Thesis for the Degree of Master of Engineering

Experiment on Luminous Characteristics and Illuminance Distribution of LED Lighting with Hanji Diffuser

by

IIRIS AHOLA

Department of Architectural Engineering

The Graduate School

Pukyong National University

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LED조명 디퓨저의 빛 특성 및 조도 분포에 관한 실험적 연구

Advisor: Prof. Gun Joo Jung

by

IIRIS AHOLA

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IIRIS AHOLA

Pukyong National University Department of Architectural Engineering

Abstract

This research covers the features of an light emitting diode (LED) light source paired with different diffuser types. The research was conducted in two phases. The first phase included different colored LEDs with three diffusers and illuminance, luminance, radiance and the spectrum of the light were measured. The LED colors used in the experiment were red, green, blue and two shades of white. The diffusers used were made of clear glass, acrylic and the Korean traditional paper, hanji. The LEDs were measured without a diffuser for comparison. The measurements were conducted in a closed space, with no outside light entering the room. One measurement point was used to measure the features of the light.

The second phase was conducted in an office environment. The light source was made of three white LED downlight luminaires. The measurements covered the distribution and the uniformity of the produced light. The luminaires were paired with a diffuser made of acrylic and a diffuser made of the Korean traditional paper, hanji. As a comparable, the light was measured without any diffusers. In order to measure the distribution and uniformity, a grid of 50x50mm was prepared. This grid produced 60 points of measurement in total.

The research concluded that the diffuser made of hanji paper will alter the lighting characteristics by muting the strength of the produced light qualities. This effect has it's advantages and disadvantages, since hanji will require a more efficient lighting in order to achieve illuminance standards required for spaces with different purposes. The advantage is the effective diffusion the hanji paper produces. Since this research covered only the objective research on one type of hanji paper, further studies on different types of hanji and subjective experiments are to be considered.

Keywords: LED, lighting, illuminance, diffuser, hanji

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I. Introduction

LED lighting has become a widespread option in commercial and residential lighting these days, making the research on the lighting properties and qualities of LEDs more important than before. The lighting characteristics of a light source have been researched considerably broadly for several decades [1], [2], and the research conducted is regularly defined into two categories, objective [3] or subjective [4] research.

This study covers the objective study of a lighting environment. Red, green, blue and cold and warm white LED lighting, and how their lighting characteristics diverse is researched when a diffuser is added. A 4 mm clear glass plate, a conventional opal acrylic diffuser and a diffuser made of the traditional Korean paper, hanji, are compared to the light produced by the LEDs without any added diffuser. The uniformity of the lighting is studied in a common office-type room with LED lighting and acrylic and hanji diffusers.

Hanji was picked up as the comparative diffuser for its continuous use in Korea and the fact that very little research has been conducted of hanji in lighting, although hanji is used to diffuse and soften light also in present day Korea.

The hypothesis concerning the hanji paper in this study is the diffuser made of hanji will alter the produced light and affect the lighting characteristics and the features of diffusion of the LED light source.

Figure 1 shows the process of this study.

In this study the objective is to investigate different diffusers attached to a LED luminaire, emphasis being on a diffuser made of the traditional Korean paper hanji. Hanji has been used in light diffusion for a long time, but the use of hanji in ordinary lighting setting has not been yet investigated. The goal of using hanji as a diffuser was to find out ways to improve the quality of the indoor lighting environment with new type of diffuser. The research was conducted in two parts.

The first part covers the lighting characteristics that an LED luminaire with different diffusers produces. The lighting characteristics measured were illuminance, luminance, irradiance and the wavelength of the produced light. The diffusers used in the study were a conventional acrylic diffuser, a diffuser made of clear glass, a diffuser made of the traditional Korean paper hanji. As a comparison, the lighting characteristics of the luminaire were measured without a diffuser.

The second part of the study covers the distribution of an LED light source with different diffusers. Diffusers used in the experiment were a conventional acrylic diffuser and a diffuser made of hanji. A measurement without any diffuser was conducted for comparison. The measured parameter was the illuminance distributed in an office room. The main focus was to investigate the uniformity and the peak mitigation of the light produced by the different diffusers. The peak mitigation was measured in the room with only one separate luminaire on and the uniformity was measured with the whole lighting of the room turned on. The focus of the arrangement with one luminaire was to check the peak migration when the diffuser is changed. Uniformity of the lighting was measured with the complete lighting system on.

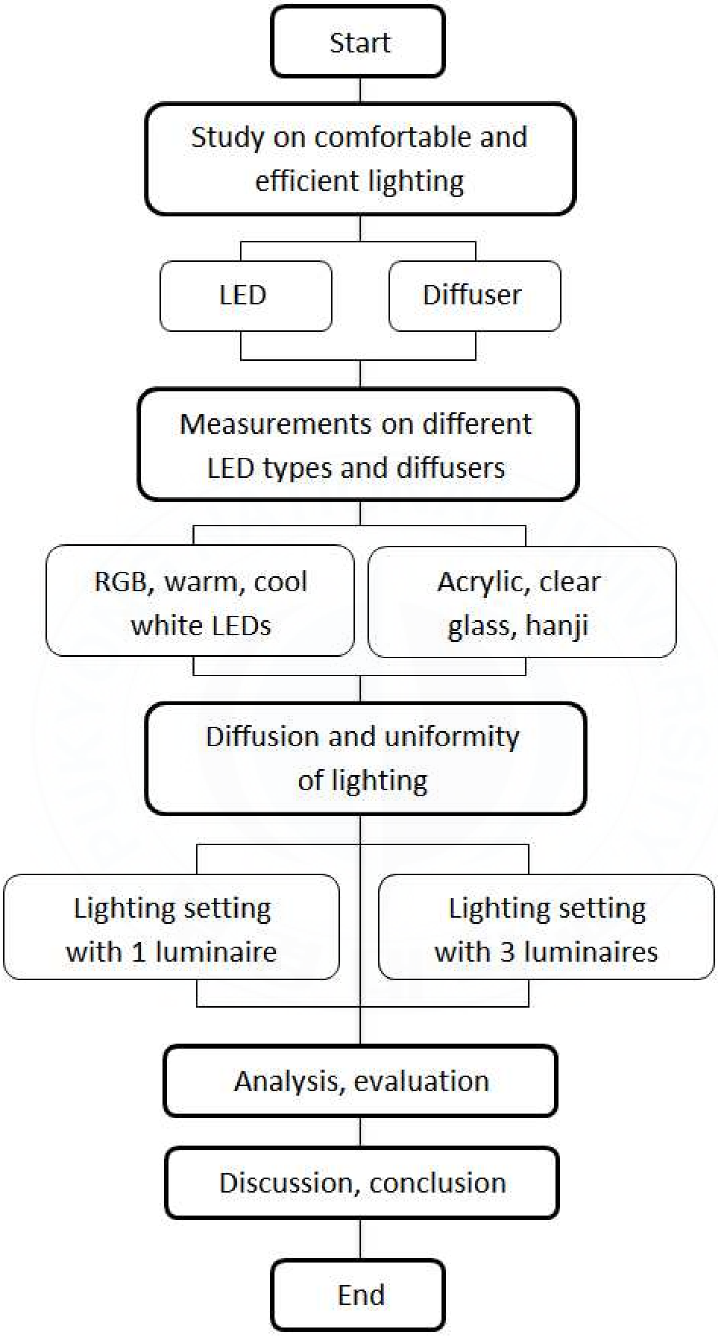

Figure 1. Process of the study

II. Literature review

The lighting characteristics of a light source have been researched considerably broadly for several decades [1], [2], and the research conducted is regularly defined into two categories, objective [3] or subjective [4] research. In the research conducted by T. Tamura and co. on “Illumination characteristics of lighting array using 10 candela-class white LEDs under AC 100 V operation” the main focus is on the illumination and the wavelength of the light and the intensity of the emission, with the temperature of the LED light source taken into consideration. Their experiment is of interest when designing the LED luminaires, since the results indicate that the spectrum can be alternated by the change of the surrounding temperature. As humans have a preference for light that is considered “natural”, i.e. with a spectrum corresponding with sunlight. What the research conducted by T. Tamura and co. concluded was the yellow emission intensity decreases as the temperature goes up and the blue emission intensity is strengthened. F. Behar-Cohen and co. [5] have researched LEDs in domestic lighting and the possible harms the LED lighting can produce. The research does rise and alarm of the exposure to blue and violet light. Previous light sources have not produced shades of blue light in such a substantial way, which makes the shift to blue light slightly alarming as it is.

