

IMPACT OF BIOMIMETIC WINDOW SYSTEM  
ON BUILDING ENERGY CONSUMPTION AND OCCUPANTS' PERCEPTION  
IN THE EDUCATIONAL ENVIRONMENT

By

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# **ABSTRACT**

## **IMPACT OF BIOMIMETIC WINDOW SYSTEM ON BUILDING ENERGY CONSUMPTION AND OCCUPANTS' PERCEPTION IN THE EDUCATIONAL ENVIRONMENT**

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Although people are spending more time indoors, their perception of the indoor environment is not improved; meanwhile, building energy consumption continues to rise. About 40 percent of all U.S. energy was consumed by residential and commercial sectors whereas educational buildings consumed 11 percent and 13 percent of total electricity and natural gas consumption, respectively. These days, extensive studies have sought to reduce building energy consumption through various mechanical methods. However, these methods focus exclusively on building energy. Therefore, other methods need to be proposed to enhance the perception of the building occupants.

The purpose of this study was to examine the enhancement of energy consumption and occupants' perception by using strategies that adopt the characteristics of nature, called biomimetic design. In this study, the biomimetic solutions were designed to bring daylight into an interior space in educational buildings, where daylight generally cannot reach. Specifically, this study investigated how the daylight achieved through biomimetic windows affected building energy consumption and students' perceptions in educational spaces. Therefore, this study looked for biomimetic approaches that could bring more daylight into the interior space and determined that such approaches changed the energy consumption and perception of occupants in the educational building.

This study investigated the positive effects of daylight on people and found a strategy from biomimicry methods. This study proposed a new biomimetic window system based on the fur of polar bears, which reflects daylight. This research had two research phases. Through computer simulations, this study examined how the new biomimetic window system saved building energy consumption. This study created a 3D model which is the currently existing MSU main library and compared its energy consumption and actual energy consumption. Using the created 3D model, this study conducted simulations only for the basement floor, which does not have windows. When the simulations were conducted with the basement floor, about 13 percent of energy was saved from the installation of a biomimetic window system.

The second phase of the study was to collect occupants' perceptions in virtual reality spaces with biomimetic windows using an experimental research approach. Three major findings need to be highlighted. First, students were more satisfied with an area where daylight entered through the biomimetic window system than the one without a window. Second, when the biomimetic window system was installed, students preferred an enclosed space over an open space. Third, their seating preference depending on the average study time of students did not vary much whether there is the biomimetic window system. However, there was weak relationship between students' average study time and their perception with spaces.

Using a biomimetic solution to utilize daylight, this study found practical ways to reduce building energy consumptions for indoor lighting by using actual daylight. Using this nature-inspired new method, this study proposed a way to reduce energy consumption in educational buildings while simultaneously improving occupants' perception and satisfaction. The results of this study will be a milestone for developing a biomimetic window system and helping energy saving in the educational building environment while improving occupants' perceptions therein.

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# **CHAPTER 1**

## **INTRODUCTION**

### **1.1. Research Background**

The National Human Activity Pattern Survey (NHAPS) reported that most of people spend about 93 percent of their lives indoors (Klepeis et al., 2001). However, it is difficult to improve occupants' perception due to the dissatisfaction with the limited daylight available in indoor spaces, where they spend so much time (Abbaszadeh, Zagreus, Lehrer, & Huizenga, 2006). As time spent indoors increases, building energy consumption continues to increase (Pile, 1988). About 40 percent of all energy in the U.S. was consumed by residential and commercial sectors (Conti et al., 2016). The commercial sector's total electricity consumption was 1,242 billion kWh, and its total natural gas consumption was 2,193 billion cubic feet (US Energy Information Administration, 2012). Meanwhile, educational facilities used 134 billion kWh and 284 billion cubic feet, respectively, which was equivalent to 10.79 percent of the total electricity usage and 12.95 percent of the total natural gas usage in the commercial sector (US Energy Information Administration, 2012). This amount of energy consumption costed educational facilities about 6 billion dollars annually, which was more than what was being spent on textbooks and computers combined (EnergyStar, 2018). In an earlier study, Pile (1988), one of the most renowned interior design educators addressed that the interior space is closely related to the occupants' perception and energy consumption of buildings, and its redevelopment can improve occupants' perception and reduce energy consumption.

Two major systems, passive and active, as reported by Malik, Tiwari, Kumar, and Sodha (1982) can be used to enhance occupants' perception of indoor environment and reduce energy consumption. Active systems include improvement of HVAC systems, electrical lighting, and

other building applications while passive systems aim to capture energy from renewable sources, such as sunlight, as it comes into buildings (Sadineni, Madala, & Boehm, 2011; Sun, Gou, & Lau, 2018).

Biomimetic solutions in buildings has emerged as the key solution to reducing energy consumption and improving occupants' perception of indoor environment (Singh & Nayyar, 2015). To maximize energy efficiency in man-made settings, it is important to understand the principles of nature in terms of energy preservation. Terms such as "biomimetics" and "biomimicry" refer to the approaches aimed specifically at using the knowledge gathered from living systems to improve human-created technology. Otto H. Schmitt coined the term "biomimetics" in 1969 as a derivative of the Greek words "bios" and "mimesis," (Schmitt, 1969) and the term "biomimicry" is defined as imitating or taking inspiration from nature's strategies to solve the problems (Benyus, 1997). Biomimetics concentrated on producing a device that explicitly mimicked nature's strategies, and biomimicry was expanded as part of the field of natural sciences. As an example, El-Zeiny (2012), who is currently the most active professional specialized in research on biomimicry and interior spaces, indicated that the ability to effectively bring daylight into an interior space reduces the need for artificial lighting. In this example, biomimetics can be a tool for developing the device providing daylight into an interior space, while biomimicry refers to the overall production process.

However, due to limitations, more systematic methods are needed to reduce building energy consumption and to improve occupants' perception of indoor environment. If the energy consumption in buildings can be reduced using biomimetic solutions, this would play a huge role in protecting the environment in the long term.

## 1.2. Problem Statement

Many studies have already offered solutions for saving building energy use (Abdullah, Cross, & Aksamija, 2014; Hviid, Nielsen, & Svendsen, 2008; Sadineni et al., 2011; Stoppel & Leite, 2013); however, a more comprehensive study on the conservation of building energy in building environment is still needed. Therefore, this study paid attention to two major issues that should be resolved as follows:

***Problem #1:*** *Energy saving solutions using biomimetic methods applied to the interior spaces are lacking.*

According to Sadineni et al. (2011), the current method of using passive systems including insulated walls, windows, roof, materials of buildings, and using of other renewable energy could save about 20 percent of energy. However, additional studies are needed to further increase energy savings in a built environment. While the various previously developed passive systems help reduce energy, this study expected that the integrated passive and active system inspired by nature will have much greater effects on reducing building energy and consequently, on enriching the environment.

***Problem #2:*** *No effective solutions have been applied to enhance occupants' perception of indoor environment through biomimetic methods.*

Occupants' perception of indoor environment is associated with indoor environmental quality and building features, including size, esthetic appearance, furniture, and cleanliness. The importance of different indoor environmental factors, such as thermal, visual, and acoustic, in occupants' perception, varied slightly across the studies, but no study has investigated correlations between factors using biomimetic methods and occupants' perception of indoor environment.

### 1.2.1. Biomimicry as a Design Approach

Biomimicry, as a design approach, is generally divided into two main categories direct and indirect. The direct approach mimics the strategy of organisms and behavioral patterns in nature directly, and the indirect approach uses abstract ideas and concepts from nature (Panchuk, 2006). A direct approach requires an understanding of design issues, which can be done in two ways. First, problem-based understanding requires finding a problem and setting up a design method, followed by getting ideas from nature. Second, solution-based understanding requires bringing an idea from nature to design buildings and solve problems (Helms, Vattam, & Goel, 2009; J. O. Wilson, 2008; Zari & Storey, 2007). The problem-based understanding needs to seek solutions via nature first, but a solution-based understanding first needs to study nature and match it to solve

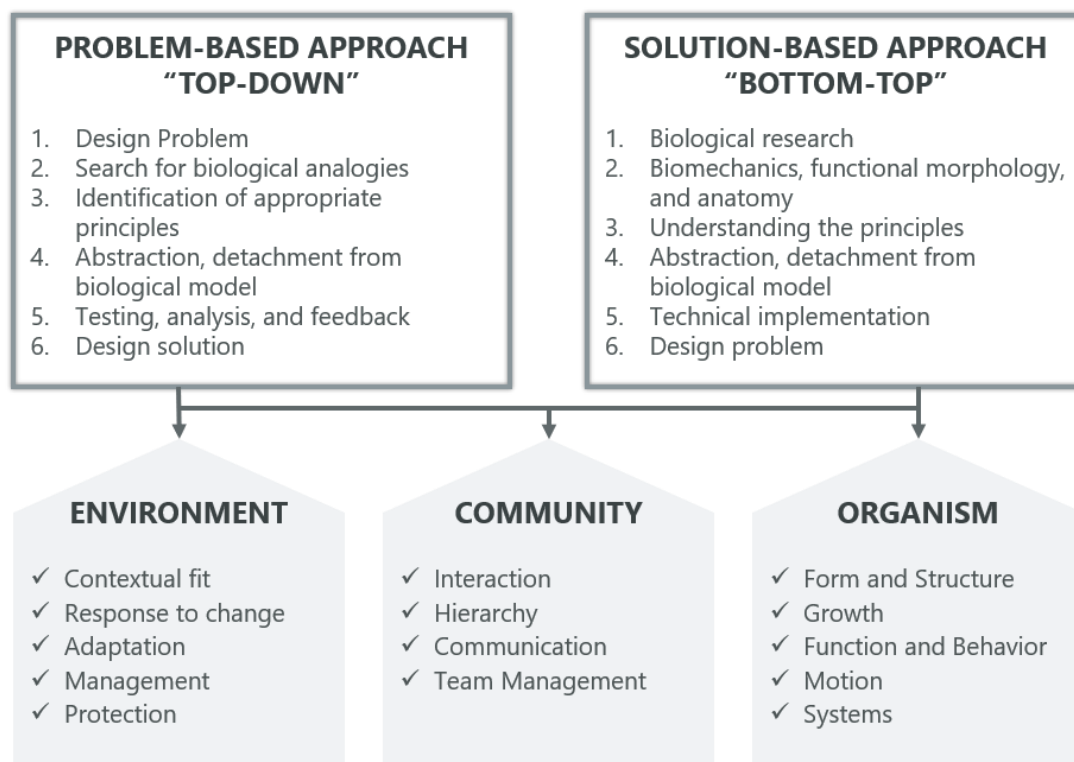


Figure 1-1. A framework for understanding biomimicry

*Diagram credited to Juntae Son*

design problems. Both types of understanding can have advantages and disadvantages (J. O. Wilson, 2008).

This study proposed a daylight strategy based on nature to solve significant energy consumption in educational building sectors using the biomimetic method and employed a problem-based approach that requires finding solutions from nature. Biomimetic solutions can be inspired by a variety of fauna and flora for this study (Radwan & Osama, 2016). Human can mimic the strategy of heat conservation and light transmission from the lifestyle of animals in arctic regions such as polar bears, penguins, and sea otters. Therefore, polar bear hairs (fur) had been considered mainly because of their significant structural mechanism that makes them highly reflective; thus, they can be used to help bring daylight into the building spaces (Bohren & Sardie, 1981; Grojean, Sousa, & Henry, 1980; Grow, 1987; Q.-L. Wang, He, & Li, 2012). This biomimetic method has been provided as solutions for sustainability, shorten the designing process, and the strategy of life.

### **1.2.2. Influence on Building Design Process**

When designing a building using a biomimetic approach, thinking about what factors should be taken into account makes one wonder about innovative strategies that can be derived from nature and applied to architectural design. The ability to adapt to external factors is one of the most fundamental phenomena of biology, which also explains how living things to better adapt to their habitats. We can also look at the psychological adaptation of animals, such as indigenous plants or animals, to their habitats, topography and climatic conditions, such as wind, solar path, temperature, humidity and rainfall. Plant species may have similar physical characteristics, but their shape, size, color, and texture may be adapted to the climates and other environmental

conditions; otherwise, they would die (Kay, 2003). When we design buildings, we need to learn to adapt their features, including their shape, size, color, and pattern, all of which are affected by the characteristics of climate. The link between species in the habitat will help keep the ecosystem balanced. For this reason, when mimicking strategies from nature in the field of architecture, architectural designs must be considered according to these adaptive strategies along with solar paths, light, and climate conditions.

Nature offers humans the potential to find new ideas, but the process of generating ideas in this field of architecture may have technical limitations. Alternatively, it may have to be thought of as a concept where different methods should be synthesized from a technical standpoint. Therefore, architects, architectural engineers and designers often use biomimicry's findings as a design approach. They are actively using biological insights as design methods or design tools (Pohl & Nachtigall, 2015). Developing a biomimetic design will have a slow influence on the design process because more biomimetic ideas must be generated compared to traditional design processes. However, after the development of biomimetic design, this design element will help in the current design process, boosting the speed.

Today's architects not only develop technical elements but also apply ecological elements to design, as mentioned earlier. This would involve the development of a design approach that would use fewer resources without harming nature. Despite attempts to address these challenges, some critics argue that most green buildings are the result of performance initiatives in environmental policies, benchmarks and rating systems (Yeang & Woo, 2010). This showed that our society still lacks an understanding of the importance of synthesis between technology and ecological elements (Van der Ryn & Cowan, 2013). In addition, it is often possible to limit the application of new elements that are applied in a familiar working environment. Thus, in the future, an ecological

design approach that explores relationships with the environment will require further development. It took a long time to understand the integration between the physical properties and efficiency of a building; therefore, learning to imitate the ecosystem is also expected to take a long time. In the book title, *Entering an Ecological Age; The Engineer's Role*, Head (2009) insisted that in the future, humankind should find a way to live in more harmony with nature. To do so, we need alternatives to deal with carbon dioxide reduction and the scale on which humans are involved in nature.

### **1.3. Research Purpose and Objectives**

The purpose of this study was to examine the energy consumption and occupants' perception of indoor environment, using strategies that adopt the characteristics of nature called biomimetic solutions designed to bring daylight into an interior space in educational buildings where daylight cannot be reached. Specifically, this study investigated how the daylight achieved via biomimetic windows would affect students' perception of educational spaces. Since the only way to get the sunlight is through windows on the exterior walls in most buildings, occupants heavily depend on artificial lighting. When the probability of solar heat entering the room is low, the buildings consume a large amount of energy using HVAC systems to fit the thermal comfort of the occupants. This research proposed an interior lighting solution using biomimetic approach and investigates the biomimetic windows where sunlight can enter from the interior walls inspired by features of polar bears' hair.

This study aimed to answer three major research questions;

***Research Question #1:*** *What is the appropriate biomimetic approach to improve the daylight effect to interior spaces?*

**Research Question #2:** *If biomimetic windows added to on interior spaces that could receive daylight like windows on exterior walls in educational buildings, how will it affect the building energy consumption?*

**Research Question #3:** *Will biomimetic windows added to spaces influence occupants' perception of educational spaces?*

The research proposed the following hypotheses.

**Research Hypothesis #1:** *Biomimetic windows can reduce energy consumption.*

**Research Hypothesis #2:** *Biomimetic windows can affect the perception of students in learning environments.*

**Research Hypothesis #2-1:** *There are significant differences in seating preferences among three space conditions.*

**Research Hypothesis #2-2:** *There are significant differences in seating preferences between open space and enclosed space when the biomimetic window system is installed.*

**Research Hypothesis #2-3:** *The more time students spend studying, the more positive perception they will have in the space with the biomimetic window system.*

Based on the research questions and hypotheses, the objectives of this research were to provide empirical evidences as follows.

**Objective #1:** *Provide quantitative evidences to reduce energy consumption in educational buildings.*

**Objective #2:** *Provide empirical evidence to improve students' perceptions and satisfaction in educational spaces.*

At the end of this study, the results of this study provided multiple empirical evidences to reduce energy consumption in educational buildings and to improve the quality of learning environments for students. In this study, the main library at the campus of Michigan State University in East Lansing, Michigan, was used as the subject of the experiment. Since the main library can be accessed by students for 24-hours a day during the semester, the difference in energy consumption was expected if the biomimetic window system would be applied. This study more focused on the potential of the biomimetic window system, but future studies will consider the lifecycle cost of the biomimetic window system. It was predicted that the practical use would be only possible when the system fabrication, installation, and operation costs would be compared with the reduced energy costs.

#### **1.4. Significance of the Study**

By proposing a new biomimetic window system inspiring the fur of polar bears, this study is significant to the field of biomimicry and sustainable design. The biomimetic window system could affect occupants' seating preference, and could save the building energy consumption in learning environment. The transmission of lighting and thermal energy using a polar bear's hair was studied to understand its structure (Bahners, Schlosser, Gutmann, & Schollmeyer, 2008; Grow, 1987; He, Wang, & Sun, 2011; Jia et al., 2017; Khattab & Tributsch, 2015; Tributsch, Goslowsky, Küppers, & Wetzal, 1990; Q.-L. Wang et al., 2012), but the previous study has not been examined for the built environment.

The proposed biomimetic window system in this study would have positive effects on our environment. The proposed approach would be environmentally friendly, and it could offer long-term solutions to the lack of daylight in buildings. In 2017, about 40 percent of total U.S. energy

was consumed by the residential and commercial sectors (Conti et al., 2016). Besides, the average cost of energy use for the 2005-2006 school year was \$1.15/ft<sup>2</sup>, and 63 percent of which was electricity consumption in the United States (Kats, 2006). The methods presented in this study are expected to have positive effects on reducing energy consumption in buildings. To maximize energy efficiency in natural settings, it is important to understand principles of nature in terms of energy preservation and secure inhabitants' comfort. This is particularly relevant in the development of technology aimed at replacing the use of fossil fuels and addressing the effects of climate change on the built environment.

### **1.5. Definitions of Terms**

- *Building energy*: Energy used in buildings is diverse, but the energy used in this study refers to the energy used in heating and cooling.
- *Simulation programs*: The simulation programs used in this study mostly refer to the programs for day lighting and building energy prediction. When this term is mentioned, it refers to with a brief description.
- *Biomimetic window*: refers to the new type of window that this study would suggest. Because these types of windows do not exist at this time, this study refers to the word biomimetic window, meaning the windows in the form of windows that embody the way of nature. This study has detailed explanation about biomimetic window system in Chapter 3.3. Proposed Novel Biomimetic Window System.
- *Learning Environment*: refers to various spaces where users learn and participate to learning skills. While learners learn a variety of skills, this term can be applied to a variety

of spaces including traditional classrooms. Therefore, the term is not limited to the space where blackboards, desks, and chairs are placed.

## CHAPTER 2

### LITERATURE REVIEW

#### 2.1. Theoretical Background

Biomimicry can be explained based on the Gaia theory (Lovelock, 1983), which proposes that living organisms interact with their inorganic surroundings on Earth to form a complex synergistic and self-regulating system that helps maintain and perpetuate the conditions for life on the planet (Benyus, 1997; El-Zeiny, 2012; Gamage & Hyde, 2012; Panchuk, 2006; Radwan & Osama, 2016). The hypothesis was formulated by Lovelock (1983), a chemist, and co-developed by Lynn Margulis, a microbiologist in 1974. Lovelock named the idea after Gaia, the primordial goddess who personified the Earth in Greek mythology. The benefits of contact with nature often depend on repeated experience. People may possess an inherent inclination to affiliate with nature, but like much of what makes us human, this biological tendency needs to be nurtured and developed to become functional (Kellert, 2012; Wilson, 1986). Designs inspired by nature have a wide range of applications for both interior and exterior environments. Ryan, Browning, Clancy, Andrews, and Kallianpurkar (2014) said that these design patterns have the potential to reposition the environmental quality conversation to give the individual's needs equal consideration alongside conventional parameters for building performance and occupants' perception. Gray and Birrell (2014) also found that a strong positive effect from incorporating aspects of designs inspired by nature boosted productivity, ameliorates stress, enhanced well-being, fostered a collaborative work environment, and promoted occupants' perception, thereby contributing to a high-performance interior space.

The *theory of solar energy conversion* was first discovered by a French scientist named Edmond Becquerel. He discovered the photovoltaic effect in the summer of 1839 (Yadav, Kumar,

& RPSGOI, 2015). He theorized that certain elements on the periodic table, such as silicon, reacted to exposure to sunlight in very unusual ways. Solar power is created when solar radiation is converted to heat or electricity. Between 1873 and 1876, English electrical engineer Willoughby Smith discovered that, when selenium is exposed to light, it produced a high amount of electricity. The use of selenium was highly inefficient, but it proved Becquerel's theory that light could be converted into electricity through the use of various semi-metals on the periodic table, which were later labeled as photo-conductive materials. Chapin, Fuller, and Pearson (1957) discovered that using silicon to produce solar cells was extremely efficient and produced a net charge that far exceeded that of selenium. Today solar power has many uses, from heating to electrical production, thermal processes, water treatment, and the storage of power, that are highly prevalent in the world of renewable energy.

The theory of solar energy conversion based on the polar bear hair model was proposed several decades ago (Øritsland & Ronald, 1978). Solar energy conversion describes technologies devoted to the transformation of solar energy to other forms of energy, including electricity, fuel, and heat (Crabtree & Lewis, 2007). It covers light-harvesting technologies, including traditional semiconductor photovoltaic devices (PVs), emerging photovoltaics (Graetzel, Janssen, Mitzi, & Sargent, 2012; Hagfeldt & Graetzel, 1995; Ramamurthy & Schanze, 2003), solar fuel generation via electrolysis, artificial photosynthesis, and related forms of photo-catalysis directed at the generation of energy-rich molecules (Magnuson et al., 2009).

*The theory of environmentally significant behavior* can be reasonably defined by its impact—namely, the extent to which it changes the availability of materials or energy from the environment or alters the structure and dynamics of ecosystems or the biosphere itself (Gatersleben, Steg, & Vlek, 2002; Stern, 1997, 2000). Some behaviors, such as clearing forests or disposing of

household waste, directly or proximally cause an environmental change (Stern, Young, & Druckman, 1992). Other behaviors are environmentally significant indirectly and broadly by shaping the context in which choices are made that directly cause environmental change. For example, behaviors that affect international development policies, commodity prices on world markets, and national environmental and tax policies can have a greater environmental impact indirectly than behaviors that directly change the environment.

## **2.2. Previous Studies Regarding Biomimetic Design for Buildings**

There have been many researchers who have defined biomimicry. Janine Benyus, a biologist and a leader of the emerging discipline of biomimicry provides one foundation for biomimicry and she defined biomimicry as “a new discipline that studies nature’s best ideas and then imitates the designs and process to solve human problems” (Benyus, 1997). Zari and Storey (2007) noted various representative examples that clearly present this strategy. Table 2-1 shows the main criteria for the energy efficient building design based on his case studies. It shows the possible animals and plants when human focus on a specific mechanism. Based on the case studies, Table 2-1 includes the main criteria needed in order for the building design to be energy efficient and is showing the possible animals and plants when human focus on a specific mechanism. Since the research would be focusing on the insulation of the building in cold climate region, polar bears, penguins, and sea otters can be the possible inspiration for this research.

The Council House 2 in Melbourne was built in 2006 and designed by City of Melbourne with association of Mick Pearce in a design company (Webb, 2005). This building was inspired by a trees bark. The Council House 2 is based on linking the building façade to its external environment and living organisms.

Table 2-1. Design Matrix

| Mechanism           |                                         | Thermal regulation behaviors | Water efficiency and sustainable properties | Insulation and conserving heat        | Dynamic behavior and response to the environment | Communication and attraction of colors        | Water collection and skin protection   |
|---------------------|-----------------------------------------|------------------------------|---------------------------------------------|---------------------------------------|--------------------------------------------------|-----------------------------------------------|----------------------------------------|
| Site context        | Tropical                                |                              | X                                           | X                                     |                                                  | X                                             |                                        |
|                     | Polar                                   |                              |                                             | X                                     |                                                  | X                                             |                                        |
|                     | Arid/desert                             | X                            | X                                           | X                                     | X                                                | X                                             | X                                      |
| Communication       | Color change                            |                              |                                             |                                       | X                                                |                                               |                                        |
|                     | Communication with external environment | X                            | X                                           |                                       | X                                                | X                                             |                                        |
|                     | Colors for attraction                   |                              |                                             |                                       | X                                                |                                               |                                        |
|                     | Creating enthusiasm for the user        |                              |                                             |                                       | X                                                |                                               |                                        |
|                     | Attracting users                        | X                            | X                                           |                                       | X                                                |                                               |                                        |
|                     | Heat conservation                       | Heat storage                 |                                             | X                                     | X                                                |                                               |                                        |
| Light harvesting    |                                         | X                            | X                                           |                                       |                                                  |                                               |                                        |
| Heating of interior |                                         |                              | X                                           |                                       |                                                  |                                               |                                        |
| Insulation          |                                         |                              | X                                           |                                       |                                                  |                                               |                                        |
| Water efficiency    | Water use reduction                     |                              | X                                           |                                       |                                                  |                                               | X                                      |
|                     | Recycling of water                      |                              | X                                           |                                       |                                                  |                                               | X                                      |
|                     | Water collection                        |                              | X                                           |                                       |                                                  |                                               | X                                      |
|                     | Air filtration                          |                              | X                                           |                                       |                                                  |                                               |                                        |
|                     | Self-cleaning façade                    |                              | X                                           |                                       |                                                  |                                               |                                        |
| Thermal regulation  | Regulation of internal temperature      |                              | X                                           | X                                     |                                                  |                                               |                                        |
|                     | Creation of sun shields varying in size | X                            |                                             |                                       |                                                  |                                               |                                        |
|                     | Follow sun path diagram                 | X                            |                                             |                                       | X                                                | X                                             |                                        |
|                     | Responsive façade                       | X                            |                                             |                                       | X                                                | X                                             |                                        |
|                     | Skin protection                         | X                            | X                                           | X                                     |                                                  |                                               | X                                      |
|                     | Responsive to external environment      | X                            | X                                           | X                                     | X                                                | X                                             | X                                      |
|                     | Possible inspiration                    | Reptiles (Lizards, Snakes)   | Plants and Flowers                          | Polar bears, Penguins, and Sea otters | Violet tailed hummingbird, Chameleon             | Geometric patterns (Water foams, Cells, etc.) | Namibian desert beetle or thorny devil |

Note. Radwan & Tributsch, 2015.

Therefore, the usage of biomimicry appeared throughout the entire building. For example, while the other sides of the facades were inspired by the bronchi of the tree, one of the façades is the epidermis of the tree (Webb, 2005). These designs were implemented as wind pipes and allowed for air ducts on the exterior of the building as shown in the Figure 2-1 and Figure 2-2. Since most of the toilets installed on the one of the façades, east side, the wet area spaces are well ventilated. As a result, the air is 100% filtered in this building and 65% energy is saved due to the natural lighting and ventilation (Radwan & Osama, 2016).

