing capabilities. This could, for example, be used to indicate the areas with the most and the least incident solar radiation using colored light arrays on the inside to visualize the different power production of individual PV modules depending on their exterior orientation.

During the process of the project, I explored the perception of gradual changes in brightness and color. This raised the question how to assess the dynamic qualities of daylight and electric light conditions in buildings. This project could provide a basis for more comprehensive research on time lapse analysis that combines quantitative and qualitative data to complement existing lighting simulation programs.

6.2 Method – Combining Quantitative and Qualitative

In this project I combined quantitative and qualitative design and research methods. I understood quantification as a form of abstraction and representation that can be used to illustrate and explore natural phenomena. The qualitative methods which I have used in this project were suitable to evaluate representations of the studied phenomenon through my perception. This was done intuitively and based on my experience. The quantitative methods were suitable to explore a natural phenomenon with the help of numerical data and explain it by revealing its characteristics through technology. ADD DIAGRAM

Mixed methods of the combined approach during the immersive case study

- Interpretation of qualitative visual representations of quantitative data

Visualizations are important tools to interpret quantitative data. They enable the observer to identify patterns and relationships that are hard to see by looking at large lists of numbers. In this project I took this a step further. To create the protocols for the dynamic LED lighting I translated analog information (variations in solar radiation over time) to digital energy monitoring data. I modified the collected data using digital tools (computer programs) to create lighting control protocols. Finally, I translated the digital lighting control protocols back to perceptible analog representations of the original information using PWM dimming protocols and RGB LED luminaires. This way the LED lighting represented a natural phenomenon and revealed the dynamic nature of sunlight visually through variations in brightness and color.

- Reciprocal assessment of qualitative and quantitative results

The dynamic LED lighting control protocols were based on quantitative PV energy monitoring data. I visualized the energy monitoring data with graphs and analyzed the response characteristics of the PV panel. This helped me to design color gradients for the lighting control protocols. I evaluated visualizations of the LED lighting protocols using time lapse videos. The videos were recorded during LED light studies using a digital camera. I also analyzed individu-

al frames of the videos quantitatively using computer programs. During the immersive case study, I continuously went back and forth between assessing quantitative and qualitative results to cross-check my observations.

- Measuring brightness with digital camera

I used RGB color information to determine the average pixel brightness of an image, or part of an image, using RGB value analysis programs. This way I could measure the influence of the sunlight and the LED light on the brightness inside the model using a digital camera. Light sensors provide one measurement based on the illuminance (entire amount of light) of the detection area. The RGB value analysis of images from the digital camera provided position dependent luminance for each pixel comparable to renderings created with light simulation programs (e.g. Radiance).

- Quantitative and qualitative evaluation of photo sequences

The digital camera I used was not accurate enough for scientific purposes, but it enabled me to conduct a combined evaluation of the same data (photo sequences) with both quantitative and qualitative methods for the comparison of sunlight and dynamic LED light. The results were sufficiently accurate to design dynamic LED lighting control protocols which reproduced the dynamics of sunlight. However, the method of measuring brightness with digital cameras could be improved for future research by using cameras with high quality light sensors and the ability to use fixed values for ISO speed and exposure time.

The qualitative evaluation of the photo sequences involved my personal intuitive observations. I note that my own observations included personal bias, raising the question of whether others with different backgrounds, age, gender, education, etc. would have interpreted the results differently. Future research involving feedback from a reasonable number of research partners/subjects would increase the validity of the project outcomes due to a greater variety of intuitive interpretations of the results.

Future opportunities

The results of this project will be used to inform a real-time field study in the Sandbox with the goal to collect user feedback about their perception of dynamic LED lighting. I hope to find that the intervention addresses the reported discomfort by introducing a temporal stimulus that reconnects the occupants with the exterior.

During the analysis of the images in the photo sequences I found that the camera adjusted the exposure time and ISO speed to the scene brightness so that the recorded images would not be over- or underexposed. This is comparable to the process of eye adaptation in which the eye's sensitivity to brightness changes based on the current illuminance. When I evaluated whether the dynamic LED light would be noticeable I consulted Weber's concept of JND. The Weber fractions for brightness were specified for a simultaneous comparison of two stimuli. To evaluate at what point a gradual change in brightness is noticeable, it would be interesting to investigate the influence of eye adaptation. Using a digital camera sensor with similar adaptation properties as a measurement device could be beneficial for this investigation.

The methods used in this project improved my understanding of retrieving the qualitative information inherent in quantitative data. The energy monitoring data, which is normally used to evaluate the performance of the monitored system, contained information on the variation of solar radiation over time. The variation of sunlight in brightness and color was revealed through a translation process and represented with dynamic LED lighting. Further research could expand on retrieving qualitative information from more complex systems in which several PV panels are oriented in different directions and monitored individually to create lighting control protocols for multi-area LED lighting.

I built a scaled model of the Sandbox to develop and evaluate the design of PV-integrated skylights for the Sandbox. Using a model with a functional dynamic electric lighting system enabled me to assess my design for a proposed implementation scenario at a later stage. This method represented a simple evaluation tool that was used for comparative studies of both daylight and dynamic LED light with the same object. I regarded this as a valuable tool that could supplement digital light simulation tools in the early design stage.

6.3 Potential applications and future research

I developed two main concepts for potential applications of this project. The first is a PV-integrated skylight providing both daylight and dynamic LED light. The second application is a simulated skylight continuously providing dynamic LED light.

1) Luminous Solar Skylight for continuously used spaces

Dynamic sunlight (DAY, live) – Dynamic LED light (CLOUDY DAY, live - NIGHT, playback)
Sense of time passing / no direct influence on the circadian rhythm - intended continuous use of the space.

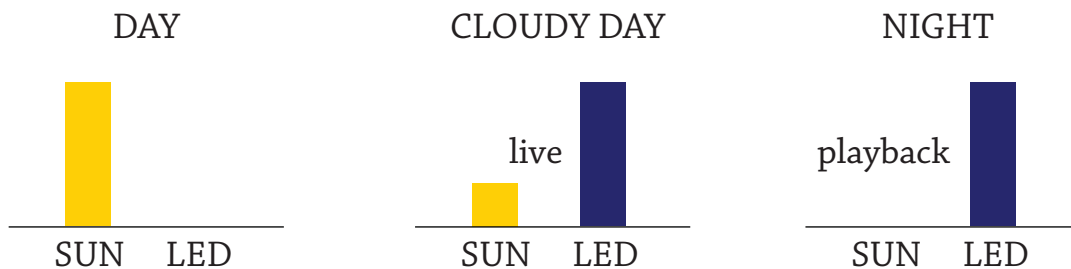


Fig. 6.3 Luminous Solar Skylight operation modes

2) LED Skylight for spaces with no access to daylight

Dynamic LED light (DAY, live translation) – (NIGHT, protocol)
White light matching the color temperatures of daylight / supports the circadian rhythm - further research on biological lighting required.