Diffusion and uniformity of light sources have been researched mainly to avoid glare in an artificially lit room. L.M. Geerdick and co. has researched the relation between discomfort glare in real office environment and the set of parameters typical for LED lighting in offices. [6] The studied features were peak luminance, luminance contrasts and spatial luminance distribution. The study contained various luminaires with different luminance patterns paired up with various luminance levels. The beam shapes were a Lambertian like beam and a beam with reduced intensity at large angles. The results showed a clear negative effect caused by spottiness in high illuminance (over 500 lux) while it was less pronounced in low luminance. They concluded that non-uniform luminance patterns and high luminance contrasts cause discomfort glare in open office environment. The result of the research is meaningful for lighting design in office environment, since office spaces tend to be lit with higher luminous flux levels since the IESNA recommended illuminance level is 500 lux. [7]

IESNA, or Illuminating Engineering Society of North America, has published their recommendations of illuminance in different environments in their Lighting handbook. The illuminance recommendations are found in figure 10-9 in the Lighting handbook. Office environment goes to the area of "performance of visual tasks of high contrast and small size, or visual tasks of low contrast and large size". In this research the illuminance level was measured by a illuminance meter (lux meter), but the illuminance L can be calculated by multiple different methods. The most common one is the lumen method, where the fenestration and exterior lighting are taken into the equation. presented in the following equation (1).

$$E_i = E_x \cdot NT \cdot CU \qquad (1)$$

where E_i and E_x are interior and exterior illuminance in lux, NT is net transmittance and CU the coefficient of utilization. The formula is used in normal lighting environments without any toplighting, which is usually used in daylighting.[7]

Similar to the need of decent amount of illuminance, low contrast is considered as an important aspect of lighting in an office environment. Spaces with low contrast provide an easy environment to see and perform tasks that require concentration. High-contrast environment is used in environments, such as restaurants or art galleries, where the focus of the user of the space is to be directed in certain, bright lit areas of the room. Thus spotty high-contrast environment is not preferred in an office environment. [8]

Contrast of light C can be calculated by one of the two simple formulas presented in equations (2) and (3).

$$C = \frac{|L_b - L_t|}{L_b} \qquad (2)$$

where L is luminance. The luminances L must be in same unit.

or

$$C=\frac{|\rho_b-\rho_t|}{\rho_b} \qquad (3)$$

where ρ is reflectance. The subscript t refers to the target and b to the background. High contrast is above 0.3 and low contrast is 0.3 or less. [7]

III. Features of lighting

When the lighting characteristics are researched, the characteristics are generally divided into illuminance, luminance, irradiance and the spectrum of the light. [4] The LEDs as a light source produce light in different wavelength of the spectrum of visible light, depending on the color of the LED in question and the components used to manufacture the LED. The whole spectrum of visible light perceived by the human eye is from approximately 380 nm to 760 nm. [8] For the red LED, the wavelength of the light is mainly from 600 to 650 nm, the green LED is from mainly from 500 to 600 nm and the blue LED conventionally from 400 to 500 nm. As for the white LEDs, because of the production process and the different manufacturing systems [9],[10], the spectrum of a white LED covers mostly the whole visible light spectrum. The conventional white LEDs focus mainly on the wavelengths of blue and red color of the spectrum [11], depending on the base component of the white LED in question. The research on the spectrum of the LED is relatively connected to human health and seeking a lighting environment that is perceived as more natural is an important aspect of the research of LEDs and other light sources [12].

The illuminance, luminance and irradiance levels are common metrics used in measuring the strength and qualities of the produced light. Illuminance has a way to affect how the surrounding space is perceived. [4] Certain luminance and illuminance levels for different situations are recommended by ASHRAE and other national standards [7], [13], to make the brightness level of indoor facilities suitable for the human physique and the tasks relevant to the environment.

3.1 Lighting characteristics

As mentioned before, illuminance, luminance and irradiance are common metrics used in the measurements on lighting and it's qualities. Thus these three were selected to study the qualities of light produced by LED luminaires used in the study. These were chosen as they demonstrate the energy on a surface, produced by a light source.

3.1.1 Illuminance

Illuminance is the areal density of the luminous flux (lux) falling on a surface. An illuminance meter, or lux meter, is an instrument for measuring illuminance on a surface. [7]

3.1.2 Luminance

Luminance, or photometric brightness, is the quotient of the luminous flux at an element of the surface surrounding the point, directed in a solid angle. The luminous flux can be leaving, passing through or arriving at the surface. The unit used is candela per square meter, cd/m^2. [7]

3.1.3 Irradiance

Irradiance is the density of radiant flux occurring on a surface. The unit is power per square meter, W/㎡. [7]

3.2 Experiment set-up and conducting the experiment

3.2.1 Experiment set-up

The experiment was to be conducted in an environmental chamber that doubled as a dark room. The dimensions of the environmental are 2400 mm (L) x 2400 mm (D) x 2300 mm (H). The chamber contained few windows which were covered with thick foam panels to keep the outside light out. The inner walls of the chamber have a metallic finish, hence the inside walls, ceiling and the floor were covered with black vinyl sheet to minimize the possible reflectance caused by the glossy walls.

For the light source, a basic luminaire with a changeable LED-plate was prepared. The LED plates contained 10 pieces of LED modules with 3 LEDs in each module. LEDs in red, green, blue and warm and cold white were prepared. The LED modules were 0.72 W each and used a 12 V voltage. A 30 W 220 V/12 V converter was installed between the LEDs and the output.

The luminaire casing itself was 200 mm by 200 mm, the distance between the LED modules and the various diffusers was 50 mm. The casing was made of plywood for making any modifications simplified and to lessen the weight of the luminaire. Since the walls and ceiling of the chamber were magnetic, strong magnets were glued on the back of the luminaire. This made the change of the luminaire more convenient. After the assembly of the case, they inside was sprayed matt black to reduce any in-luminaire reflection.

A glass plate, an opal acrylic diffuser and a piece of natural white hanji were prepared as the diffusers in this experiment. The plates used were 200 mm x 200 mm in order to match the luminaire casing. The thickness of the clear glass plate used was 4mm. For the opal acrylic diffuser, the thickness was 1.5 mm. The thickness of the hanji was less than 1mm.

The point of measurement and luminaire were placed in the center of the chamber. The ceiling height of the chamber was considerably lower than the normal room height; hence the measurement place was lowered to 550 mm, in order to produce a distance of 1750 mm between the light source and the measurement sensor. This distance of 1750 mm is similar to the one found in classrooms, between the light source and the desk plane. This of course can vary depending on the built year of the building in question and the use of the classroom. It should also be noted that the lighting measurement guidelines mostly specifies the height of the measurement point, not the distance from the light source.

Figure 2 shows the simplified experiment setting inside the chamber. Figure 3 is the equivalent experiment setting executed inside the chamber with the blue luminaire without any diffuser and the stool to provide the accurate height of measurement point.