The Water Cube, also known as the Beijing National Aquatic Center, was built in 2007 for the 2008 Olympics. This 4-story high building was designed by an architect, Tristan Carfrae. In this building, the biomimetic solution was exemplified by mimicking the form of bubbles (Arkinstall, Carfrae, & Fu, 2011). The soap films in the bubbles have the ability to reduce the surface area and surface energy. Since the surface tension of the partitions reduces surface area of the bubbles (Figure 2-3), the construction was able to reduce budget and saved materials to build the building (Arkinstall et al., 2011). Therefore, the approach was to visualize the array of bubbles in a certain orientation. The building skin offers the transparency, so it engages the people both inside and outside experience water throughout. The Water Cube achieved many environmental outcomes: about 30% of energy consumption reduces by capturing solar energy and saved 55% of energy used in artificial lighting (Radwan & Osama, 2016).

The Esplanade Theatre (Figure 2-5) in Singapore was designed to solve problems that people who live in Singapore. Since Singapore has a feature of tropical climate, they use much energy for air conditioning. To make sun shades, the skin of this building consists of spikes based on Durian (Figure 2-6), a fruit grown in tropical regions (Arnold, 2002). The spikes allow natural light to enter the building but prevent inside of the building from heat by providing shades. The

triangular spikes are made from insulating glass with aluminum fixtures concerning the intermediate points. This biomimetic solution reduces the use of HVAC by 30% and the use of artificial lighting by 55% (Radwan & Osama, 2016).

The final example is the Eastgate Center in Harare, Zimbabwe (Figure 2-8). According to Fehrenbacher (2012), this large office building was inspired by termite mounds to solve a ventilation problem. This scheme takes advantage of the buoyant stream of hot air inside of the building. Cool air is blown from the atrium into this Biomimetic system and transported to the individual rooms through slits. Based on the systems of the termite, heated air masses are passively siphoned out through the altogether 48 chimneys by the effect of solar heated and rising chimney air alone (Fehrenbacher, 2012). The heat is stored in concrete and remains for the night and early morning. To run this Biomimetic system, the center of this building opens and draws air to help fans and is pushed up through ducts (Zari & Storey, 2007). By using this biomimetic solution, the temperature is regulated throughout the year with no need of mechanical Heating, Ventilation, and Air Conditioning systems (Radwan & Osama, 2016).

As the examples described in this chapter, various building types have already been used biomimicry methods to reduce their energy consumption, but it is still hard to find examples of biomimicry methods on educational buildings. Of course, there are many cases that have been applied with green design or sustainable design, but there is no example of biomimicry methods in educational buildings that this study intended to address.



Figure 2-1. The façade of the Council House 2 in Melbourne, Australia. From “Council House 2,” by City of Melbourne, 2010.



Figure 2-2. The façade is opened (left), and the façade is closed (right). From “Council House 2,” by City of Melbourne, 2010.



Figure 2-3. The Beijing National Aquatic Center has a design of bubbles enclosing the building that is based on the Weaire-Phelan structure. From “China.org.cn,” on Beijing 2008, 2006.



Figure 2-4. The assembly stem of the vertical surface made from ETFE. From “China.org.cn,” on Beijing 2008, 2006.



Figure 2-5. The Esplanade theatre in Singapore is inspired by Durian’s shape. From “The Esplanade,” on Architecture & Building Design, 2019.



Figure 2-6. A fruit grown in tropical regions, Durian. From “How the Durian Got Its Sulfuric Stench,” by Emma Young, 2017.



Figure 2-7. Eastgate office building inspired by termite mound. From “Biomimetic Architecture: Green Building in Zimbabwe Modeled after Termite Mounds,” by Jill Fehrenbacher, 2012.



Figure 2-8. Inside of the Eastgate office building. From “Biomimetic Architecture: Green Building in Zimbabwe Modeled after Termite Mounds,” by Jill Fehrenbacher, 2012.

### 2.3. Previous Studies Regarding the Characteristics of Polar Bears

Regarding the thermal and lighting energy, plenty of relevant researches work on exploring new and more effective solar light and thermal traveling devices have been done by many researchers (Wang, Liu, Fang, & Zhang, 2016). In this study, polar bear hairs (fur) have been focused on mainly because of their significant structural mechanism and outstanding optical properties (Bohren & Sardie, 1981; Grojean et al., 1980; Grow, 1987; Q.-L. Wang et al., 2012).

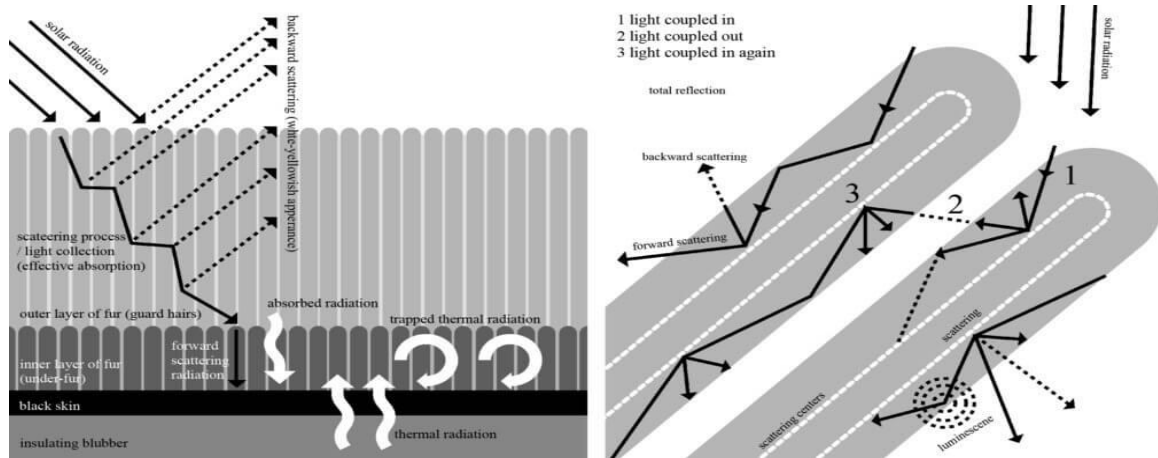


Figure 2-9. Polar bear hairs which have hollow core with the rough inner surface. The scattering process happens in polar bear hairs (Khattab & Tributsch, 2015, p. 10-11).

It has been demonstrated that the base of tube has an ability to collect light energy, and the rough inner surface of hollow core can double the collection efficiency (Tributsch et al., 1990). Since the scattering process at the core of the capillary thus aids the coupling of light into the glass tube, a complex light collection mechanism begins in the hair core by two processes, namely light scattering process and combined scattering-fluorescent process. The polar bear hairs can also guide light transmission like optical fibers by trapping more sunlight, especially in the wavelengths of ultraviolet radiation (Zhao et al., 2014). This continuous process repeats all the time and then leads to the guiding of light toward the polar bear's black skin where it is absorbed and finally converted into heat. Polar bear fur plays vital role in energy harvesting and reserving, which serve and work like transparent thermal insulation materials in this way. These unique properties of polar bear thus contribute largely to the polar bears' survival in such an extreme environment on earth (Jia et al., 2017).

## **2.4. Previous Studies Regarding Daylight**

### **2.4.1. Academic Performance Related to Daylight**

Many studies have examined whether students have better learning skills in classrooms with daylight through windows (Gilavand, Gilavand, & Gilavand, 2016; Hathaway, 1992; Heschong, 1999; Heschong, Wright, & Okura, 2002; Nicklas & Bailey, 1996). In order to determine that the influence of daylight on students' learning ability works through a perceptual system, it is necessary to look at previous studies in which researchers conducted experiments by changing the mood and visibility.

Heschong et al. (2002) examined the effects of daylight entering through windows at the Capistrano School Unified District in Orange County, California, which had different building

plans to bring in natural light. The results indicated that students in classrooms with the most daylight had a 20% faster learning rate in math and a 26% faster learning rate in reading during one school year compared to students in classrooms with the least amount of daylight (Heschong et al., 2002). Heschong et al. (2002) concluded that schools will save up to a month of education time on reading and math courses for students by using effective daylight through windows. The results of the experiment also indicated that variables in daylight, not the number of windows or presence of windows, had a greater impact on students' ability to learn. Therefore, when analyzing students' ability to learn, daylight needs to be counted as an important element.

Heschong (1999) showed that students in California improved their academic performance in the presence of daylight. The study considered year-end final test scores of second- and fifth-grade students in Orange County, California; Seattle, Washington; and Fort Collins, Colorado. The data were collected for a year to assess the learning rate in those schools. The study found that, in the Seattle Public School District in Seattle, Washington, students in the classroom with the least daylight had a 9 percent lower math score whereas students in the classroom with the most daylight had 13 percent higher reading scores than other students. Students in Fort Collins, Colorado, who studied in a classroom with enough sunlight scored 7 percent more in reading and math than those in classrooms with the lowest daylight levels. The children in Seattle and Fort Collins, compared to California, could see greater effects from daylight because they see less sun in their geographical locations.

In Gilavand et al. (2016)'s article, the researchers assumed that physical school space with windows is the most necessary element of students' various educational activities. Gilavand et al. (2016) examined the effects of daylight on learning and academic performance of elementary school students. A total of 210 students in Ahvaz, Iran, were selected as samples for the study. The

researchers collected data by randomly distributing questionnaires among students, and cluster sampling was done through appropriate allocation. The content of the questionnaire consisted of a checklist to investigate the parameters of daylight in the learning environment; students were also interviewed after completing the survey. The results indicated that daylight entering via windows is a very necessary element for students to achieve their academic abilities, and it is an important factor for students to receive natural light when designing an educational space. Gilavand concluded that light, temperature, air quality, and color affect classroom space. Although various factors affect students' academic performance, the impact on learning progress in an environment with quality daylight is significant.

One study about daylight effects in the classroom explored how daylight affects students' attendance (Hathaway, 1992). A number of studies have been conducted to analyze the relationship between students' attendance rates in five different classrooms with sufficient daylight through windows and those with insufficient daylight. Hathaway (1992) set up a total of five study settings: a classroom with high-pressure sodium vapor lighting, a classroom with full-spectrum fluorescent lighting without UV enhancement, a classroom with full-spectrum fluorescent lighting with UV enhancement, a classroom with cool-white fluorescent lighting, and a classroom with sufficient daylight through windows (Hathaway, 1992). Schools incorporating natural light showed higher student and teacher attendance than schools depending on artificial lighting. The 283 students who participated in the research studied in five different schools and had an average age of 12.02 years; 148 were male, and 135 were female. Researchers compared attendance rates of students attending different schools to show a change in student attendance according to the level of natural light. Schools with sufficient natural lighting reported an attendance rate of 3.2 to 3.8 days more per year than those with fluorescent lights (Hathaway, 1992).

In another study, Nicklas and Bailey (1996) examined the relationship between the use of daylight coming from windows in classrooms and the academic performance of elementary and middle school students in three schools built for the Johnston County School system in North Carolina. To investigate students' performance, researchers compared and analyzed the California Achievement Tests results and the end-of-grade test results for every school (16 elementary and 8 middle schools) within Johnston County. The authors also used the State of School Systems in North Carolina data from 1995 to analyze student attendance. They argued that recently built schools without daylight did not guarantee better grades. According to the study's findings, students at schools with daylight demonstrated 5 to 14 percent better academic performance than students at schools using artificial lighting. Finally, students who studied in classrooms with sufficient daylight had about 3 days more attendance per year than other students.

#### **2.4.2. Perception Related to Daylight**

Since occupants' perception is subjective, it is difficult to investigate using certain values. The nine studies in Table 2-2 identified factors that contribute to occupants' perception and satisfaction in relation to indoor environmental quality (Astolfi & Pellerey, 2008; Bluysen, Aries, & van Dommelen, 2011; Choi, Aziz, & Loftness, 2009; Humphreys, 2005; Lai, Mui, Wong, & Law, 2009; Marans & Spreckelmeyer, 1982; Schakib-Ekbatan, Wagner, & Lussac, 2010; Veitch, Charles, Farley, & Newsham, 2007; Wong, Mui, & Hui, 2008). In the 1960s, Demos and Zuwaylef (1965) conducted a study of the effects of a classroom without windows in California upon fifth-grade students and their teachers by comparing students in two classrooms, one with windows and one without. Numerous measures relating to academic performance, physical health and classroom behavior were examined during the two-year study. Pupil opinion toward the classroom was

solicited by means of questionnaires. These researchers surveyed students in a classroom without windows and found that in their first year the students preferred the windowless classroom, but in their second year, the students strongly disliked the situation.

The study by Boyce, Hunter, and Howlett (2003) identified that fewer problems are associated classrooms with daylight in the district. Some schools in the district had skylights, some had windows, and others had windows covered due to vandalism. When students are in the windowless rooms, Peterson (Edwards & Torcellini, 2002) found the students are more edgy in their seats, do not hold attention well, and are not at ease. Therefore, daylighting was included in some schools because Peterson had seen studies discussing the benefits of natural light for students. “Even though it costs more initially,” he says, “the daylighting was worth the money after a few years”.

Table 2-2. Summary of studies investigating for occupants' perception of indoor environmental quality

| <b>Study</b>                | <b>Data Analysis Method</b>                                              | <b>Population</b>                                                 | <b>Summary</b>                                                                                                                                                     |
|-----------------------------|--------------------------------------------------------------------------|-------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Astolfi and Pellerey (2008) | Pearson Correlation                                                      | 852 students in a secondary school in Italy (Response rate: 85%)  | Occupants’ satisfaction was correlated with acoustic, thermal, visual, and air quality.                                                                            |
| Bluyssen et al. (2011)      | Principal component analysis, Pearson correlation, and linear regression | 5732 occupants in 59 office buildings in eight European countries | Occupants’ satisfaction was affected by thermal, acoustic and lighting environment, air quality, amount of privacy as well as layout, decoration, and cleanliness. |
| Choi et al. (2009)          | Pearson correlation                                                      | 492 occupants in 29 office buildings in USA                       | Satisfaction was correlated with air quality, thermal, lighting, acoustics, and spatial conditions.                                                                |
| Humphreys (2005)            | Multiple linear regression                                               | 4655 responses in 26 office buildings in five European countries  | Comfort was affected by warmth, air quality, air movement, noise, humidity, and light.                                                                             |

|                                 |                                                                               |                                                                               |                                                                                                                                                                                               |
|---------------------------------|-------------------------------------------------------------------------------|-------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Lai et al. (2009)               | Multivariate logistic regression                                              | 125 occupants in 32 residential apartments in Hong Kong                       | Overall satisfaction was affected by thermal environment, acoustics, lighting and air quality.                                                                                                |
| Marans and Spreckelmeyer (1982) | Pearson correlation                                                           | Nearly 1000 occupants in 13 office buildings in USA                           | Satisfaction was correlated with lighting, noise, air quality, heating, amount of space, furniture quality, privacy, and color/area of walls & partitions.                                    |
| Schakib-Ekbatan et al. (2010)   | Correspondence analysis and principal component analysis with optimal scaling | 867 occupants in 14 office buildings (Response rate: 79%)                     | Satisfaction was influenced by temperature, lighting, air quality, acoustics, spatial condition, furniture, and layout.                                                                       |
| Veitch et al. (2007)            | Exploratory and confirmatory factor analysis and structural equation modeling | 779 occupants in nine office buildings in Canada and USA (Response rate: 90%) | Satisfaction was influenced by noise, air movement, air quality, temperature, lighting, privacy, view to outside as well as size of the spaces, esthetic appearance, and degree of enclosure. |
| Wong et al. (2008)              | Multivariate logistic regression                                              | 293 occupants of office buildings in Hong Kong                                | Occupants' satisfaction was affected by acceptability of thermal environment, air quality, noise level, and lighting level.                                                                   |

### 2.4.3. Human Health and Daylight

Daylight has physiological and psychological benefits for teachers and students. Physiological benefits due to daylight on school children are less dental decay (cavities), improved eyesight, increased growth, and improved immune system (Hathaway, 1992). The sun is a primary source of vitamin D, and increasing vitamin D intake stimulates calcium metabolism. There is a strong correlation between the amount of sunlight and students' physiological benefits, making daylighting a very important element for children (Hathaway, 1992).

National Renewable Energy Laboratory published a report and it shows that students' rates of dental decay have decreased in schools with daylight (Edwards & Torcellini, 2002). Research in the 1930s already provided evidence of the effects daylighting in school buildings has on students' health. McBeath and Zucker (1938) conducted a study showing children are more prone to deterioration of health when they spend more time inside a school and less prone to poor health during the summer months when they are outside in the sun. These results are supported by a study that compared full-spectrum light schools in Canada to traditional schools with fluorescent lighting (Hathaway, 1992). Full-spectrum fluorescent light closely resembles daylight, but it does not provide the same spectral content. The full-spectrum fluorescent schools reported that student dental decay decreased nine times compared to schools with fluorescent lights as a result of the increase in vitamin D.

#### **2.4.4. Financial Benefits and Daylight**

The results of Hathaway's study (1992) from 1981 to 1985 show how daylight affects finance. The study conducted an experiment based on information that the daily education cost per student from 1984 to 85. The rate of absence per student at schools that relied on artificial lights because they did not have enough daylight was 9.49 days per year. The study concluded that providing daylight would have a social benefit of \$290.03 per year. It also drew the conclusion that if these benefits were generalized to all 430,000 students in Alberta, Canada, the schools would save a huge amount of budget.

Most previous studies in this chapter show that the students are more hostile, hesitant, and maladjusted in a windowless classroom (Gilavand et al., 2016; Hathaway, 1992; Heschong, 1999; Heschong et al., 2002; Nicklas & Bailey, 1996). The students also tend to be less interested in

windowless classrooms. However, most of these studies have been conducted in elementary schools. Therefore, further researches on the effects of daylight on the educational environment for adults are needed.

## **2.5. Previous Studies Regarding Methodology**

### **2.5.1. Phase 1: Building Energy Simulation**

#### **(1) Simulation Programs**

The study was divided into two phases. The first was about building energy consumption and the second was about occupants' perception of indoor environment and their psychological health. In the first phase, this study looked the reduction of heating and cooling energy consumed in the building if the sunlight can enter through the interior wall of the building. Therefore, simulations conducted how the heating and cooling energy vary between an actual and virtual buildings. Many studies have researched simulating the daylight and energy consumption of thermal and cooling energy (Abdullah et al., 2014; Aflaki, Mahyuddin, Mahmoud, & Baharum, 2015; Chan, Che-Ani, & Ibrahim, 2013; Hviid et al., 2008; Konis, Gamas, & Kensek, 2016; Sadineni et al., 2011; Stoppel & Leite, 2013). Aflaki et al. (2015) conducted a study to investigate HVAC system energy consumption compared with other passive design strategies in tropical climates using computational fluid dynamics (CFD) simulations. The results showed that ventilation, window area to wall ratio, and orientation of the building should be reviewed in future construction projects (Aflaki et al., 2015). Konis et al. (2016) conducted a study to demonstrate the use of passive design and energy optimization using a building energy simulation programs such as iDbuild to see energy and indoor environment performance requirements, visual programming language (VPL) for whole-building energy simulation of dynamic solar shading,

and DIVA and DAYSIM in order to find optimized performance of daylight, daylight control and ventilation strategies in early stages of the projects (Konis et al., 2016). These various methods of previous research showed that building energy simulation programs were used for various aspects of research, and experiments that were not actually implemented could be simulated and predicted under various conditions.

In order to model the building using the simulation programs, this study selected cold climate zones, according to NASA's Earth Observing System Data and Information System (CIESIN, 2012). The study pre-tested the building with the same settings in each climate zone. The pre-test looked at how much heat and cooling energy the building uses on models without biomimetic window system inspired by polar bear hairs.

## **(2) Settings of Windows and Rooms for Simulations**

Ghisi and Tinker (2005) researched about specifying an ideal window area for a space in which there was a balance between daylight provision and solar thermal load would lead to a scenario whereby the energy consumption of the space was optimized. Using the VisualDOE program (Lokmanhekim et al., 1979) for the climatic conditions of chosen cities in this article, the energy consumption was calculated. The authors modeled five different rooms with different ratio of width to depth of rooms. So as not to use random room sizes, the dimensions of each room were calculated as a function of the room index, as used in artificial lighting design. In addition to the room ratio, the authors defined daylight factors to represent the ratio of indoor to outdoor daylight illuminance as following. 1) The sky component, 2) The external reflected component, and 3) The internal reflected component. Therefore, they found results from the analysis of using the ideal window area concept in conjunction with daylight integration to evaluate the potential for energy

savings on artificial lighting. In terms of room sizes, it was shown that smaller rooms and rooms with a greater width, have a greater potential for energy savings on lighting due to daylight reaching the working surface through windows. In terms of room ration, rooms of greater width tend to provide more energy savings on lighting due to the integration of daylight and artificial light. The rooms with a narrower width have lower energy consumptions due to the lower solar heat gains or losses through windows.

According to an earlier study that analyzed the daylight coming through the different window shapes and sizes under overcast sky conditions (Acosta, Munoz, Campano, & Navarro, 2015), computer simulations were conducted with a total of eight different window sizes. The simulations were conducted with the ratio of windows to walls where the windows were installed, not the exact size of the windows. Therefore, the simulations were conducted from 10 percent of window surface to wall surface ratio to 80 percent of window surface to wall surface ratio in the study (Acosta et al., 2015). The results of this study said that more daylight could enter the room when the window was square-shaped than rectangular-shaped windows. It also found that the larger the window, the better daylight. However, if the distance from the window was more than 3 meters, there is no big difference in the amount of daylight (Acosta et al., 2015).

### 2.5.2. Phase 2: Virtual Reality and User Experience

In the second phase, the study tested occupants' perception using a virtual reality system. When we look at the real world and the virtual world, as shown in Figure 2-10, virtual reality located in a completely virtual world, and a world where we can see without using any device is a completely real world. Augmented reality can be seen as a system that combines the real world and the virtual world (Bowman, Gabbard, & Hix, 2002; McMillan, Flood, & Glaeser, 2017; Rebelo, Noriega, Duarte, & Soares, 2012). Users can obtain additional information from the real world by overlaying the virtual information or images, but the system is still being developed because of the limitations of the display. Mixed reality can be seen as a system that blends the virtual world with the real world. If virtual objects are overlaid based on the real world through augmented reality, the real world is based on the virtual world and vice versa in mixed reality. In mixed reality, however, this virtual- and real-world distinction is vague to tell which objects are real or virtual. Finally, when we look at the cross-reality, it refers to a system in which real-time communication between devices is made by networking sensors that are installed around the world, making it impossible for users to distinguish between reality and virtuality. Although networked sensors allow users to visit real people or spaces in virtual space, it is difficult for users to tell which ones are virtual and which are real. Finally, the differences among virtual reality, augmented reality, mixed reality, and cross-reality are in Table 2-3.

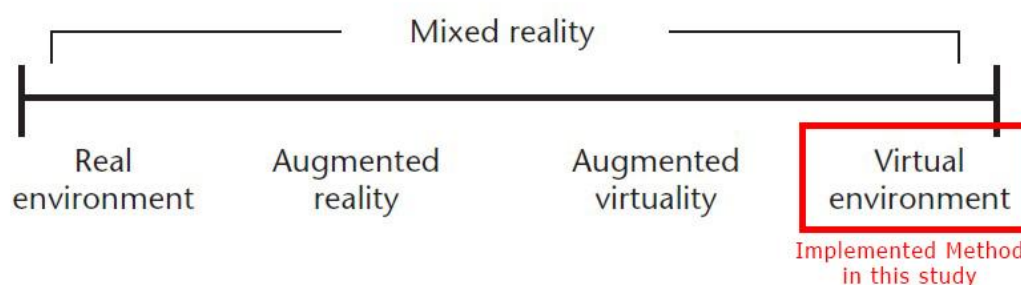


Figure 2-10. Milgram's reality-virtuality continuum (Milgram & Kishino, 1994, p. 3).

When looking at the characteristics of the mixed reality system, we can make users feel windows even in a windowless space, and it is possible to delete windows when they do not want. However, more research will be also needed on mixed reality and cross-reality at this point. Although augmented reality is considered a good example to be applied to this study, as explained earlier, the display that drives augmented reality might be difficult to implement on the real-world objects. For example, when experimenting in a space where windows exist, it would be difficult to make a windowless space. The costs of implementing augmented reality is also another problem.

Virtual environments are a relatively new type of human-computer interface in which users perceive and act in a three-dimensional world (Bowman et al., 2002). After designing virtual spaces, this study conducts a survey and recruit subjects based on the previous studies. Rebelo et al. (2012) studied about assessment methods of user experience using virtual reality. Therefore, subjective self-reported and questionnaires before, during, and after exposure as well as physiological measures were assessed. In addition, the authors said that virtual reality can be used to gather insights on the users' needs and expectations in user research studies. Therefore, the users' behavior was evaluated in their study. Virtual reality definitely has many advantages for the evaluation of the interior spaces. However, its utility and application should be carefully considered.

According to this literature review, Augmented Reality (AR) might be most suitable for subjects to have a virtual experience in the real space. However, AR is not suitable for experiments of virtual daylight. The study by Azuma et al. (2001) addressed that the most commonly used and developed AR displays still do not have enough brightness, resolution or vision to seamlessly combine real and virtual images. The 360-degree virtual reality is the most basic stage in the virtual reality continuum (Figure 2-10), but subjects are able to easily access the real spaces with virtual

elements in the virtual spaces. Therefore, the 360-degree virtual reality implemented in this study to compare and analyzed how users' perception was different in the space with and without windows.

Table 2-3. Key differences among virtual reality, augmented reality, mixed/merged reality, and X reality

|                       | <b>Virtual Reality</b>                                                                                       | <b>Augmented Reality</b>                                                                 | <b>Mixed/merged Reality</b>                                                              | <b>X Reality (Cross Reality)</b>                                                                                                                                 |
|-----------------------|--------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>Display device</b> | Special headset or smart glasses                                                                             | Headsets optional                                                                        | Headsets optional                                                                        | Network Sensor, various types of devices                                                                                                                         |
| <b>Image source</b>   | Computer graphics or real images produced by a computer                                                      | Combination of computer-generated image and real-life objects                            | Combination of computer-generated images and real-life objects                           | Combination of computer-generated images and real-life objects                                                                                                   |
| <b>Environment</b>    | Fully digital                                                                                                | Both virtual and real-life objects are seamlessly blended                                | Both virtual and real-life objects are seamlessly blended                                | Both virtual and real-life objects are seamlessly blended                                                                                                        |
| <b>Perspective</b>    | Virtual objects will change their position and size according to the user's perspective in the virtual world | Virtual objects behave based on user's perspective in the real world                     | Virtual objects behave based on user's perspective in the real world                     | the user's perception of the virtual object is fully realized within the cross-real world, and the actual effect can be demonstrated within the virtual reality. |
| <b>Presence</b>       | Feeling of being transported somewhere else with no sense of the real world                                  | Feeling of still being in the real world, but with new elements and objects superimposed | Feeling of still being in the real world, but with new elements and objects superimposed | Feeling of still being in the real world, but with new elements and objects superimposed                                                                         |

|                  |                                                                               |                                                                                                                 |                                                                               |                                                                                                                             |
|------------------|-------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------|
| <b>Awareness</b> | Perfectly rendered virtual objects cannot be distinguished from the real deal | Virtual objects can be identified based on their nature and behavior, such as floating text that follows a user | Perfectly rendered virtual objects cannot be distinguished from the real deal | connecting all networks of sensors that cover the world and removing the separation between reality and virtual encounters. |
|------------------|-------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------|

*Note.* K. McMillan, K. Flood, & R. Glaeser, 2017, p. 163.