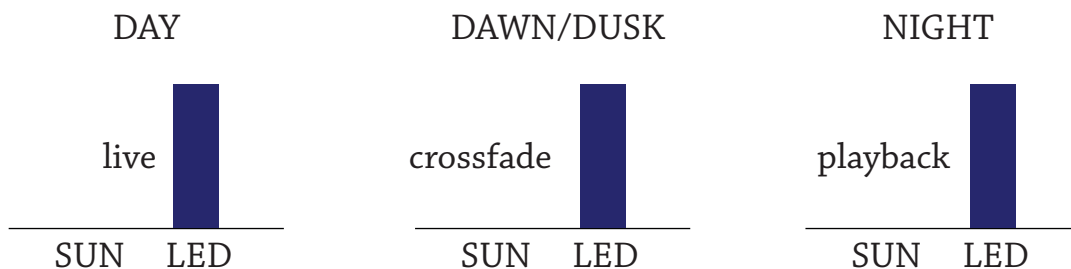


Fig. 6.4 LED Skylight operation modes

SUN (recorded solar radiation patterns)

LED (dynamic lighting control protocols)

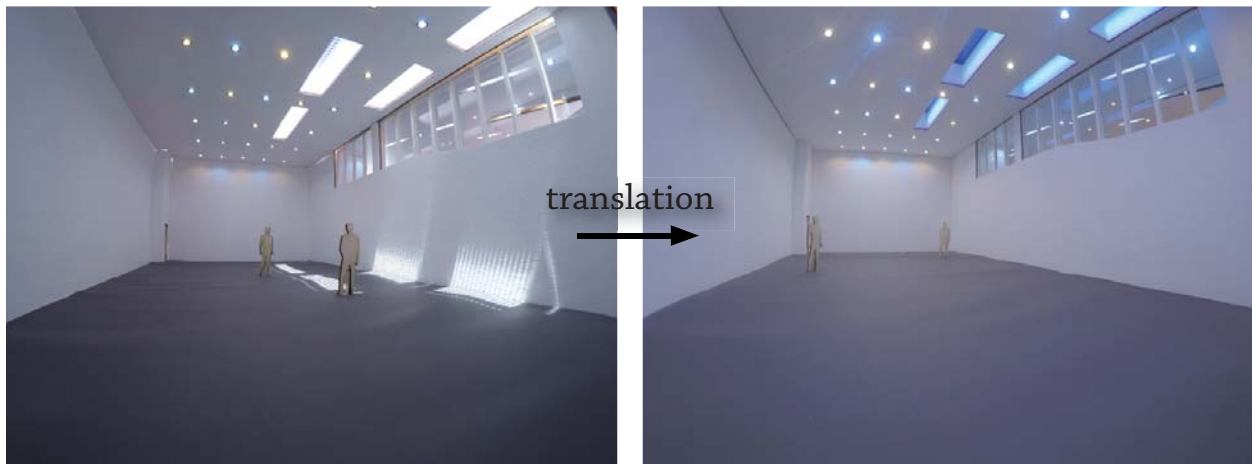


Fig. 6.5 Luminous Solar Skylight for continuously used spaces - day and night mode

Both applications were designed as an overlay to the existing base lighting of the space respecting the minimum illumination required by lighting design standards. Whether or not the dynamic lighting can be applicable as a base light system depends on the function of the space. For some uses, variable light levels and color are acceptable or even beneficial, while for other uses the dynamic light presents an undesirable distraction. However, in daylight spaces with functions that rule out dynamic light the dynamic LED lighting could still be applied when the dynamics are reversed. In such a scenario the electric light is adjusted to compensate daylight during times when it is not providing the desired illumination.

As mentioned in chapter 1, I conducted a case study of the Plus-Energy Office High Rise Building in Vienna. For this project the building physicists designed an interior lighting system that adjusts the brightness of LED luminaires based on the sensed daylight level to minimize the energy demand of the electric space lighting. The presence of time passing is thus reduced somewhat. It would be interesting to explore how electric lighting with reversed dynamics could be modified so that it reassumes its function as a *zeitgeber*. The capabilities of RGB LED lighting could be helpful to design a lighting system that represents the passing of time through variations in color while maintaining the brightness respecting the minimum illumination.

6.4 Lessons learned

I documented my observations in a journal which I continuously consulted during the immersive case study. This way I could keep track of my experiences during the process and summarize the lessons learned as follows.

Theory

- the color of the sky dominated the color of daylight entering the room
- the light scattering of the PV cells in the model was much less pronounced than that in a simulation (Rhino rendering)
- perceived brightness is color dependent and nonlinear
- the variation in brightness of sunlight was greater than that of the LED light, however, this could be compensated with a higher variation in LED light color
- the response characteristics of the PV panel were not identical to the pyranometer but they were sufficiently similar for the translation of insolation sensing to lighting control protocols

Method

- the GoPro camera varied exposure time and ISO speed based on the scene brightness which required an adjustment of the results
- the reaction of the camera to the brightness of the scene could be considered to be comparable to the adaptation of the human eye
- the question of how digital cameras sense brightness compared to the human eye requires additional research
- using a physical model benefited the comparative evaluation of sunlight studies and LED light studies
- the scaling of time facilitated the observation of patterns in the variation in brightness and color

