Komorebi 木漏れ日 :

Embedding Dappled Sunlight in the Built Environment

by

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Abstract

Humans are increasingly disconnected from nature. Urbanization, resource exploitation, and changes in ways of living have diminished people's access to nature. Exposure to nature is beneficial to human beings in many aspects. Researches in environmental psychology and public health have shown the positive impacts of nature connections for people's happiness, concentration, and restoration. In creating the living environment with the connectedness to nature, various researches have been invested, such as the study of green space in the living environment, the application of virtual nature in psychiatric and medical care, the implementation of natural scenery in augmented reality. However, the idea of imitating natural phenomena in the built environment via tangible building systems has not been explored yet. This thesis aims to provide people with the perception of connectedness to nature in the built environment by embedding the sensory experience of nature, *Komorebi*, in the building system. *Komorebi* is a Japanese term that describes the dappled sunlight filtered through tree foliage. Through analysis of this visual effect and experimenting with various materials and actuators, a daylight-filtering system is developed to bring the dappled light phenomenon into the built environment. Environmental performance simulations of the *Komorebi* system is conducted in comparison with no-shading and the *Venitian* blind. The system builds on the existing infrastructure to integrate elements of improvisational nature into the building system, creating natural sensory experiences in the built environment. In practice, it would have great potential at places where natural connections are limited, and relinking occupants to nature would be highly beneficial. The impact of this work includes 1) creating a port for people who have limited access to nature due to work demand or mobility limitation, 2) invoking people's memories in nature, and encouraging more exposure to nature.

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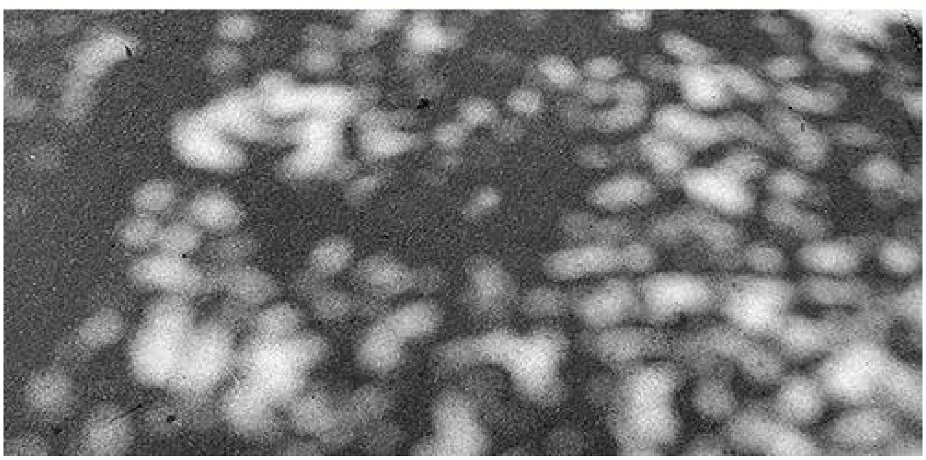

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Contents

Chapter 1

Background

1.1 Disconnections from nature

Humans are increasingly disconnected from nature. Historically, humans have lived, traveled, and socialized in nature. Slowly, technologies that protect humans from nature were invented [1]. Nowadays, urbanization, resource overexploitation, and changes in lifestyles have diminished people's access to nature [2]. 55 percent of the world's population resides in urban areas, and over 80 percent of the United States' population lives in cities. In addition, most Americans spend about 90 percent of their time indoors [3].

1.2 Positive impacts of nature connections and related work

Exposure to nature is beneficial to human beings in many aspects. Research in environmental psychology and public health have shown the positive impacts of connections to nature for people’s happiness, concentration, and restoration [4] [5] [6]. Patients who have access to natural views are shown to have better recovery in their hospital stays [7]. Natural lighting helps concentration and productivity in schools [8]. As Edward Wilson claims in his Biophilia Hypothesis, human beings tend to seek connections with nature [9]. This concept of biophilia is listed in the WELL Building Standard, recommending nature patterns and access to nature in the built environment [10]. Ongoing research conducted at Stanford explores the integration of structures that allow greenery and digital natural scenery projection [11]. Urban studies have found positive associations between urban green space and human mental states, such as attention and mood [12] [13]. In addition, the World Health Organization suggests that increased exposure to urban green spaces is correlated with decreased mortality and improved mental health in its 2016 report, “Urban Green Spaces and Health” [14]. Virtual Reality (VR) nature has played a significant role in psychiatric and medical care for people with mobility limitations, e.g., elderly, disabled, or under medical treatment [15]. In the realm of Augmented

Reality (AR), a user-controlled atmosphere of ambient nature that supports user well-being and productivity has been tested [16].

1.3 Thesis outline

The work mentioned above addresses natural connections for the living environment in various ways; however, the idea of imitating the natural phenomenon in the built environment via tangible building systems has not been explored yet. This thesis aims to provide people with the perception of connectedness to nature in the built environment by embedding the sensory experience of nature, *Komorebi*, in the building system. Building upon this, Chapter 2 provides the introduction of *Komorebi,* analysis of this natural dappled sunlight phenomenon, and the application of *Komorebi* in other design work. Chapter 3 presents the methodology for embedding *Komorebi* in the built environment in five sections: material and actuator experiments, prototype design and fabrication, system parameters calculation, prototype tests, and environmental performance simulation. The design outcomes, analyses of the performance, and potential impacts of the work are summarized in Chapter 4, together with a discussion of the limitations and future work.

Chapter 2

Introduction

2.1 Introduction of *Komorebi*

Komorebi (木漏れ日) is a Japanese term that describes the dappled sunlight filtered through the tree foliage. From literal translation, *Komorebi (木漏れ日)* means tree filters sun. The phenomenon of *Komorebi* is mentioned in Marcel Minner's book *Light and Color in the Outdoors* [17]. As he illustrates in Figure 1, in the shade of the trees, elliptical fuzzy light spots randomly appear on the ground; the light spot would be round when the sun ray is intercepted by a perpendicular plane. The fuzzy circular light spots in various sizes and luminous overlap with each other produces the light phenomenon shown in Figure 2. Besides the dynamic visual effect, the temporality of *Komorebi* from the improvisational movements of leaves makes it a unique sensory experience from nature.

Figure 1 Illustration of the dappled sunlight from Light and Color in the Outdoors, pg.2 [17]

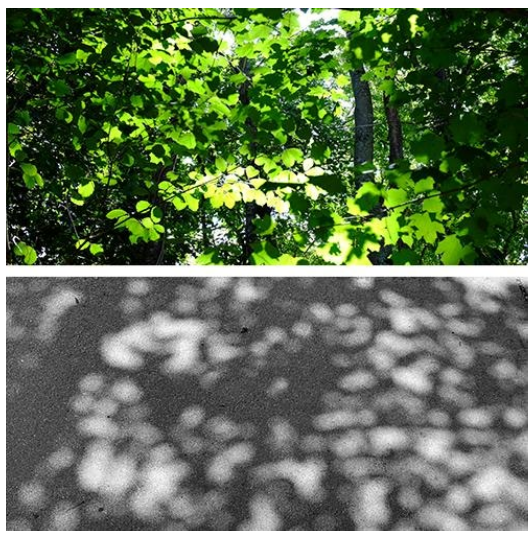

Figure 2 Photo of sunlight dappled light spots under the trees. Image credit: the author.