## CHAPTER 3

### RESEARCH DESIGN AND METHODS

#### 3.1. Research Design

The conceptual framework of the study is shown in Figure 3-1. First of all, this study identified current problems and clarified hypotheses. After setting the hypotheses, this study intensively reviewed previous studies that have been conducted and collected various characteristics of polar bears. Based on the case study about the characteristics of polar bears, simulations to see building energy consumptions and a survey using virtual reality for user experience and perception were conducted. After collecting the data, a discussion on the new biomimetic window system was made through the examination of hypotheses and analysis of the research design. Finally, the study found out what future researches will be needed after this study.

The study was divided into two parts (Figure 3-2). The first part was to find an appropriate light strategy by looking at behaviors, anatomy and physiology of flora and fauna. After deciding upon a specific thermoregulatory strategy, which is a characteristic of polar bear fur, a specific climate zone was selected and a new biomimetic window system proposed.

The second part of the study was further divided into two sub-parts. The first sub-part was conducting building energy simulation and assessment and the second part was conducting a virtual reality experiment to assess occupants' perception with the biomimetic windows. In order to test the hypothesis 1: *Biomimetic windows can reduce energy consumption*, the energy simulation was conducted to predict the reduction of cooling and heating energy consumed by the building if the daylight entered through the biomimetic windows. Therefore, simulations were conducted how the cooling and heating energy vary by comparing building energy consumption with different window types.

The second sub-part was to examine occupants' perception and opinions. Therefore, a virtual reality experiment with a survey was conducted in the second part. Virtual environments are a relatively new type of human-computer interface in which users perceive and act in a three-dimensional world. In this study, the virtual spaces were designed with new biomimetic windows that can transmit the sunlight on the interior wall. For the virtual spaces, this research conducted case studies with educational buildings in the campus of Michigan State University to find out proper spaces. After creating virtual spaces, this study recruited participants and assessed their perception after experiencing the virtual spaces.

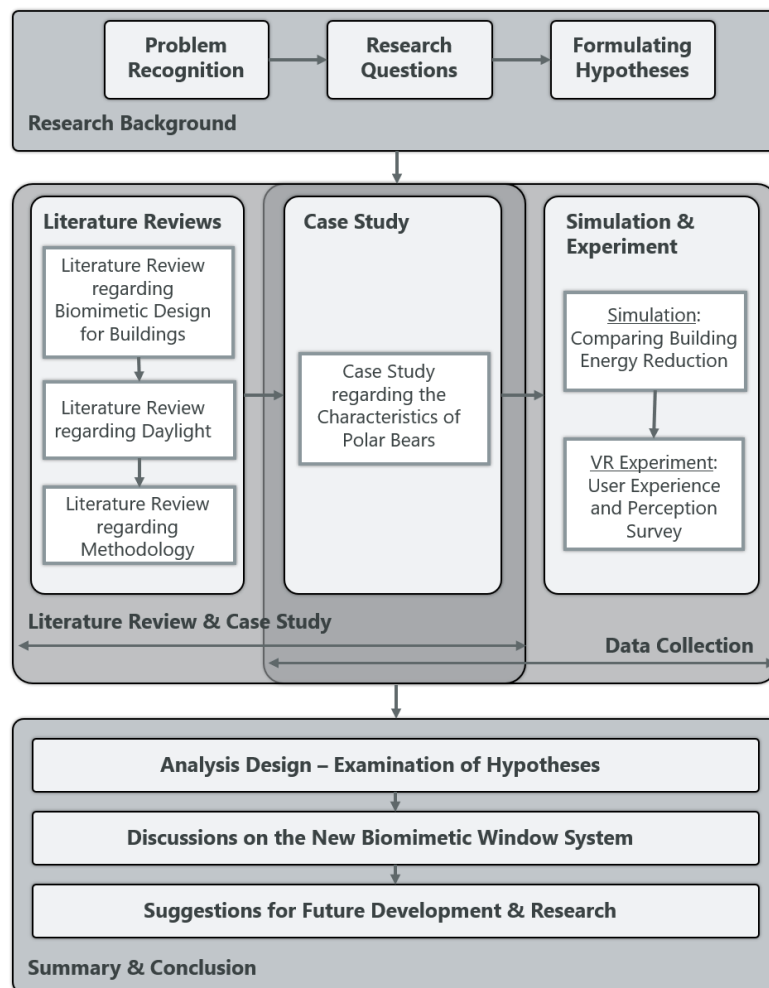


Figure 3-1. Conceptual Framework of the Study

*Diagram credited to Juntae Son*

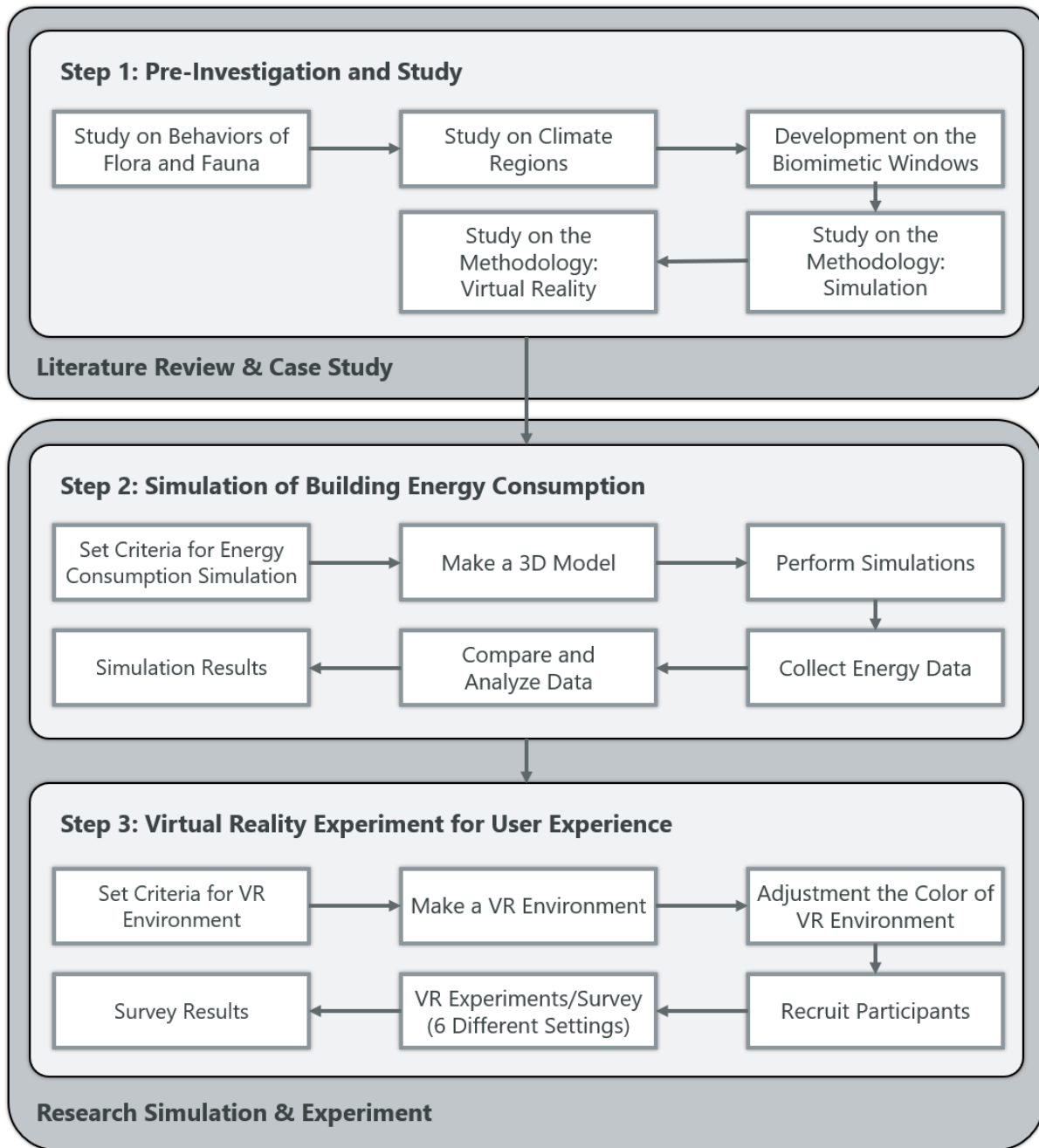


Figure 3-2. Research Design and Structure for Data Collection

*Diagram credited to Juntae Son*

## 3.2. Study Area

### 3.2.1. Target Climate Region

This study focused on a cold climate region, which has many heating degree days (HDD), to see the effect of saving heating energy through bringing daylight into a building. According to NASA's Earth Observing System Data and Information System (CIESIN, 2012), the global climate zone can be divided into five categories: Tropical, Dry, Temperate, Cold, and Polar. The regions are divided into smaller subregions: Tropical wet, Tropical wet and dry, Semiarid, Desert, Mediterranean, Marine west coast, Humid Subtropical, Humid Continental, Subarctic, Tundra, Ice Cap, and Highland. Therefore, the target climate zones should have enough sunlight, which has

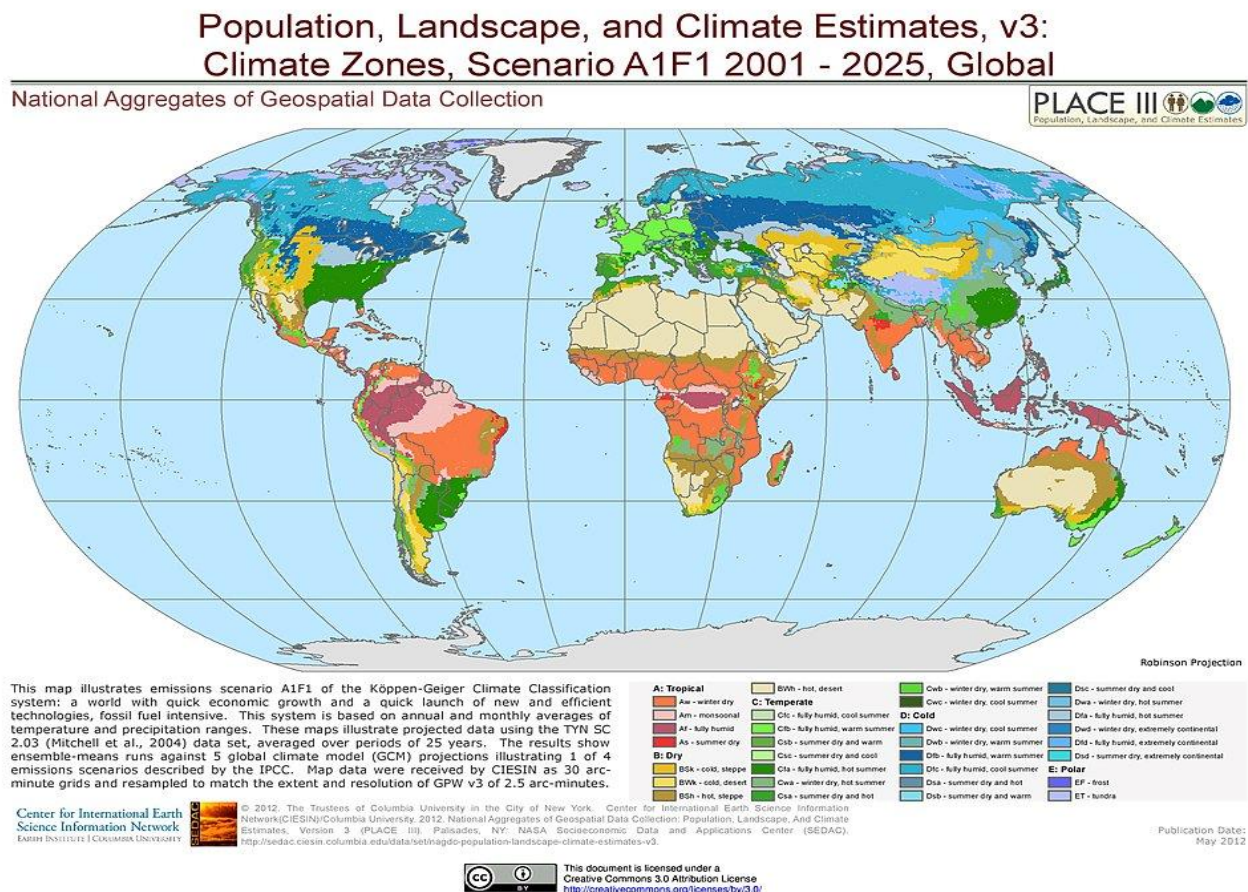


Figure 3-3. Köppen-Geiger climate classification system. This system is based on annual and monthly averages of temperature and precipitation ranges (CIESIN, 2012).

four seasons and not too much precipitation. Semiarid and Mediterranean may be possible additional climate regions where this biomimetic solution could be adopted based on the global climate zones (Figure 3-3). To decide the target climate regions, various parameters were considered, such as amount of sunlight, precipitation, and humidity of the climate zones. If the amount of sunlight is not enough or too much, it causes another problem. Clouds caused by rain and snowfall are not able to receive enough sunlight for the new biomimetic window system because they block the sunlight. In addition, if the humidity is too high, the sunlight is likely to diffuse. In areas where buildings are densely constructed, such as megapolis (e.g. Chicago and New York), occupants may see the exterior walls of the adjacent building or they may not be even able to open or close the windows. In these spaces, if the daylight is transmitted into the building using a system like the biomimetic window system, occupants could get benefits of daylight that this study mentioned in Chapter 2.4. Previous Studies Regarding Daylight.

### **3.2.2. Target Building**

Michigan State University (MSU) is located in the cold climate region which is a target area in this study. According to MSU webpage (<https://msu.edu/about/thisismsu/facts.php>), the total number of students was about 49,809 in 2019 and the school has various types of building, making it suitable for this study. Therefore, the target areas in this study were various lecture rooms and study lounges that various students can use. MSU has 562 buildings in total and the report of the MSU Infrastructure Planning and Facilities (MSU-IPF) showed that a total of 106 buildings are located on campus (APPENDIX A.). In order to select a target building, this study excluded 1) destroyed buildings, 2) buildings that are not able to measure the size, 3) buildings used only by specific majors or departments, and 4) buildings that are less than 100,000 square feet. After

looking at the entire MSU academic buildings as of 2019, about 100 buildings were selected except razed structures and the structures that do not have any gross square feet acquisition by a guideline of AIA (1995). However, even though MSU was defined generally as an academic space, each specific building itself often had various functions. For example, it is recognized that many buildings support a variety of functions that may not be similar (e.g. a residence hall may contain academic office and/or classroom space). Therefore, MSU categorized the buildings with more than one function into the category that most closely matches to its primary function and users' main activity.

After screening the initial set of buildings, selection was narrowed to those with 100,000 square feet or over to clearly see the increase and decrease of the building energy consumption. Among them, the buildings used only by students in certain specialties, such as music, computers, and acting were then excluded because energy consumption used by students in certain specialties can be biased. However, general computer labs and classrooms were included in this study as students from many majors or colleges use those spaces.

After excluding these buildings, a total of 12 buildings finally met the applicable conditions for this study. Of these, the Main Library, Union, and Student Services are mostly occupied buildings by students of greatest diversity of majors. In order to see the difference in energy consumption in buildings, a building with the large area should be selected and many people should occupy the building at any one time. Therefore, the Main Library building with a total of 458,913 square feet was selected as the target building for this study.

### 3.3. Proposed Novel Biomimetic Window System

Until today, many researchers have conducted experiments to develop more effective solar conversion devices (Wang et al., 2016). In addition, the theory of solar energy conversion based on polar bear fur has been discussed for decades (Øritsland & Ronald, 1978). A previous study (He et al., 2011) showed that researchers observed individual polar bears' fur through a microscope and found that the individual hairs were hollow and transparent. It has been shown that light scattering is occurring in polar bears' fur, and more sunlight can be trapped especially the ultraviolet wavelength (Zhao et al., 2014).

Various studies have been conducted previously to develop new fibers and heat collectors to collect solar energy inspired by the structure and function of polar bear hair (Banaei & Abouraddy, 2012, 2013; Sharafi, ElMekkawy, & Bibeau, 2015). In addition, previous studies have shown that PMMA fiber bundles are more efficient in transmission than conventional heat exchangers (Rahou, Mojiri, Rosengarten, & Andrews, 2016). Therefore, PMMA fiber bundles could be used as an example to identify examples of developing new materials and considered possible designs (Jia et al., 2017). PMMA fiber bundles were explained in more detail in 0

#### Previous Studies Regarding the Characteristics of Polar Bears.

A previous study (Jia et al., 2017) suggested a new photothermal conversion fiber structure based on polar bear hair. The study also claimed that the results of the experiments had shown

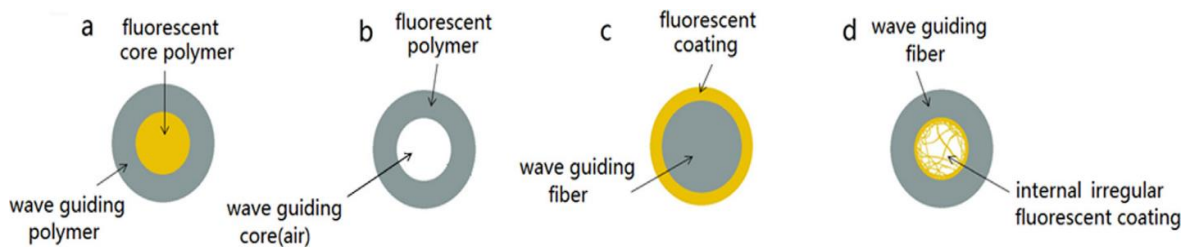


Figure 3-4. Design concepts of optically active fibers: (a) Bi component fiber; (b) hollow fiber; (c) surface coated fiber; (d) internal coated hollow fiber (Jia et al., 2017, p.346).

progress in solar energy harvesting devices by using a polar bear fur model to improve fiber structure. The new fiber structure presented in the study was shown in Figure 3-4. The light collection efficiency of fibers developed using this model has been improved by combining the light scattering and fluorescence process simultaneously and scattering them from the fiber core part. Tributsch's model (1990) was represented in Figure 3-4 (a-c), and the study in (Jia et al., 2017) corresponds to Figure 3-4 (d). The study argues that in previous models, some groups of researchers conducted the study used methanol in the construction of the fibers, without taking into account the harmful effects of methanol on human health (Bahners et al., 2008).

Using the internal coated flow fiber (Figure 3-4 (d)) developed in the previous study (Jia et al., 2017), when a new building is constructed, this study has a potential design that has a solar collector on a roof area and a newly suggested pipe with the internal coated hollow fiber. The biomimetic window system that this research proposes is appropriate in the cold climate region. Solar radiation at low environmental temperature may save energy by lowering the animal's lower critical temperature; however, at a high environmental temperature, it puts an extra burden on heat dissipation (Schmidt-Nielsen, 1965). To bring daylight into a building, this research assumed that a parabolic dish or reflector is set up on the roof of the building that can collect sunlight and transmit it inside through a pipe or wire, such as fiber cables. In this point, this study focused on a problem when too much sunlight would make heat build-up because parabolic dishes can create heat in excess of 3,000 °F. To solve this problem, this study looked at the types of solar collectors and what is the possible collector to be used in the biomimetic window system.

### 3.3.1. Solar Collectors

The main component of solar energy systems is solar collectors. A solar collector is a device that absorbs solar energy from the sun and converts it into heat and light to transmit them through a collector. There are basically two different types of solar collectors: stationary also known as non-concentrating collectors, and tracking, also known as concentrating collectors (Kalogirou, 2004). A fixed (non-concentrating) collector absorbs solar radiation as it is, while a tracking (concentrating) collector concentrates solar radiation via concave reflecting surfaces on the receiving area to increase solar energy. A comprehensive list was shown in Figure 3-5.

In this study, parabolic through collectors (PTCs) were chosen for the biomimetic window system. PTCs require less material for reflecting surfaces and are structurally simpler than flat plate collectors. Systems with light structures and low-cost technology for process heat applications up to 750 °F could be obtained with PTCs. Parabolic through technology is the most advanced of the solar thermal technologies because of considerable experience with such systems in a commercial industry.

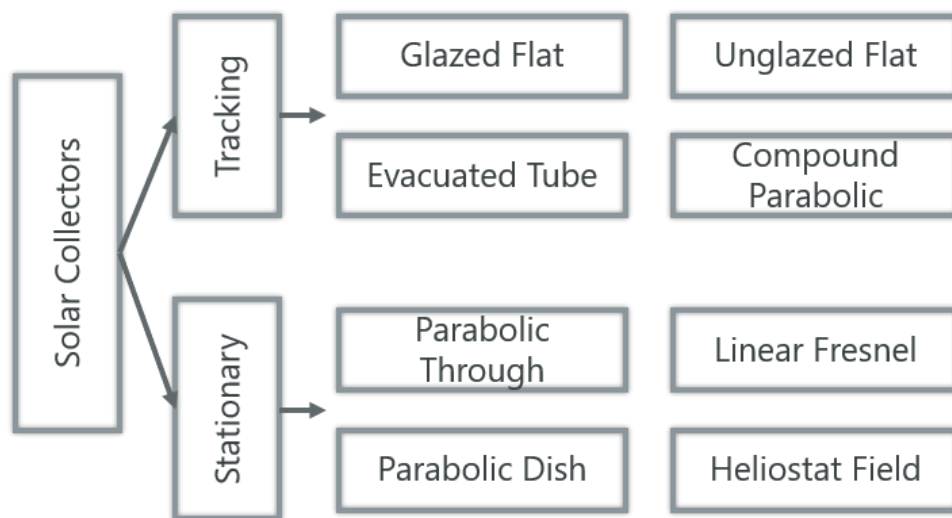


Figure 3-5. Types of Solar Collectors (Kalogirou, 2004, p. 240).

Figure 3-6 shows how the collector tube is installed on the roof of the building with PTCs. As mentioned in the previous chapter, too high temperatures, 3,000 °F, can build in the collector, which can cause a problem in the durability of the system. This study considered the PTC design to solve these problems. PTCs is an appropriate selection for collecting sunlight because the temperature does not rise above 750 °F.

### 3.3.2. Proposed Novel Collector Tube

Figure 3-7 presents the structure of the collector tube to be used in this study. In order to transmit both solar heat and light, as proposed in this study, the insulated tube can be used for the outer cover of the collector tube while the internal coated hollow fiber proposed by Jia et al. (2017) is placed inside the collector tube. The internal coated hollow fiber transmits the sunlight received into the entire collector tube, and the cold air is heated outside the internal coated hollow fiber and inside the outer cover of the collector tube to create warm air. The warm air and the solar light are transmitted to the basement level of the newly built building or to areas where the sunlight cannot reach.

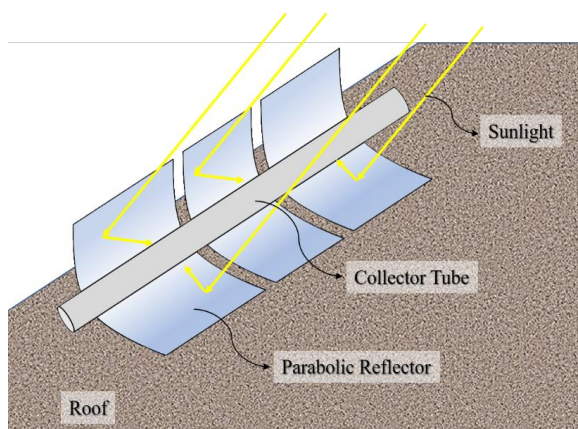


Figure 3-6. Solar collector proposed in this study

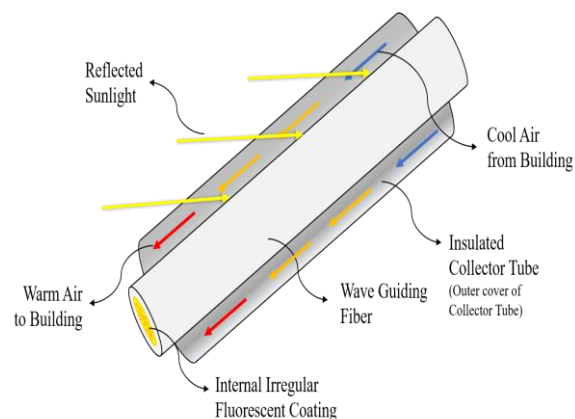


Figure 3-7. Solar collector tube proposed in this study

*All images credited to Juntae Son*

### 3.3.3. Proposed Novel Biomimetic Window System Design

Figure 3-8 schematized the concepts presented in this study. As cold air tends to sink and warm air tends to rise, these mechanics would lead to monetary savings by implementing the proposed system. However, in this study, airflow pumps were installed because warm air from the building's roof must be sent underground or inside the building. Using this pump, cold air goes up to the top of the building, where it can be heated before being sent back inside the building to warm it. The solar light gathered from the rooftop through the solar collector is transmitted inside the building through the collector tube.

### 3.3.4. Section View of the Wall

Figure 3-9 schematized the final arrival of solar light and heat into the building when the system performs well. The collector tube was a method that transports light and heat to the final destination and releases light and heat to the biomimetic windows at the final destination. The system presented in this study might be difficult to install in existing buildings due to the process of installing the collector tube inside the building wall. Therefore, future research will explore how this system can be installed in existing buildings.

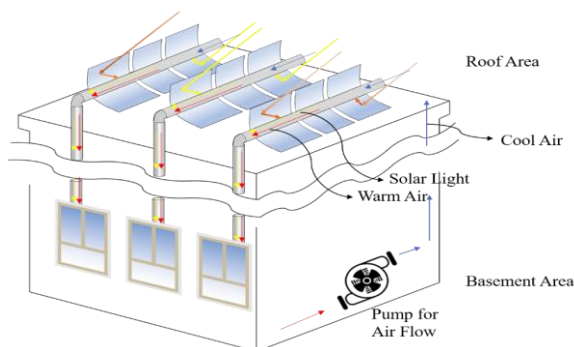


Figure 3-8. Overall system design proposed in this study

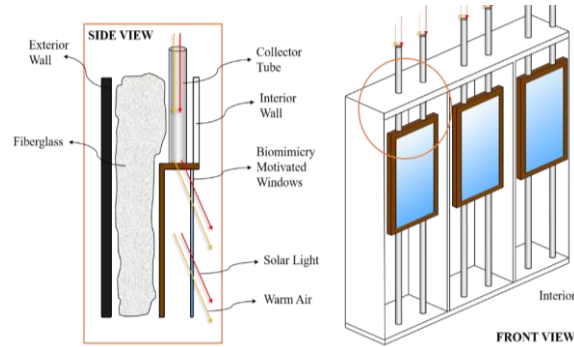


Figure 3-9. Section and front view of the system

*All images credited to Juntae Son*

### **3.4. Research Process**

#### **3.4.1. Phase 1: Building Energy Simulation**

A simulation software called DesignBuilderSoftwareLtd (2019) has a set of features including significant productivity for LEED, ASHRAE 90.1 works, climate-based daylight modeling, and graphical output of simulation results by allowing the EnergyPlus module to simulate the building energy consumption and daylighting simulation.