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 is improved. [used with permission]
 (Source: www.cambridgeincolour.com)
 a) https://cdn.cambridgeincolour.com/images/tutorials/gamma_gradient3b.jpg
 b) https://cdn.cambridgeincolour.com/images/tutorials/gamma_gradient2b.png
 c) https://cdn.cambridgeincolour.com/images/tutorials/gamma_gradient1b.png
 (accessed Feb. 1, 2018)
 used with permission from Sean McHugh; email attached
- Fig. 5.22 Gamma correction - sequence of operational steps [used with permission] 140
 (Source: www.cambridgeincolour.com)
 a) https://cdn.cambridgeincolour.com/images/tutorials/gamma_chart5c.png
 b) https://cdn.cambridgeincolour.com/images/tutorials/gamma_chart3c.png
 c) https://cdn.cambridgeincolour.com/images/tutorials/gamma_chart4d.png
 d) https://cdn.cambridgeincolour.com/images/tutorials/gamma_display22.png
 (accessed Dec. 15, 2017)
 used with permission from Sean McHugh; email attached

Internet resources

A. A. Kruithof's research explained:

<http://agi32.com/blog/2015/01/12/the-kruithof-curve>

Color Temperature definition:

http://lowel.tiffen.com/edu/color_temperature_and_rendering_demystified.html

Color Temperature to RGB conversion:

<http://www.vendian.org/mncharity/dir3/blackbody>

<http://www.tannerhelland.com/4435/convert-temperature-rgb-algorithm-code>

History of the Photovoltaic & Photoelectric effect:

https://en.wikipedia.org/wiki/Photoelectric_effect

LED circuit design:

<http://ledcalculator.net>

Measuring light color temperature with a digital camera:

[Color Temp Meter app for Android - purchased from Google Play Store](#)

RGB luminance calculation & gamma correction:

<https://stackoverflow.com/questions/596216/formula-to-determine-brightness-of-rgb-color>

<https://www.cambridgeincolour.com/tutorials/gamma-correction.htm>

Technical definitions:

<https://en.wikipedia.org/wiki/MOSFET>

Using the sun to tell the time:

<https://www.backpacker.com/skills/let-your-fingers-tell-time>

Appendix B

Used software and materials	202
Program source code	203
Time-lapse video links	220

Used software and equipment

SOFTWARE

student license:

3D modeling - Rhinoceros 5
2D drafting - Rhinoceros 5, AutoCAD
parametric design tool - Grasshopper
daylight simulation - DIVA for Rhinoceros
PV simulation - ArchSIM for Grasshopper
PCB design - Autodesk Eagle

Microsoft - Word, Excel, Powerpoint

Adobe - Photoshop CC, Illustrator CC, InDesign CC, Premiere Pro CC,
Acrobat DC

freeware:

programming - Python 3.0
libraries for Python - pigpio, pygame, numpy, scipy, pypng, PIL
image processing - XnViewMP

EQUIPMENT

provided by Elizabeth Grant:

pyranometer - Onset S-LIB-M003
light meter - EXTECH LT300

provided by College of Architecture and Urban Studies:

75W PV module - BP Solar BP275U
emonPi open energy monitor
custom built resistive load

provided by Innovation Space Virginia Tech:

digital camera - GoPro Hero 4 silver

purchased:

RGBSIGHT Programmable LED Time Controller
5mm flat top LEDs (warm white, cool white)
custom designed printed circuit boards
1/4W resistors, 1/2W resistors
Raspberry Pi 3
6V power adaptor
5mm diffuse RGB LEDs
MOSFET transistors

Program source code

4 COLOR GRADIENT

```
import csv
import os
import numpy as np
from scipy import interpolate
import scipy.misc
import png

sizeX = 300
sizeY = 300

x_array = []
image_array = []
line = []

Q1 = [128,0,255]
Q2 = [255,182,98]
Q3 = [255,237,218]
Q4 = [238,239,255]

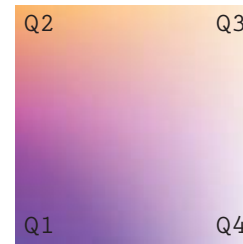
leftR = map(int, np.linspace(Q2[0],Q1[0],sizeY))
rightR = map(int, np.linspace(Q3[0],Q4[0],sizeY))
leftG = map(int, np.linspace(Q2[1],Q1[1],sizeY))
rightG = map(int, np.linspace(Q3[1],Q4[1],sizeY))
leftB = map(int, np.linspace(Q2[2],Q1[2],sizeY))
rightB = map(int, np.linspace(Q3[2],Q4[2],sizeY))

fR = np.zeros((sizeX,sizeY))
fG = np.zeros((sizeX,sizeY))
fB = np.zeros((sizeX,sizeY))

image_array = []

for x in range(sizeX):
    line = []
    lineR = map(int, np.linspace(leftR[x],rightR[x],sizeX))
    lineG = map(int, np.linspace(leftG[x],rightG[x],sizeX))
    lineB = map(int, np.linspace(leftB[x],rightB[x],sizeX))
    for y in range(sizeY):
        line.append(lineR[y]);line.append(lineG[y]);
        line.append(lineB[y])
    image_array.append(line)

f = open('test.png', 'wb')
w = png.Writer(sizeX, sizeY)
w.write(f, image_array) ; f.close()
```



MULTICOLOR GRADIENT

```

import csv
import os
import numpy as np
from scipy import interpolate
import scipy.misc
import png

resX = int(raw_input('resX: '))
resY = int(raw_input('resY: '))
filename = raw_input('color file: ')
saveas = raw_input('save as: ') + '.png'

with open(filename, 'r') as csvfile:
    content = csv.reader(csvfile,delimiter=',')
    data = list(content)

    colorpoints = [[[[] for i in range(len(data))]]
for i in range(len(data[0]))]

    for y,row in enumerate(data):
        for x,column in enumerate(row):
            value = map(int, column.split(','))
            colorpoints[x][y] = value

numY = len(colorpoints[0]) - 1
numX = len(colorpoints) - 1
print(numX,numY)

sizeX = resX*numX
sizeY = resY*numY

calc_array = np.zeros((sizeX,sizeY,3))
image_array = []
lineadd = []

left = [[[],[],[]]
right = [[[],[],[]]

for fieldX in range(numX):
    for fieldY in range(numY):
        for i in range(3):
            leftadd = map(int, np.linspace
                (colorpoints[fieldX][fieldY][i],
                 colorpoints[fieldX][fieldY+1][i],resY))

            left[i] = leftadd