2.2 *Komorebi* and pinhole effect analysis

Komorebi results from the sunlight filtered through holes in the tree foliage. Under the principle of the pinhole effect, each dappled light spot of *Komorebi* can be considered as an image of the sun. As early as the 17th century, Johannes Kepler had used the pinhole effect to study the diameter of the sun [18]. G. Hon and Y. Zik's paper, *Kepler's Optical Part of Astronomy (1604): Introducing the Ecliptic Instrument* [18], gives a comprehensive review of Kepler's study of the pinhole camera. Kepler tried to create optical instruments to get precise images of the sun with minimal blurriness on edge. Although the precise images of the sun produced by Kepler's optical instruments are slightly different from the improvisational dappled light, *Komorebi,* in nature, it would still be beneficial to understand the basic formation of the image behind the pinhole.

As shown in Figure 3 from G. Hon and Y. Zik's paper, from the center C to the periphery A of the sun, the sun rays project from every point of the sun through the square pinhole ED onto a surface. GF (center_C') and KH (center_C'') on the projection surface are the cast images from the rays. The distance between the center of two images could be calculated as:

$$C'C'' = L \times \tan a.$$

Each point source from the sun creates a square light spot on the projection surface, and overlapping images produce various composite results with different projection distance L and sizes of the pinhole d. For example, when the projection surface is placed very close to the pinhole, the distance C'C'' would be much smaller than the light spot produced by each light source. As a result, the composite image would be an image of the shape of the pinhole, square, with a fuzzy edge. In a different scenario, if C'C'' is larger than the radius of the individual light spot, the composite image would be in the shape of the sun. The radius of the circular image would C'C''+C"K.

To achieve the *Komorebi* effect, the dappled light effect in the shape of the sun, it is important to use the fundamental principle of the pinhole effect to optimize the distance from the pinholes to the projection surface and the size of the pinholes.

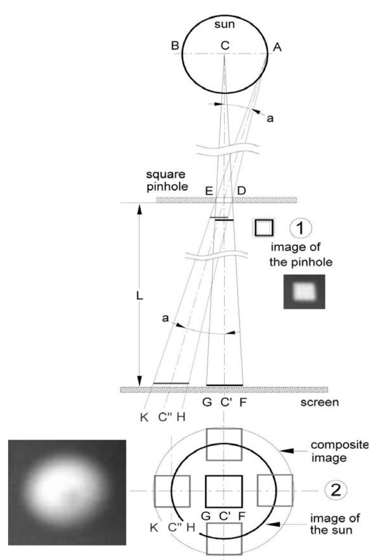

Figure 3 Illustration of the pinhole effect from paper, Kepler's Optical Part of Astronomy (1604): Introducing the Ecliptic Instrument [18]

2.3 *Komorebi* in other design work

The phenomenon of *Komorebi* has been recognized and adopted in many design fields. Figure 4 shows an installation of the *Komorebi* effect in Gonde House. Figure 5 presents a *Komorebi* light projector by Leslie Nooteboom. *Komorebi* pattern is also used in textile design by Japanese textile artist Reiko Sudo.

Figure 4

Figure 5

Figure 6

Figure 4 *Komorebi* installation for Gonde House

Figure 5 *Komorebi* light projector designed by Leslie Nooteboom

Figure 6 *Komorebi* Textile by Reiko Sudo

In structure design, Japanese structure engineer Jun Sato uses 2D spectrum analysis, shown in Figure 7, to compare images of structures designed by him with the image of sunlight filtering through tree leaves.

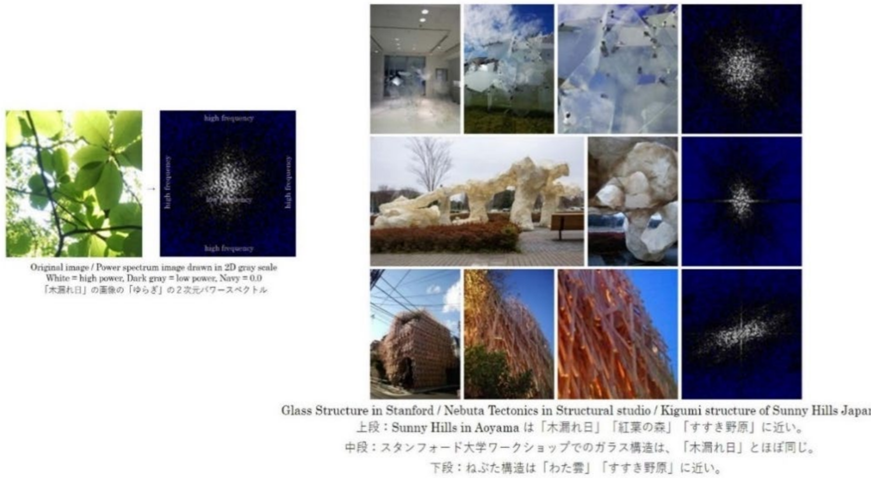

Figure 7 2D spectrum analysis comparison between images of structure and image of *Komorebi* by Jun Sato, image from the website http://junsato.k.u-tokyo.ac.jp/essay12.htm#_%E2%97%8F_2D_Spectrum

Although the idea of Komorebi has been developed and used in various design disciplines, direct incorporation of this charming light effect into the building component has not been explored yet. In contrast with the prior art where Komorebi is used as a guiding principle for design in specific contexts, this thesis aims to design a new building system to embed the sensory experience of *Komorebi* in the built environment, which thus broadens the potential adoptions and impacts of the system to enhance people's connection to nature in their daily life.

Chapter 3

Methodology

3.1 Conceptual overview

The scope of the thesis includes the design of the building system that produces *Komorebi* in the built environment and the evaluation of the proposed system. The proposed design and evaluation process consists of five main components: (1) material and actuator test; (2) prototype design and fabrication; (3) airflow calculation and test; (4) pinhole parameterization and test; and (5) environmental performance evaluation. In this chapter, each of these five components is explained in detail in its separate section, which all together reveals the thought and experimental process that forms the convergence to the final design solution.

3.2 Material and actuator experiments

The study is started by exploring and evaluating various materials and actuators that can produce dynamic pinholes when collaged together. Three types of material and actuation systems are tested, including an origami system embeded with shape memory alloy (SMA) (inspired by Media Lab Responsive Environement Group's graduate Dr. Jie Qi's post on *Creators Project* about Robotic Origami [19]; a pneumatic system using airbag with special seam pattern (inspired by Media Lab Tangible Media Group's publication on aeroMorph [20]), and an air-activated floating film system. As shown in Figure 8, the shape memory alloy (SMA) origami is able to fold and unfold due to the shrinkage of the SMA heated by electricity. The next experiment tested the pneumatic airbag shown in Figure 9. When air fills in, the volume and dimension changes in the airbag will make the airbag flap, the motion of which is guided by the specific placement of sealed lines on the airbag. The third experiment studied on blowing wind to the light film shown in Figure 10. In evaluating these experiments: the motion of SMA is too slow, the motion of the pneumatic airbag is faster but still fixed, the motion of the third experiment is the most similar to the improvisational motion of leaves blown by the wind in nature.