EnergyPlus is a building energy simulation engine developed in 1996 with financial support from the Department of Energy in the United States (DesignBuilderSoftwareLtd, 2019). The program is integrated with thermal and mass balance-base area simulation including features of simulating sub-hourly time steps allowing the user configurable modular HVAC systems. It also has a structure that can facilitate the development of interfaces with various programs such as DesignBuilder and SketchUp. It is a program showing the relationship between simulated building energy performance data and actual building energy performance data. EnergyPlus is, therefore, important in overall building energy prediction research.

##### **(1) Data Collection**

It is possible to predict the reduction of heating and cooling energy consumed in the building if the sunlight can enter the building through the biomimetic window system. Therefore, simulation was conducted to examine how the heating and cooling energy consumptions vary after modeling actual and virtual buildings located in the Michigan area. At first, this study used actual data information from Main Library at Michigan State University. In this study, three-dimensional modeling was designed through a program called Revit based on actual library's floor plans and HVAC system. The Revit model was exported to DesignBuilder calculating building energy

consumption based on EnergyPlus. The calculated and predicated energy consumption were compared to the actual energy consumption data to assess the reliability of the model. With this model, further simulations were conducted and energy prediction data from the basement floor with and without the biomimetic window system. The simulated energy consumption data were analyzed to determine how much energy was saved.

## **(2) Procedure & Analysis**

Prediction of energy consumption required the process of designing a model from a real building using a computer. Therefore, the 3D model of the library with the biomimetic window system were created using Revit after receiving the actual floor plans from the library. The structure of biomimetic window system was described in 3.3. Proposed Novel Biomimetic Window System. After modeling the 3D building and window system in Revit, the model was exported to DesignBuilder, to predict the energy usage of the library building.

DesignBuilder provides access to all of the most commonly required simulation capabilities covering building fabric, thermal mass, glazing, shading, renewables, HVAC and financial analysis. EnergyPlus module has various key features as follows: (DesignBuilderSoftwareLtd, 2019).

- 1) EnergyPlus is tightly integrated within this module providing advanced dynamic thermal simulation at sub-hourly timesteps.
- 2) Provide environmental performance data such as energy consumption, carbon emissions, room comfort at annual, monthly, daily, hourly, and sub-hourly intervals.
- 3) Report solar gains on surfaces, surface temperatures and radiant exchanges.
- 4) Access an extensive range of results for buildings and systems.

- 5) Assess passive performance, thermal mass, and temperature distribution.
- 6) Export surface temperatures and airflow rates as boundary conditions for detailed CFD analysis.
- 7) Size heating and cooling systems.

The input values, such as a type of building, operating hours of building, and building materials, were set to the same conditions as the actual library building, and simulations were conducted to see the difference between the predicted energy data and the actual data. Discrepancies between simulated and actual energy usage in buildings indicate that these gaps can be substantial, and in the range from 10 to 30 percent (Abdullah et al., 2014; Diamond, Opitz, Hicks, Von Neida, & Herrera, 2006; Scofield, 2009; Stoppel & Leite, 2013). Therefore, the model which has 10 to 30 percent difference could be used to predict building energy consumption for further simulations.

If the model was within the margin of error of 10 to 30 percent, the prediction can be carried out based on the model. In this study, to see how much energy could be saved if biomimetic windows are placed in a windowless space, energy predictions were conducted on the basement floor. When there is no window in the study and lounge areas on the basement floor compared to when biomimetic windows were installed in those spaces, the study examined how much energy usage was different between two conditions. It had validity that the biomimetic windows should be installed to reduce energy consumption.

### **3.4.2. Phase 2: Virtual Reality and User Experience**

This research created virtual reality environments using a virtual reality headset for the participants because the biomimetic window is not an existing product. Virtual reality definitely

has many advantages for the evaluation of the interior spaces and human's perception. However, its utility and application should be carefully considered. After experiencing the virtual spaces, this study collected data through questionnaires about how biomimetic windows affect occupants' perception of indoor environment. Therefore, virtual space in the virtual reality system was designed for two types of spaces. One was an open space and the other was an enclosed space in the MSU Main Library. The questionnaire for the experiment provided empirical evidence for students' seating preference in educational spaces. A quantitative analysis contained the elements of an empirical analytical scientific approach with a survey using the Likert scale questions.

### **(1) Virtual Reality Production Process**

To create these 360-degree panoramic virtual spaces, images of the real world should be captured. A 360-degree image capture involves the creation of an equirectangular projection. To convert the 360-degree panorama into a 2D projection, a panoramic camera with multiple fish-eye lenses used. In this study, Ricoh Theta V 360-degree spherical panorama camera was used to capture the 360-degree images. Since the main library is a public place, permission was needed from the main library (APPENDIX C. Permission to Film Within the MSU Libraries). When filming the 360-degree images in the library, the images were taken carefully not to let anyone take in the images and not to disturb anyone who used the library. In this study, the open space (S1) and enclosed spaces (S2) in the main library of Michigan State University were used with three different virtual reality conditions. The three conditions are 1) no windows (C1), 2) biomimetic windows space with only daylight (C2), and 3) biomimetic windows space with daylight and view (C3). These three different conditions applied equally to the two spaces. These conditions of each space were created using Adobe Photoshop CC 2019.

After each condition was created, the hue of a specific light source was calculated in each condition since the experiment should not be affected by the color of light when participants do this virtual reality experiment. In order to have a constant illumination comfort in the virtual reality environment, illumination level should have needed to measure in each virtual reality environment. However, this study designed a virtual reality environment with 360-degree 2D images. Since it is not possible to measure the illumination level from 2D images, this study designed virtual reality experiments with similar K values in each virtual reality environment to make participants not had a bias when experiencing virtual reality environments. All chromaticity values visible to the HVS appear inside the horseshoe-shaped spectral locus (Dufaux, Le Callet, Mantiuk, & Mrak, 2016). The International Commission on Illumination (CIE, the abbreviation came from its French name, “*Commission internationale de l’éclairage*”) created international standards related to light and color in 1931. CIE 1931 color spaces were the first defined quantitative links between distributions of wavelengths in the electromagnetic visible spectrum, and physiologically perceived colors in human color vision (Smith & Guild, 1931). In this CIE 1931 color spaces the Planckian locus (Figure 3-10) is the path that the color of an incandescent black body would take in a particular chromaticity space as the blackbody temperature changes. It goes from deep red at low temperatures through orange, yellowish white, white, and finally bluish white at very high temperatures. Some daylight in the early morning and late afternoon has a lower color temperature due to increased scattering of shorter-wavelength sunlight by atmospheric particles. Depending on

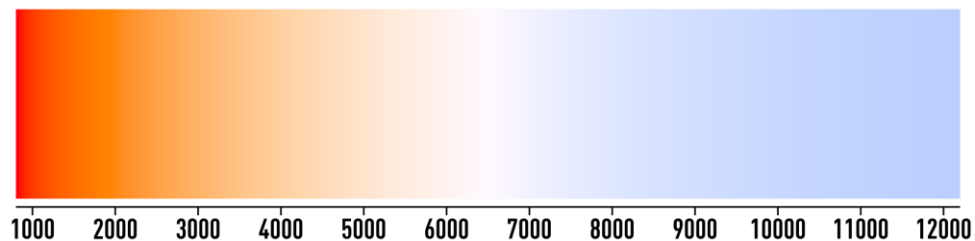


Figure 3-10. The color temperature of the Planckian locus on a linear scale (values in Kelvin), (Daufaux et al., 2016).

day, time, and weather, the color temperature of sunlight is different. According to Williams (2004), the color temperature of the sunlight below the atmosphere is about 5,780 K, and the color temperature of sunlight above the atmosphere is about 5,900K.

To extract the color temperature of each virtual reality image, RGB values were first extracted from each 2D projection image. RGB values were extracted using R which is a programming language and environment for statistical computing and graphics. The RGB histogram images for each condition are from Figure 3-12 to Figure 3-17. In addition, the RGB values for each condition is on Table 3-1. Each RGB value can be used to derive the  $x, y$  value which was used in the aforementioned Chromaticity diagrams (Figure 3-11). This  $x, y$  value can be used to derive Kelvin values from each condition, and the derived Kelvin value is on Table 3-1. Finally, Figure 3-18 shows a graph in detail where each condition is located with each Kelvin value in Chromaticity diagrams.

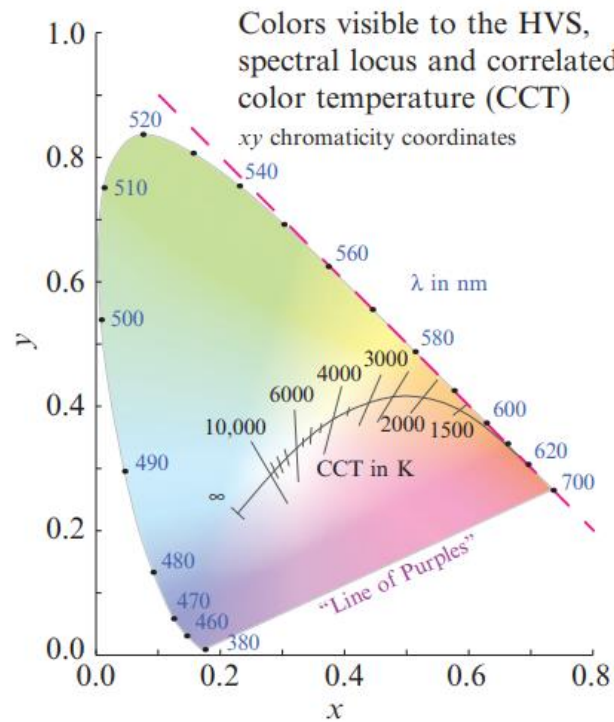


Figure 3-11. Chromaticity diagrams in CIE xy showing the fundamental components of color imaging and color spaces (Daufaux et al., 2016).

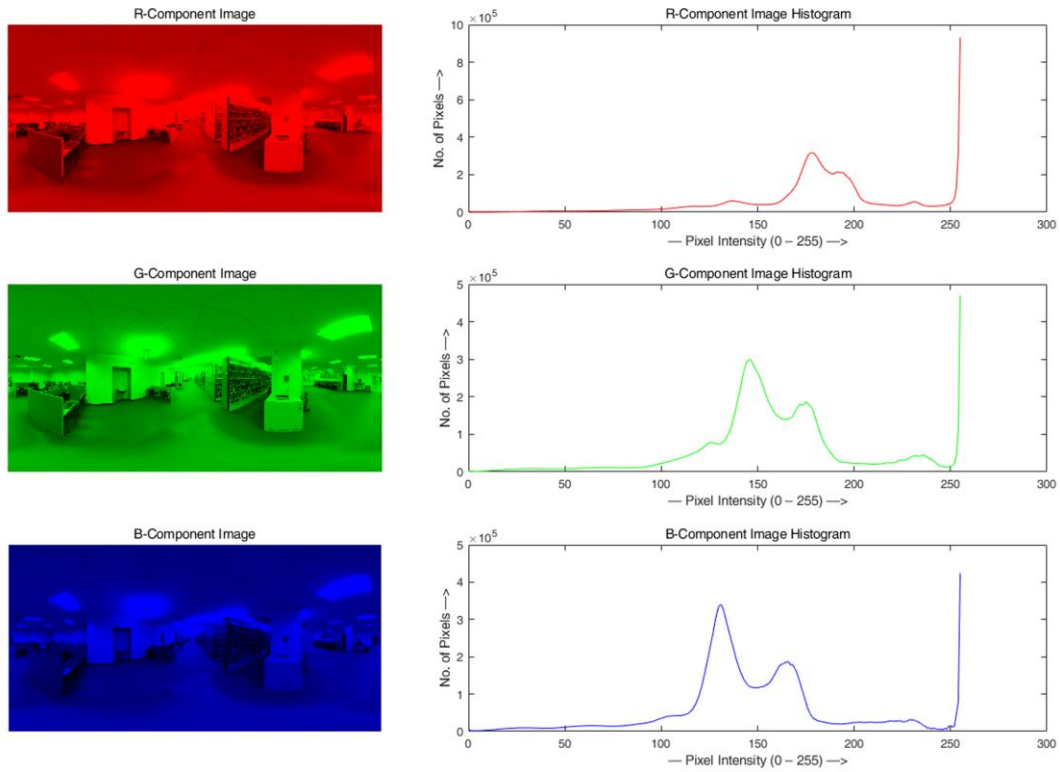


Figure 3-12. RGB component image histogram of the open space with condition 1 (S1C1)

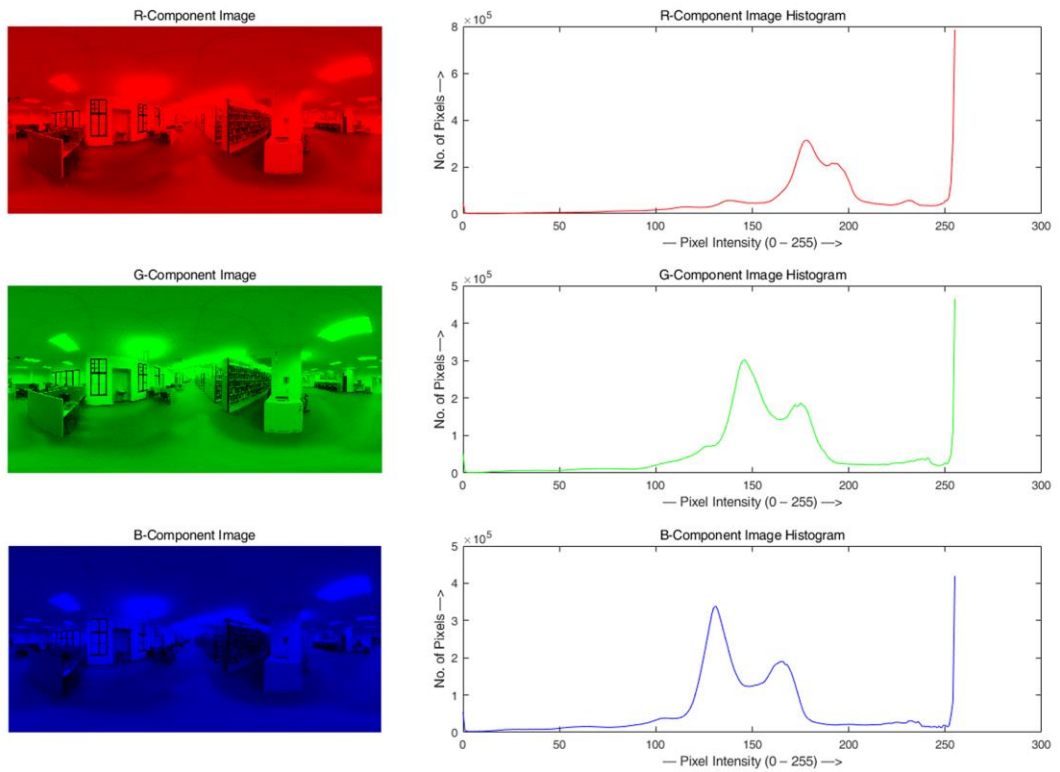


Figure 3-13. RGB component image histogram of the open space with condition 2 (S1C2)

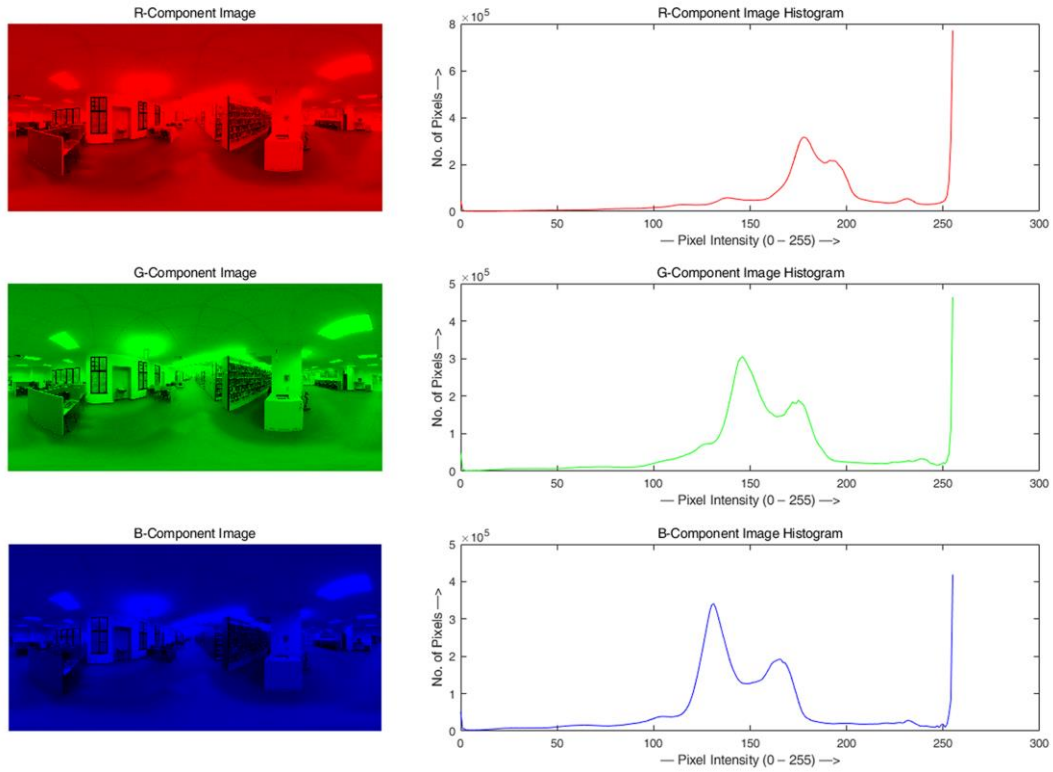


Figure 3-14. RGB component image histogram of the open space with condition 3 (S1C3)

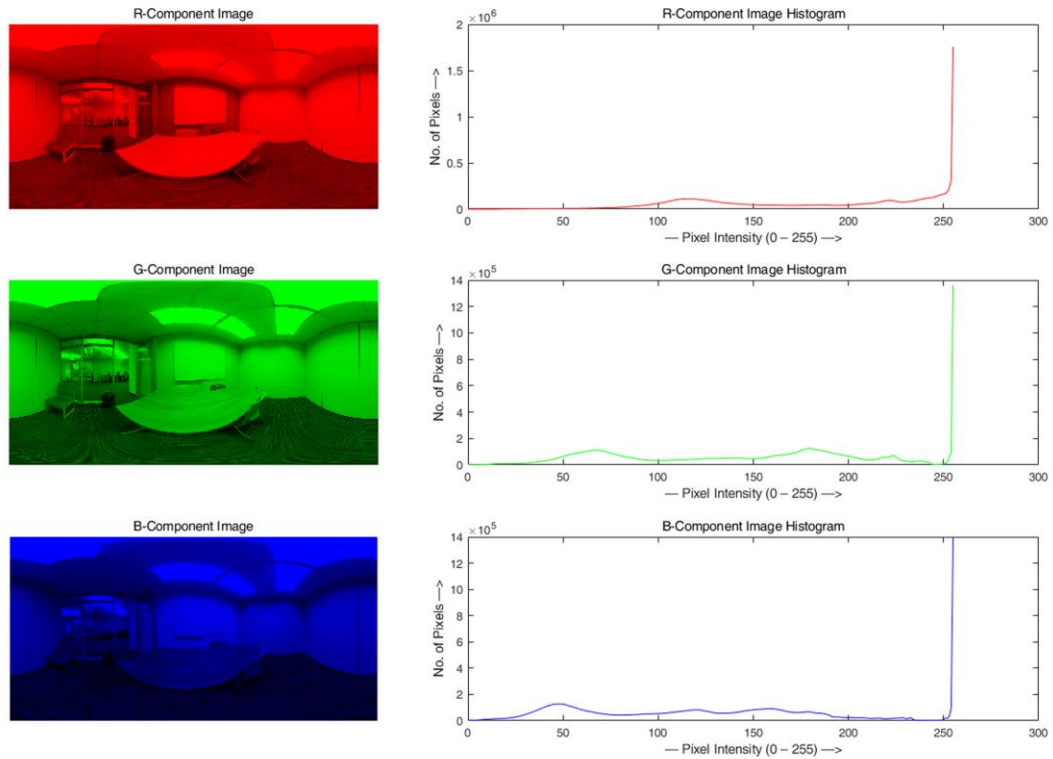


Figure 3-15. RGB component image histogram of the enclosed space with condition 1 (S2C1)

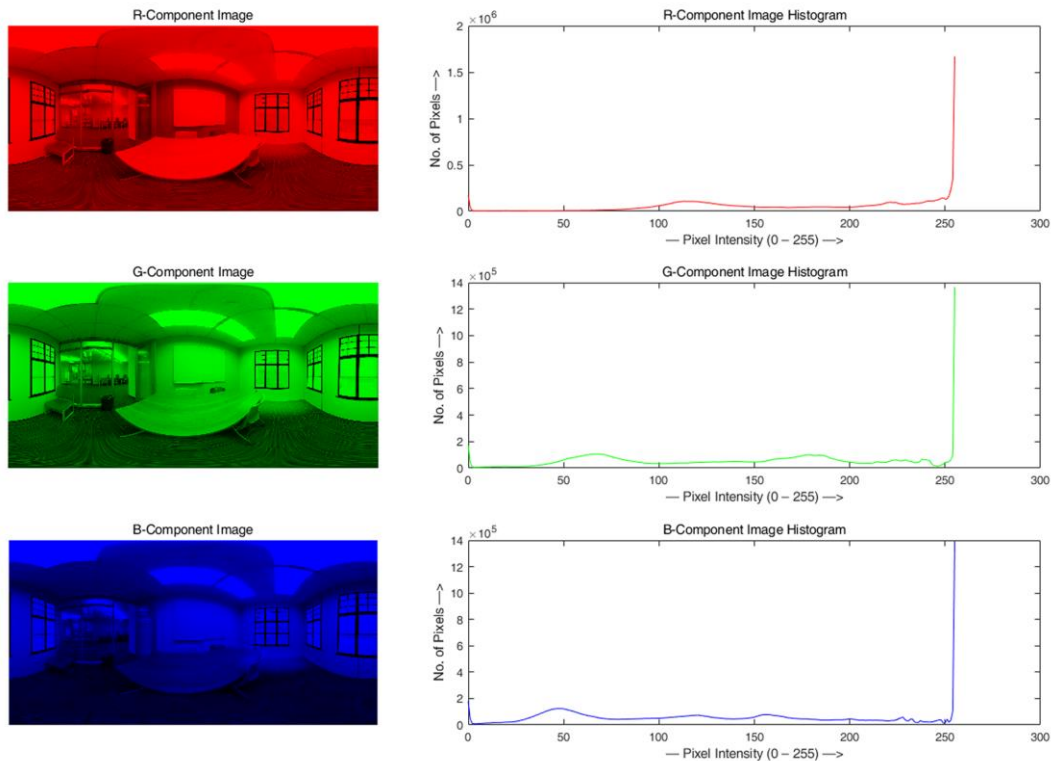


Figure 3-16. RGB component image histogram of the enclosed space with condition 2 (S2C2)

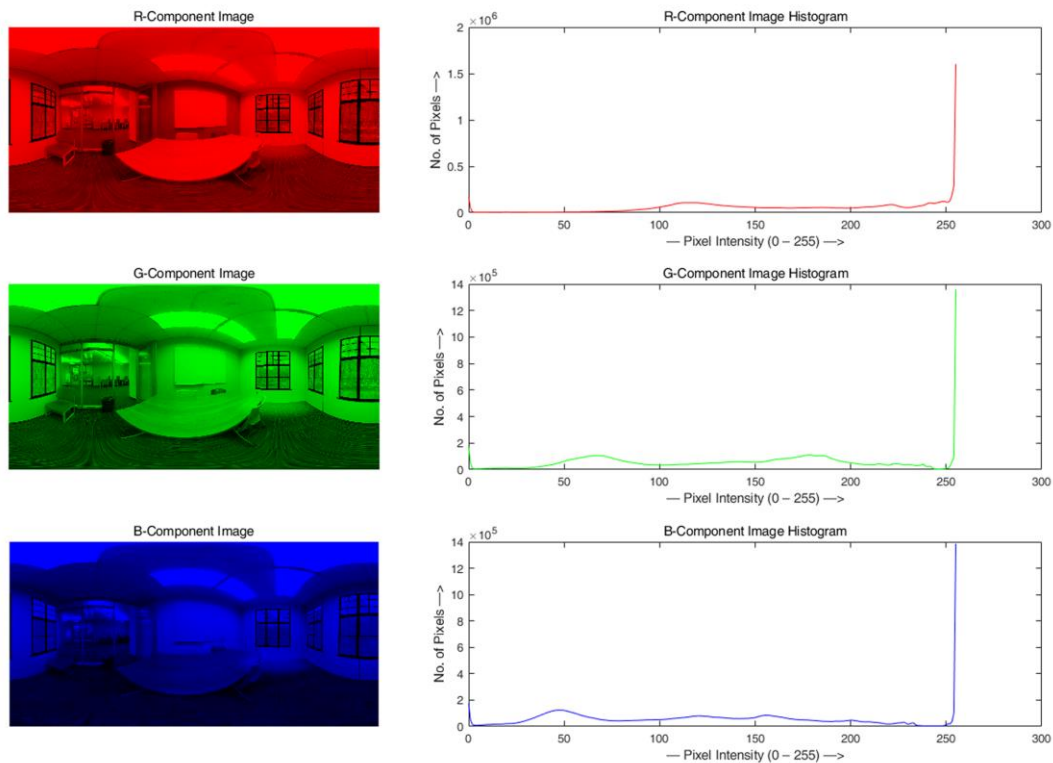


Figure 3-17. RGB component image histogram of the enclosed space with condition 3 (S2C3)

Table 3-1. RGB, XY, and Kelvin values depending on each space and condition.

|             | R value  | G value  | B value  | X value | Y value | K value |
|-------------|----------|----------|----------|---------|---------|---------|
| <b>S1C1</b> | 183.1946 | 158.5080 | 146.5241 | 0.352   | 0.347   | 4,723.1 |
| <b>S1C2</b> | 182.7399 | 158.8432 | 147.3166 | 0.350   | 0.346   | 4,774.7 |
| <b>S1C3</b> | 181.9101 | 158.0135 | 146.3581 | 0.351   | 0.347   | 4,763.1 |
| <b>S2C1</b> | 178.6077 | 140.0049 | 118.0096 | 0.387   | 0.364   | 3,719.3 |
| <b>S2C2</b> | 173.7231 | 139.7239 | 121.9468 | 0.376   | 0.358   | 3,977.2 |
| <b>S2C3</b> | 169.8517 | 135.8721 | 117.4444 | 0.379   | 0.360   | 3,913.6 |

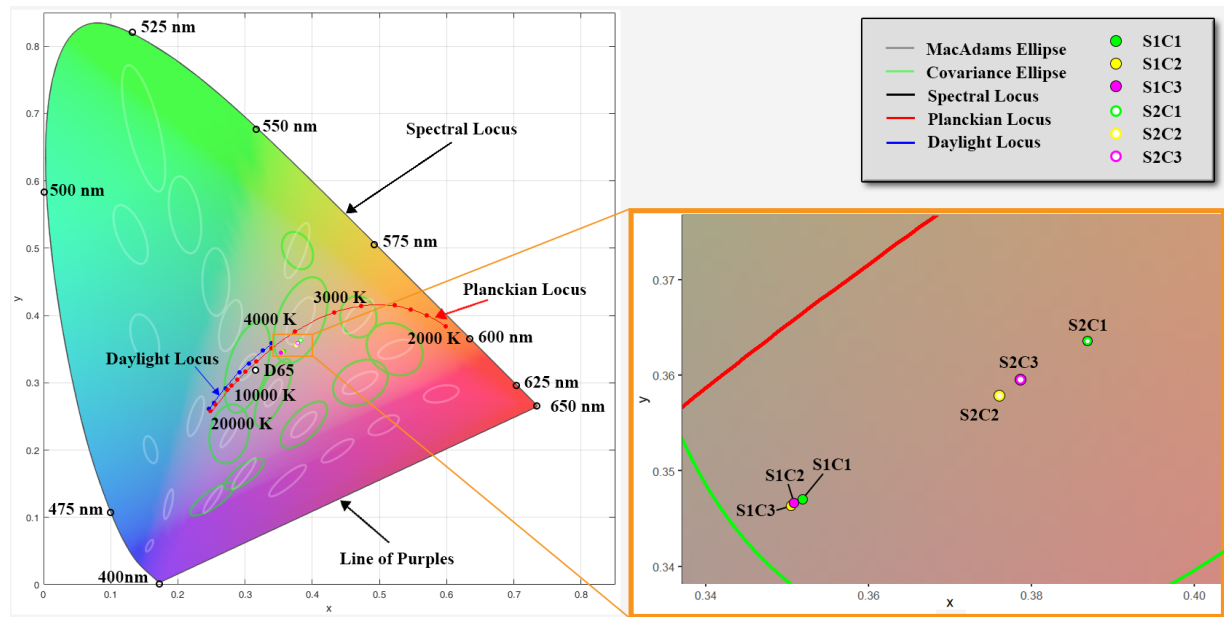


Figure 3-18. Chromaticity diagrams showing each space and condition

*Graph credited to Juntae Son*

In color vision study, MacAdam's Ellipses indicate areas within the chromaticity diagram that cannot distinguish color differences with human eyes (Wood, 2010). Therefore, the colors in the MacAdam's Ellipse areas are recognized by the human eye as the same colors. In addition, the covariance ellipses made the MacAdam's Ellipses more generalized to average human eyes (Koenderink, van Doorn, & Gegenfurtner, 2018). In this study, 6 different virtual reality

environments were clustered in the covariance ellipse, meaning that participants could not detect color differences in the 6 different virtual reality environments.