```



```

        rightadd = map(int, np.linspace
            (colorpoints[fieldX+1][fieldY][i],
             colorpoints[fieldX+1][fieldY+1][i],resY))

    right[i] = rightadd

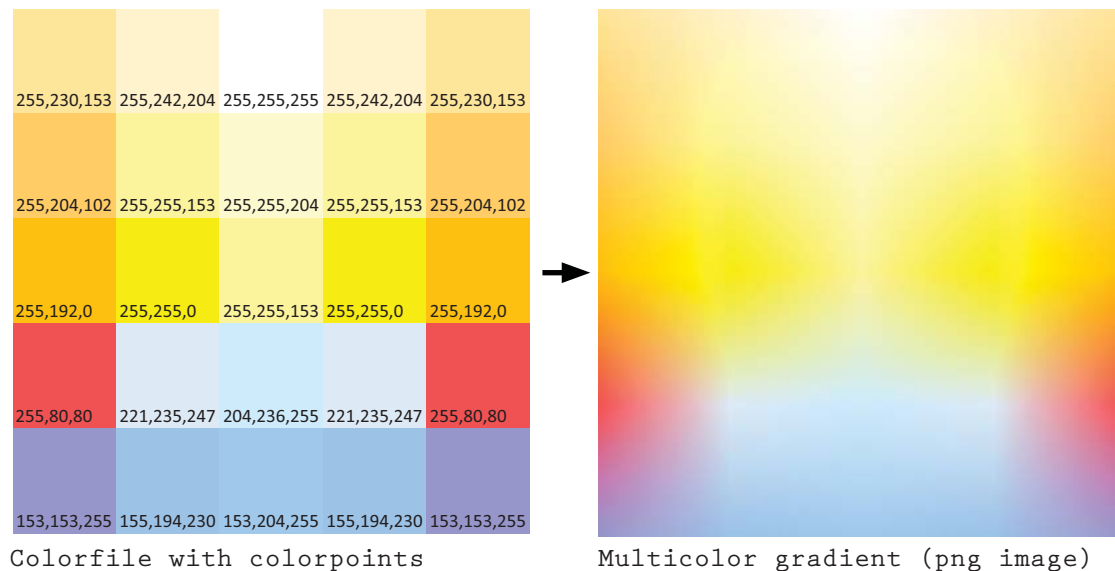
    for y in range(resY):
        line = map(int, np.linspace
            (left[i][y],right[i][y],resX))
        for x in range(resX):
            calc_array[x+(resX*fieldX)]
                [y+(resY*fieldY)][i]=int(line[x])

rotated = list(reversed(list(reversed(zip(*calc_array)))))

for x in range(len(rotated)):
    lineadd = []
    for y in range(len(rotated[0])):
        for i in range(3):
            lineadd.append(int(rotated[x][y][i]))
    image_array.append(lineadd)

f = open(saveas, 'wb')
w = png.Writer(len(rotated[0]), len(rotated))
w.write(f, image_array) ; f.close()

```



GRADIENT TRANSITION

```

import csv
import os
import numpy as np
from scipy import interpolate
import scipy.misc
import png

resX = int(raw_input('resX: '))
saveas = raw_input('save as: ') + '.png'

with open('M.csv', 'r') as csvfile:
    content = csv.reader(csvfile,delimiter=',')
    data = list(content)

    grad1 = []

    for row in data:
        grad1.append(row)

with open('H.csv', 'r') as csvfile:
    content = csv.reader(csvfile,delimiter=',')
    data = list(content)

    grad2 = []

    for row in data:
        grad2.append(row)

print(grad1[0][1])
print(len(grad1)); print(len(grad1[0]))

sizeX = resX
sizeY = len(grad1)

calc_array = np.zeros((sizeX,sizeY,3))
image_array = []
lineadd = []
strip1 = strip2 = []
strip1_array = strip2_array = []

for y in range(len(grad1)):
    for i in range(3):
        grad1col = int(grad1[y][i]); grad2col = int(grad2[y][i])
        addvalue = map(int, np.linspace(grad1col,grad2col,resX))
        for x in range(len(addvalue)):
            calc_array[x][y][i] = addvalue[x]

```

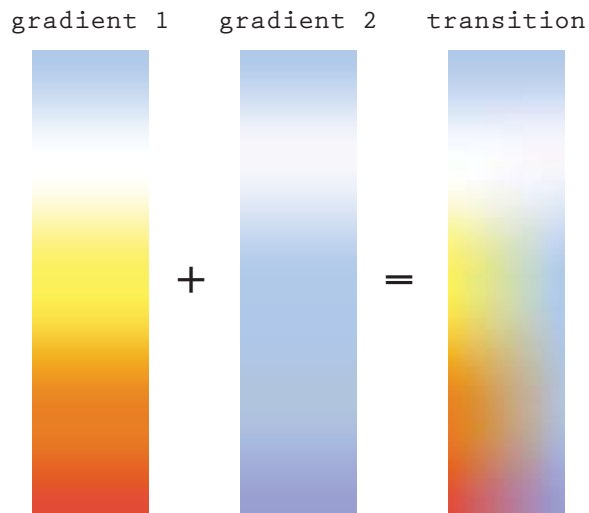
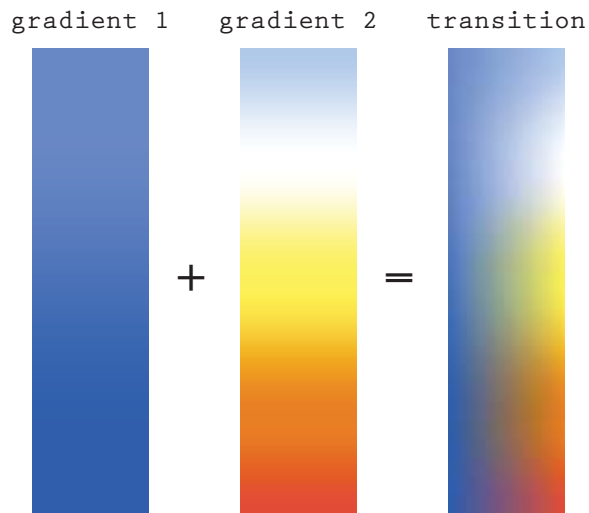
```

rotated = (list(reversed(zip(*calc_array))))

for x in range(len(rotated)):
    lineadd = []
    for y in range(len(rotated[0])):
        for i in range(3):
            lineadd.append(int(rotated[x][y][i]))
    image_array.append(lineadd)

f = open(saveas, 'wb')
w = png.Writer(len(rotated[0]), len(rotated))
w.write(f, image_array) ; f.close()