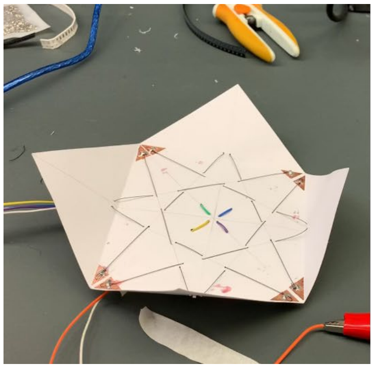
Figure 8

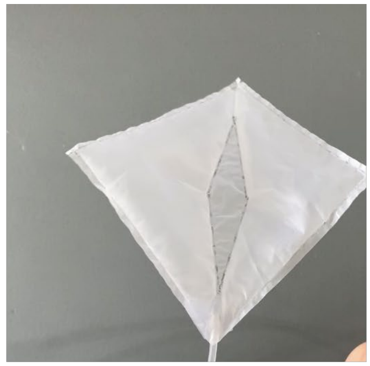
Figure 9


Figure 10

Figure 8 Test of shape memory alloy embedded origami, actuator: heat, motion: slow

Figure 9 Test of the pneumatic airbag, actuator: wind, motion: fixed

Figure 10 Test of blowing air to the light film, actuator; wind, motion: improvisational


Figure 11

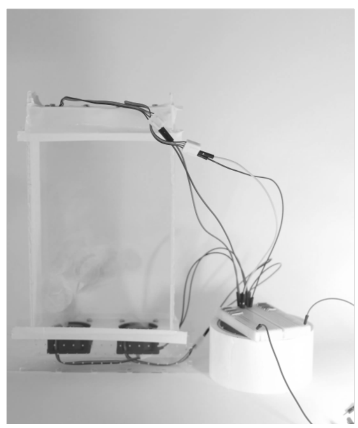
Figure 12

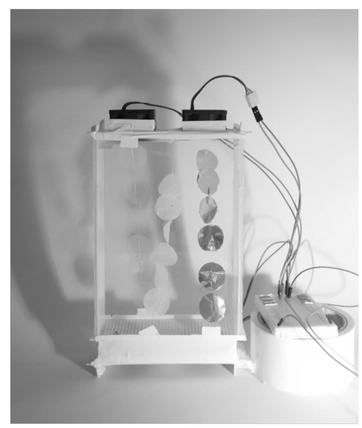
Figure 13

Figure 11 Wind blowing in one direction, material arrangement: free-floating

Figure 12 Wind blowing in and out, material arrangement: free-floating

Figure 13 Wind blowing in and out, material arrangement: randomly organized

Proceeding with further studies on the wind blowing mechanism, Figure 11 to 13 illustrate a series of tests of air circulations and material arrangements. To achieve a more dramatic improvisational motion of the films, the air circulation, which provides the motion's driving force, needs to be maximized. As a result of the circulation experiments shown in Figure 11-13, the "wind-blowing-in-and-out" configuration that have the fans on the one end blowing and the other end sucking (Figure 12), gives a better effect than the "wind-blowing-in-one-direction" configuration (Figure 11). In the material arrangement, prescribing a certain material organization, in this case stringing the films on wires (Figure 13) works better than leaving the material free-floating (Figure 12), where the mutual attraction force generated by static electricity among the free-floating pieces prevents the film pieces to move freely.

3.3 Prototype design and fabrication

With the material and actuator tested out, to bring the improvisational visual effect of *Komorebi* into the built environment, a daylight-filtering system (illustrated in Figure 14 and Figure 15) was developed. The system integrates a double-glazing system with solar air collectors. As wind triggers the movement of leaves, the airflow caused by the expansion of air from temperature rise in the solar air chamber would trigger the dynamic motion of the shading elements in the system. The speed of the airflow generated from the system would be affected by the area of sunlight absorption and the cross-sectional area for the airflow under the thermal fluid principle. Detailed calculations of the airflow are demonstrated in section 3.4. The size, blurriness, and roundness of the dappled lights would be affected by the dimensions of the holes, which is decided by the shading elements' shape and their distance to the projection surface according to the principle of the pinhole effect mentioned in section 2.2. Parameterization of the pinhole in the shading system is presented in section 3.5.

The air passing the air chamber would be heated slightly due to the solar radiation. As illustrated in Figure 14, the color of the shading flakes would change from color to no-color when the temperature rises above 85° F (32° C). As depicted in Figure 16, the system allows free control of guiding in or out the slightly heated air for the comfort in the built environment. In cold days, the heated air could contribute to the comfort of the indoor environment; in the hot days, the air could be guided out and only trigger the movement of the shading flakes. In addition, as shown in Figure 17, the shading system is integrated with the scissor mechanism, which allows open, close, and dynamic movement of the shading system.