In this study, Oculus Go virtual reality headset was used to do the experiment for occupants' perception with the presence of the biomimetic window system. Virtual reality technologies can be divided into three categories depending on how hardware is connected, as summarized in Table 3-2. PC-based virtual reality headsets require connectivity between the headset and PC via cable. The first-generation headsets are Oculus Rift, HTC Vive, HTC Pro, HTC Eye, Pimax 5K & 8K, and Valve Index, while the second-generation headsets are Oculus Rift, HTC Vive Cosmos, and WMR virtual reality headsets. The second-generation headsets use an inside-out tracking method, which do not require base stations using embedded cameras. All PC-based headsets support six degrees of freedom (DOF) tracking and can be moved and rotated along three perpendicular axes. Stand-alone devices are being developed and trending due to their convenience and portability (Huang, Shakya, & Odeleye, 2019). All headsets except Oculus Go support 6 DOF. Oculus Go is a lower-end headset, so there is no embedded camera, and only 3 DOF is possible. Cell phone-based headsets fall within an entry-level virtual reality headset category and employ a mobile phone housing that can use virtual reality. Virtual reality headsets that rely on mobile phones are similar to Oculus Go, so only 3 DOF is possible. In this study, 6 DOF support was unnecessary because the study used 360-degree panoramic virtual reality. Therefore, a stand-alone device was used to provide a better environment for participants in the experiment, thereby adopting the Oculus Go headset.

In addition to this, the users feel less dizziness when experiencing virtual reality with Oculus products. Therefore, Oculus Quest and Oculus Go were tested and selected Oculus Go for the virtual reality experiment in this study. The 360 virtual reality images were added to the

Qualtrics survey system. Therefore, participants experienced virtual reality and answered questions while they are wearing the virtual reality headset (Figure 3-19).

Table 3-2. A summary of existing virtual reality headsets as of 2019

| Connection      |                                | Tracking      | Headset Devices                                                   |
|-----------------|--------------------------------|---------------|-------------------------------------------------------------------|
| PC-based        | 6 DOF<br>(position + rotation) | Base stations | Oculus Rift<br>HTC Vive/Pro/Eye<br>Pimax 5K/8K<br>Valve Index     |
|                 |                                | Inside-out    | Oculus Rift S<br>HTC Vive Cosmos<br>WMR VR Headsets               |
| Standalone      | 6 DOF<br>(position + rotation) | Inside-out    | Oculus Quest<br>HTC Vive Focus/Plus<br>Lenovo Mirage Solo         |
|                 | 3 DOF (rotation)               |               | Oculus Go                                                         |
| Cellphone-based | 3 DOF (rotation)               |               | Samsung Gear VR<br>Google Daydream<br>View<br>Generic VR headsets |

*Note.* Huang, Shakya, & Odeleye, 2019 p. 410.

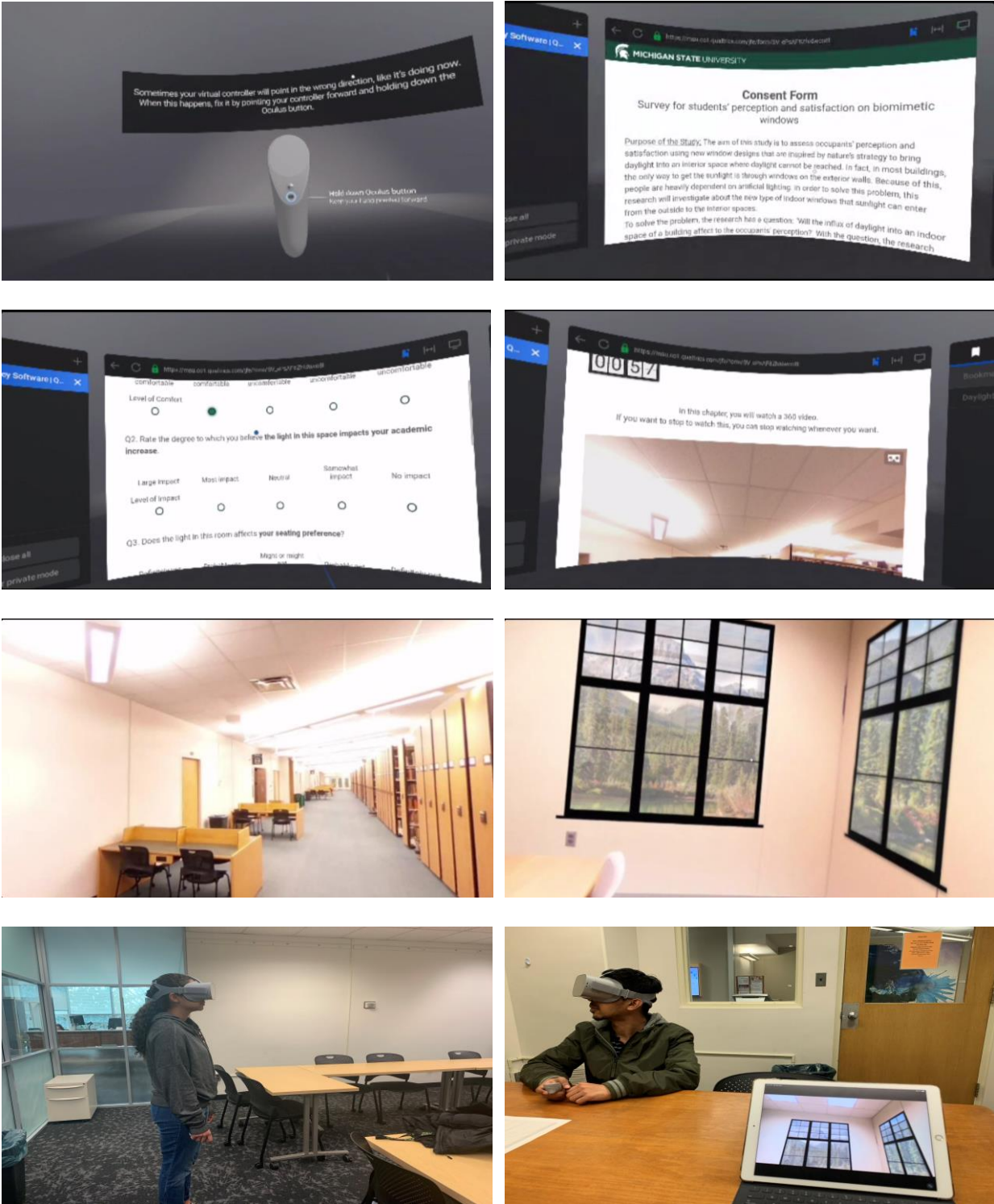


Figure 3-19. Screen-captured images of virtual reality survey and participants during the survey

*All images credited to Juntae Son*



Figure 3-20. 360 Panoramic image of condition 1 (No Window) in the open space



Figure 3-21. 360 Panoramic image of condition 2 (Biomimetic Windows with Daylight) in the open space

*All images credited to Juntae Son*



Figure 3-22. 360 Panoramic image of condition 3 (Biomimetic Windows with Daylight and View) in the open space



Figure 3-23. 360 Panoramic image of condition 1 (No Window) in the enclosed space

*All images credited to Juntae Son*



Figure 3-24. 360 Panoramic image of condition 2 (Biomimetic Windows with Daylight) in the enclosed space



Figure 3-25. 360 Panoramic image of condition 3 (Biomimetic Windows with Daylight and View) in the enclosed space

*All images credited to Juntae Son*

## **(2) Sampling and Participants**

This study targeted areas of an educational environment (i.e., the Main Library on the Michigan State University campus) where daylight cannot currently enter indoor spaces. This study thus mainly focused on an open area on a basement floor and an enclosed area of the library. The participants were undergraduate and graduate students who often used the lecture room or the study lounge located on the basement or the windowless enclosed spaces.

There are various analyses to calculate a sample size. A priori power analysis was conducted to calculate the sample size for this study to achieve a power of at least 0.80 in a one-way repeated measures ANOVA, a paired-samples t-test, and a one-way between-groups ANOVA using the software G\*Power 3.1.9.7 (Faul, Erdfelder, Buchner, & Lang, 2009; Faul, Erdfelder, Lang, & Buchner, 2007). If the power is not high enough for targeting at comparing various analytical methodologies, it is possible to achieve incorrectly the compared methods results, and the power value of 0.80 is a value generally considered the minimum desirable (Araujo & Frøyland, 2007). The priori analysis is able to compute the necessary sample size as a function of user specified values for the required significance level  $\alpha$ , the desired statistical power  $1 - \beta$  to find effect sample size (Faul et al., 2009). Power is dependent on a number of factors and is usually set at 0.80, and it means that there is a 20 percent chance of accepting the null hypothesis in error (Araujo & Frøyland, 2007).

In determining the required sample size, this study referred previous studies for a virtual reality experiment (Manzoni et al., 2016; Pulijala, Ma, Pears, Peebles, & Ayoub, 2018; Ruotolo et al., 2013; Rutter, Dahlquist, & Weiss, 2009). With effect sizes of 0.25 (medium effect for ANOVA), 0.40 (medium effect for t-test) and an alpha value of 0.05 (Cohn, 1988b), results indicated that sample sizes of 36 participants for a one-way repeated measures ANOVA, 34

participants for a paired-samples t-test, and 42 participants for a one-way between-groups ANOVA were needed. Therefore, total sample size for this study needed over 42 participants to achieve over the power value of 0.80.

This study used a flyer and email methods to recruit participants (APPENDIX G. The Flyer to Recruit Participants of Virtual Reality Experiment). The flyer was posted in Wells Hall, Engineering Building, Kedzie Hall, and the Human Ecology Building where there are transition of students from many colleges and majors through these buildings to take classes on the MSU campus. The flyer was posted from February 11th to March 24th, 2020, and emails were sent twice in March 9<sup>th</sup> and 16<sup>th</sup> to students who attend the School of Planning, Design, and Construction. Participants were able to reach an online scheduler website called Doodle Poll through a web link or a QR code in the flyer or email. Participants participated in this experiment by selecting their available time on the online scheduler website. After participants made their schedule, the experimenter sent an email with detailed information explaining this experiment is not a lab experiment and a building map of the MSU main library to visit the basement floor or enclosed space of the library.

### **(3) Study Instrument**

The questionnaire for this study was developed based on the previous studies (Freihoefer, Guerin, Martin, Kim, & Brigham, 2015; Kilic & Hasirci, 2011; Othman & Mohd Mazli, 2018), and the questions were modified for this study.

The study was conducted using a questionnaire consisting of seven parts including 6 different conditions and demographic questions. In order to measure the participants' perception of indoor environment, the participants were asked to evaluate how much light affects their seating

preference on a 1 to 5 scale where “1” meant “Definitely Not Prefer” and “5” meant “Definitely Prefer” after experience each virtual reality environment. The participants experienced six different virtual reality environments with two different spaces, an open space (S1) and an enclosed space (S2), and three different conditions, no window (C1), biomimetic windows with daylight (C2), and biomimetic windows with daylight and view (C3). Their demographic information regarding age, gender, school year, and current average studying hours also collected. In order to test hypothesis 2-3: *The more time students spend studying, the more positive perception they will have in the space with the biomimetic window system*, students were asked about their current average study hours per a day in the selection of 1) Less than an hour, 2) 1-2 hours, 3) 2-3 hours, 4) 4-5 hours, 5) 5-6 hours, 6) 6-7 hours, 7) 7-8 hours, 8) 8-9 hours, and 9) More than 9 hours.

#### **(4) Experiment Design and Procedure**

This experiment used one-group crossover repeated measure design to assess occupants’ perceptions of three different space conditions. All treatments were randomized the order of exposures. The study tested occupants’ perception using a virtual reality system using a virtual reality headset. Subjects experienced a virtual reality environment where the daylight entered through the biomimetic windows. However, various factors could affect occupants’ perception, including daylight, temperature, humidity, and outside views through windows. This study attempted to identify how daylight and outside views affect the occupants’ perception through a pilot test (Figure 3-26). Therefore, the pilot test was conducted in an enclosed area that is a small study lounge that can be occupied up to 5 people at the same time with three conditions: 1) no window, 2) biomimetic windows with daylight, and 3) biomimetic windows with daylight and

view. Participants acted as their own control group and their perception about artificial light, daylight, and views was measured through questionnaires.

After completing the pilot test, the main experiment was tested with larger number of subjects in two different spaces (Table 3-3). The study designed this experiment that all participants visited the library to experience both open and enclosed spaces in a randomized order. Both spaces were areas where windows do not currently exist. The open space on the basement floor was a public space where carrels were located and people could walk through the area as they move between areas. The enclosed space was a more private study room, and the space could accommodate up to 5 people at the same time.

At the beginning of the experiment (Figure 3-27), an experimenter introduced the experimental procedure and let participants read and sign the consent form. After that, the experimenter set up the devices and provided general instructions on safety and navigation in virtual reality environment. During this time, participants were given about 5 minutes to get familiar with the virtual reality experience. Afterwards, participants were asked about their demographic information. During the virtual reality experience, participants were randomly assigned to view three different virtual environments under one space type which was either the open space (S1) or the enclosed space (S2).

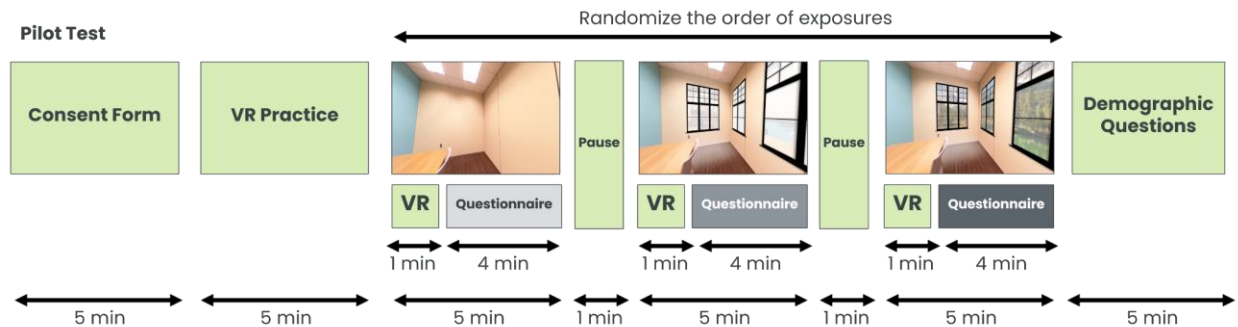


Figure 3-26. Pilot Experiment Design

*Diagram credited to Juntae Son*

In each virtual environment, participants started with a one-minute rest while seated with only the default gray background environment showing in virtual reality. This period allows their physiological conditions to stabilize. Following the period of rest, participants were virtually exposed to each different virtual environment for 60 seconds, which has been shown in previous research to be a sufficient period of time for changing acute physiological conditions (Barton & Pretty, 2010; Omidfar Sawyer & Chamilothoni, 2019; Van den Berg et al., 2015; Yin, Zhu, MacNaughton, Allen, & Spengler, 2018). They could observe the surrounding environment freely in this period. After experiencing each virtual environment, they were asked a 5-minute questionnaire about their perception of each space condition. The entire experiment required about 30 minutes (Figure 3-27). Finally, an experimenter let them know the purpose and reasons for the experiments, although they may have been guessed this during the experiment. After learning the purpose of the experiments, which was about the correlation between daylight and occupants' perception, the experimenter asked "If you have any answers you would like to change, please do so". If participants were willing to change their answers more positively, this action would be

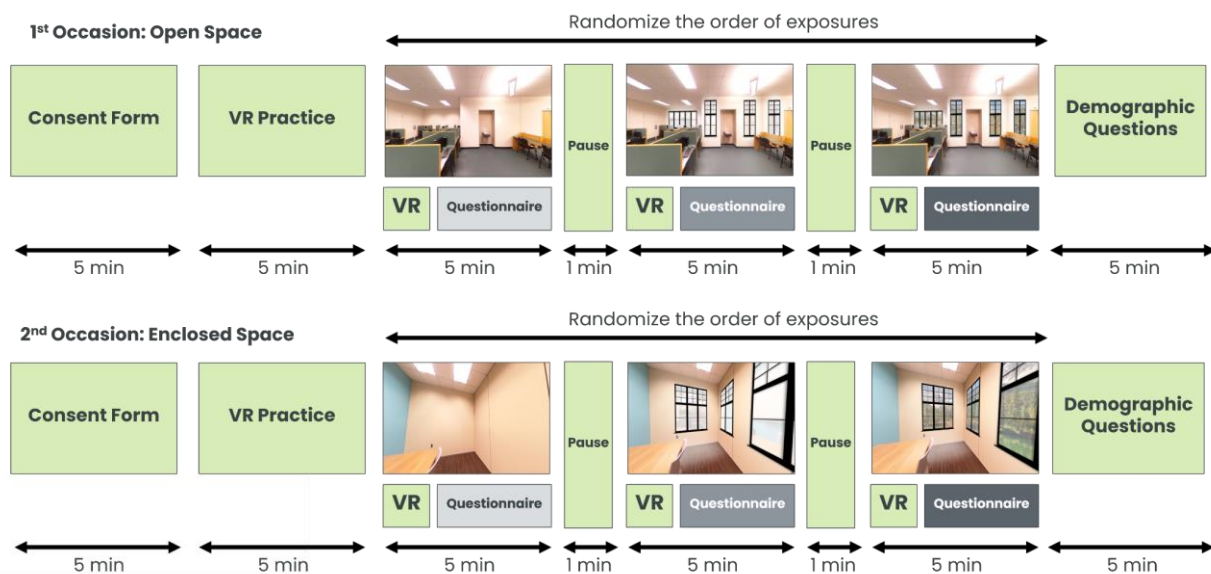


Figure 3-27. Main Experiment Design

*Diagram credited by Juntae Son*

considered to have prevented the Hawthorne effect, and the data analysis was conducted with the answers previously written. After all participants complete the experiments, the data obtained were examined by a priori power analysis. Below is the survey flow of this experiment.

Table 3-3. Three different conditions in two spaces

| Conditions                                                                  | Open Space (S1)                                                                     | Enclosed Space (S2)                                                                  |
|-----------------------------------------------------------------------------|-------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------|
| <b>No window<br/>(C1: Control)</b>                                          |    |    |
| <b>Biomimetic Windows<br/>with Daylight<br/>(C2: Experimental)</b>          |   |   |
| <b>Biomimetic Windows<br/>with Daylight and View<br/>(C3: Experimental)</b> |  |  |

*Note: All images credited to Juntae Son*

### 3.5. Experimental Validity

After building modeling using a simulation program, this study compared and analyzed the actual energy usage and the energy usage results in the simulation to determine that the building modeling was successfully modeled. Although the simulated model had about 17 percent

difference from the actual building energy consumption, it was within the range of representing the actual building energy consumption.

The study should have surveyed over 42 students using a priori power analysis. During the recruitment and experiment, Michigan State University decided to close all facilities due to the COVID-19. Therefore, all MSU buildings were closed and this experiment was suspended on March 24<sup>th</sup>. However, the study was able to recruit a total of 56 participants which was enough for the sample size of this study.

In addition, unlike the original experiment plan, participants experimented with two spaces at once, eliminating factors that might result in different answers from the two experiments. Moreover, it is difficult to experience the smell of space or ambient noise such as white noise in virtual reality, these shortcomings were supplemented by conducting the experiment in the same space as the virtual space. In addition, the experimenter sent a reminder email to the participants the day before their scheduled date. The study collected enough sample size to have power value of 0.80 to ensure that the results of this experiment were reasonable before recruiting participants. Each statistical analysis had a power value of 0.80.

## **CHAPTER 4**

### **RESULTS**

#### **4.1. Phase 1: Building Energy Simulation**

T.B. Simon Power Plant at Michigan State University has been supplying energy to the East Lansing campus from 1965. This cogeneration facility supplies electrical power and steam to the campus. From this power plant, the MSU Main Library uses steam energy. Energy consumption was predicted using DesignBuilder software since it also comes with extensive data templates for a variety of building simulation inputs such as typical envelope construction assemblies, lighting systems, and occupancy schedules. The purpose of energy simulation was to see how the energy consumption in MSU Main Library varies with and without the installation of biomimetic windows.

##### **4.1.1. Comparison Energy Consumption: A Virtual and Actual Building**

The study had conducted a pre-test by comparing between the actual library energy consumption and the simulated energy consumption using the model created in this study. In this study, three-dimensional modeling was conducted through a program called Revit based on actual library's floor plans (Figure 4-1 and Figure 4-2). The model was designed based on the actual materials of the library for its exterior wall, interior wall, and windows. Since furniture pieces do not have a significant impact on energy analysis, furniture was not placed in the 3D model. The building type was set to a library in Revit, and operating time was set to 24 hours and 7 days. Weather data for energy simulations were extracted from the weather station 7.9 miles away from East Lansing, where the library is located. This weather station collects the weather data for Lansing Capital Region Airport (Figure 4-3). The holidays of the year were automatically calculated, as these affect the calculation of energy use.

Since the actual library energy consumption showing monthly for a year, simulated energy data also extracted for a year. The library has been using steam energy for heating that is produced at the T.B. Simon Power Plant at Michigan State University and two steam absorption chillers for cooling in the summer. However, variable air volume type of HVAC using water-cooled chiller with full humidity control since the simulation program, Design Builder, does not have an exact same HVAC model. The actual data uses a unit of KLBS, the author changed it into KWH because the simulation program only shows the unit of KWH. The changed units are shown in Table 4-1. In addition, the actual library energy data shows the steam energy that include both cooling and heating energy consumption together. However, the simulation program can separate the cooling and heating energy consumption.

The actual data and the simulated data were also shown in Table 4-1, and it showed that the actual energy was consumed 83 percent of the simulated data which used more energy than the actual energy data. Therefore, further simulations could be conducted because the initial simulation had 17 percent difference in the range of 10 to 30 percent (Abdullah et al., 2014; Diamond et al., 2006; Scofield, 2009; Stoppel & Leite, 2013).

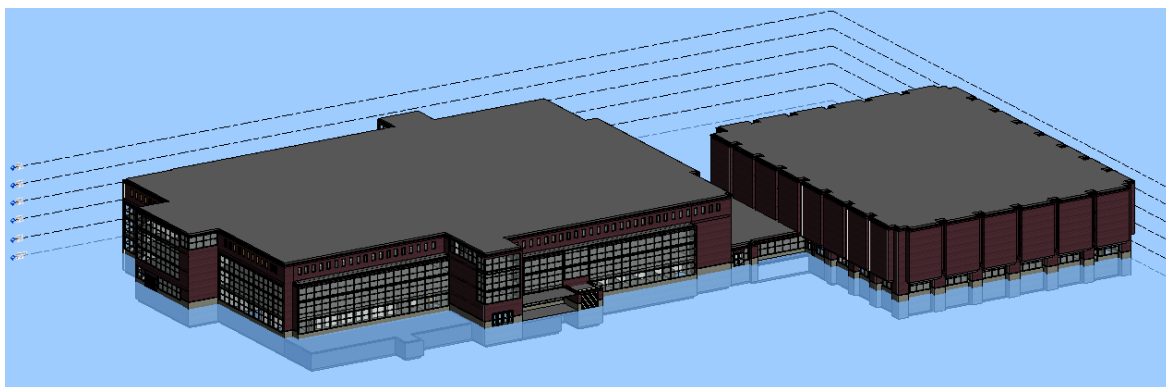


Figure 4-1. South West view of the 3D model of the MSU Main library

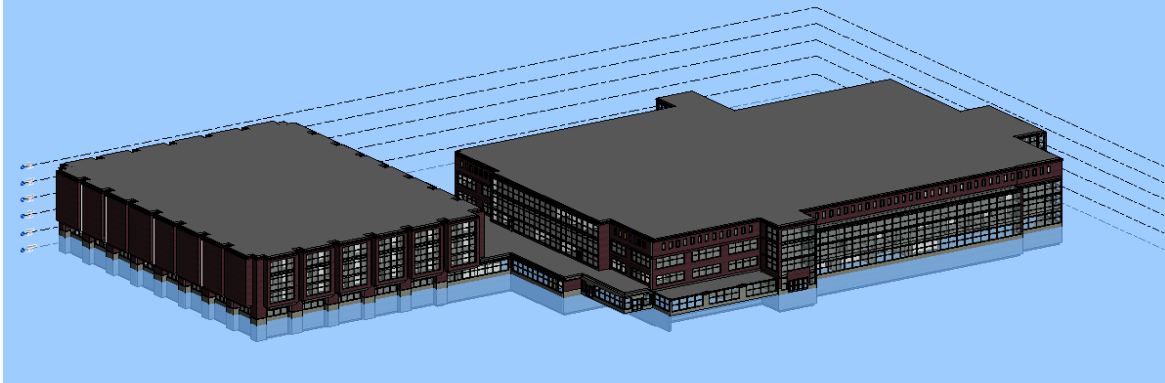


Figure 4-2. North East view of the 3D model of the MSU Main library

Location Weather and Site

Location Weather Site

Define Location by:

Internet Mapping Service

Project Address:

East Lansing, MI

Search

Weather Stations:

|                          |
|--------------------------|
| 59330 (5.60 miles away)  |
| 40670 (7.90 miles away)  |
| 40671 (7.90 miles away)  |
| 40889 (7.90 miles away)  |
| 40890 (9.70 miles away)  |
| 40451 (18.60 miles away) |

☐ Use Daylight Saving time

OK Cancel Help

Figure 4-3. The location of the weather station which is located in Lansing Capital Region Airport 7.9 miles away from the MSU Main library.