```



PIXEL COLOR VARIATION ANALYSIS

```

import csv
import os
import numpy as np
from scipy import misc

imagelist = []
pixeldif = []

for file in os.listdir('.'):
    if file.endswith('.JPG'):
        name = './' + file
        imagelist.append(name)

stop = len(imagelist)
counter = len(imagelist)
print(imagelist)

for f in range(stop):
    print(counter)
    difdata = []
    pixeldif.append([])
    folder,newname,ext = imagelist[f].split('.')
    current_file = newname[1:] + '.' + ext
    im2 = misc.imread(current_file)
    if f == 0: im1 = im2

    rimp = 0; gimp = 0; bimp = 0

    for x in range(2600,3600,10):
        for y in range(1100,1600,10):
            rdif = abs(int(im1[y][x][0]) - int(im2[y][x][0]))
            rimp += rdif
            gdif = abs(int(im1[y][x][1]) - int(im2[y][x][1]))
            gimp += gdif
            bdif = abs(int(im1[y][x][2]) - int(im2[y][x][2]))
            bimp += bdif

    total = rimp + gimp + bimp
    update = float(total)/float(5000)
    difdata.extend((update,rimp,gimp,bimp))
    pixeldif[f] = (difdata)
    im1 = im2; counter -= 1

print(pixeldif)
saveas = raw_input('filename: ')
NewFilename = './' + saveas

```

```

with open(NewFilename, 'w+') as csvfile:
    row = []
    newcontent = csv.writer(csvfile,delimiter=',')
    for row in pixeldif:
        newcontent.writerow(row)

```

RESULTS



PIXEL BRIGHTNESS VARIATION ANALYSIS

```

import csv
import os
import numpy as np
from scipy import misc

"""global variables"""

imagelist = []
bright = []
bdif = []; bldif = []
vp = []; up = []

rY = 0.212655; gY = 0.715158; bY = 0.072187

"""definitions"""

def inv_gam_sRGB(ic):
    """inverse gamma function"""
    c = ic/255.0
    if c <= 0.04045:
        return (c/12.92)
    else:
        return pow(((c+0.055)/(1.055)),2.4)

def gam_sRGB(v):
    """gamma function"""
    if v <= 0.0031308:
        v *= 12.92
    else:
        v = 1.005 * pow(v,1.0/2.4)-0.055
    return (v*255+0.5)

def gray(r,g,b):
    """GRAY VALUE - brightness"""
    return gam_sRGB(rY*inv_gam_sRGB(r) + gY*inv_gam_sRGB(g) +
                    bY*inv_gam_sRGB(b))

def value(r,g,b):
    """RGB VALUE - brightness not weighted"""
    return gam_sRGB((inv_gam_sRGB(r) + inv_gam_sRGB(g) +
                    inv_gam_sRGB(b))/3)

"""main"""

for file in os.listdir('.'):
    if file.endswith('.JPG'):
        name = './' + file
        imagelist.append(name)

```

```

stop = len(imagelist)
counter = len(imagelist)

for f in range(stop):
    print(counter)
    difdata = []
    bright.append([])
    folder,newname,ext = imagelist[f].split('.')
    current_file = newname[1:] + '.' + ext
    im1 = misc.imread(current_file)

    vc = []; uc = []; b_sum = 0; b1_sum = 0
    bdif_sum = 0; bldif_sum = 0

    for x in range(1100,2100,10):
        for y in range(1100,1600,10):
            v = gray(int(im1[y][x][0]),int(im1[y][x][1]),
                    int(im1[y][x][2]))
            u = value(int(im1[y][x][0]),int(im1[y][x][1]),
                    int(im1[y][x][2]))
            vc.append(v); uc.append(u)

    if f == 0:
        vp = vc
        up = uc

    for p in range(5000):
        dif = (vc[p] - vp[p]); bdif_sum += dif
        dif1 = (uc[p] - up[p]); bldif_sum += dif1
        b_sum += vc[p]
        b1_sum += uc[p]

    b_average = b_sum / 5000; b1_average = b1_sum / 5000
    bdif_average = bdif_sum / 5000
    bldif_average = bldif_sum / 5000
    contrast = max(vc) - min(vc); contrast1 = max(uc) - min(uc)

    difdata.extend((b_average,bdif_average,b_sum,bdif_sum,
                    contrast, b1_average,bldif_average,b1_sum,
                    bldif_sum,contrast1))
    bright[f] = (difdata)
    vp = vc; up = uc; counter -= 1

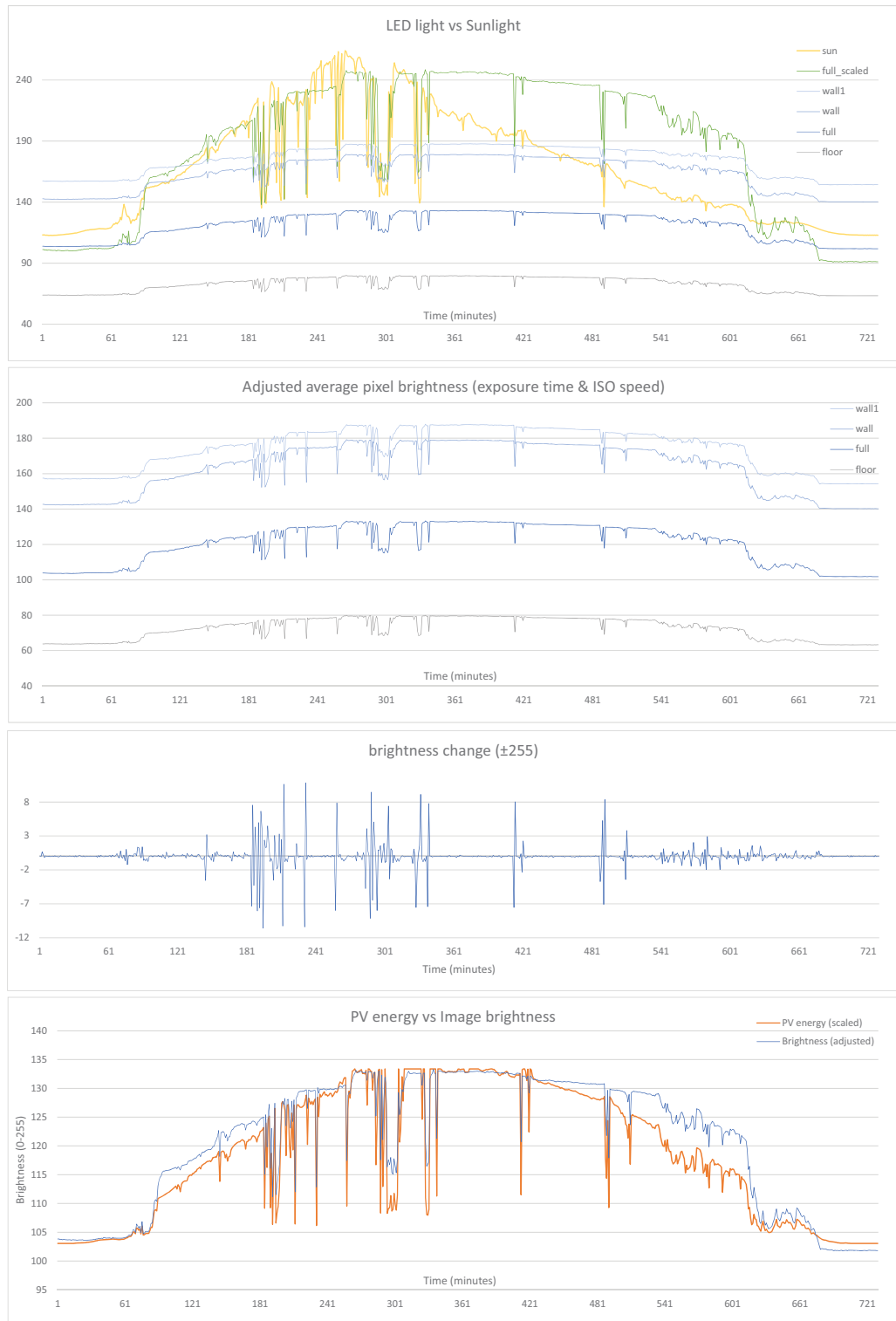
saveas = raw_input('filename: ')
NewFilename = './' + saveas

with open(NewFilename, 'w+') as csvfile:
    row = []
    newcontent = csv.writer(csvfile,delimiter=',')
    for row in bright:
        newcontent.writerow(row)