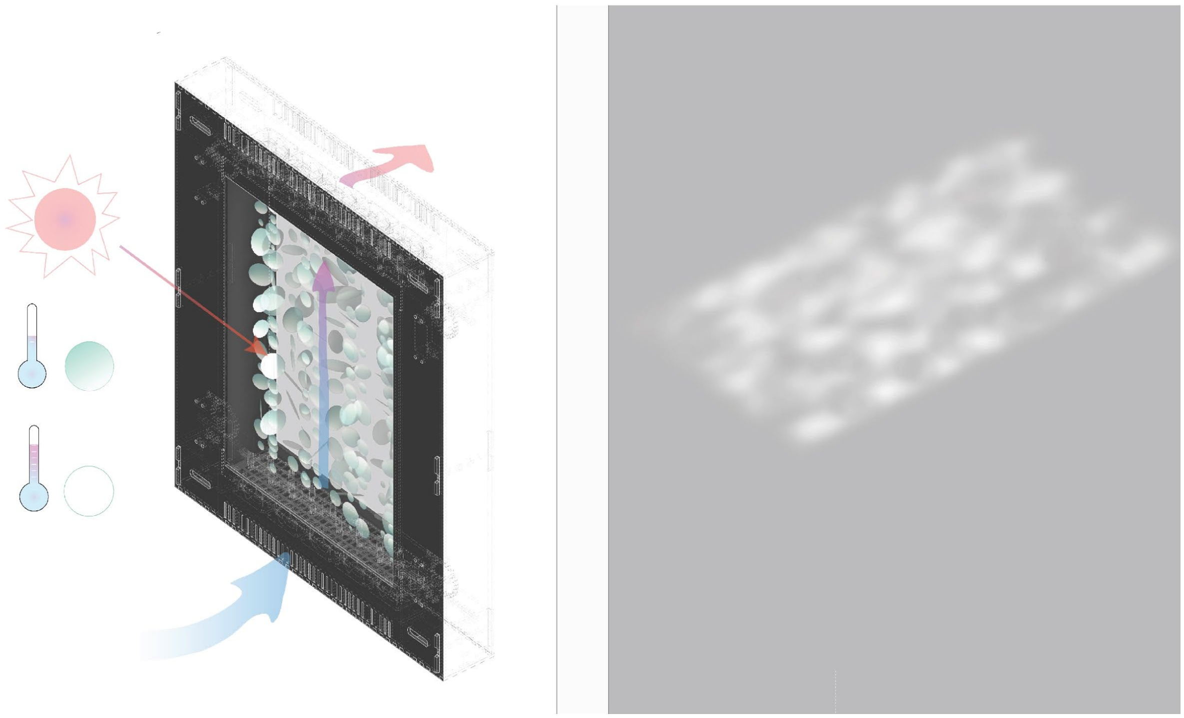

Figure 14 Daylight filtering system work with sunlight and wind

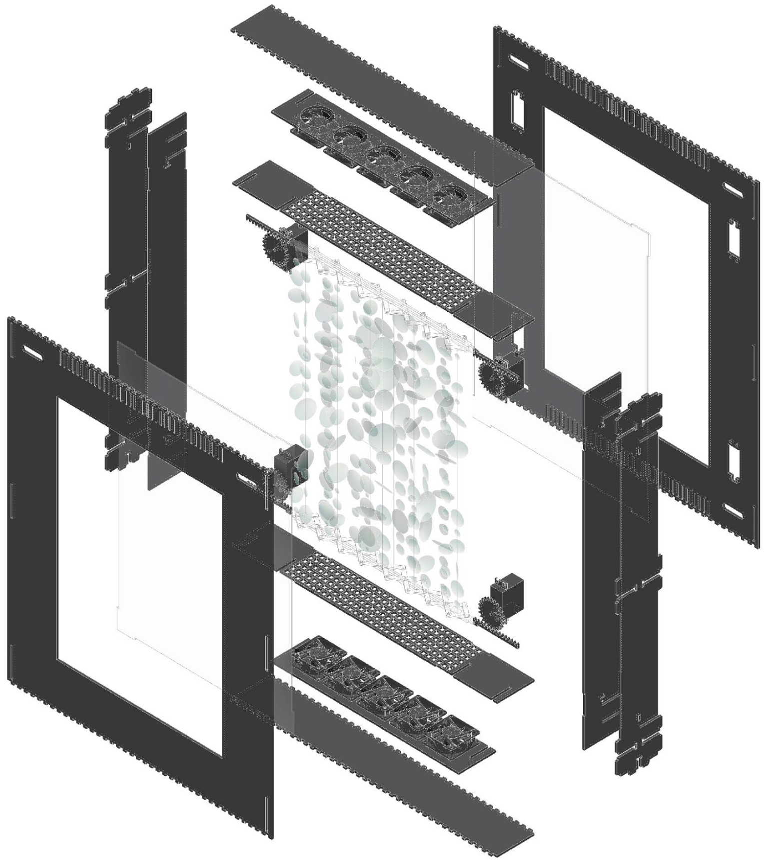

Figure 15 Exploded axonometric view of the *Komorebi* System

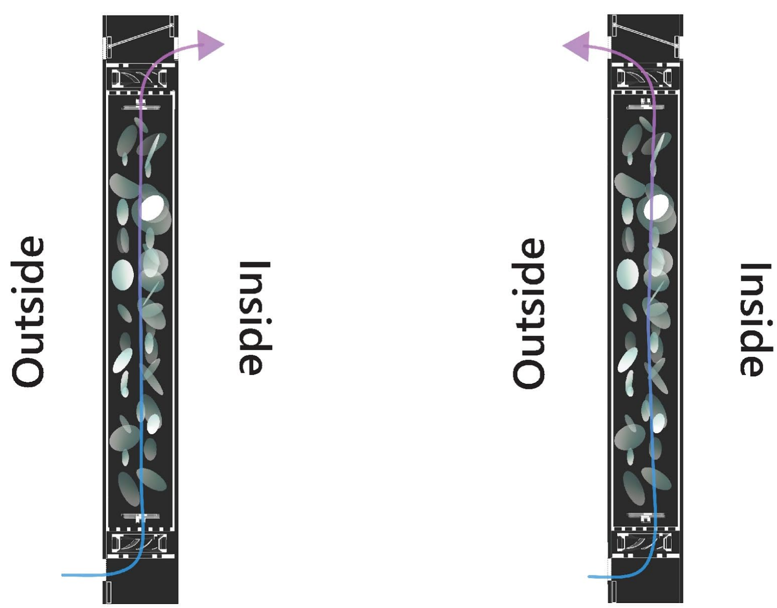

Figure 16 Controllable air guide that directs the heated air in or out

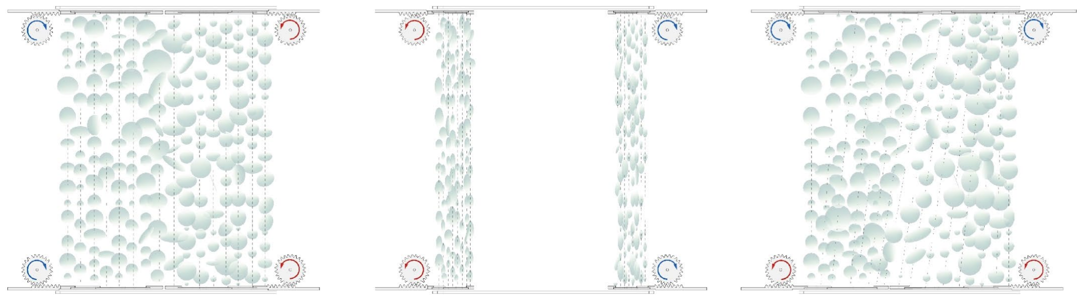

Figure 17 Shading system open, close and dynamic movement

3.4 Airflow calculation and test

The air circulation in the system triggering the movement of the shading elements is an essential factor for imitating the improvisational dappled light effect. As mentioned in section 3.3, the model of solar air collector is integrated into the system. Solar energy gets converted to producing air circulation in the *Komorebi* system. The airflow speed in the designed system can be calculated by the thermal fluid principle. The collector efficiency, η, could be calculated as

$$\eta = m \times C_p \times \Delta T / (I \times A_c);$$

and the mass flow rate, m, could be calculated as

$$m = \rho \times A_S \times C_d \times (2g \times h \times \Delta T / T_f)^{1/2}.$$

Assuming the collector efficiency $\eta = 35\%$; and knowing the specific heat of air C_p=1000 J/kg K, the global irradiance incident on solar air heat collector I = 500 W/m², in this prototype, the area of absorber A_c =0.5 m²; the formula of collector efficiency,

$$\eta = m \times C_p \times \Delta T/(I \times A_c),$$

can be written as $0.35 = m \times 1000$ J/kg K $\times \Delta T/(500$ W/m² $\times 0.5$ m²). The expression of m can be simplified as $m = 0.1/\Delta T$ (①). Knowing the density of air ρ = 1.2 kg/m³, C_d =0.6, the absolute air temperature T_f =300° C, the height h of air circulation in the system is 1m; the formula

$$m = \rho \times A_S \times C_d \times (2 \times g \times h \times \Delta T/ T_f)^{½},$$

can be calculated as $m = 1.2 \times 0.036 \times 0.6 \times (2 \times 0.98 \times 1 \times \Delta T/300)^{½}$. The expression of m can be simplified as, $m = 0.006 \times \Delta T^{½}$ (②). Combining the two formulas ① and ②, m can be calculated out, m=0.016m³/s. As

$$m = V \times A_s,$$

the airflow speed V can be calculated as $V = 0.016$ m³/s $\div 0.05$ m² $= 0.32$m/s.

In the first built prototype, for the purpose of testing the system without replacing a real window, ten nano fans are installed in the top and bottom of the system to create the air circulation. When tested with the hot-wire thermos anemometer, the shading flakes are able to move in airspeed at 0.32 m/s.

3.5 Pinhole parameterization and test

In addition to the air circulation described in the previous section, the pinholes composed by the shading flakes are the other essential factor for imitating *Komorebi*. As mentioned in section 2.2, *Komorebi* visual effect depends on the distance to the projection surface and the sizes of the pinhole. In order to study the parameters of the shading system, it is crucial to understand the projection distance in the built environment and the dimensions of the pinhole.