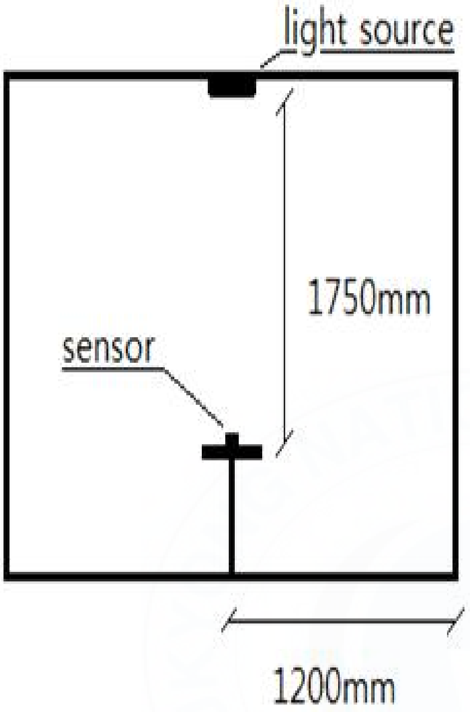

Figure 2. Experiment setting

Figure 3. Experiment setting inside the chamber

3.2.2 Conducting the experiment

The experiment was conducted by measuring the illuminance (lux), luminance (cd/m^2), irradiance (W/m^2) and wavelength (nm) generated by the five different LED light sources. The LEDs in question were red, blue, green and warm and cold white LEDs. The LED luminaire was measured without any diffuser for comparison and then with three different diffusers. The illuminance, luminance and irradiance were measured with DeltaOhm's LP471PHOT, LP471LUM2 and LP471RAD measurement sensors, respectively, attached to the DeltaLogger DO9847 instrument. DeltaLog3 software was used to process the data collected in the experiment. The DeltaLogger DO9847 and the illuminance sensor LP471PHOT attached to the logger are shown in Figure 4.

Figure 4. DeltaLogger DO9847 and illuminance sensor LP471HPHOT

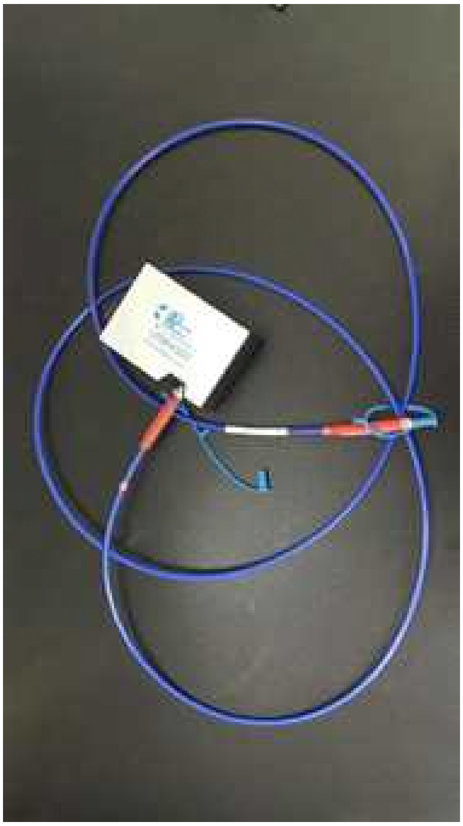

Figure 5. OceanOptics USB400 spectrometer and VIS-NIR fiber

The wavelengths were measured with OceanOptics USB4000 spectrometer, with a VIS-NIR fiber optic attached to the instrument.

The data was gathered with the OceanOptics OOIBase32 spectrometer operating software. The OceanOptics USB4000 spectrometer with the VIS-NIR optic fiber used in this experiment are shown in the Figure 5.

The diffusers utilized in the experiment were a 4mm glass plate diffuser, an acrylic diffuser and a diffuser made of white hanji paper.

The measuring time of the features was 60 seconds. Before the measurement, the measured LED light source in question was left on for 10 to 15 minutes in order to make sure the light produced was of equal state to the previous ones.

All the measurements were done for each of the five LED color types with each diffuser attached to the luminaire at a time.

3.2.3 Results

The following illuminance levels (lux) were obtained in the experiment with DeltaOhm's DeltaLogger DO9847 and the LP471LUM2 sensor, shown in Table 1.

As presented in the Table 1, the illuminance level drops with the use of diffuser. The drop in illuminance between no diffuser and the opal acrylic diffuser is 37~48% in each of the different LED types, the warm white LED being the worst and the red LED being the least affected, and the difference between the measurements without any diffuser and with the diffuser made of the hanji paper is over 70% in each of the LED types.

Table 1. Illuminance levels

Diffuser type (lux)				
LED-type	No diffuser	Clear glass	Acrylic	Hanji
Red	14.01	11.71	8.82	3.97
Green	35.59	32.64	19.39	9.34
Blue	7.98	6.82	4.3	2.3
Warm white	51.58	48.08	26.82	13.61
Cold white	45.32	41.75	26.83	12.18

Table 2 shows the luminance levels (cd/㎡) obtained in the experiment with DeltaOhm's DeltaLogger DO9847 and theLP471PHOT sensor.

Table 2. Luminance levels

Diffuser type (cd/m2)				
LED-type	No diffuser	Clear glass	Acrylic	Hanji
Red	43.1	1166	610	283
Green	2010	2870	1691	732
Blue	857	614	419	154.4
Warm white	2010	3320	2170	905
Cold white	4660	2770	2220	975

As in the illuminance levels, the luminance has a significant drop when it comes to the opal acrylic and hanji diffuser. The opal acrylic diffuser seems to be less worsening option while the hanji drops the luminance level of all LED types with 80% and more from the luminance obtained without any diffuser.

The red LED seems to give very low luminance levels without a diffuser. The red LED was indeed re-measured to rule out the possible error in the measurement process, but the low luminance level without a diffuser was continuously obtained as a result.

Nevertheless, in the case of the red LED, the difference between the clear glass and the opaque diffusers, the acrylic one and the hanji one, is 48% and 76%, respectively.

The irradiance levels (W/m^2) obtained in the experiment with DeltaOhm's DeltaLogger DO9847 and the LP471RAD sensor are shown in Table 3.

As for the results of irradiance, they seem to follow the pattern observed in the illuminance and luminance levels.

The irradiance levels in Table 3 show a major drop from the levels attained without a diffuser when the opal acrylic and hanji paper diffusers are attached. The opal acrylic diffuser causes a drop of 33~49% depending on the LED type, red being the least affected and the warm white LED the most affected. The diffuser made of the hanji paper is responsible for a drop of 70~74%, red LED being again the least affected whilst the warm white LED was the most affected in this case also.

Table 3. Irradiance levels

	Diffuser type (W/㎡)			
LED-type	No diffuser	Clear glass	Acrylic	Hanji
Red	0.0516	0.0471	0.0345	0.0152
Green	0.064	0.0595	0.0344	0.0165
Blue	0.1335	0.111	0.0716	0.0349
Warm white	0.127	0.1186	0.065	0.0327
Cold white	0.1374	0.1279	0.0803	0.0361

Figures 6 to 10 show the change in wavelength of the spectrum of three LED light sources, red, warm white and cold white, when a diffuser is added to the luminaire or changed. In the figures, counts of intensity are plotted against the wavelength in nanometers.

The spectrum figures were obtained from the OceanOptics OOIBase32 spectrometer operating software that uses “counts” of photons as a unit for the intensity. This explains why no conventional optics related intensity unit is shown on the tables.

As the added diffuser does affect the intensity of all of the LEDs, especially when considering the opal acrylic diffuser plate and the hanji, the wavelength of the light does not change considerably in most cases.