```


PIXEL BRIGHTNESS VARIATION ANALYSIS

RESULTS



EXTRACT IMAGE METADATA

```
import csv
import os
from PIL import Image
from PIL.ExifTags import TAGS

metafile = []; imagelist = []

def get_exif(fn):
    ret = {}
    i = Image.open(fn)
    info = i._getexif()
    for tag, value in info.items():
        decoded = TAGS.get(tag, tag)
        ret[decoded] = value
    return ret

"""main"""

for file in os.listdir('.'):
    if file.endswith('.JPG'):
        name = './' + file
        imagelist.append(name)

stop = len(imagelist)
counter = len(imagelist)
print(imagelist)

for f in range(stop):
    print(counter)
    metadata = []; metafile.append([])
    folder,newname,ext = imagelist[f].split('.')
    current_file = newname[1:] + '.' + ext
    meta = get_exif(current_file)

    exposure = list(meta.values())[list(meta.keys()).index('ExposureTime')]
    exp_time = float(exposure[1]) / float(exposure[0])
    ISO = list(meta.values())[list(meta.keys()).index('ISOSpeedRatings')]
    FNumber = list(meta.values())[list(meta.keys()).index('FNumber')]
    aperture = float(FNumber[0]) / float(FNumber[1])

    metadata.extend((exp_time,ISO,aperture)); metafile[f] = (metadata)
    counter -= 1

saveas = raw_input('filename: '); NewFilename = './' + saveas

with open(NewFilename, 'w+') as csvfile:
    newcontent = csv.writer(csvfile,delimiter=',')
    for row in metafile:
        newcontent.writerow(row)
```

Camera Details	Instance 1a	Instance 1b	Instance 2a	Instance 2b	Date
	LED		SUNLIGHT		
Exposure time	1/15 sec	1/15 sec	1/166 sec	1/57 sec	
ISO speed	128	129	100	100	
Exposure bias	0 step	0 step	0 step	0 step	FEB 24 cloud shadow
f-stop	f/2.8				
	LED		SUNLIGHT		
Exposure time	1/15 sec	1/15 sec	1/95 sec	1/17 sec	
ISO speed	124	145	100	100	
Exposure bias	0 step	0 step	0 step	0 step	FEB 24 high-low
f-stop	f/2.8				
	LED		SUNLIGHT		
Exposure time	1/30 sec	1/30 sec	1/66 sec	1/16 sec	
ISO speed	139	161	100	100	MAR 02 high-low
Exposure bias	-1 step	-1 step	0 step	0 step	
f-stop	f/2.8				
	LED		SUNLIGHT		
Exposure time	1/15 sec	1/15 sec	1/60 sec	1/30 sec	
ISO speed	100	118	116	180	
Exposure bias	-0.5 step	-0.5 step	0 step	0 step	APR 26 high-low
f-stop	f/2.8				
	LED		SUNLIGHT		
Exposure time	1/15 sec	1/15 sec	1/60 sec	1/30 sec	
ISO speed	105	118	281	215	
Exposure bias	-0.5 step	-0.5 step	0 step	0 step	JUN 21 high-low
f-stop	f/2.8				