The distance from the pinhole to the projection surface varies due to changes in the sun angle and the various surfaces that the sun cast light on. In order to observe and test such concept, the Southeast-facing windows at Steam Café in MIT building 7, 4th floor, are chosen for observation and experimentation. As shown in Figure 18, a sun path simulation of the chosen site is conducted. Through observation, the site is most busy around 12:00 pm, and the distance to the projection surface is the smallest.

As for the pinhole, in nature, the dappled sunlight under the tree foliage mostly are circular and fuzzy regardless of the shapes of the holes composed by tree leaves. The parameterization of holes is tested on the chosen site. As shown in Figure 19, two sheets of paper with three shapes of holes, square, circle, and triangle, in two different widths, 2.6cm and 1.3cm, are placed on windows of different height, at 12:13 pm. In evaluation, the light spots filtering through 1.3cm holes become circular and fuzzy from at least about 136 cm away; at about 296cm away from the projection surface, the light spots from 2.6 cm holes all become circular as well.

A comparison is conducted between the results from the physical test method with the calculation method mentioned in section 2.2. According to the proportional relationship between the pinhole and projected image, the width of the light spots, D, could be calculated as

$$D = (d/l) \times (L+l),$$

where d is the width of the pinhole, l is the distance from the sun to the pinhole, and L is the distance from the pinhole to the projection surface. Since L is extremely small comparing to l, d could be considered approximately the same as D, $D \approx d$. As described in section 2.2, if the shifting distance C'C'' ($C'C'' = L \times \tan a$) is equal to or larger than d, the fuzzy circular image of the sun would form. In the formula, it could be written as $D/2 = L \times \tan a$. To get minimum projection distance, L, for the given pinhole width, d, L could be calculated as $L = d/2 \div \tan a$. For $d = 1.3\text{cm}$, $L = 1.3\text{cm} \div 2 \div \tan(16 \text{ arc minutes}) = 138 \text{ cm}$; for $d = 2.6\text{cm}$, $L = 2.6\text{cm} \div 2 \div \tan(16 \text{ arc minutes}) = 276 \text{ cm}$. In comparison, the calculated results are very close to the results from the physical tests

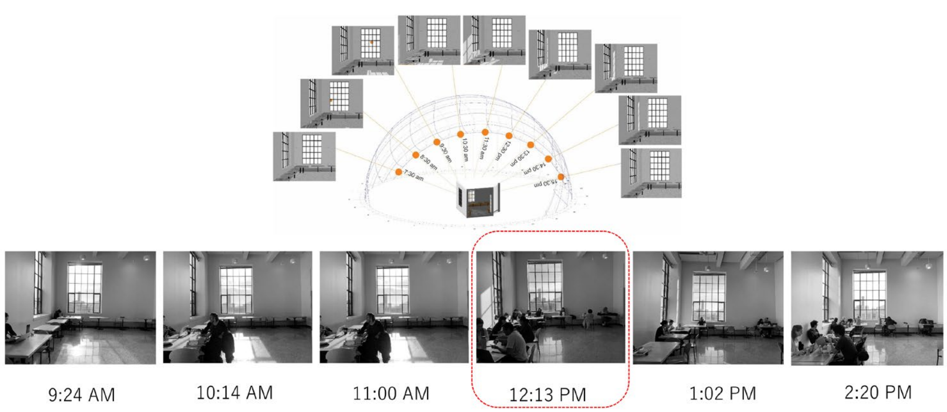

Figure 18 Sun path simulation and photograph records at the Steam Café during the daytime