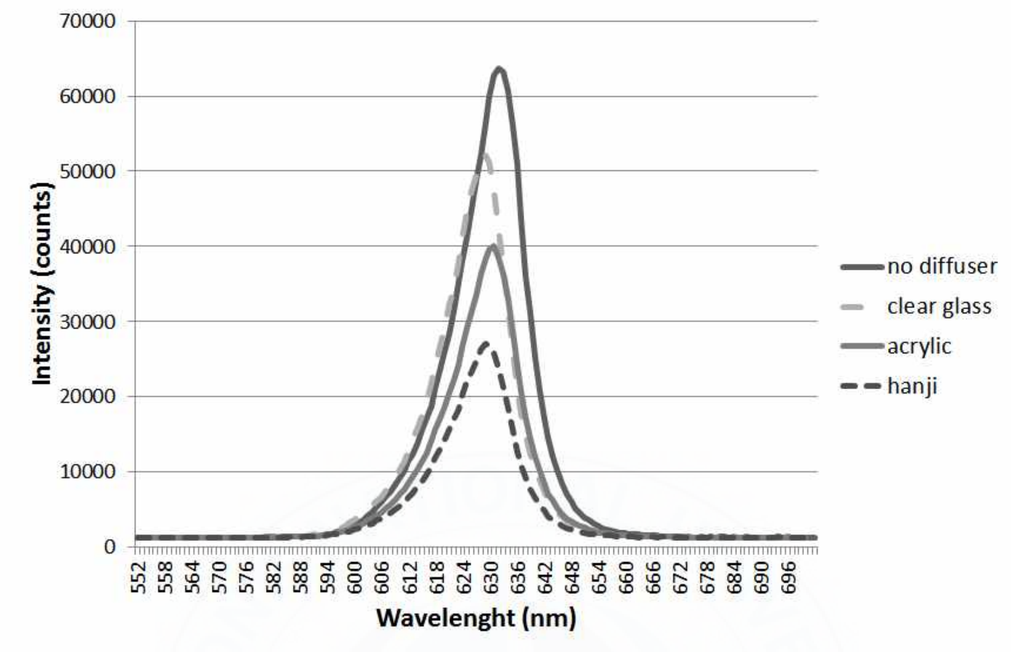

Figure. 6 Red LED spectrum

The restricted patterns on green and blue LED graphs in Figures 7 and 8 are caused by the fact that the measurement equipment used in the experiment had a limitation of 65000 counts on the intensity it was able to measure [14]. Thus the blunt peaks on the graphs were formed. This makes the results unclear in the cases of measurements achieved with a clear glass diffuser and without any added diffuser. From the part up to 65000 counts of intensity, it can be perceived that the results seem to follow a similar pattern shown on the graphs made from the measurements on red, warm white and cool white LED.

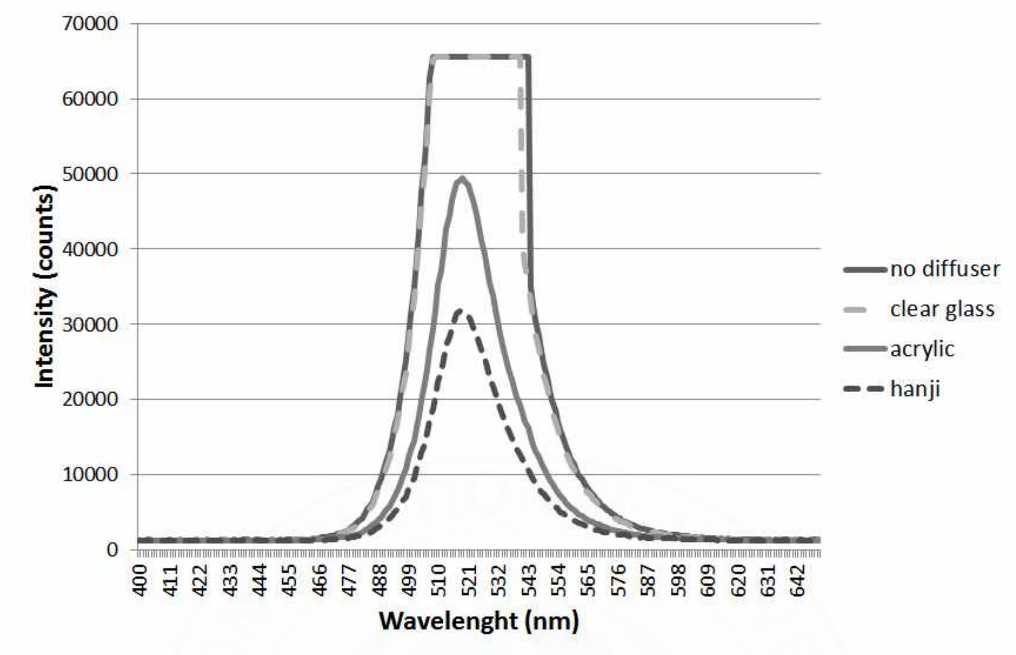

Figure 7. Green LED spectrum

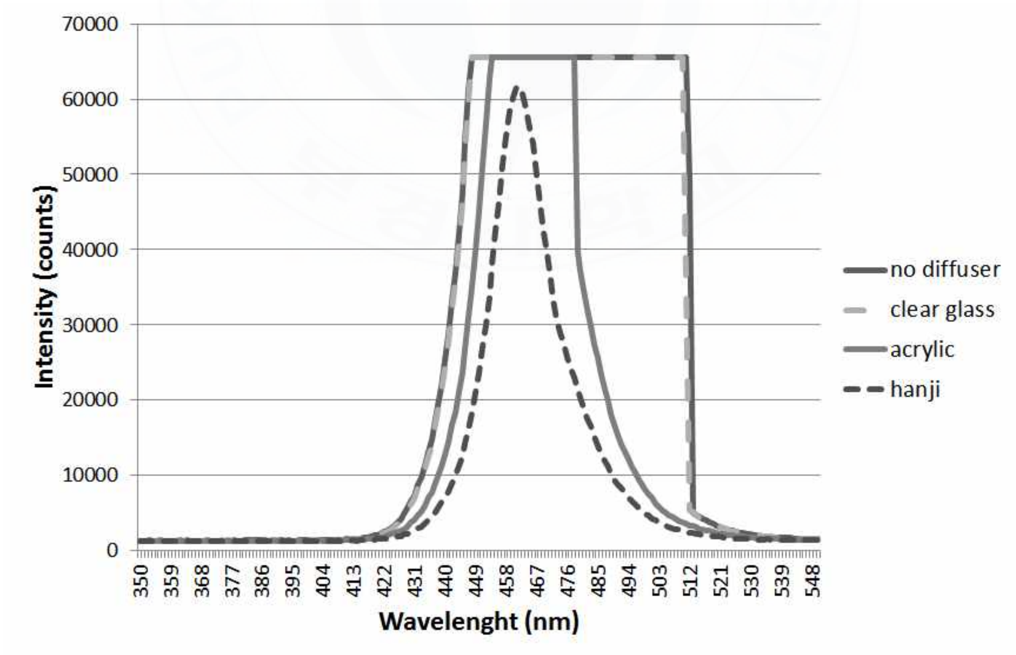

Figure 8. Blue LED spectrum

The cool white LED doesn't show much variation on its spectrum. The clear glass diffuser follows the same wavelength as without any diffuser. The opaque diffusers - the opal acrylic diffuser and the diffuser made of hanji - have an almost identical spectrum.