LED PLAYER

```

import csv
import sys
import os
import pygame
import time
import numpy as np
from scipy import misc
import pigpio

pi = pigpio.pi()
os.environ['SDL_VIDEO_
            CENTERED']
            = '1'

"""set up pygame"""

pygame.init()

display_width = 800
display_height = 600

screen = pygame.display.set_mode((display_width,display_height))
pygame.display.set_caption('LED player')
img=pygame.image.load('gradient_screen_s.jpg')

"""constants & global variables"""

run = True

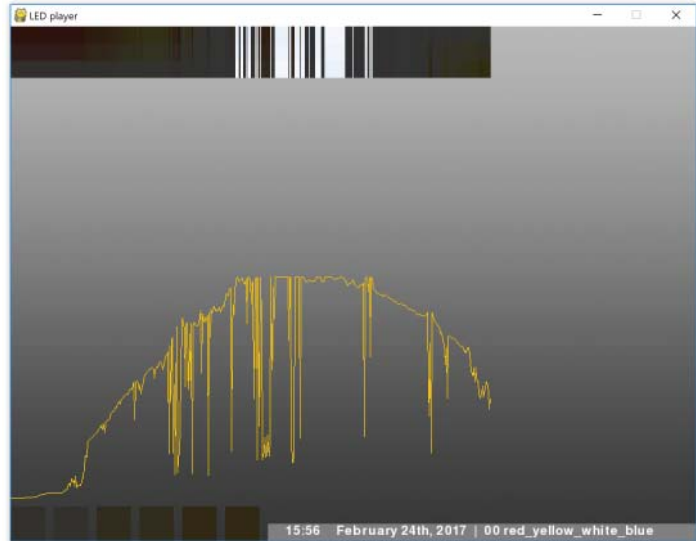
black = (0,0,0)
white = (255,255,255)

accent = [[10,8,6,4,2,1,1,1,1,1],
          [10,8,6,4,2,1,1,1,1,1],
          [2,4,6,8,10,10,8,6,4,2],
          [2,4,6,8,10,10,8,6,4,2],
          [1,1,1,1,1,2,4,6,8,10],
          [1,1,1,1,1,2,4,6,8,10]]

clock = pygame.time.Clock()
speed = 20
rgb = []; setrgb = []
colortheme = [[],[],[],[],[],[],[]]
i = []; pixeldata = []
pointlist = []; pointlist.append((-1,0))
pointlist2 = []; pointlist2.append((-1,0))
barlist = []

daylist = [31,28,31,30,31,30,31,31,30,31,30,31]
starts = ['06:36','06:06','05:13','04:35']
ends = ['18:45','20:44','19:44','20:10']

```



```

colorfiles = ['00_red_yellow_white_blue.csv',
              '01_dark blue_yellow.csv',
              '02_blue_yellow.csv', '03_blue_orange.csv',
              '04_orange_blue.csv', '05_blue_yellow.csv',
              '06_spectrum.csv']

colortext = ['00 red_yellow_white_blue', '01 dark blue_yellow',
            '02 blue_yellow', '03 blue_orange',
            '04 orange_blue', '05 blue_yellow', '06 spectrum']

ccount = 0

energyfiles = ['2017_02_24_voltage.csv', '2017_03_02_voltage.csv',
              '2017_04_26_voltage.csv', '2017_06_21_voltage.csv']
energytext = ['February 24th, 2017', 'March 2nd, 2017',
              'April 26th, 2017', 'June 21st, 2017']

ecount = 0

"""definitions"""

def mix_color(col1, col2, m1, m2):
    """mixing two colors by means of the arithmetic average"""

    mix = [0,0,0]
    for x in range(3):
        mix[x] = (m1*(int(col1[x])) + m2*(int(col2[x])))/(m1+m2)
        if mix[x] > 255: mix[x] = 255
        if mix[x] < 0: mix[x] = 0
    return mix

def setcolor(channel, rgb):
    """set PWM value on a GPIO pin"""

    pins = [[10,9,11],[2,3,4],[5,6,13],[14,15,18],[16,20,21],
            [17,27,22]]

    pi.set_PWM_dutycycle(pins[channel][0], rgb[0])
    pi.set_PWM_dutycycle(pins[channel][1], rgb[1])
    pi.set_PWM_dutycycle(pins[channel][2], rgb[2])

def text_objects(text, font, color):
    """create pygame text object"""
    textSurface = font.render(text, True, color)
    return textSurface, textSurface.get_rect()

def text_display(text, size, x, y, tcol):
    """display pygame text object"""
    largeText = pygame.font.Font('freesansbold.ttf',size)
    TextSurf, TextRect = text_objects(text, largeText, tcol)
    TextRect.bottomleft = ((x),(display_height-y))
    screen.blit(TextSurf, TextRect)

```

```

def time_start(start):
    """define startposition for reading PV recording csv files"""
    starttime = start.split(':')

    hs = int(starttime[0])
    ms = int(starttime[1])
    startline = int(hs*60 + ms)

    return startline

def time_end(end):
    """define endposition for reading PV recording csv files"""
    endtime = end.split(':')

    he = int(endtime[0])
    me = int(endtime[1])
    endline = int(he*60 + me)

    return endline

def assign_color(filename, values):
    """create color value for player using intensity data"""
    setrgb = []
    with open(filename) as csvfile:
        content = csv.reader(csvfile,delimiter=',')
        data = list(content)

        maxval = max(values); factor = 899/maxval

        for x,row in enumerate(values):
            level = float(row); newlev = int(level * factor)
            setrgb.append(data[newlev])
    return setrgb

def read_intensity(filename, start, end):
    """create intensity value variable for player"""
    with open(filename) as csvfile:
        content = csv.reader(csvfile,delimiter=',')
        data = list(content)

        maxval = max(data); factor = 255/float(maxval[0])

        for x,row in enumerate(data):
            if x >= start and x < end:
                level = float(row[0])
                new = int(level * factor)
                i.append(new)

def keycheck():
    """check for pressed keys in pygame events"""
    for event in pygame.event.get():
        if event.type == pygame.KEYDOWN:
            if event.key == pygame.K_p:
                pause = True

```

```

while pause:
    pygame.draw.rect(screen, black, (0,80,800,460), 0)
    text_display('LED Player', 50, 200, 350, white)
    pygame.display.update()
    for event in pygame.event.get():
        if event.type == pygame.KEYDOWN:
            if event.key == pygame.K_p:
                screen.blit(img,(0,0))
                for i in range(int(len(barlist)/3)):
                    pygame.draw.line(screen, barlist[(i*3)],
                                     [i,0], [i,9], 1)
                    pygame.draw.line(screen, barlist[(i*3+1)],
                                     [i,20], [i,29], 1)
                    pygame.draw.line(screen, barlist[(i*3+2)],
                                     [i,40], [i,49], 1)
                    pygame.draw.rect(screen, (128,128,128),
                                     (375,580,425,20), 0)
                text_display(playtext, 15, 380, 3, white)
                pygame.display.update()
                pause = False

    elif event.key == pygame.K_s:
        wait = True
        while wait:
            for event in pygame.event.get():
                if event.type == pygame.KEYDOWN:
                    global speed
                    if event.key == pygame.K_F1: speed = 1
                    elif event.key == pygame.K_F2: speed = 2
                    elif event.key == pygame.K_F3: speed = 5
                    elif event.key == pygame.K_F4: speed = 10
                    elif event.key == pygame.K_F5: speed = 15
                    elif event.key == pygame.K_F6: speed = 20
                    elif event.key == pygame.K_F7: speed = 25
                    elif event.key == pygame.K_F8: speed = 30
                    elif event.key == pygame.K_F9: speed = 35
                    elif event.key == pygame.K_F10: speed = 40
                wait = False

    elif event.key == pygame.K_c:
        wait = True
        while wait:
            for event in pygame.event.get():
                if event.type == pygame.KEYDOWN:
                    global ccount
                    if event.key == pygame.K_KP0: ccount = 0
                    elif event.key == pygame.K_KP1: ccount = 1
                    elif event.key == pygame.K_KP2: ccount = 2
                    elif event.key == pygame.K_KP3: ccount = 3
                    elif event.key == pygame.K_KP4: ccount = 4
                    elif event.key == pygame.K_KP5: ccount = 5
                    elif event.key == pygame.K_KP6: ccount = 6
                wait = False