Table 4-1. Comparing the actual energy consumption data of the library with the simulated energy consumption data of the modeled library.

| Actual Energy Consumption | Month | Steam (KLBS)<br>①  | Steam (LBS)<br>②   | Steam (BTU)<br>③     | Steam (KWH)<br>④           |
|---------------------------|-------|--------------------|--------------------|----------------------|----------------------------|
|                           | Jan   | 4,800              | 4,800,400          | 4,656,388,000        | 1,364,648                  |
|                           | Feb   | 3,840              | 3,840,200          | 3,724,994,000        | 1,091,684                  |
|                           | Mar   | 4,818              | 4,818,300          | 4,673,751,000        | 1,369,736                  |
|                           | Apr   | 4,553              | 4,553,790          | 4,417,176,300        | 1,294,542                  |
|                           | May   | 9,000              | 9,000,610          | 8,730,591,700        | 2,558,675                  |
|                           | Jun   | 9,801              | 9,801,500          | 9,507,455,000        | 2,786,350                  |
|                           | Jul   | 10,729             | 10,29,400          | 10,407,518,000       | 3,050,131                  |
|                           | Aug   | 10,275             | 10,275,000         | 9,966,750,000        | 2,920,955                  |
|                           | Sep   | 8,978              | 8,978,600          | 8,709,242,000        | 2,552,418                  |
|                           | Oct   | 6,864              | 6,864,500          | 6,658,565,000        | 1,951,426                  |
|                           | Nov   | 3,966              | 3,966,990          | 3,847,980,300        | 1,127,728                  |
|                           | Dec   | 4,912              | 4,912,110          | 4,764,746,700        | 1,396,404                  |
|                           | Total | 82,541             | 82,541,400         | 80,065,158,000       | 23,464,696                 |
| Simulation Result         | Month | Heating (KWH)<br>⑤ | Cooling (KWH)<br>⑥ | Total (KWH)<br>⑦=⑤+⑥ | Energy Comparison<br>⑧=④/⑦ |
|                           | Jan   | 1,820,458          | 196                | 1,820,654            | 75%                        |
|                           | Feb   | 1,445,910          | 135                | 1,446,045            | 75%                        |
|                           | Mar   | 991,034            | 592                | 991,626              | 138%                       |
|                           | Apr   | 438,579            | 847,067            | 1,285,646            | 101%                       |
|                           | May   | 123,373            | 2,473,025          | 2,596,398            | 99%                        |
|                           | Jun   | 54,204             | 3,098,467          | 3,152,671            | 88%                        |
|                           | Jul   | 6,483              | 4,463,805          | 4,470,288            | 68%                        |
|                           | Aug   | 23,448             | 5,723,554          | 5,747,002            | 51%                        |
|                           | Sep   | 93,313             | 3,922,033          | 4,015,346            | 64%                        |
|                           | Oct   | 566,216            | 249,002            | 815,219              | 239%                       |
|                           | Nov   | 620,686            | 109,721            | 730,407              | 154%                       |
|                           | Dec   | 1,351,674          | 132                | 1,351,806            | 103%                       |
|                           | Total | 7,535,378          | 20,887,729         | 28,423,107           | 83%                        |

#### **4.1.2. Comparison Energy Consumption: The Biomimetic Windows and No Window**

To extract only the basement floor where the windows do not exist, the actual energy consumption data from the library could not be used because it included all energy consumption of the building. Therefore, a new simulation was conducted to compare the energy consumption data in the basement floor when the biomimetic window system was installed and when there was no window (Figure 4-4 and Figure 4-5). By comparing two simulated data sets focused on the basement only, the biomimetic windows could work to reduce building energy consumption (Table 4-2). The two simulation results were compared and analyzed. The cooling and heating energy for the basement floor resulted in an energy savings of about 13 percent per year. This was about \$110,519.28, because the average cost per KWH in Michigan was 13 cents in 2020 (US Energy Information Administration, 2020). If this simulation would be applied to the whole building floors, the building could save more energy and cost of energy consumption. In Table 4-2, the reduction rate in each month showed that the biomimetic window system was effective in fall and winter seasons (October to March) with the reduction rate between 18 percent to 31 percent, but it was lower in spring and summer seasons (April to September) with the reduction rate between 9 percent to 13 percent. If the biomimetic window system would be actually built in the future, the overall reduction rate would be lower than this simulated results because the actual fiber materials could have heat or light loss during the transmission. However, the simulation results showed that the building would be able to save the energy consumption annually because the amount of energy saved in fall and winter seasons was greater than that saved in spring and summer seasons.

The simulation program predicted artificial lighting energy consumption by predicting the number of occupants based on the information, such as the size and type of the building. The predicted amount of lighting energy consumption was 276,336 KWH/year. However, lighting

energy consumption was not included in this energy result because lighting energy consumption could be comparable when photosensors were installed to measure the daylight. The photosensors currently do not exist in the MSU main library, so the occupants turn the light on and off by themselves. To compare the artificial lighting energy consumption, additional photosensors should be installed in the simulation program. Since the simulation program predicted the lighting energy consumption depending on the number of occupants, however, there was no lighting energy consumption difference between the conditions without windows and with biomimetic windows. Therefore, this study compared only heating and cooling energy consumption in the MSU main library.

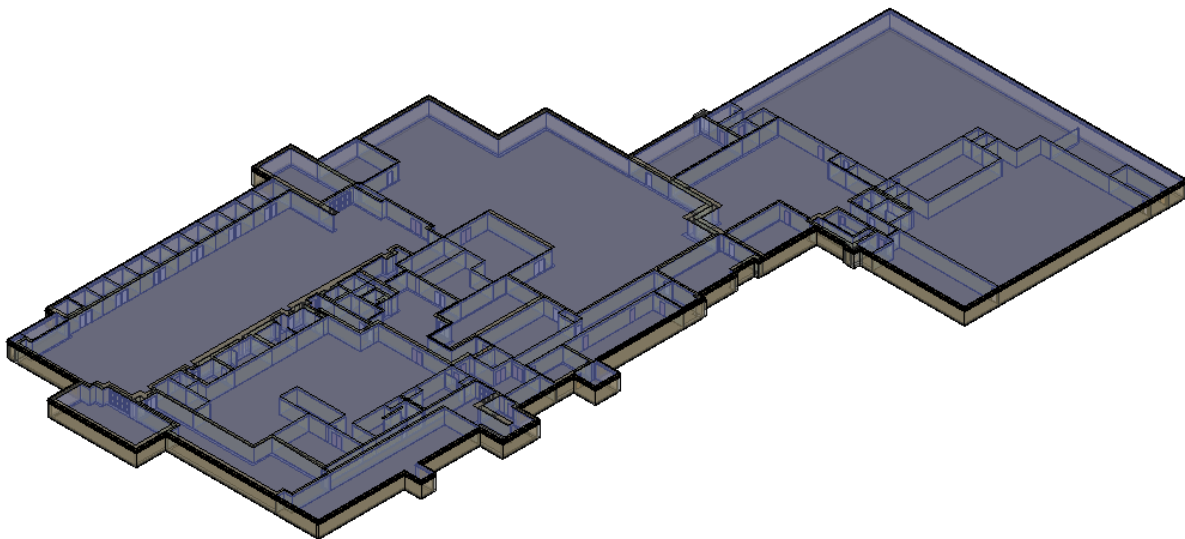


Figure 4-4. The basement floor energy model of the MSU Main library without biomimetic window system

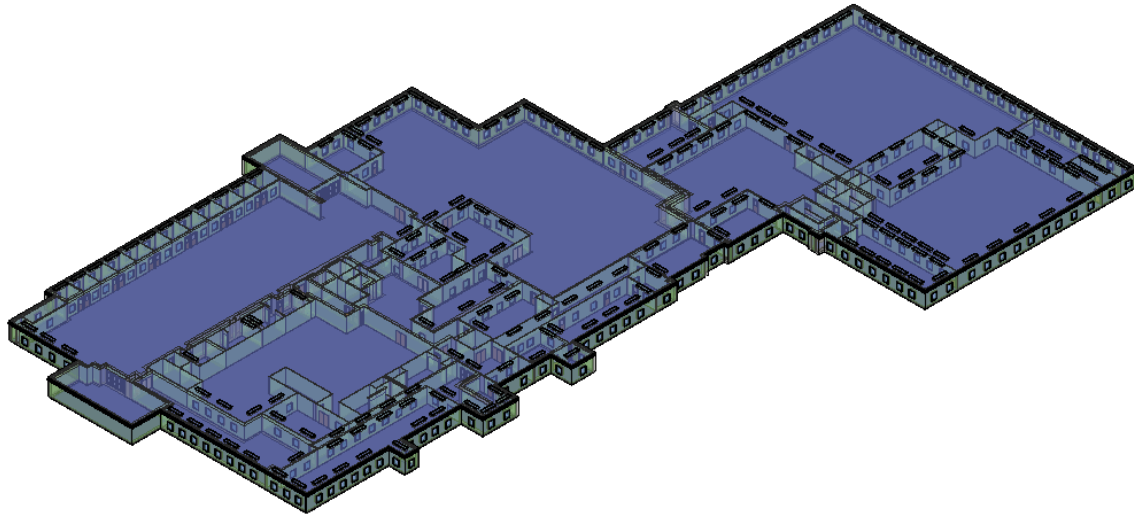


Figure 4-5. The basement floor energy model of the MSU Main library with biomimetic window system

Table 4-2. Comparing energy consumption data sets on the basement floor with the biomimetic windows and without the windows

| Month        | Without Windows<br>(KWH) | With Windows<br>(KWH) | Reduction<br>(KWH) | Reduction Rate |
|--------------|--------------------------|-----------------------|--------------------|----------------|
| Jan          | 392,589                  | 320,541               | 72,048             | 18%            |
| Feb          | 305,326                  | 248,973               | 56,353             | 18%            |
| Mar          | 218,072                  | 178,818               | 39,254             | 18%            |
| Apr          | 279,335                  | 243,513               | 35,822             | 13%            |
| May          | 605,908                  | 517,148               | 88,761             | 15%            |
| Jun          | 729,687                  | 655,034               | 74,654             | 10%            |
| Jul          | 1,011,308                | 924,571               | 86,737             | 9%             |
| Aug          | 1,301,359                | 1,179,528             | 121,831            | 9%             |
| Sep          | 915,012                  | 913,030               | 101,983            | 11%            |
| Oct          | 239,262                  | 164,130               | 75,132             | 31%            |
| Nov          | 154,002                  | 120,892               | 33,110             | 21%            |
| Dec          | 295,522                  | 231,058               | 64,465             | 22%            |
| <b>Total</b> | <b>6,447,382</b>         | <b>5,597,234</b>      | <b>850,148</b>     | <b>13%</b>     |

#### **4.1.3. Summary**

In this study, the simulation was conducted after making the 3D model which was similar to the actual building, MSU Main library. Previous studies had confirmed that the difference from 10 percent to 30 percent between a virtual model and an actual model is an acceptable range to simulate building energy (Abdullah et al., 2014; Diamond et al., 2006; Scofield, 2009; Stoppel & Leite, 2013), and this study resulted in 17 percent difference between the 3D model and the actual building. Using the 3D model, this study conducted a simulation only for the basement floor which does not have windows. When the simulation was conducted with only the basement floor, about 13 percent of energy savings came out as a result when the biomimetic window system installed. If simulations were performed on all floors, the result would show more energy-saving.

### **4.2. Phase 2: Virtual Reality and User Experience**

#### **4.2.1. Participant Profile**

Table 4-3 contains demographic data of participants in the virtual reality experiment. A total of 56 MSU students participated in the experiment, and 78.6 percent (n=44) were 16-20 years old and 21.4 percent (n=12) were 21-25 years old. Male students were 23.2 percent (n=13) with mostly female students (76.8 percent, n=43) participating in this experiment. Most of the participants were undergraduates (92.9 percent, n=52), and 7.1 percent (n=4) were graduate students. Among undergraduate students, freshmen were 16.1 percent (n=9), sophomores were 32.1 percent (n=18), juniors were 30.4 percent (n=17), and seniors were 14.3 percent (n=8). Through this experiment, students were also asked how much time they spend on studying per a

day. Students who study two to three hours a day accounted for 41.1 percent (n=23), followed by students who study three to four hours a day with 33.9 percent (n=19). About 17.9 percent (n=10) of students studied four to five hours a day, while those who studied less than two hours accounted for about 7.2 percent (n=4).

Table 4-3. Demographic data of the Virtual Reality participants

| <b>Variables</b>                   | <b>Frequency</b> | <b>Percent (%)</b> |
|------------------------------------|------------------|--------------------|
| <b>Age</b>                         |                  |                    |
| 16-20 years old                    | 44               | 78.6               |
| 21-25 years old                    | 12               | 21.4               |
| Total                              | 56               | 100                |
| <b>Gender</b>                      |                  |                    |
| Male                               | 13               | 23.2               |
| Female                             | 43               | 76.8               |
| Total                              | 56               | 100                |
| <b>Year</b>                        |                  |                    |
| Freshman                           | 9                | 16.1               |
| Sophomore                          | 18               | 32.1               |
| Junior                             | 17               | 30.4               |
| Senior                             | 8                | 14.3               |
| Graduate Student                   | 4                | 7.1                |
| Total                              | 56               | 100                |
| <b>Average Study Hours per Day</b> |                  |                    |
| Less than an hour                  | 2                | 3.6                |
| 1-2 hours                          | 2                | 3.6                |
| 2-3 hours                          | 23               | 41.1               |
| 3-4 hours                          | 19               | 33.9               |
| 4-5 hours                          | 10               | 17.9               |

|       |    |     |
|-------|----|-----|
| Total | 56 | 100 |
|-------|----|-----|

#### 4.2.2. One-way ANOVA Results for Participant Perceptions on Space Conditions

Participants' perception of three space conditions were measured by asking their seating preferences. Participants answered using the Likert scale for their seating preferences. Therefore, the higher the score, the higher their seating preference. A one-way repeated measures ANOVA was conducted to compare scores on the seating preference based on three space conditions: 1) No window, 2) Biomimetic Windows with Daylight, and 3) Biomimetic windows with Daylight and View. The means and standard deviations are presented in Table 4-4. In Table 4-4 오류! 참조

원본을 찾을 수 없습니다., the mean values were higher when the biomimetic window system was installed ( $M = 3.2500$  and  $M = 3.4643$ ) than when there was no window ( $M = 1.4643$ ). The participants tended to have stronger seating preferences when the daylight entered into the interior space. In addition, if participants were able to see the views through the windows as well as light, their preference was slightly higher. There was a significant effect for conditions in the open space at MSU Main library, Wilks' Lambda = 0.155,  $F(2, 54) = 146.694$ ,  $p < .001$ , multivariate partial eta squared = 0.845.

In Table 4-4, the mean values of the participant seating preference were higher when the biomimetic window system was installed. It can also be said that their preference was slightly higher when they could see the view via windows as well as the daylight. There was a significant effect for conditions in the enclosed space at MSU Main library, Wilks' Lambda = 0.028,  $F(2, 54) = 950.561$ ,  $< 0.001$ , multivariate partial eta squared = 0.972. However, the results of Post-Hoc test showed that there was no significant difference between the condition of the biomimetic windows with daylight and the condition of the biomimetic windows with daylight and view (Table 4-5).

When the mean values in Table 4-4 are compared, this study found that the participants preferred the enclosed space to the open space in the library. When there were no windows, the preference for the opens space ( $M = 1.4643$ ) was slightly higher than for the enclosed space ( $M = 1.2857$ ). However, if the biomimetic window system was installed and they could feel the daylight and see the view through the window, their seating preference was higher for the enclosed space ( $M = 4.3571$ ) than for the open space ( $M = 3.4643$ ). The preference based on spaces was examined in more detail using *t*-test in Chapter 4.2.3.

Table 4-5. One-way repeated measured ANOVA with Post-Hoc test

| Factor | Factor | Mean Difference | Std. Error | Sig.  | Factor | Factor | Mean Difference | Std. Error | Sig.  |
|--------|--------|-----------------|------------|-------|--------|--------|-----------------|------------|-------|
| S1C1   | S1C2   | -1.78571*       | 0.13023    | 0.000 | S2C1   | S1C1   | -0.17857        | 0.10953    | 0.579 |
|        | S1C3   | -2.00000*       | 0.13023    | 0.000 |        | S1C2   | -1.96429*       | 0.10953    | 0.000 |
|        | S2C1   | 0.17857         | 0.10953    | 0.579 |        | S1C3   | -2.17857*       | 0.10953    | 0.000 |
|        | S2C2   | -2.71429*       | 0.10953    | 0.000 |        | S2C2   | -2.89286*       | 0.08387    | 0.000 |
|        | S2C3   | -2.89286*       | 0.10953    | 0.000 |        | S2C3   | -3.07143*       | 0.08387    | 0.000 |
| S1C2   | S1C1   | 1.78571*        | 0.13023    | 0.000 | S2C2   | S1C1   | 2.71429*        | 0.10953    | 0.000 |
|        | S1C3   | -0.21429        | 0.13023    | 0.230 |        | S1C2   | 0.92857*        | 0.10953    | 0.000 |
|        | S2C1   | 1.96429*        | 0.10953    | 0.000 |        | S1C3   | 0.71429*        | 0.10953    | 0.000 |
|        | S2C2   | -0.92857*       | 0.10953    | 0.000 |        | S2C1   | 2.89286*        | 0.08387    | 0.000 |
|        | S2C3   | -1.10714*       | 0.10953    | 0.000 |        | S2C3   | -0.17857        | 0.08387    | 0.087 |
| S1C3   | S1C1   | 2.00000*        | 0.13023    | 0.000 | S2C3   | S1C1   | 2.89286*        | 0.10953    | 0.000 |
|        | S1C2   | 0.21429         | 0.13023    | 0.230 |        | S1C2   | 1.10714*        | 0.10953    | 0.000 |
|        | S2C1   | 2.17857*        | 0.10953    | 0.000 |        | S1C3   | 0.89286*        | 0.10953    | 0.000 |
|        | S2C2   | -0.71429*       | 0.10953    | 0.000 |        | S2C1   | 3.07143*        | 0.08387    | 0.000 |

|      |           |         |       |      |         |         |       |
|------|-----------|---------|-------|------|---------|---------|-------|
| S2C3 | -0.89286* | 0.10953 | 0.000 | S2C2 | 0.17857 | 0.08387 | 0.087 |
|------|-----------|---------|-------|------|---------|---------|-------|

*Note.* In the Factor column, S1 (Space 1) means “Open Space” and S2 (Space 2) means “Enclosed Space”. C1 (Condition 1) means “No Window”, C2 (Condition 2) means “Biomimetic Windows with Daylight”, and C3 (Condition 3) means “Biomimetic Windows with Daylight and View”.

\* The mean difference is significant at the 0.05 level.

#### *t*-test Results for Seating Preference based on the Types of Spaces.

In this study, the *p*-value was less than 0.05; therefore, this study could conclude that there was a statistically significant effect for each condition. Partial Eta Squared value obtained in this study are 0.845 and 0.972 in each space type. Using the commonly used guidelines proposed by Cohn (1988a), the author reported that if the value is 0.01, it was a small effect size. In addition, if the value was 0.06 and more than 0.14, they had moderate and large effect size respectively. Therefore, the results of this study suggested a very large effect size.

Table 4-4. One-way repeated measured ANOVA results

| Space Type     | Condition                                 | N  | Mean   | SD      | F       | Sig.  | Partial Eta Squared |
|----------------|-------------------------------------------|----|--------|---------|---------|-------|---------------------|
| Open Space     | No Window                                 | 56 | 1.4643 | 0.50324 | 146.694 | 0.000 | 0.845               |
|                | Biomimetic Windows with Daylight          | 56 | 3.2500 | 0.66742 |         |       |                     |
|                | Biomimetic Windows with Daylight and View | 56 | 3.4643 | 0.85204 |         |       |                     |
| Enclosed Space | No Window                                 | 56 | 1.2857 | 0.45584 | 950.561 | 0.000 | 0.972               |
|                | Biomimetic Windows with Daylight          | 56 | 4.1786 | 0.38646 |         |       |                     |
|                | Biomimetic Windows with Daylight and View | 56 | 4.3571 | 0.48349 |         |       |                     |

Table 4-5. One-way repeated measured ANOVA with Post-Hoc test

| Factor | Factor | Mean Difference | Std. Error | Sig. | Factor | Factor | Mean Difference | Std. Error | Sig. |
|--------|--------|-----------------|------------|------|--------|--------|-----------------|------------|------|
|--------|--------|-----------------|------------|------|--------|--------|-----------------|------------|------|

|      |      |           |         |       |      |      |           |         |       |
|------|------|-----------|---------|-------|------|------|-----------|---------|-------|
| S1C1 | S1C2 | -1.78571* | 0.13023 | 0.000 | S2C1 | S1C1 | -0.17857  | 0.10953 | 0.579 |
|      | S1C3 | -2.00000* | 0.13023 | 0.000 |      | S1C2 | -1.96429* | 0.10953 | 0.000 |
|      | S2C1 | 0.17857   | 0.10953 | 0.579 |      | S1C3 | -2.17857* | 0.10953 | 0.000 |
|      | S2C2 | -2.71429* | 0.10953 | 0.000 |      | S2C2 | -2.89286* | 0.08387 | 0.000 |
|      | S2C3 | -2.89286* | 0.10953 | 0.000 |      | S2C3 | -3.07143* | 0.08387 | 0.000 |
| S1C2 | S1C1 | 1.78571*  | 0.13023 | 0.000 | S2C2 | S1C1 | 2.71429*  | 0.10953 | 0.000 |
|      | S1C3 | -0.21429  | 0.13023 | 0.230 |      | S1C2 | 0.92857*  | 0.10953 | 0.000 |
|      | S2C1 | 1.96429*  | 0.10953 | 0.000 |      | S1C3 | 0.71429*  | 0.10953 | 0.000 |
|      | S2C2 | -0.92857* | 0.10953 | 0.000 |      | S2C1 | 2.89286*  | 0.08387 | 0.000 |
|      | S2C3 | -1.10714* | 0.10953 | 0.000 |      | S2C3 | -0.17857  | 0.08387 | 0.087 |
| S1C3 | S1C1 | 2.00000*  | 0.13023 | 0.000 | S2C3 | S1C1 | 2.89286*  | 0.10953 | 0.000 |
|      | S1C2 | 0.21429   | 0.13023 | 0.230 |      | S1C2 | 1.10714*  | 0.10953 | 0.000 |
|      | S2C1 | 2.17857*  | 0.10953 | 0.000 |      | S1C3 | 0.89286*  | 0.10953 | 0.000 |
|      | S2C2 | -0.71429* | 0.10953 | 0.000 |      | S2C1 | 3.07143*  | 0.08387 | 0.000 |
|      | S2C3 | -0.89286* | 0.10953 | 0.000 |      | S2C2 | 0.17857   | 0.08387 | 0.087 |

*Note.* In the Factor column, S1 (Space 1) means “Open Space” and S2 (Space 2) means “Enclosed Space”. C1 (Condition 1) means “No Window”, C2 (Condition 2) means “Biomimetic Windows with Daylight”, and C3 (Condition 3) means “Biomimetic Windows with Daylight and View”.

\* The mean difference is significant at the 0.05 level.

#### 4.2.3. *t*-test Results for Seating Preference based on the Types of Spaces

A paired-samples *t*-test was conducted to evaluate students’ seating preference between the open space and the enclosed space. There was a statistically significant decrease in seating preference scores of no window condition from the open space ( $M = 1.4643, SD = 0.50324$ ) to the enclosed space ( $M = 1.2857, SD = 1.2857$ ). However, when comparing the two different

spaces using *t*-test, the *p*-value (0.067) was greater than 0.05 in Table 4-6. If this value was greater than 0.05, this study could conclude that there was no significant difference between two spaces.

However, there was a statistically significant increase in seating preference scores of Biomimetic Windows with Daylight from the open space ( $M = 3.2500, SD = 0.66742$ ) to the enclosed space ( $M = 4.1786, SD = 0.38646$ ),  $t(55) = 8.391, p < 0.001$  (*two – tailed*). In addition, when comparing seating preference scores of Biomimetic Windows with Daylight and View from the open space ( $M = 3.4643, SD = 0.8524$ ) to the enclosed space ( $M = 4.3571, SD = 0.48349$ ),  $t(55) = 7.525, p < 0.001$  (*two – tailed*), the *p*-values which was Sig.(two-tailed) were less than 0.05, and this study could conclude that there was a significant difference in these two conditions between two spaces.

The mean increase in seating preferences of the condition of Biomimetic Windows with Daylight was 0.92857 with a 95% confidence interval ranging from (-)1.15033 to (-)0.70681. The eta squared statistic (0.56) indicated a large effect size. In addition, the mean increase in seating preferences of the condition of Biomimetic Windows with Daylight and View was 0.89286 with a 95% confidence interval ranging from (-)1.13063 to (-)0.65508. The eta squared statistic (0.51) indicated a large effect size.

To sum up, students' seating preferences did not vary much from an open space to an enclosed space when there is no window. However, if the biomimetic window system was installed, they preferred an enclosed space to an open space. This indicated when the biomimetic window system would be considered to install in the future, the system should be installed in enclosed spaces first to increase the preference of the occupants.

Table 4-6. Paired differences results comparing seating preferences between open and enclosed spaces

| Condition                                 | Space          | Paired Differences |               |           |           |                 |
|-------------------------------------------|----------------|--------------------|---------------|-----------|-----------|-----------------|
|                                           |                | Mean Difference    | SD Error Mean | <i>t</i>  | <i>df</i> | Sig. (2-tailed) |
| No Window                                 | Open Space     | 0.17857            | 0.09571       | 1.866     | 55        | 0.067           |
|                                           | Enclosed Space |                    |               |           |           |                 |
| Biomimetic Windows with Daylight          | Open Space     | (-) 0.92857        | 0.11066       | (-) 8.391 | 55        | 0.000           |
|                                           | Enclosed Space |                    |               |           |           |                 |
| Biomimetic Windows with Daylight and View | Open Space     | (-) 0.89286        | 0.11865       | (-) 7.525 | 55        | 0.000           |
|                                           | Enclosed Space |                    |               |           |           |                 |

#### 4.2.4. One-way ANOVA Results for Seating Preference based on Study Time

A one-way between-groups ANOVA was conducted to explore the seating preference, as measured by the virtual reality experiment. Participants were divided into two groups according to their current average study time (Group 1: 0 to 3 hours and Group 2: 3 to 5 hours). The average study time was answered on five different categories when students conducted the survey: 1) Less than an hour, 2) 1-2 hours, 3) 2-3 hours, 4) 3-4 hours, and 5) 4-5 hours. However, there were not enough respondents to some of categories, so the students were divided into two groups for this statistical analysis. A statistical analysis of the results with five groups can be found on APPENDIX B. ANOVA with Post-Hoc test.