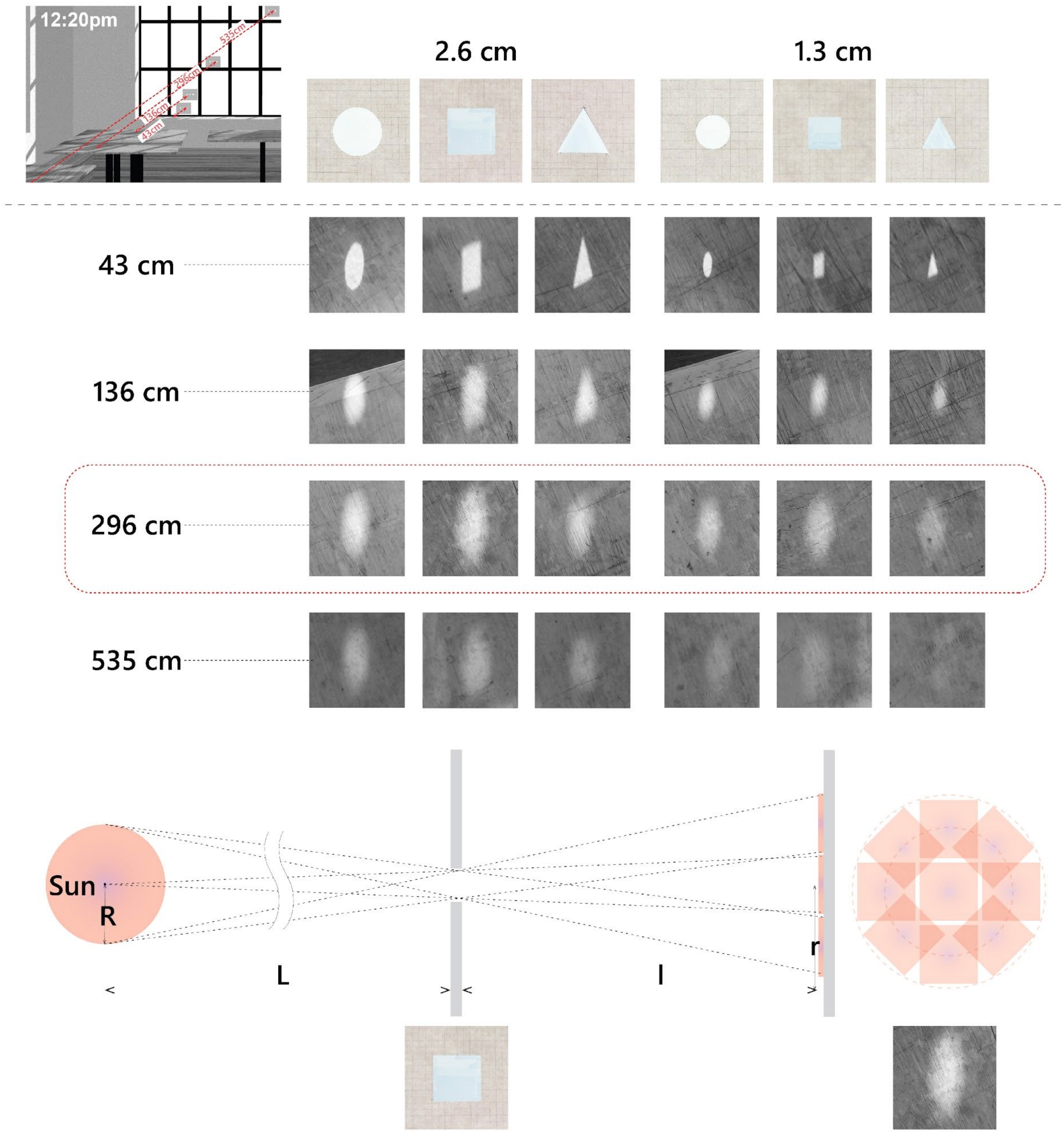

Figure 19 Physical pinhole test at the Steam Café

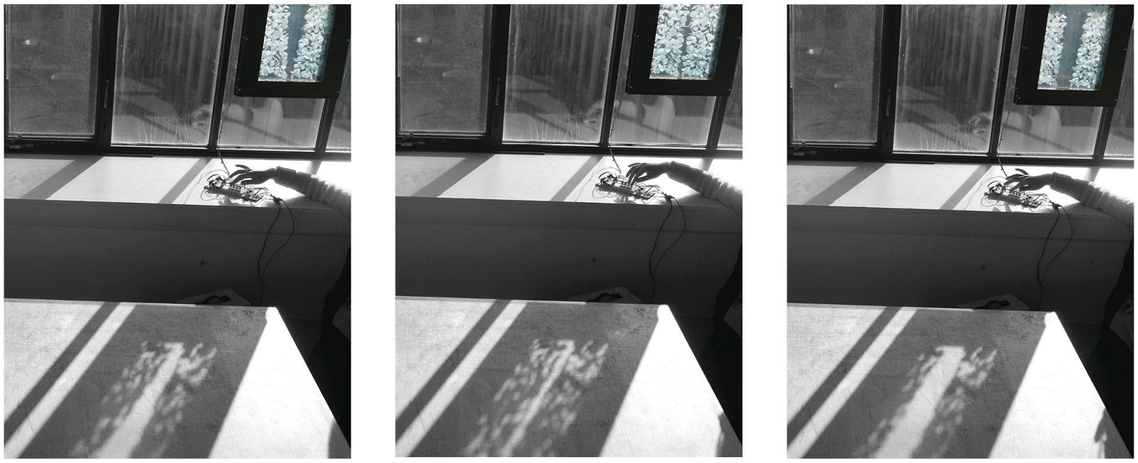

Figure 20 *Komorebi* system prototype test on-site

Figure 21 Physical prototype of the *Komorebi* system

For the prototype designed for the lower row shown in Figure 20, the projection distance at noon would be the smallest and around 130 cm. In order to get the *Komorebi* effect, the sizes pinholes composed by the shading flakes would be controlled around 1.3 cm, shown in Figure 21.

Figure 22 illustrates the parameterization of the shading system: the sizes of composed holes in the shading system could vary according to different heights; the density of the shading system could also be tuned depending on the exposure to sun and requirement of the program.

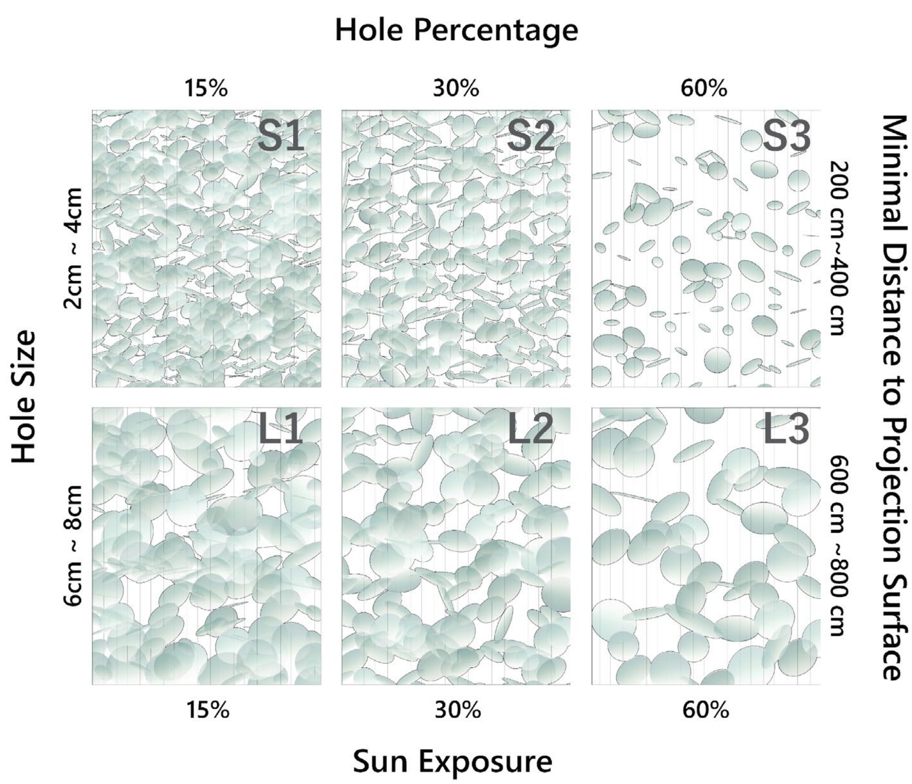

Figure 22 Parameterization of the *Komorebi* system

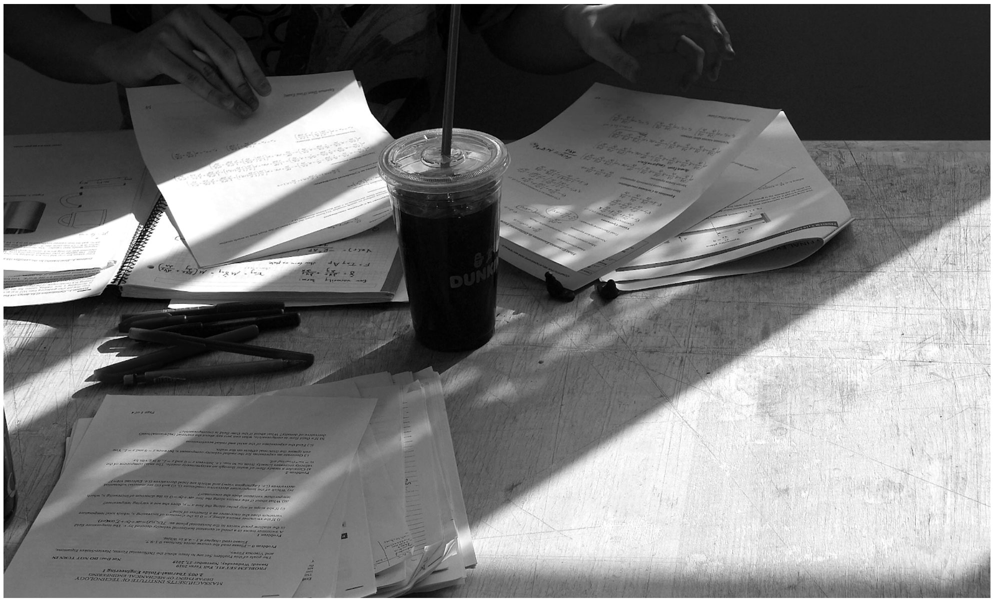

Figure 23 A girl doing homework in *Komorebi* at Steam Cafe

Figure 23 presents the improvisational dappled light of the *Komorebi* system interacting with the activity of the occupant at the Steam Cafe. A full video of *Komorebi* and the created system could be watched at https://youtu.be/iavcW96EyaA.

3.6 Environmental performance simulation

As the first step in evaluating the environmental performance of the *Komorebi* system, its performance in daylight autonomy and the annual glare is compared, with no shading and the Venetian blind. The simulations are conducted using the Climate Studio, and three scenarios are examined: office, hospital, and kindergarten, shown in Figure 24. The simulation uses the ray trace engine. The *Komorebi* system is modeled as circular flakes rotated by various degrees and applied with transluscent material in the Climate Studio. For the simulation, it assumes a static state of the shading system.