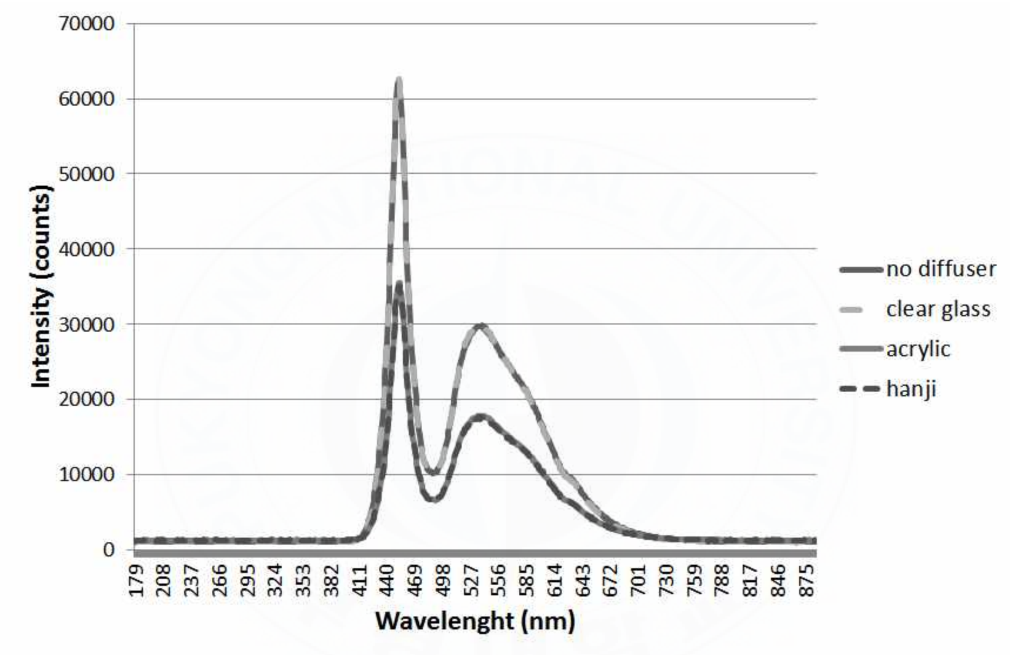

Figure 9. Cool white LED spectrum

In the case of the warm white LED luminaire, the spectrum gets affected by the diffuser in all of the cases. Compared to measurements without any diffuser, the clear glass enhances the intensity level of the warm white LED light source. The opal acrylic diffuser does mute the intensity, but in no means in a similar way as the diffuser made of hanji does. Compared to the intensity of the spectrum the light source produces without any diffuser, the hanji diffuser reduces the intensity into less than half of the intensity created without any diffuser. This makes the peaks of the intensity less prominent and the wavelength is more even compared to the other results.

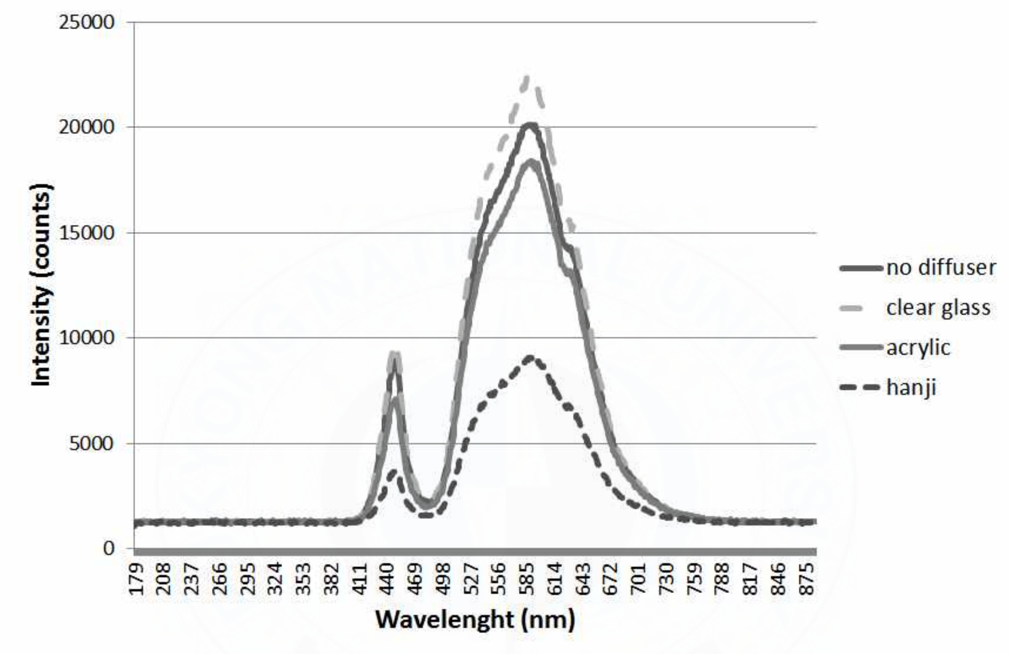

Figure 10. Warm white LED spectrum

IV. Light distribution

4.1 Distribution of light

4.1.1 Experiment on light distribution

An experiment was conducted in order to grasp the distributional characteristics of a single light source. The space used in the experiment was a conventional office type room with four work spaces located around the perimeter of the room.

The lighting of the room was executed with three rectangular LED luminaires with dimensions of 1280mmx320mm, positioned in a line in the center of the room. Figure 11 above shows the luminaire used in the room.

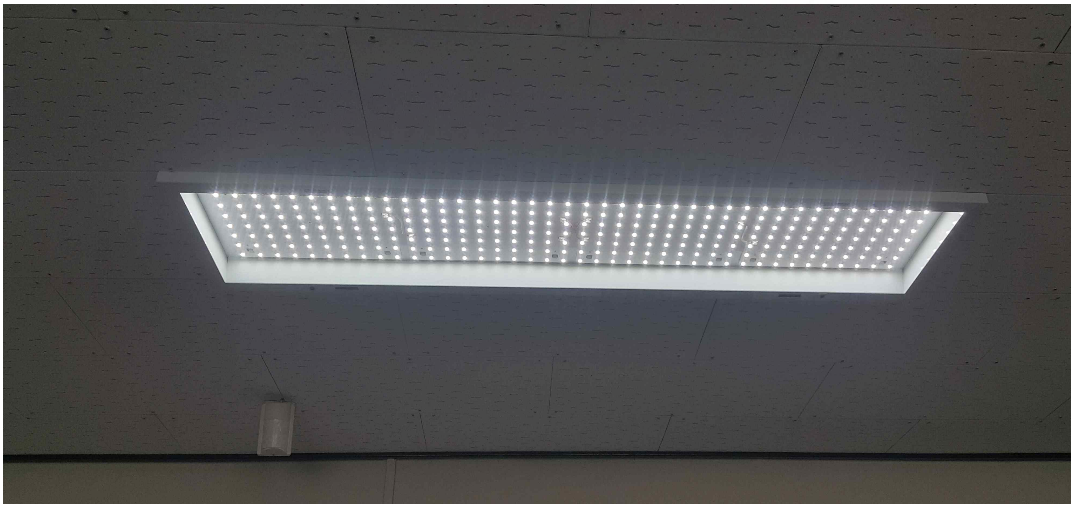

Figure 11. Luminaire used in the experiment

The control of the lighting in the room was divided into two groups, handled by two switches. One would light up the first two from the door; the other would light up the luminaire nearest to the window. In order to find out the distribution of a single luminaire, the luminaire nearest to the window had to be chosen as the luminaire to be examined. A presumption of the light source being completely symmetrical had to be adopted, since the distribution on the window side of the luminaire could not be measured sufficiently.

The measurement grid for the experiment was first calculated with the formulas provided in the Factfile no. 3 “Measurement of illuminance in electrically lit spaces”, provided by The Society of Light and Lighting, presented in the equation (4)

$$p = 0.2 \times 6^{\log d} \quad (4)$$

where p is the number of measurement points and d is the distance of the longer dimension of the space measured [15]. As the object of the experiment was not measure the illuminance of the room to check the level of illuminance and it’s sufficiency to office room, the grid was modified from 700 mm x 700 mm to 500 mm x 500 mm, since it would give out a more detailed measurement of the distribution of the light in the room.