At first, the author assumed that the longer students' study time, the higher their preference. The results showed that the mean values of students' seating preferences were not much different based on their average study time. The result of S1C1 which was the open space with no window showed that the students who study less than 3 hours had the mean value of 1.4815, and the students who study more than 3 hours had the mean value of 1.4483. Like the result of S1C1, the result of S2C1 which was the enclosed space with no window showed that the student who study

less than 3 hours had the mean value of 1.2222, and the students who study more than 3 hours had the mean value of 1.3448. However, the mean values of the seating preference when the biomimetic window system was installed in both open and enclosed spaces were higher than when there was no window. The factors of S1C2, S1C3, S2C2, and S2C3 were the virtual reality environments that the biomimetic window system was installed. In these virtual reality environments, students' seating preferences ranged between 2.2222 and 4.3704, but there were no significant differences between the students who study less than 3 hours and the ones who study more than 3 hours.

Table 4-7 gave both between-groups and within-groups sums of squares, degrees of freedom, mean square, F-value, and significant value ( $p$ -value). If the  $p$ -value was less than or equal to 0.05, there was a significant difference somewhere among the mean scores. The results of ANOVA with Post-Hoc test showed that the  $p$ -values (Sig.) of all spaces and conditions were higher than 0.05 except the factor, S1C3, with  $p$ -value of 0.039. It means that there was a statistically significant difference at the  $p < 0.05$  level in the open space with the condition of biomimetic windows with daylight and view:  $F(1, 54) = 4.474, p = 0.039$ .

In this study, however, most dependent variables for the two groups had  $p$ -values more than 0.05. Therefore, it could be seen that students' average study time was not affected by their preferences through the biomimetic window system in those spaces.

Table 4-7. ANOVA with Post-Hoc test results using current students' average study time

| Factor      | Time | N  | Mean   | SD     |                | Sum of Squares | df | Mean Square | F     | Sig.  |
|-------------|------|----|--------|--------|----------------|----------------|----|-------------|-------|-------|
| <b>S1C1</b> | 0-3h | 27 | 1.4815 | .50918 | Between Groups | 0.015          | 1  | 0.015       | 0.060 | 0.808 |
|             | 3-5h | 29 | 1.4483 | .50612 | Within Groups  | 13.913         | 54 | 0.258       |       |       |
| <b>S1C2</b> | 0-3h | 27 | 3.2963 | .72403 | Between Groups | 0.112          | 1  | 0.112       | 0.247 | 0.621 |
|             | 3-5h | 29 | 3.2069 | .61987 | Within Groups  | 24.388         | 54 | 0.452       |       |       |
| <b>S1C3</b> | 0-3h | 27 | 2.2222 | .64051 | Between Groups | 3.055          | 1  | 3.055       | 4.474 | 0.039 |
|             | 3-5h | 29 | 3.6897 | .96745 | Within Groups  | 36.874         | 54 | 0.683       |       |       |
| <b>S2C1</b> | 0-3h | 27 | 1.2222 | .42366 | Between Groups | 0.210          | 1  | 0.210       | 1.012 | 0.319 |
|             | 3-5h | 29 | 1.3448 | .48373 | Within Groups  | 11.218         | 54 | 0.208       |       |       |
| <b>S2C2</b> | 0-3h | 27 | 4.2222 | .42366 | Between Groups | 0.099          | 1  | 0.099       | 0.661 | 0.420 |
|             | 3-5h | 29 | 4.1379 | .35093 | Within Groups  | 8.115          | 54 | 0.150       |       |       |
| <b>S2C3</b> | 0-3h | 27 | 4.3704 | .49210 | Between Groups | 0.009          | 1  | 0.009       | 0.038 | 0.845 |
|             | 3-5h | 29 | 4.3448 | .48373 | Within Groups  | 12.848         | 54 | 0.238       |       |       |

*Note.* In the Factor column, S1 (Space 1) means “Open Space” and S2 (Space 2) means “Enclosed Space”. C1 (Condition 1) means “No Window”, C2 (Condition 2) means “Biomimetic Windows with Daylight”, and C3 (Condition 3) means “Biomimetic Windows with Daylight and View”.

#### 4.2.5. Summary and Discussions

In this study, a total of 56 MSU students participated in the experiment for user experience through virtual reality. Most of the students were undergraduates, with a large proportion of women. In addition, seventy-five percent of these students studied two to four hours a day.

The first results from this study were one-way repeated measures ANOVA to see how students' preferences change when the biomimetic window system was installed. As a result, students were more satisfied with the room where the daylight entered through the biomimetic window system than where window did not exist. It also showed slightly greater perception when the daylight and the view were seen together than when only the daylight entered the room.

The second result from this study was come up by conducting a pared samples *t*-test to identify the students' preferred space when the biomimetic window system was installed. In this study, open space and enclosed space were compared. When there was no window, the *p*-value was higher than 0.05, indicating that there was no significant difference in students' preferences. However, when the biomimetic window system was installed, students preferred the enclosed space over the open space. This suggested that the biomimetic window system should be installed in the encased space first, assuming that the biomimetic window system will be installed later.

The third result from this study was one-way between-groups ANOVA to find out how students' current average study hours and their preferences differ. As a result, the *p*-values of the data were higher than 0.05, so the students' preference of the spaces according to their average study time was not correlated.

### 4.3. Results of Hypotheses Testing

This study began with two main hypotheses. The first was that biomimetic windows can reduce energy consumption, and the second was that biomimetic windows can increase the positive perception of students in learning environments. To test the first hypothesis, this study conducted a simulation by computerizing models with the actual MSU main library, and demonstrated that the biomimetic window system proposed in this study brought the results in about 13 percent in energy savings. To test the second hypothesis, the study conducted a virtual reality survey of 56 MSU students. The one-way repeated measures ANOVA was conducted to see how students' preferences are different among three space conditions. As a result, students preferred the room where the daylight entered through the biomimetic window system more than where window does not exist. Students also showed that they preferred the enclosed space more than in the open space when the biomimetic window system was installed. When there was no window, the  $p$ -value was higher than 0.05, indicating that there was no significant difference in students' preferences. However, when the biomimetic window system was installed, students preferred the enclosed space over the open space. Finally, this study examined for differences in perception of spaces or conditions depending on the current study time of the students. The  $p$ -values of the data were higher than 0.05, so the statistical evidence was not strong. But, the average values of the students' preference still showed that they tended to prefer the spaces with biomimetic window than the spaces with no window.

To sum up, the first hypothesis was demonstrated by the simulation results that the biomimetic window system can help reduce the energy consumption in learning environments. In addition, this study proved that students prefer the space with biomimetic windows and the

enclosed space through the virtual reality survey. However, there was weak relationship between students' average study time and their perception with spaces.

Table 4-8. Results of Hypotheses Tests

| Hypotheses                                                                                    |                                                                                                                                                       | Results                                                   |
|-----------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------|
| <i>H1. Biomimetic windows can reduce energy consumption.</i>                                  |                                                                                                                                                       | Supported                                                 |
| <i>H2. Biomimetic windows can affect the perception of students in learning environments.</i> |                                                                                                                                                       |                                                           |
| H2-1.                                                                                         | <i>There are significant differences in seating preferences among three space conditions.</i>                                                         | Supported                                                 |
| H2-2.                                                                                         | <i>There are significant differences in seating preferences between open space and enclosed space when the biomimetic window system is installed.</i> | Supported                                                 |
| H2-3.                                                                                         | <i>The more time students spend studying, the more positive perception they will have in the space with the biomimetic window system.</i>             | Not significantly supported, but showed some relationship |

## CHAPTER 5

### SUMMARY AND CONCLUSION

#### 5.1. Summary of the Research

The purpose of this study was to examine the energy consumption and occupants' perception by using strategies that adopt the characteristics of nature called biomimetic solutions designed to bring daylight into an interior space in educational buildings where daylight cannot reach. Specifically, this study investigated how the daylight achieved via biomimetic windows affected students' perception in educational spaces. This research proposed an interior lighting solution using a biomimetic approach and investigated the biomimetic windows where sunlight can enter from the interior walls inspired by features of polar bears' fur.

Prior to deciding on the solution based on polar bears, this study examined various animal and plant behavior. Using the strategies of various plants and animals, humans can achieve solutions in terms of thermal regulation, water efficiency, water collection, insulation/conserving heat, dynamic behavior, and communication. Among them, this study was inspired by polar bears and studied how to bring daylight into a building to reduce building energy consumption and

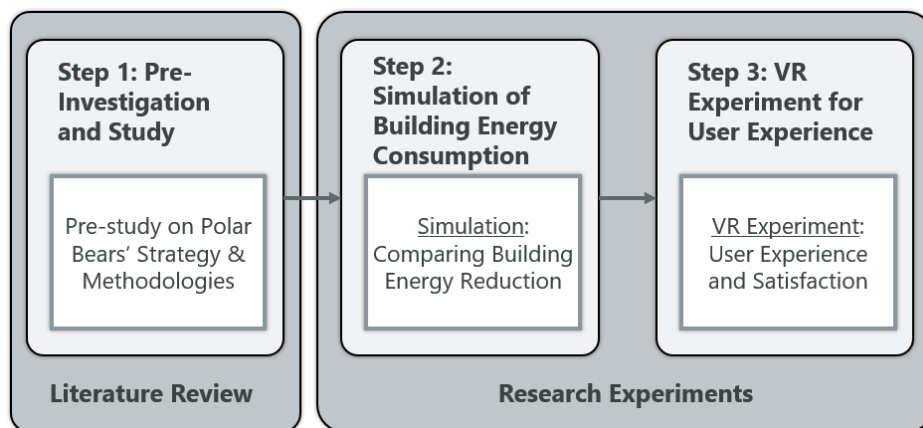


Figure 5-1. Summary of the Research

*Diagram credited to Juntae Son*

improve occupants' perception. The experiments of this study were divided into two parts; the first part conducted building energy simulation and assessment while the second part conducted the virtual reality experiment to determine occupants' perception when the biomimetic windows were installed.

## **5.2. Summary of Findings**

The study conducted a pre-test by comparing between the actual library energy consumption and the simulated energy consumption using the 3D model created in this study. The model was designed with the actual materials of the library for its exterior wall, interior wall, and windows. By comparing the actual model and the 3D model for simulation, the result shows that the actual energy was consumed 83 percent of the simulated data. Therefore, further simulations can be conducted because the initial simulation has 17 percent difference in the range of 10 to 30 percent which is reasonable difference to conduct simulations (Abdullah et al., 2014; Diamond et al., 2006; Scofield, 2009; Stoppel & Leite, 2013).

After created and assessed the 3D model, new simulations were conducted to see the results of the building energy consumption when the biomimetic window system was installed and when no window existed. By comparing two simulated data sets, the biomimetic window system could work for reducing building energy consumption. The cooling and heating energy for the basement floor resulted in energy savings of about 13 percent per year. This was about \$110,519.28, because the average cost per KWH in Michigan is 13 cents in 2020 (US Energy Information Administration, 2020). If this simulation would be applied to the whole building floors, the building could save more energy and cost of energy consumption.

In this study, a total of 56 MSU students participated in the experiment for user experience through virtual reality. Most of the students were undergraduates, with a large proportion of women. In addition, seventy-five percent of these students studied two to four hours a day.

The first result from this study was one-way repeated measures ANOVA to see how students' preferences change when the biomimetic window system was installed. As a result, students were more satisfied with the room where the daylight entered through the biomimetic window system than where window did not exist. It also showed slightly positive perception when the daylight and the view were seen together than when only the daylight entered the room.

The second result from this study was come up by conducting a pared samples *t*-test to identify the students' preferred space when the biomimetic window system was installed. In this study, open space and enclosed space were compared. When there was no window, the *p*-value was higher than 0.05, indicating that there was no significant difference in students' preferences. However, when the biomimetic window system was installed, students preferred the enclosed space over the open space. This suggested that the biomimetic window system should be installed in the encased space first, assuming that the biomimetic window system will be installed later.

The third result from this study was one-way between-groups ANOVA to find out how students' current average study hours and their preferences differed. As a result, the *p*-values of the data were higher than 0.05, so the students' preference of the spaces according to their average study time was not correlated.

### **5.3. Conclusion**

As mentioned in the introduction, people spend most of their time indoors. As a result, the amount of energy used in buildings has been steadily increasing. However, no research has sought

to improve occupants' perception while reducing energy use. Therefore, this study conducted experiments using simulations and virtual reality on how to bring daylight indoors using a biomimicry method inspired by the fur of polar bears. Through the simulations, this study confirmed that the amount of energy used in buildings can be reduced enough by bringing daylight through the biomimetic window system into the interior of educational buildings. In addition, the seating preference of students in studying and lounge areas varied depending on the interior environment, but the results of their seating preference were better in the space where the biomimetic window system was installed. Students preferred the enclosed study area with the biomimetic window system and their perceptions were improved by daylight through the window system.

This study could contribute practical and theoretical ways. First, this research had an effect on the occupants' perception, especially their seating preference in educational settings by implementing biomimetic window system. The lack of natural light and view was the greatest concern related to the educational spaces. This study created a virtual biomimetic window system that does not exist as a real model and looked at how the perception of the students would change if it existed. Since many people spend a considerable amount of time indoors in the building, a new way to increase perception within the building has been suggested.

The study contributed to the integrated passive and active system with the biomimetic design for the future applications. There are currently a variety of mechanical methods for reducing building energy, but ultimately, these are the ways that energy is continuously consumed. Therefore, this study researched how less energy consumed in buildings by applying a new integrated passive and active system. An integrated passive and active energy control system that utilizes biomimetic solutions in buildings has emerged as the key solution to reducing energy

consumption. To maximize energy efficiency in man-made settings, it is important to understand the principles of nature in terms of energy preservation. This study focused on suggesting a biomimetic method for applying natural lighting and thermal transmission in the building. This input in the built environment had a significant impact on occupants' perception and their productivity in buildings.

This study assisted interior architects and construction managers with developing interior layout and building orientation to improve daylight efficiency in educational spaces. Contemporary interior spaces on the basement floor do not receive enough daylight, but biomimetic windows allow daylight to reach to all interior spaces. Optimally, the long sides of the building should be facing to the north in the southern hemisphere and to the south in the northern hemisphere. However, buildings with biomimetic windows can be oriented in any position.

Lastly, this study proposed and tested a new method using biomimicry strategy. This study adopted one of the biomimicry strategies and studied how much energy consumption in buildings decreased and how much occupants' perception could be increased. There were various methods of biomimicry strategies, but this study researched the way that daylighting reflection and brought daylight inside the building using polar bear's fur.

The world is experiencing many negative influences from the changing climate. This change has also been affected by humans using fossil fuels, but it is time to change. Although many scholars have studied the climate, correcting environmental problems is not an easy task. Therefore, it is clear that people must be prepared for an uncertain future. At this moment, many experts, scholars, and scientists are looking for ways to solve the problem of climate change and to reduce energy use in the world. One of the methods could be biomimicry. Biomimetic solutions are necessary to try to understand and solve this problem in various fields simultaneously rather than

in one field. Therefore, if we decided to use biomimicry to reduce the energy use in buildings by as little as 1 percent, we would be one step closer to a better world. If the life of people is changed by following the rules of nature, our next generation would be able to meet the new environment where they can coexist with nature.

#### **5.4. Limitations**

There are some limitations to this study. First, this study was adopted as a computer-designed simulation method instead of using a real-world window system. Although this study designed the biomimetic window system based on previous studies, it should be considered the possibility of other problems when the system is actually built. Second, it is necessary to predict how much an initial budget is required when the system is actually built. It means that this study did not calculate the life cycle cost of the biomimetic window system. It will also be necessary to compare energy consumption to the required initial budget. Third, this study was simulated based on weather data in cold regions and it did not compare/analyze all climate regions. Different results may be predicted if the biomimetic window system is built in different climatic regions. Fourth, when this study conducted the survey, one of the survey questions made participants confuse by using an inappropriate word (i.e., academic increase). Therefore, it was difficult to know whether the answers to the question were correct in this study. The study did not use for analysis with the question in this study, but more accurate data analysis would have been possible if the survey was conducted with more accurate wording to get the answers the study wanted from participants. Lastly, in order to have a constant illumination comfort in the virtual reality environment, illumination level should have needed to measure in each virtual reality environment. However, this study designed a virtual reality environment with 360-degree 2D images. Since it is not

possible to measure the illumination level from 2D images, this study designed virtual reality experiments with similar K values in each virtual reality environment to make participants not have a bias when experiencing virtual reality environments. In order to control a more accurate illumination level, all spaces and conditions should have to be created virtually, not filmed with a 360-degree spherical panorama camera.

## **5.5. Future Research**

Various further studies will be needed to solve the limitations of this study. Ultimately, more simulation works will be required to install the actual biomimetic window system in buildings.

1. Further research needs to explore that the biomimetic window system is apparently effective through various energy consumption results in different climate regions and different types of buildings. If the system is energy-efficient in various climatic regions, it is important to look at the increase of occupants' perception in different types of buildings.
2. In further research, the Life-cycle Cost Analysis (LCCA) of the biomimetic window system needs to be carried out. LCCA is useful when comparing initial costs and operating costs of a project to its net energy savings. Therefore, future research needs to calculate initial, operation, maintenance, repair costs, and other costs, such as non-monetary benefits to building owners and occupants.
3. If further studies mentioned in 1 and 2 are completed, the process of developing, creating, and testing the actual biomimetic window system will be necessary. This will validate the

biomimetic window system that the current research proposed and helped this system to be commercialized to save more energy.

## **APPENDICES**

## APPENDIX A. MSU Facilities Data

Table A- 1. MSU Facilities data report by MSU Infrastructure Planning and Facilities

| <b>Building Data Summary</b>                 | <b>Square Feet</b> | <b>Number of Buildings</b> | <b>Replacement Value</b> |
|----------------------------------------------|--------------------|----------------------------|--------------------------|
| <b>General Fund Facilities</b>               |                    |                            |                          |
| Academic                                     | 9,932,099          | 97                         | \$2,435,182,628          |
| Athletics                                    | 1,135,189          | 7                          | \$293,783,541            |
| Farms                                        | 854,880            | 122                        | \$63,859,592             |
| Other                                        | 93,707             | 8                          | \$12,452,987             |
| Parking                                      | 269,155            | 1                          | \$10,670,358             |
| Support                                      | 1,486,281          | 82                         | \$575,381,676            |
| <b>Subtotal – General Fund Facilities</b>    | <b>13,771,311</b>  | <b>317</b>                 | <b>\$3,391,330,782</b>   |
| <b>Self Supporting Facilities</b>            |                    |                            |                          |
| Academic                                     | 460,666            | 9                          | \$112,708,663            |
| Athletics                                    | 906,514            | 42                         | \$236,238,464            |
| Farms                                        | 11,600             | 8                          | \$352,584                |
| Housing                                      | 6,662,634          | 138                        | \$1,124,553,995          |
| Other                                        | 83,637             | 12                         | \$11,110,477             |
| Parking                                      | 1,865,703          | 15                         | \$113,631,732            |
| Support                                      | 737,027            | 21                         | \$164,980,565            |
| <b>Subtotal – Self Supporting Facilities</b> | <b>10,727,781</b>  | <b>245</b>                 | <b>\$1,763,576,480</b>   |
| <b>Total</b>                                 | <b>24,499,092</b>  | <b>562</b>                 | <b>\$5,154,907,262</b>   |

## APPENDIX B. ANOVA with Post-Hoc test with Five Groups

Table B- 1. ANOVA with Post-Hoc test results using current students' average study time as the criterion in the open space

| Factor | Time  | N  | Mean   | SD      |                | Sum of Squares | df | Mean Square | F     | Sig.  |
|--------|-------|----|--------|---------|----------------|----------------|----|-------------|-------|-------|
| S1C1   | <1h   | 2  | 2.0000 | .00000  | Between Groups | 0.640          | 4  | 0.160       | 0.614 | 0.655 |
|        | 1h-2h | 2  | 1.5000 | .70711  |                |                |    |             |       |       |
|        | 2h-3h | 23 | 1.4348 | .50687  |                |                |    |             |       |       |
|        | 3h-4h | 19 | 1.4737 | .51299  | Within Groups  | 13.289         | 51 | 0.261       |       |       |
|        | 4h-5h | 10 | 1.4000 | .51640  |                |                |    |             |       |       |
|        | Total | 56 | 1.4643 | .50324  |                |                |    |             |       |       |
| S1C2   | <1h   | 2  | 4.0000 | 1.41421 | Between Groups | 3.665          | 4  | 0.916       | 2.243 | 0.077 |
|        | 1h-2h | 2  | 3.0000 | .00000  |                |                |    |             |       |       |
|        | 2h-3h | 23 | 3.2609 | .68870  |                |                |    |             |       |       |
|        | 3h-4h | 19 | 3.0000 | .00000  | Within Groups  | 20.835         | 51 | 0.409       |       |       |
|        | 4h-5h | 10 | 3.6000 | .96609  |                |                |    |             |       |       |
|        | Total | 56 | 3.2500 | .66742  |                |                |    |             |       |       |
| S1C3   | <1h   | 2  | 4.0000 | 1.41421 | Between Groups | 6.081          | 4  | 1.520       | 2.291 | 0.072 |
|        | 1h-2h | 2  | 4.0000 | 1.41421 |                |                |    |             |       |       |
|        | 2h-3h | 23 | 3.0870 | .41703  |                |                |    |             |       |       |
|        | 3h-4h | 19 | 3.6316 | .95513  | Within Groups  | 33.847         | 51 | 0.664       |       |       |
|        | 4h-5h | 10 | 3.8000 | 1.03280 |                |                |    |             |       |       |
|        | Total | 56 | 3.4643 | .85204  |                |                |    |             |       |       |

Table B- 2. ANOVA with Post-Hoc test results using current students' average study time as the criterion in the enclosed space

| Factor | Time  | N  | Mean   | SD     |                | Sum of Squares | df | Mean Square | F     | Sig.  |
|--------|-------|----|--------|--------|----------------|----------------|----|-------------|-------|-------|
| S2C1   | <1h   | 2  | 1.5000 | .70711 | Between Groups | 0.784          | 4  | 0.196       | 0.939 | 0.449 |
|        | 1h-2h | 2  | 1.0000 | .00000 |                |                |    |             |       |       |
|        | 2h-3h | 23 | 1.2174 | .42174 |                |                |    |             |       |       |
|        | 3h-4h | 19 | 1.4211 | .50726 | Within Groups  | 10.645         | 51 | 0.209       |       |       |
|        | 4h-5h | 10 | 1.2000 | .42164 |                |                |    |             |       |       |
|        | Total | 56 | 1.2857 | .45584 |                |                |    |             |       |       |
| S2C2   | <1h   | 2  | 4.0000 | .00000 | Between Groups | 0.732          | 4  | 0.183       | 1.248 | 0.303 |
|        | 1h-2h | 2  | 4.0000 | .00000 |                |                |    |             |       |       |
|        | 2h-3h | 23 | 4.2609 | .44898 |                |                |    |             |       |       |
|        | 3h-4h | 19 | 4.0526 | .22942 | Within Groups  | 7.482          | 51 | 0.147       |       |       |
|        | 4h-5h | 10 | 4.3000 | .48305 |                |                |    |             |       |       |
|        | Total | 56 | 4.1786 | .38646 |                |                |    |             |       |       |
| S2C3   | <1h   | 2  | 4.5000 | .70711 | Between Groups | 1.303          | 4  | 0.326       | 1.438 | 0.235 |
|        | 1h-2h | 2  | 5.0000 | .00000 |                |                |    |             |       |       |
|        | 2h-3h | 23 | 4.3043 | .47047 |                |                |    |             |       |       |
|        | 3h-4h | 19 | 4.2632 | .45241 | Within Groups  | 11.554         | 51 | 0.227       |       |       |
|        | 4h-5h | 10 | 4.5000 | .52705 |                |                |    |             |       |       |
|        | Total | 56 | 4.3571 | .48349 |                |                |    |             |       |       |

*Note.* In the Factor column, S1 (Space 1) means “Open Space” and S2 (Space 2) means “Enclosed Space”. C1 (Condition 1) means “No Window”, C2 (Condition 2) means “Biomimetic Windows with Daylight”, and C3 (Condition 3) means “Biomimetic Windows with Daylight and View”.

## APPENDIX C. Permission to Film Within the MSU Libraries

Figure C-1. First page of the permission to film within the MSU Libraries

### Permission to Film and/or Photograph Within the MSU Libraries

Person(s) seeking approval: Juntae Son

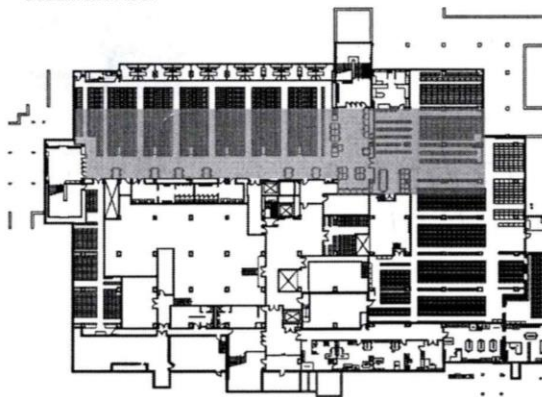
**Purpose (note course and professor if affiliated):** This is for my dissertation and this research will see about how much the students' perception and satisfaction can be improved if daylight can enter a space where daylights cannot reach, such as a basement floor. Using VR videos, the research will provide a virtual space of the library to students and will see their satisfaction when daylights get into the space.

**Intended distribution (audience):** The participants of this research would be MSU students. Most of the students will watch the VR videos with an experimenter (me), but some of them will participate the experiment via the Internet and watch the VR videos which are uploaded on the Internet. After the experiment, the uploaded videos will be completely deleted.