Figure 24 Rendering simulation of *Komorebi* in the office, hospital, and kindergarten

Figure 25 indicates that in the office, the *Komorebi* system enables 78% of the fully daylit area, and 22 % of the practically daylit area, which is a little less than the 1oo% daylit area in the no-shading setting but a lot better than the 25% partially daylit area and 75% non-daylit area from the *Venetian* Blind. As for the annual glare performance, the *Komorebi* system reduces about half of the space in which at least 5% of the occupied hours are covered by disturbing glare comparing with the no-shading setting; the percentage of glare area drops from 32% to 14%. The test results from the other two scenarios shown in Figure 26, 27 varies a little bit due to differences in measuring surfaces and occupation schedule. Still, they all show that the Komorebi system offers a comfortable intermediate between the no-shading and Venetian blind settings. It enables more daylit area comparing to the Venetian blind and improves glare significantly comparing to no shading.

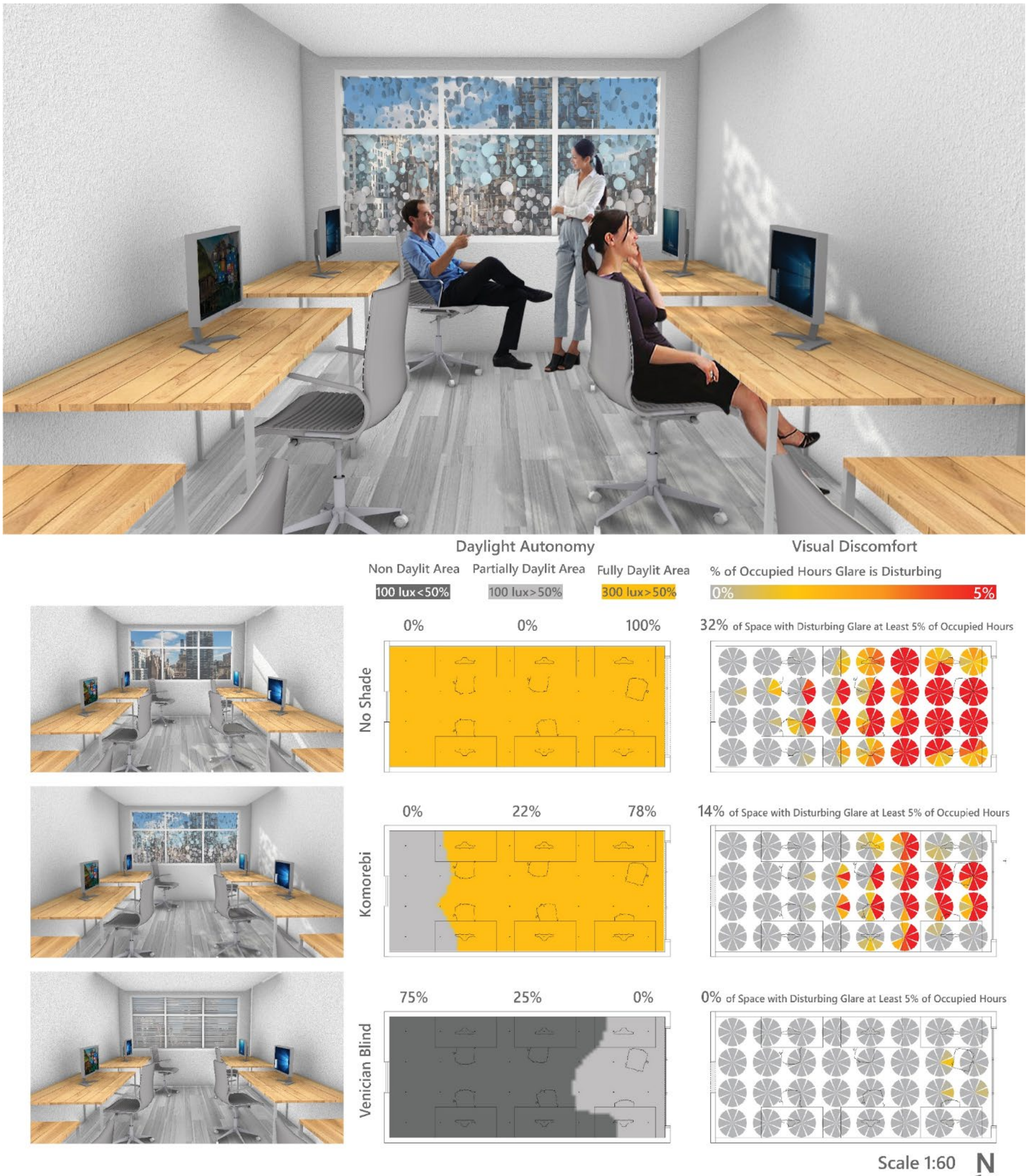

Figure 25 Daylight autonomy and annual glare simulation test in an office context