4.1.2 Measurement scheme

The experiment was conducted in a small office room. The measurements of the room are 3800 mm x 5700 mm. A grid of approximately 500 mm x 500 mm squares was formed on the floor of the room with parallel and crossing threads. The room could have not been perfectly divided into 500 mm x 500 mm squares, since the measurements were as mentioned before and clearly not dividable by 500 mm. The measurement points were on the crossings of the threads. Dividing the width and length of the room by 500 mm gave 6 and 10 points of measurement. This concluded in 60 points of measurement. The grid and the room layout with the luminaire positions can be seen in the Figure 12. Figure 13 shows the grid executed on the floor of the room in question.

Each one of the points was measured for illuminance (lux). The height of the measurement point was marked at 800 mm from the ground, which is the height of a normal working plane in an office room by IESNA 9th Edition Handbook [7]. The equipment used in the measurements were DeltaOhm's LP471PHOT measurement sensor for illuminance, attached to the DeltaLogger DO9847 logging instrument.

Since the experiment area was a room used as an office room, one point could not be measured due to massive amount of office supplies and equipment in that area. The point is marked with a red circle on the right-hand side in the room layout.

The illuminance for all the three diffusers were measured consequently. The light produced in the room by one single luminaire was measured. The diffuser was changed after measuring the illuminance, without turning off the light and hence keeping the condition of the luminaire same as in the previous measurements. The measurements were conducted at night, to minimize the ambient light coming from outside through the blinds of the windows in the room.

The results were written down on an excel sheet for further analyzation. The results are presented in the next part.

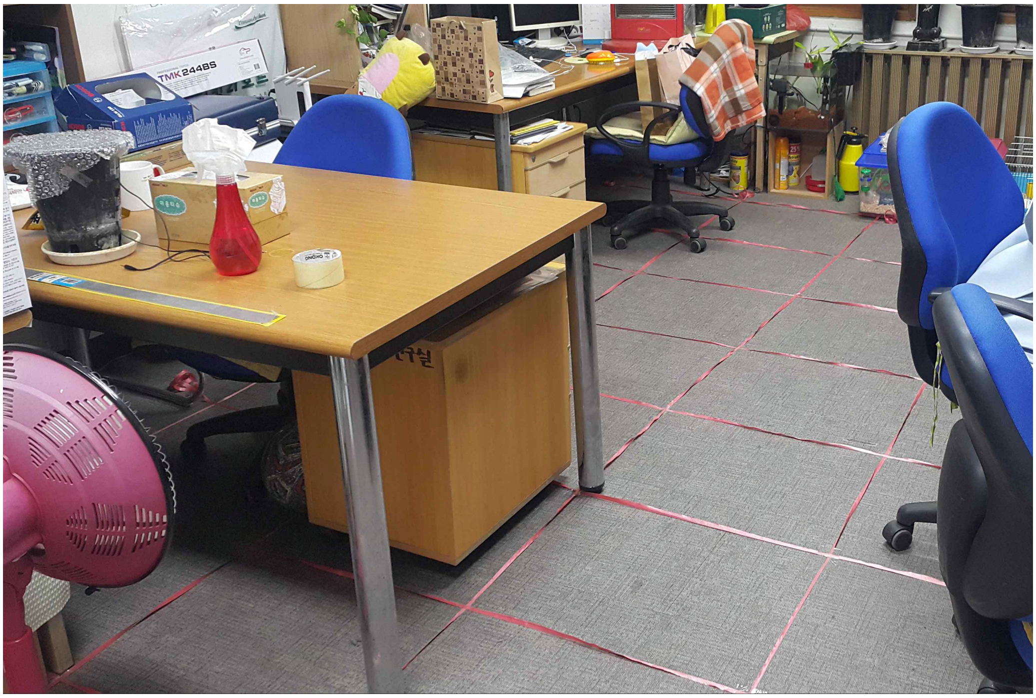

Figure 13. Measurement grid in the room

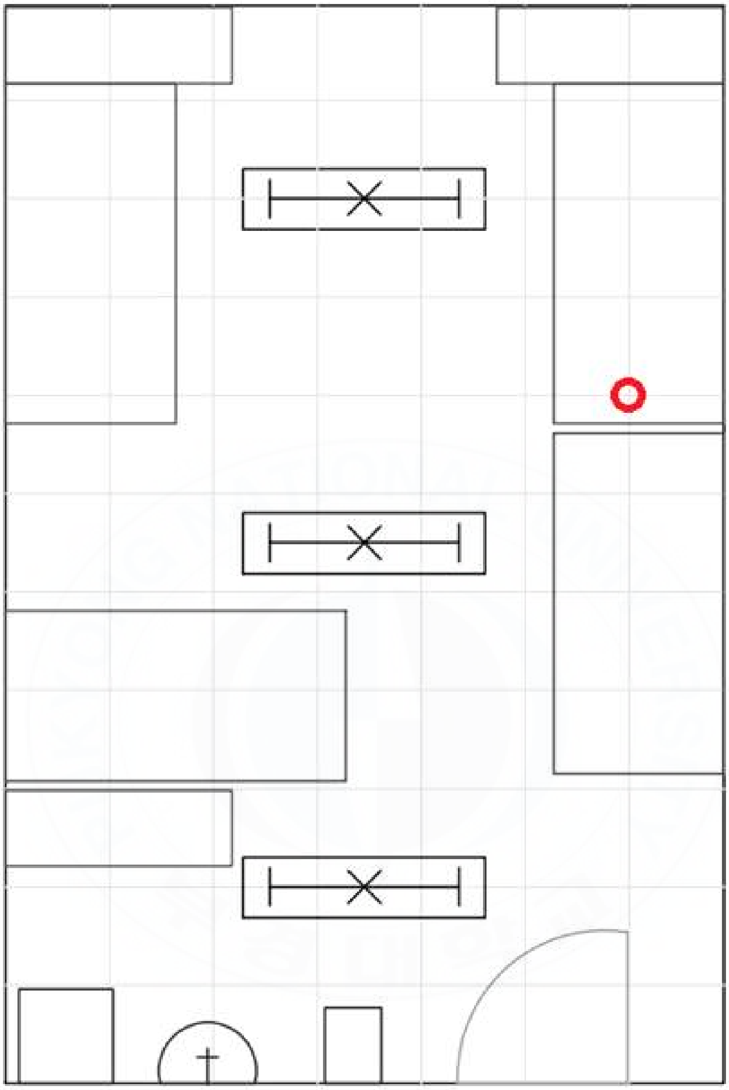

Figure 12. Experiment room layout

4.1.3 Results

The results achieved in the experiment were analyzed with excel and a contouring and surface modeling program called Surface 13 in order to visualize the distributive qualities of the light source. Surface 13 produced a contouring map where the brightly lit areas are lighter and the dimly lit areas are darker.

A simplified map of the layout of the room is placed in the background of the contouring map in order to demonstrate the placement of the furniture and the luminaire in the room.