**Date/times requested:** December 23<sup>rd</sup>, 2019

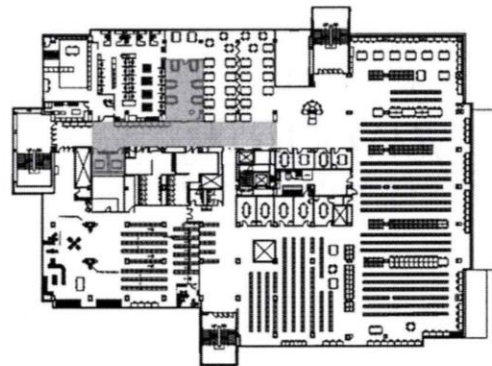
**Location(s) desired (specifically):**

Basement Floor



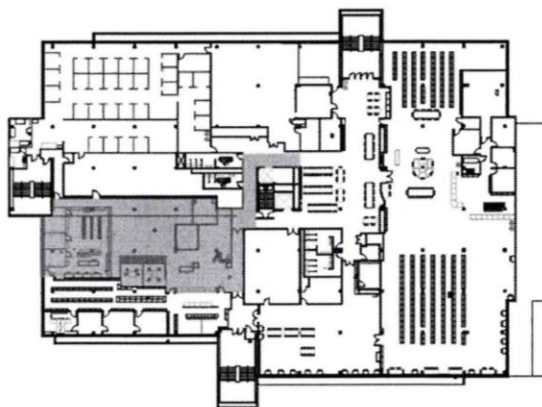
Basement floor (Area filled by blue)

3rd Floor



3W: Rm. W300 (Instruction Room) and two study lounges (Area filled by blue)

4th Floor



4W: Digital & Multimedia center (Not including the office area)

Figure C-2. Second page of the permission to film within the MSU Libraries

- Patrons will not be photographed or filmed unless individual written permission is granted.
  - Halls, aisles, doors, or access to Library materials will not be obstructed.
  - A quiet, study atmosphere must be maintained.
  - Use of electrical outlets for equipment must be approved, due to possibility of tripping a breaker..
  - Library environment must be accepted "as is." Furniture will remain in its intended location, windows will remain closed and lights will remain on.
  - MSU Libraries will not be held liable for the film or photos.
- ☒ I understand if any patrons are included in the film, written permission must be obtained from the patron; this includes people shown in film, or anyone in the foreground or background of a films
- ☒ I have attached the Appearance release forms for all people who will be involved in filming.
- ☒ I have read and agree with the aforementioned terms and conditions:

  
Administrative Approval (sign/print)

Date 12/17/19



## APPENDIX D. IRB Approval Letter

### **MICHIGAN STATE UNIVERSITY**

#### **EXEMPT DETERMINATION Revised Common Rule**

January 20, 2020

To: Suk Kyung Kim

Re: **MSU Study ID:** STUDY00003859  
**Principal Investigator:** Suk Kyung Kim  
**Category:** Exempt 3i(a)  
**Exempt Determination Date:** 1/20/2020  
**Limited IRB Review:** Not Required.

**Title:** Building Energy Reduction Methods and Occupants' Satisfaction Increase by Utilizing Biomimetic Solution

This study has been determined to be exempt under 45 CFR 46.104(d) 3i(a).

**Principal Investigator (PI) Responsibilities:** The PI assumes the responsibilities for the protection of human subjects in this study as outlined in Human Research Protection Program (HRPP) Manual Section 8-1, Exemptions.

**Continuing Review:** Exempt studies do not need to be renewed.

**Modifications:** In general, investigators are not required to submit changes to the Michigan State University (MSU) Institutional Review Board (IRB) once a research study is designated as exempt as long as those changes do not affect the exempt category or criteria for exempt determination (changing from exempt status to expedited or full review, changing exempt category) or that may substantially change the focus of the research study such as a change in hypothesis or study design. See HRPP Manual Section 8-1, Exemptions, for examples. If the study is modified to add additional sites for the research, please note that you may not begin the research at those sites until you receive the appropriate approvals/permissions from the sites.

Please contact the HRPP office if you have any questions about whether a change must be submitted for IRB review and approval.

**New Funding:** If new external funding is obtained for an active study that had been determined exempt, a new initial IRB submission will be required, with limited exceptions. If you are unsure if a new initial IRB submission is required, contact the HRPP office. IRB review of the new submission must be completed before new funds can be spent on human research activities, as the new funding source may have additional or different requirements.



**Office of  
Regulatory  
Affairs  
Human Research  
Protection Program**

4000 Collins Road  
Suite 136  
Lansing, MI 48910

517-355-2180  
Fax: 517-432-4503  
Email: [irb@msu.edu](mailto:irb@msu.edu)  
[www.hrpp.msu.edu](http://www.hrpp.msu.edu)

MSU is an affirmative-action,  
equal-opportunity employer.

**Reportable Events:** If issues should arise during the conduct of the research, such as unanticipated problems that may involve risks to subjects or others, or any problem that may increase the risk to the human subjects and change the category of review, notify the IRB office promptly. Any complaints from participants that may change the level of review from exempt to expedited or full review must be reported to the IRB. Please report new information through the study's workspace and contact the IRB office with any urgent events. Please visit the Human Research Protection Program (HRPP) website to obtain more information, including reporting timelines.

**Personnel Changes:** After determination of the exempt status, the PI is responsible for maintaining records of personnel changes and appropriate training. The PI is not required to notify the IRB of personnel changes on exempt research. However, he or she may wish to submit personnel changes to the IRB for recordkeeping purposes (e.g. communication with the Graduate School) and may submit such requests by submitting a Modification request. If there is a change in PI, the new PI must confirm acceptance of the PI Assurance form and the previous PI must submit the Supplemental Form to Change the Principal Investigator with the Modification request (available at [hrpp.msu.edu](http://hrpp.msu.edu)).

**Closure:** Investigators are not required to notify the IRB when the research study can be closed. However, the PI can choose to notify the IRB when the study can be closed and is especially recommended when the PI leaves the university. Closure indicates that research activities with human subjects are no longer ongoing, have stopped, and are complete. Human research activities are complete when investigators are no longer obtaining information or biospecimens about a living person through interaction or intervention with the individual, obtaining identifiable private information or identifiable biospecimens about a living person, and/or using, studying, analyzing, or generating identifiable private information or identifiable biospecimens about a living person.

**For More Information:** See HRPP Manual, including Section 8-1, Exemptions (available at [hrpp.msu.edu](http://hrpp.msu.edu)).

**Contact Information:** If we can be of further assistance or if you have questions, please contact us at 517-355-2180 or via email at [IRB@msu.edu](mailto:IRB@msu.edu). Please visit [hrpp.msu.edu](http://hrpp.msu.edu) to access the HRPP Manual, templates, etc.

**Exemption Category.** The full regulatory text from 45 CFR 46.104(d) for the exempt research categories is included below.<sup>1234</sup>

**Exempt 1.** Research, conducted in established or commonly accepted educational settings, that specifically involves normal educational practices that are not likely to adversely impact students' opportunity to learn required educational content or the assessment of educators who provide instruction. This includes most research on regular and special education instructional strategies, and research on the effectiveness of or the comparison among instructional techniques, curricula, or classroom management methods.

**Exempt 2.** Research that only includes interactions involving educational tests (cognitive, diagnostic, aptitude, achievement), survey procedures, interview procedures, or observation of public behavior (including visual or auditory recording) if at least one of the following criteria is met:

- (i) The information obtained is recorded by the investigator in such a manner that the identity of the human subjects cannot readily be ascertained, directly or through identifiers linked to the subjects;
- (ii) Any disclosure of the human subjects' responses outside the research would not reasonably place the subjects at risk of criminal or civil liability or be damaging to the subjects' financial standing, employability, educational advancement, or reputation; or
- (iii) The information obtained is recorded by the investigator in such a manner that the identity of the human subjects can readily be ascertained, directly or through identifiers linked to the subjects, and an IRB conducts a limited IRB review to make the determination required by 45 CFR 46.111(a)(7).

**Exempt 3.** (i) Research involving benign behavioral interventions in conjunction with the collection of information from an adult subject through verbal or written responses (including data entry) or audiovisual recording if the subject prospectively agrees to the intervention and information collection and at least one of the following criteria is met:

- (A) The information obtained is recorded by the investigator in such a manner that the identity of the human subjects cannot readily be ascertained, directly or through identifiers linked to the subjects;
- (B) Any disclosure of the human subjects' responses outside the research would not reasonably place the subjects at risk of criminal or civil liability or be damaging to the subjects' financial standing, employability, educational advancement, or reputation; or
- (C) The information obtained is recorded by the investigator in such a manner that the identity of the human subjects can readily be ascertained, directly or through identifiers linked to the subjects, and an IRB conducts a limited IRB review to make the determination required by 45 CFR 46.111(a)(7).

(ii) For the purpose of this provision, benign behavioral interventions are brief in duration, harmless, painless, not physically invasive, not likely to have a significant adverse lasting impact on the subjects, and the investigator has no reason to think the subjects will find the interventions offensive or embarrassing. Provided all such criteria are met, examples of such benign behavioral interventions would include having the subjects play an online game, having them solve puzzles under various noise conditions, or having them decide how

to allocate a nominal amount of received cash between themselves and someone else.

(iii) If the research involves deceiving the subjects regarding the nature or purposes of the research, this exemption is not applicable unless the subject authorizes the deception through a prospective agreement to participate in research in circumstances in which the subject is informed that he or she will be unaware of or misled regarding the nature or purposes of the research.

**Exempt 4.** Secondary research for which consent is not required: Secondary research uses of identifiable private information or identifiable biospecimens, if at least one of the following criteria is met:

(i) The identifiable private information or identifiable biospecimens are publicly available;

(ii) Information, which may include information about biospecimens, is recorded by the investigator in such a manner that the identity of the human subjects cannot readily be ascertained directly or through identifiers linked to the subjects, the investigator does not contact the subjects, and the investigator will not re-identify subjects;

(iii) The research involves only information collection and analysis involving the investigator's use of identifiable health information when that use is regulated under 45 CFR parts 160 and 164, subparts A and E, for the purposes of "health care operations" or "research" as those terms are defined at 45 CFR 164.501 or for "public health activities and purposes" as described under 45 CFR 164.512(b); or

(iv) The research is conducted by, or on behalf of, a Federal department or agency using government-generated or government-collected information obtained for nonresearch activities, if the research generates identifiable private information that is or will be maintained on information technology that is subject to and in compliance with section 208(b) of the E-Government Act of 2002, 44 U.S.C. 3501 note, if all of the identifiable private information collected, used, or generated as part of the activity will be maintained in systems of records subject to the Privacy Act of 1974, 5 U.S.C. 552a, and, if applicable, the information used in the research was collected subject to the Paperwork Reduction Act of 1995, 44 U.S.C. 3501 et seq.

**Exempt 5.** Research and demonstration projects that are conducted or supported by a Federal department or agency, or otherwise subject to the approval of department or agency heads (or the approval of the heads of bureaus or other subordinate agencies that have been delegated authority to conduct the research and demonstration projects), and that are designed to study, evaluate, improve, or otherwise examine public benefit or service programs, including procedures for obtaining benefits or services under those programs, possible changes in or alternatives to those programs or procedures, or possible changes in methods or levels of payment for benefits or services under those programs. Such projects

include, but are not limited to, internal studies by Federal employees, and studies under contracts or consulting arrangements, cooperative agreements, or grants. Exempt projects also include waivers of otherwise mandatory requirements using authorities such as sections 1115 and 1115A of the Social Security Act, as amended. (i) Each Federal department or agency conducting or supporting the research and demonstration projects must establish, on a publicly accessible Federal Web site or in such other manner as the department or agency head may determine, a list of the research and demonstration projects that the Federal department or agency conducts or supports under this provision. The research or demonstration project must be published on this list prior to commencing the research involving human subjects.

**Exempt 6.** Taste and food quality evaluation and consumer acceptance studies:

(i) If wholesome foods without additives are consumed, or (ii) If a food is consumed that contains a food ingredient at or below the level and for a use found to be safe, or agricultural chemical or environmental contaminant at or below the level found to be safe, by the Food and Drug Administration or approved by the Environmental Protection Agency or the Food Safety and Inspection Service of the U.S. Department of Agriculture.

**Exempt 7.** Storage or maintenance for secondary research for which broad consent is required: Storage or maintenance of identifiable private information or identifiable biospecimens for potential secondary research use if an IRB conducts a limited IRB review and makes the determinations required by 45 CFR 46.111(a)(8).

**Exempt 8.** Secondary research for which broad consent is required: Research involving the use of identifiable private information or identifiable biospecimens for secondary research use, if the following criteria are met:

- (i) Broad consent for the storage, maintenance, and secondary research use of the identifiable private information or identifiable biospecimens was obtained in accordance with 45 CFR 46.116(a)(1) through (4), (a)(6), and (d);
- (ii) Documentation of informed consent or waiver of documentation of consent was obtained in accordance with 45 CFR 46.117;
- (iii) An IRB conducts a limited IRB review and makes the determination required by 45 CFR 46.111(a)(7) and makes the determination that the research to be conducted is within the scope of the broad consent referenced in paragraph (d)(8)(i) of this section; and
- (iv) The investigator does not include returning individual research results to subjects as part of the study plan. This provision does not prevent an investigator from abiding by any legal requirements to return individual research results.

<sup>1</sup>Exempt categories (1), (2), (3), (4), (5), (7), and (8) cannot be applied to activities that are FDA-regulated.

<sup>2</sup> Each of the exemptions at this section may be applied to research subject to subpart B (Additional Protections for Pregnant Women, Human Fetuses and Neonates Involved in Research) if the conditions of the exemption are met.

<sup>3</sup> The exemptions at this section do not apply to research subject to subpart C (Additional Protections for Research Involving Prisoners), except for research aimed at involving a broader subject population that only incidentally includes prisoners.

<sup>4</sup> Exemptions (1), (4), (5), (6), (7), and (8) of this section may be applied to research subject to subpart D (Additional Protections for Children Involved as Subjects in Research) if the conditions of the exemption are met. Exempt (2)(i) and (ii) only may apply to research subject to subpart D involving educational tests or the observation of public behavior when the investigator(s) do not participate in the activities being observed. Exempt (2)(iii) may not be applied to research subject to subpart D.

## APPENDIX E. Consent Form for Experiment

### Consent Form

Survey for students' perception and perception on biomimetic windows

Purpose of the Study: The aim of this study is to assess occupants' perception and perception using new window designs that are inspired by nature's strategy to bring daylight into an interior space where daylight cannot be reached. In fact, in most buildings, the only way to get the sunlight is through windows on the exterior walls. Because of this, people are heavily dependent on artificial lighting. In order to solve this problem, this research will investigate about the new type of indoor windows that sunlight can enter from the outside to the interior spaces. To solve the problem, the research has a question: "Will the influx of daylight into an indoor space of a building affect to the occupants' perception?" With the question, the research has the following hypothesis to conduct experiments: "Biometric windows can provide psychological perception to students in learning environments".

#### Principal Researchers:

M.S. Juntae Jake Son – Michigan State University

Dr. Suk-Kyung Kim – Michigan State University

#### Information

Since the new type of windows which is inspired by nature's strategy does not exist currently, the study will use a virtual reality (VR) system and conduct a survey to the subjects. Therefore, this study will find out how the daylight, which is achieved via window designs inspired by nature, affects subjects' psychological perception in educational spaces.

#### Risks and Benefits

There are no foreseeable risks to participating in this study. You will not receive compensation for participating. We will provide a final report from this survey upon request.

#### Your participation is voluntary and anonymous

You may choose whether or not to participate in this survey. You may change your mind at any time. You can withdraw from the survey at any time with no cost to you. Only researchers associated with this project and also the MSU Human Research Protection Program (HRPP) may have access to information you provide in the pre-survey and main activity. The responses to this survey will be anonymous and no identifying information will be linked to your survey responses after you complete the survey.

#### Contact information for questions or concerns

If you have any questions, you may contact to Juntae Jake Son ([sonjun@msu.edu](mailto:sonjun@msu.edu)). If you have any questions about your rights as a volunteer in this research, they should be directed to the Human Research Protection Program.

Principal Investigator: Dr. Suk-Kyung Kim ([kimsk@msu.edu](mailto:kimsk@msu.edu))

Associate Professor, School of Planning, Design, and Construction, Michigan State University

#### Consent

I have read this information. I am 18 years of age or older. The survey should take you about 20 to 30 minutes to complete.

Thank you for your time!

## APPENDIX F. Virtual Reality Experiment Survey Questionnaire

The following questions were extracted from Qualtrix survey system.

### Questions for Condition 1

Q1. Rate the degree to your impressions of this space.

|                         | Very<br>comfortable<br>(1) | Somewhat<br>comfortable<br>(2) | Neither<br>comfortable<br>nor<br>uncomfortable<br>(3) | Somewhat<br>uncomfortable<br>(4) | Very<br>uncomfortable<br>(5) |
|-------------------------|----------------------------|--------------------------------|-------------------------------------------------------|----------------------------------|------------------------------|
| Level of<br>Comfort (1) | <input type="radio"/>      | <input type="radio"/>          | <input type="radio"/>                                 | <input type="radio"/>            | <input type="radio"/>        |

Q2. Rate the degree to which you believe the light in this space impacts your academic increase.

|                        | Large impact<br>(1)   | Most impact<br>(2)    | Neutral (3)           | Somewhat<br>impact (4) | No impact (5)         |
|------------------------|-----------------------|-----------------------|-----------------------|------------------------|-----------------------|
| Level of<br>Impact (1) | <input type="radio"/> | <input type="radio"/> | <input type="radio"/> | <input type="radio"/>  | <input type="radio"/> |

Q3. Does the light in this room affects your seating preference?

|                              | Definitely yes<br>(1) | Probably yes<br>(2)   | Might or<br>might not (3) | Probably not<br>(4)   | Definitely not<br>(5) |
|------------------------------|-----------------------|-----------------------|---------------------------|-----------------------|-----------------------|
| Seating<br>preference<br>(1) | <input type="radio"/> | <input type="radio"/> | <input type="radio"/>     | <input type="radio"/> | <input type="radio"/> |

Q4. Which factors describe the light in this space?

- ☐ Adequate illumination (1)
- ☐ Too bright (2)
- ☐ Too dark (3)
- ☐ Too much glare (4)
- ☐ Lack of control (5)
- ☐ Undesirable color (6)
- ☐ Shadows (7)
- ☐ Flickering (8)
- ☐ Others (9) \_\_\_\_\_

Q5. How many hours do you think you can concentrate on studying in this space?

- ☐ Less than an hour (1)
- ☐ 1-2 hours (2)
- ☐ 2-3 hours (3)
- ☐ 3-4 hours (4)
- ☐ 4-5 hours (5)
- ☐ 5-6 hours (6)
- ☐ 6-7 hours (7)
- ☐ 7-8 hours (8)
- ☐ 8-9 hours (9)
- ☐ More than 9 hours (10)

## Questions for Condition 2

Q1. Rate the degree to your impressions of this space.

|                         | Very<br>comfortable<br>(1) | Somewhat<br>comfortable<br>(2) | Neither<br>comfortable<br>nor<br>uncomfortable<br>(3) | Somewhat<br>uncomfortable<br>(4) | Very<br>uncomfortable<br>(5) |
|-------------------------|----------------------------|--------------------------------|-------------------------------------------------------|----------------------------------|------------------------------|
| Level of<br>Comfort (1) | <input type="radio"/>      | <input type="radio"/>          | <input type="radio"/>                                 | <input type="radio"/>            | <input type="radio"/>        |

Q2. Rate the degree to which you believe the light in this space impacts your academic increase.

|                        | Large impact<br>(1)   | Most impact<br>(2)    | Neutral (3)           | Somewhat<br>impact (4) | No impact (5)         |
|------------------------|-----------------------|-----------------------|-----------------------|------------------------|-----------------------|
| Level of<br>Impact (1) | <input type="radio"/> | <input type="radio"/> | <input type="radio"/> | <input type="radio"/>  | <input type="radio"/> |

Q3. Does the light in this room affects your seating preference?

|                              | Definitely yes<br>(1) | Probably yes<br>(2)   | Might or<br>might not (3) | Probably not<br>(4)   | Definitely not<br>(5) |
|------------------------------|-----------------------|-----------------------|---------------------------|-----------------------|-----------------------|
| Seating<br>preference<br>(1) | <input type="radio"/> | <input type="radio"/> | <input type="radio"/>     | <input type="radio"/> | <input type="radio"/> |

Q4. Which factors describe the light in this space?

- ☐ Adequate illumination (1)
- ☐ Too bright (2)
- ☐ Too dark (3)
- ☐ Too much glare (4)
- ☐ Lack of control (5)
- ☐ Too much sunlight (6)
- ☐ Insufficient sunlight (7)
- ☐ Shadows (8)
- ☐ Others (9) \_\_\_\_\_

Q5. How many hours do you think you can concentrate on studying in this space?

- ☐ Less than an hour (1)
- ☐ 1-2 hours (2)
- ☐ 2-3 hours (3)
- ☐ 3-4 hours (4)
- ☐ 4-5 hours (5)
- ☐ 5-6 hours (6)
- ☐ 6-7 hours (7)
- ☐ 7-8 hours (8)
- ☐ 8-9 hours (9)
- ☐ More than 9 hours (10)

### Questions for Condition 3

Q1. Rate the degree to your impressions of this space.

|                      | Very comfortable<br>(1) | Somewhat comfortable<br>(2) | Neither comfortable nor uncomfortable<br>(3) | Somewhat uncomfortable<br>(4) | Very uncomfortable<br>(5) |
|----------------------|-------------------------|-----------------------------|----------------------------------------------|-------------------------------|---------------------------|
| Level of Comfort (1) | <input type="radio"/>   | <input type="radio"/>       | <input type="radio"/>                        | <input type="radio"/>         | <input type="radio"/>     |

Q2. Rate the degree to which you believe the light in this space impacts your academic increase.

|                     | Large impact<br>(1)   | Most impact<br>(2)    | Neutral (3)           | Somewhat impact<br>(4) | No impact (5)         |
|---------------------|-----------------------|-----------------------|-----------------------|------------------------|-----------------------|
| Level of Impact (1) | <input type="radio"/> | <input type="radio"/> | <input type="radio"/> | <input type="radio"/>  | <input type="radio"/> |

Q3. Does the light in this room affects your seating preference?

|                        | Definitely yes<br>(1) | Probably yes<br>(2)   | Might or might not<br>(3) | Probably not<br>(4)   | Definitely not<br>(5) |
|------------------------|-----------------------|-----------------------|---------------------------|-----------------------|-----------------------|
| Seating preference (1) | <input type="radio"/> | <input type="radio"/> | <input type="radio"/>     | <input type="radio"/> | <input type="radio"/> |

Q4. Which factors describe the light in this space?

- ☐ Adequate illumination (1)
- ☐ Too bright (2)
- ☐ Too dark (3)
- ☐ Too much glare (4)
- ☐ Lack of control (5)
- ☐ Too much sunlight (6)
- ☐ Insufficient sunlight (7)
- ☐ Shadows (8)
- ☐ Others (9) \_\_\_\_\_

Q5. How many hours do you think you can concentrate on studying in this space?

- ☐ Less than an hour (1)
- ☐ 1-2 hours (2)
- ☐ 2-3 hours (3)
- ☐ 3-4 hours (4)
- ☐ 4-5 hours (5)
- ☐ 5-6 hours (6)
- ☐ 6-7 hours (7)
- ☐ 7-8 hours (8)
- ☐ 8-9 hours (9)
- ☐ More than 9 hours (10)

### Demographic Questions

Q1. What is your age?

- ☐ 15 years or younger (1)
  - ☐ 16-20 years old (2)
  - ☐ 21-25 years old (3)
  - ☐ 26-30 years old (4)
  - ☐ 31-35 years old (5)
  - ☐ 36-40 years old (6)
  - ☐ 41-45 years old (7)
  - ☐ 46-50 years old (8)
  - ☐ 51-55 years old (9)
  - ☐ 56-60 years old (10)
  - ☐ 61-65 years old (11)
  - ☐ 66-70 years old (12)
  - ☐ 71 years or older (13)
  - ☐ Prefer not to answer (14)
-

Q2. What gender do you identify as?

- ☐ Male (1)
- ☐ Female (2)
- ☐ Other (3) \_\_\_\_\_
- ☐ Prefer not to answer (4)

Q3. What year are you in?

- ☐ Freshman (1)
- ☐ Sophomore (2)
- ☐ Junior (3)
- ☐ Senior (4)
- ☐ Graduate Student - Master (5)
- ☐ Graduate Student - Doctoral (6)
- ☐ Other (7) \_\_\_\_\_
- ☐ Prefer not to answer (8)

Q4. Average hours you spend for your study (per day)?

- ☐ Less than an hour (1)
  - ☐ 1-2 hours (2)
  - ☐ 2-3 hours (3)
  - ☐ 3-4 hours (4)
  - ☐ 4-5 hours (5)
  - ☐ 5-6 hours (6)
  - ☐ 6-7 hours (7)
  - ☐ 7-8 hours (8)
  - ☐ 8-9 hours (9)
  - ☐ More than 9 hours (10)
-

Q5. When you assume that your total study time is 100%, how much spend study time with the types of LIGHTING:

Sum of the study time should be 100%.

Ex) Study time with DAYLIGHT: 30%, Study time with ARTIFICIAL LIGHT: 50%, Study time with DAYLIGHT & ARTIFICIAL LIGHT: 20% = 100%

\_\_\_\_\_ Study time with DAYLIGHT (1)

\_\_\_\_\_ Study time with ARTIFICIAL LIGHT (2)

\_\_\_\_\_ Study time with DAYLIGHT & ARTIFICIAL LIGHT (3)

---

Q6. When you assume that your total study time is 100%, how much spend study time WITH/WITHOUT WINDOWS:

Sum of the study time should be 100%.

Ex) Study time WITH WINDOWS: 20%, Study time WITHOUT WINDOWS: 80% = 100%

\_\_\_\_\_ Study time with WINDOWS (1)

\_\_\_\_\_ Study time without WINDOWS (2)

---

Q7. When do you spend your study time? (Morning: 6:00 AM ~ 11:59 AM, Afternoon: 12:00 PM ~ 5:59 PM, Night: 6:00 PM ~ 5:59 AM (Next day))

Sum of the study time should be 100%.

Ex) Study time IN THE MORNING: 20%, Study time IN THE AFTERNOON: 60%, Study time AT NIGHT: 20% = 100%

\_\_\_\_\_ Morning: 6:00 AM ~ 11:59 AM (1)

\_\_\_\_\_ Afternoon: 12:00 PM ~ 5:59 PM (2)

\_\_\_\_\_ Night: 6:00 PM ~ 5:59 AM (Next day) (3)

End of Block: Demographic Questions

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## APPENDIX G. The Flyer to Recruit Participants of Virtual Reality Experiment

# PARTICIPANTS NEEDED!

## FOR STUDIES INVESTIGATING SATISFATION OF DAYLIGHT

### Purpose of the Study

The aim of this study is to assess **occupants' perception and satisfaction** using new window designs that are inspired by nature's strategy to bring daylight into an interior space where daylight cannot be reached.

### Eligibility

- We are looking for adults **18 years and older** who are **students** at Michigan State University.
- Participants will put on a **VR head mount** to have virtual experiences. The study will use a virtual reality (VR) system and conduct a survey to the participants, because the study investigates about the new type of windows that does not exist currently.
- The experiment will take about **15 to 20 minutes**.

**We Will Provide Free Food!**

**Schedule this VR experience NOW!**

E-mail us to [sonjun@msu.edu](mailto:sonjun@msu.edu) to make a schedule or  
Scan QR Code below!

### Location

All sessions will be in MSU Main Library  
(366 W. Circle Dr., East Lansing, MI 48824)

### Questions?

Jake Son: [sonjun@msu.edu](mailto:sonjun@msu.edu) or (517) 802-8474



*Scan me*

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