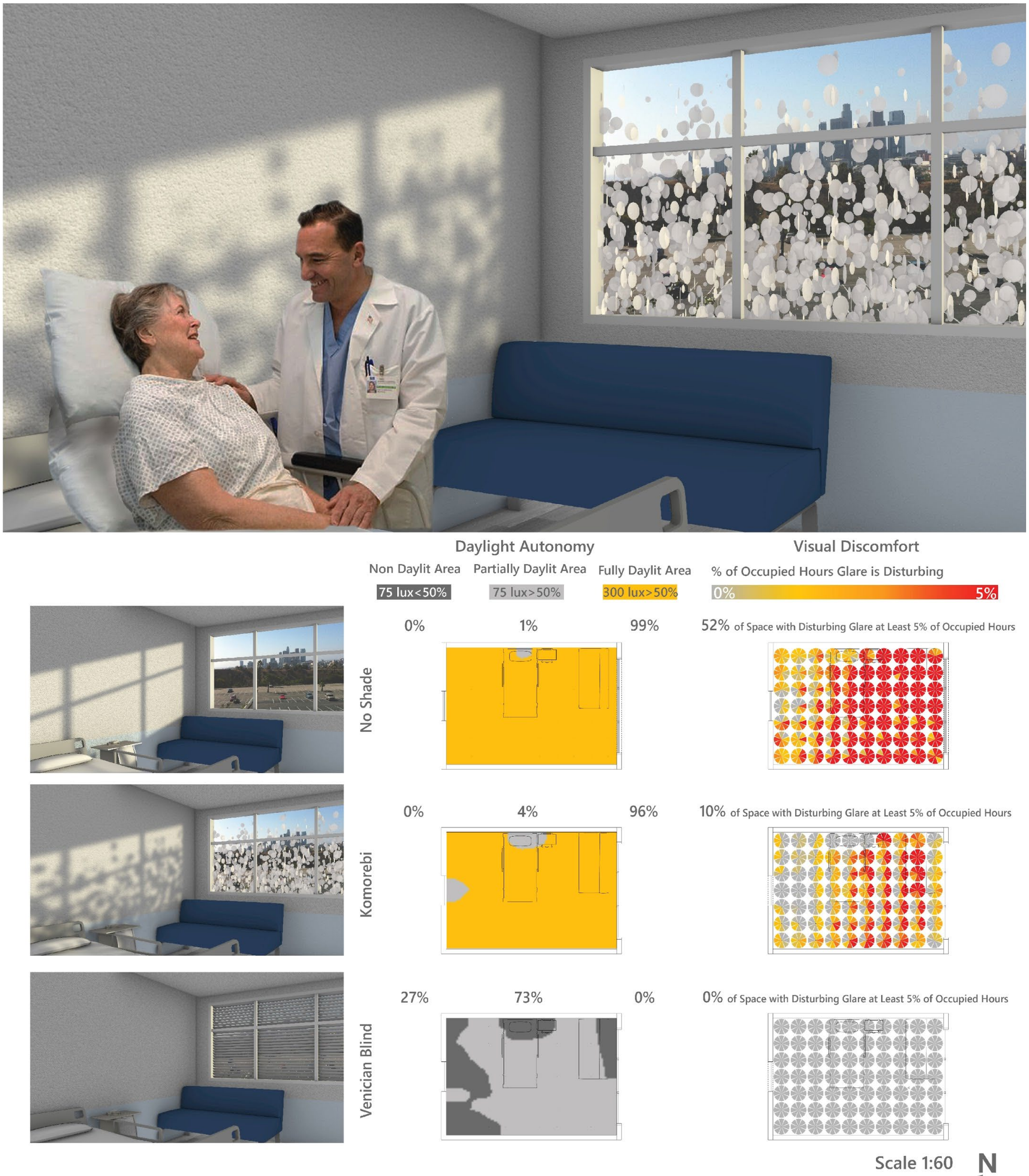

Figure 26 Daylight autonomy and annual glare simulation test in a hospital context

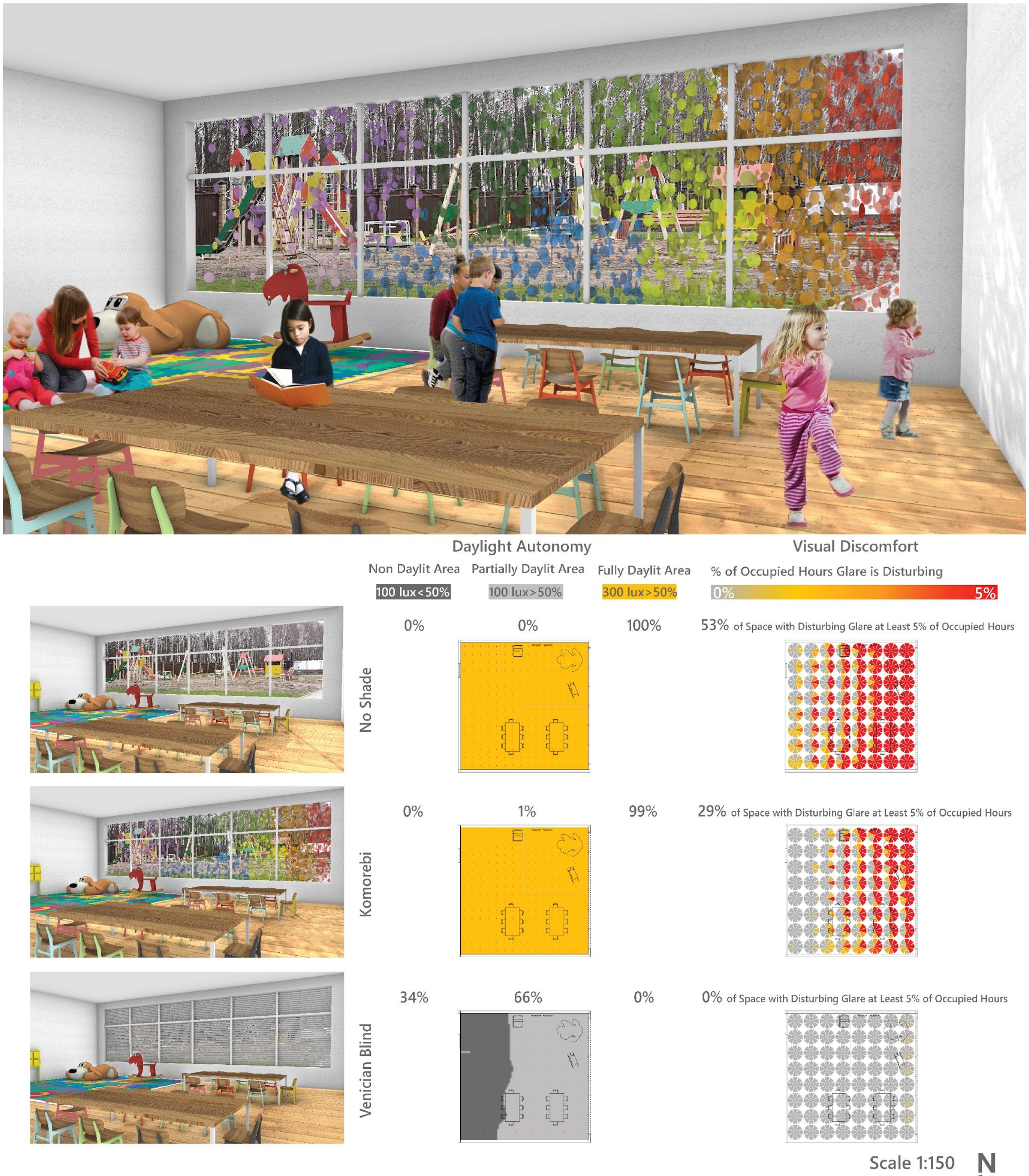

Figure 27 Daylight autonomy and annual glare simulation test in a kindergarten context

Chapter 4

Conclusions

4.1 Summary of results and contributions

This thesis introduces a new way to connect with nature in the built environment for the occupants' health and well-being. The thesis proposes embedding the natural sensory experience *Komorebi* in the built environment via a dynamic shading system. Complementing the basic function of a window shading device, the *Komorebi* system offers people perceptions of connectedness to nature in the built environment. In application, it would be beneficial for occupants with limited access to nature due to work demands or mobility constraints. On the one hand, this new system would provide people with natural sensory experiences in the built environment. On the other hand, it would invoke people's memories in nature and thus encourage more exposure to nature.

4.2 Future work and concluding remarks

The thesis presented here could be extended in a number of ways. The simulation of this thesis adopts the ray tracing rendering methods based on the algorithm that traces the path of the light. In reality, the *Komorebi* results not only from the direct path of the sun rays, but also diffraction when sunlight passing through the edge of the pinhole. A more precise rendering method could be studied in the future.

This thesis focuses on the methodology of creating a building system that embeds *Komorebi* in the built environment. In evaluating such a system, in addition to the environmental performance simulation conducted in this thesis, studies of user's perception from the created system can be done in the future. Users' physiological data such as heart rate, breath rate, and troponin levels (which reveal people's stress level) can be collected. Furthermore, occupants' behavioral and psychological data can be collected by doing user studies through observation, example sampling, or participant self-report surveys. Metrics from environmental psychology such as Connectedness to Nature Scale (CNS), Perceived Restoration

Potential (PRP), and Perceived Focus Potential (PFP) can be tested for the best nature of the study. The collected and processed data can be used not only for evaluating and optimizing the system but also to offer live feedback to the operation of the system that responds to the occupants' various states. These data and evaluation results can all together justify the importance and effectiveness of embedding natural effects in the built environment via designing specialized building systems, which pave the way for further research into this direction.

In conclusion, *Komorebi* is one of many sensory experiences from nature. This thesis is an initial step in embedding the natural sensory experiences in the built environment. The author hopes the research presented in this thesis could be the first spark that can lead to a holistic exploration of various building systems addressing other sensory experiences in nature.

Chapter 5

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