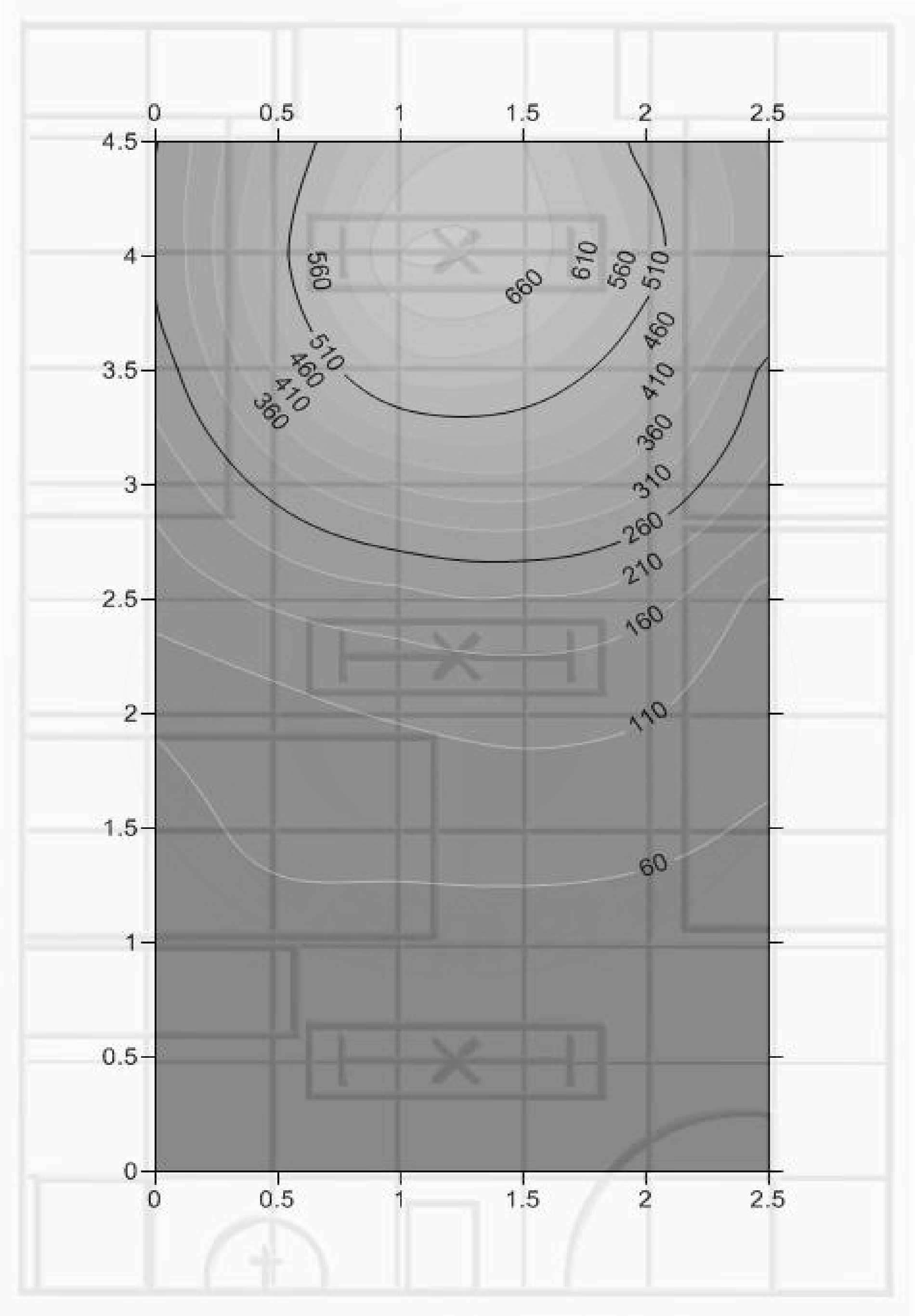

Figure 14. Illuminance distribution for one luminaire without a diffuser

In Figure 14 the comparative measurements measured without any diffuser show the level of lighting and the diffusion the luminaire without any diffuser, meaning the plain LED light source, produces.

Without a diffuser the light disperses in a circular motion from the luminaire. The illuminance levels are high directly below the luminaire, but without any added diffuser, the light doesn't travel far in the room. The peak of the level of illuminance is clearly perceived in the contoured map of the light produced. In a matter of one meter, the difference in illuminance from the peak is up to over 50%.

Figure 15 demonstrates the results acquired with an opal acrylic diffuser. The circular motion in the diffusion pattern observed in the Figure 14 is altered when an opal acrylic diffuser is added. The acrylic diffuser lowers the level of illuminance produced by the light source and reshapes the light distribution into a more square-like shape. Compared to the light distribution without any added diffuser, the acrylic diffuser makes the light to be spread more further into the room and reaching more towards the wall on the opposite side.

The peak of the level of illuminance is less prominent compared to the results acquired without any added diffuser, but the difference in the level of luminance in a meter's distance from the peak level is around 20-45%.

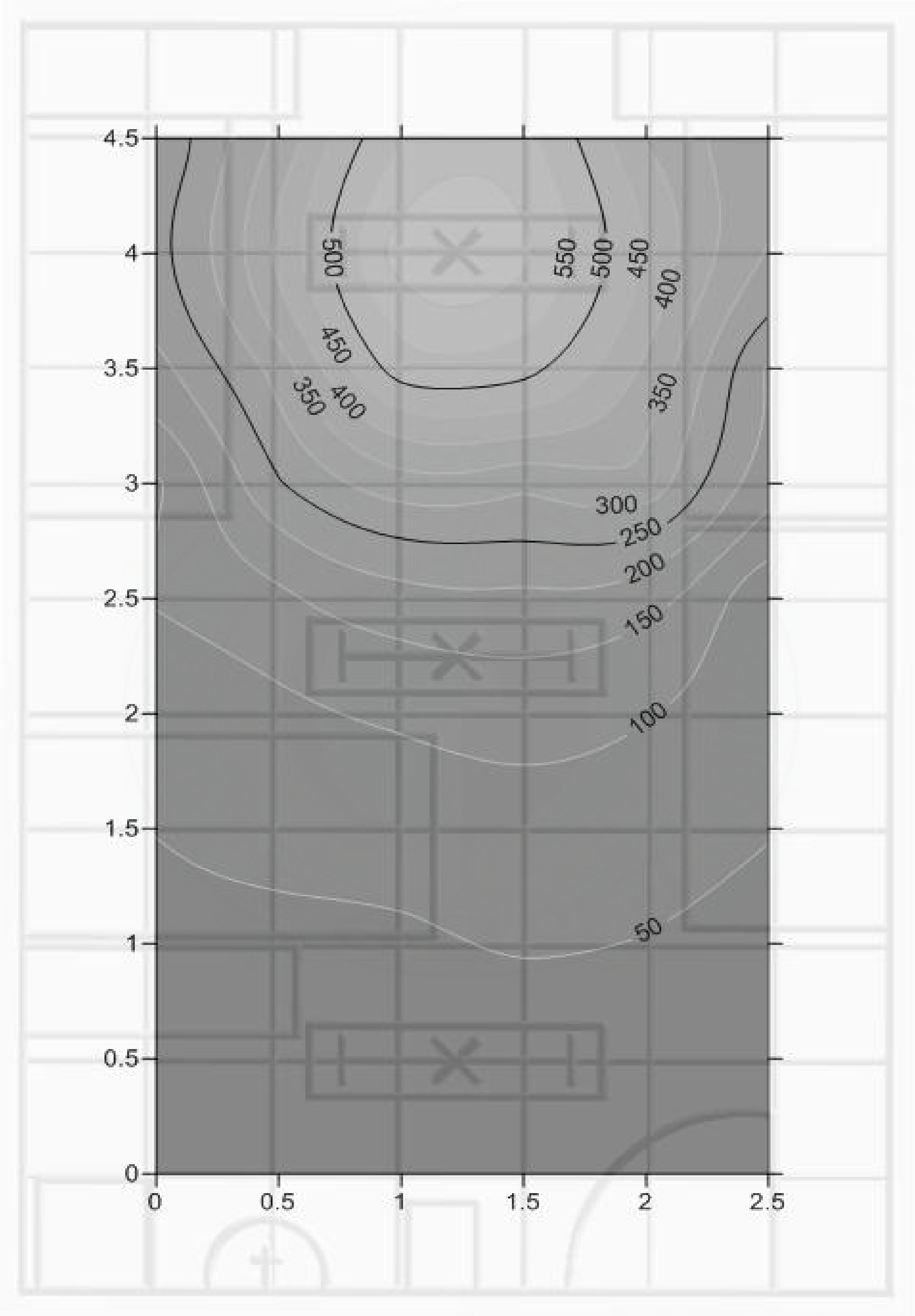

Figure 15. Illuminance distribution for one luminaire with an acrylic diffuser

Figure 16 presents the results acquired with a diffuser made out of hanji paper. As for the diffuser made out of hanji, the dispersion is more circular than square and the light and it's diffusion behaves similar to without any diffuser. Compared to the results without any diffuser and with an acrylic diffuser, the diffuser made out of hanji lowers the level of illuminance the most which results into a narrower area being lit on a proper level, even though the light seems to be traveling further into the room with the hanji diffuser. With the diffuser made out of hanji paper the peak illuminance is mostly blended into the surrounding illuminance levels.