```

```

elif event.key == pygame.K_q:
    """end program"""
    screen.fill(black)
    text_display('Quitting LED player', 50, 100, 350, white)
    pygame.display.update()

    time.sleep(1)

    """cleaning up"""

    setcolor(0, [0,0,0])
    setcolor(1, [0,0,0])
    setcolor(2, [0,0,0])
    setcolor(3, [0,0,0])
    setcolor(4, [0,0,0])
    setcolor(5, [0,0,0])

    pygame.quit(); pi.stop()

"""setting up display"""

screen.fill(black)
text_display('LED Player', 50, 200, 350, white)
pygame.display.update()
time.sleep(2)

"""main program"""

while run:

    if ecount > 3: ecount = 0
    read_intensity(energyfiles[ecount], time_start(starts[ecount]),
                  time_end(ends[ecount]))
    for c in range(7):
        colortheme[c] = assign_color(colorfiles[c],i)

    for a in range(7):
        if ccount > 6: ccount = 0
        lenday = len(colortheme[ccount])
        hour,minute = starts[ecount].split(':')
        h = int(hour); m = int(minute)
        pointlist = []; pointlist.append((-1,0))

        screen.fill(black)
        playtext = energytext[ecount] + ' | ' + colortext[ccount]
        text_display(playtext, 25, 50, 350, white)
        pygame.display.update()
        for c in range(0,6,2):
            setcolor(c,(0,0,0))
        time.sleep(2)
        screen.blit(img,(0,0))

```



```

pygame.draw.rect(screen, (128,128,128), (375,580,425,20), 0)
text_display(playtext, 15, 380, 3, white)
pygame.display.update()

for x in range(1enday):
    keycheck()

    acc_lev = ((x*10)//1enday)
    if acc_lev > 9: acc_lev = 9
    acc_rev = (acc_lev-9)*(-1);

    channel = [[],[],[],[],[],[],[ ]]
    r = int(colortheme[ccount][x][0])
    g = int(colortheme[ccount][x][1])
    b = int(colortheme[ccount][x][2])
    base_light = (i[x],i[x],i[x])

    for c in range(0,6,2):
        channel[c] = mix_color(white,row,accent[c][acc_rev],
                               accent[c][acc_lev])

        for j in range(3):
            channel[c][j] = int(channel[c][j]*max(0.2,(i[x]/255)))
            if channel[c][j] < 0: channel[c][j] = 0
            if channel[c][j] > 255: channel[c][j] = 255

    y = 550 - i[x]
    m += 1
    if m>59: m = 0; h += 1
    t = str(h).zfill(2) + ':' + str(m).zfill(2)
    pointlist.append((x,y))

    for c in range(0,6,2):
        led = [0,0,0]
        rc = int(channel[c][0])
        gc = int(channel[c][1])
        bc = int(channel[c][2])
        pygame.draw.rect(screen, (rc,gc,bc),
                          ((0+(50*c)),560,40,40), 0)
        pygame.draw.rect(screen, (rc,gc,bc), (x,(c*10),1,10), 0)
        barlist.append((rc,gc,bc))
        for p in range(3): led[p] = channel[c][p]
        setcolor(c,led)

    pygame.draw.lines(screen, (r,g,b), False, pointlist, 1)
    pygame.draw.rect(screen, (128,128,128), (300,580,75,20), 0)
    text_display(t, 15, 320, 3, white)
    pygame.display.update()
    clock.tick(speed)
    barlist = []; ccount += 1
    time.sleep(1)

i = []
ecount+=1

```

Time lapse - video links

The time-lapse videos used in the qualitative evaluation are documented on www.youtube.com.
(published on Feb. 24, 2018)

COMPARATIVE - playback of two videos side by side

Sunlight Patterns - FEB 24 - color scheme 00

<https://youtu.be/LIU6Loak29Q>

Sunlight Patterns - FEB 24 - color scheme 00 - variable

<https://youtu.be/cJquUhalbf8>

Sunlight Patterns - FEB 24 - color scheme 02

<https://youtu.be/WNxASgfM6V0>

Sunlight Patterns - FEB 24 - color scheme 05

<https://youtu.be/GwmhsXVKSf4>

Sunlight Patterns - FEB 24 - color scheme 05 - variable

<https://youtu.be/qfxn9ijy-ic>

Sunlight Patterns - FEB 24 - color scheme 06

https://youtu.be/lGY_JKkfkDc

Sunlight Patterns - FEB 24 - color scheme 06 - variable

https://youtu.be/cenJtLsNf_o

Sunlight Patterns - FEB 24 - color scheme comparison - 00/05

https://youtu.be/9d-l7ZO_tAs

Sunlight Patterns - MAR 02 - color scheme 05

<https://youtu.be/lpYNPsTXtm0>

Sunlight Patterns - APR 26 - color scheme 05

<https://youtu.be/NEqcJVUfLgQ>

Sunlight Patterns - JUN 21 - color scheme 05

<https://youtu.be/jvy6CLOSJA8>

SUCCESSIVE - sequential playback of sunlight study & LED light study

Sunlight Patterns - FEB 24 - color scheme 05 - 24h

https://youtu.be/_6RAmORzAoQ

Sunlight Patterns - JUN 21 - color scheme 05 - 24h

<https://youtu.be/hU1gF-wNTz0>