The difference in the level of illuminance in a distance of one meter from the peak is only around 20%.

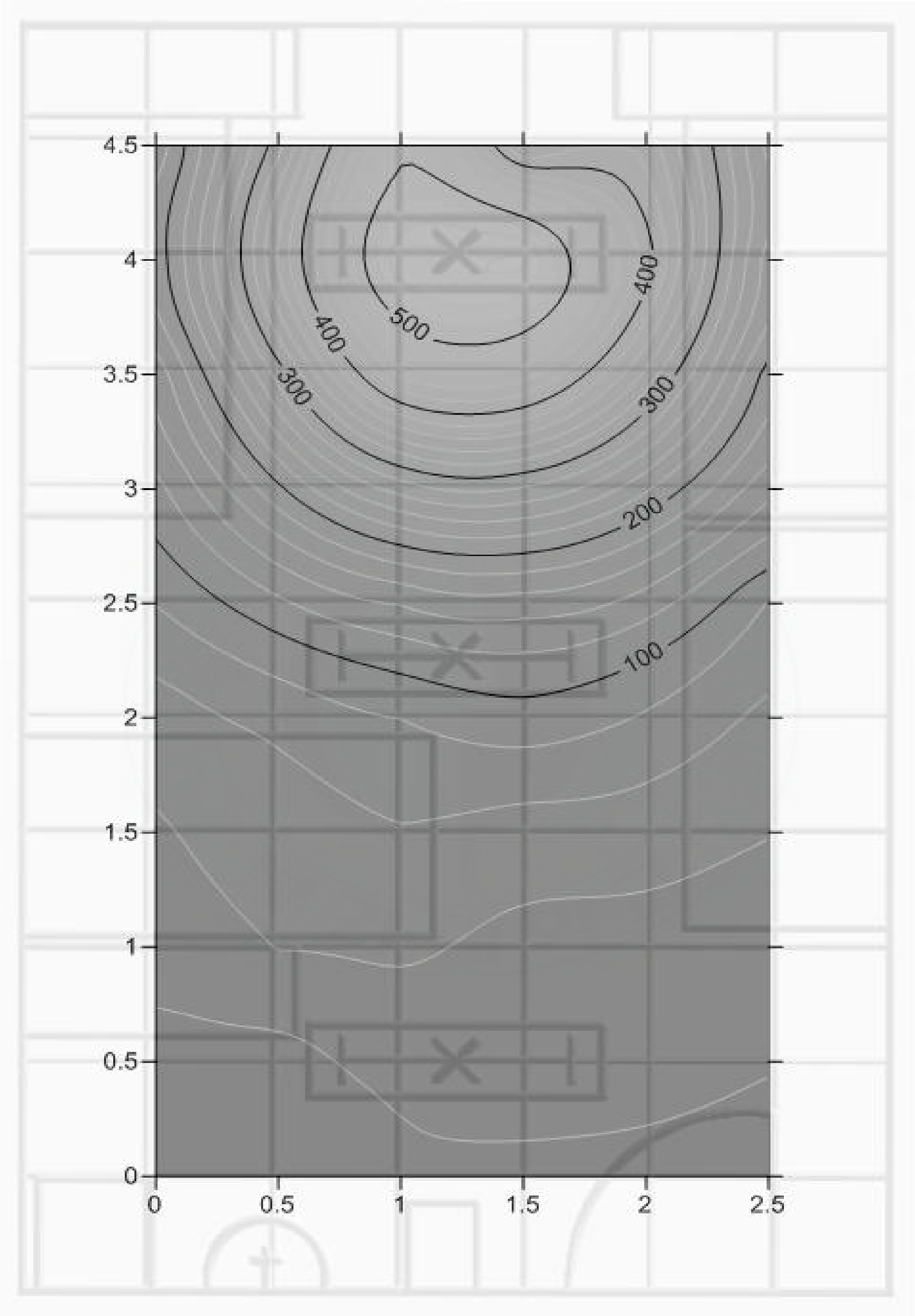

Figure 16. Illuminance for one luminaire with a hanji diffuser

Figures 17 and 18 show the distribution on XZ- and YZ-planes. The XZ-section is taken approximately 1m from the window-end wall. This was the second row of measurements from the window and nearest to the luminaire used in the experiment. The illuminance measured in this line was the highest of all the rows on the X-axis.

Figure 17 presents the XZ-section for illuminance with one luminaire. In Figure 17 some minor difference in the distribution of the light can be perceived, since the curves of the lines and their curves are near-parallel to each other.

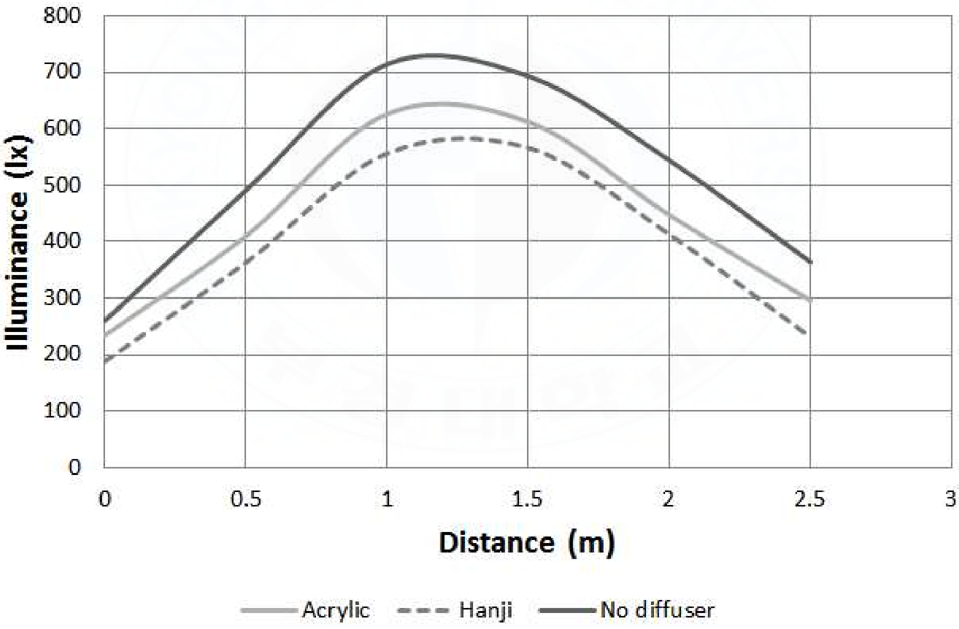

Figure 17. XZ-section for illuminance with one luminaire

The drop in the illuminance levels caused by the added diffuser is visible in the graph. In the case of the acrylic diffuser, the drop in illuminance compared to the results acquired without a diffuser is around 100 lux. The difference between the measurement results acquired with the hanji diffuser and the results without any added diffuser is around 150 lux. Therefore the illuminance level drops some 50 lux when changing the acrylic diffuser to the diffuser made of hanji paper.

Figure 18 presents the YZ-section for illuminance with one luminaire. The YZ-section is taken from the middle, 1.5m from left-hand side wall. This was where the level of illuminance measured was the highest.

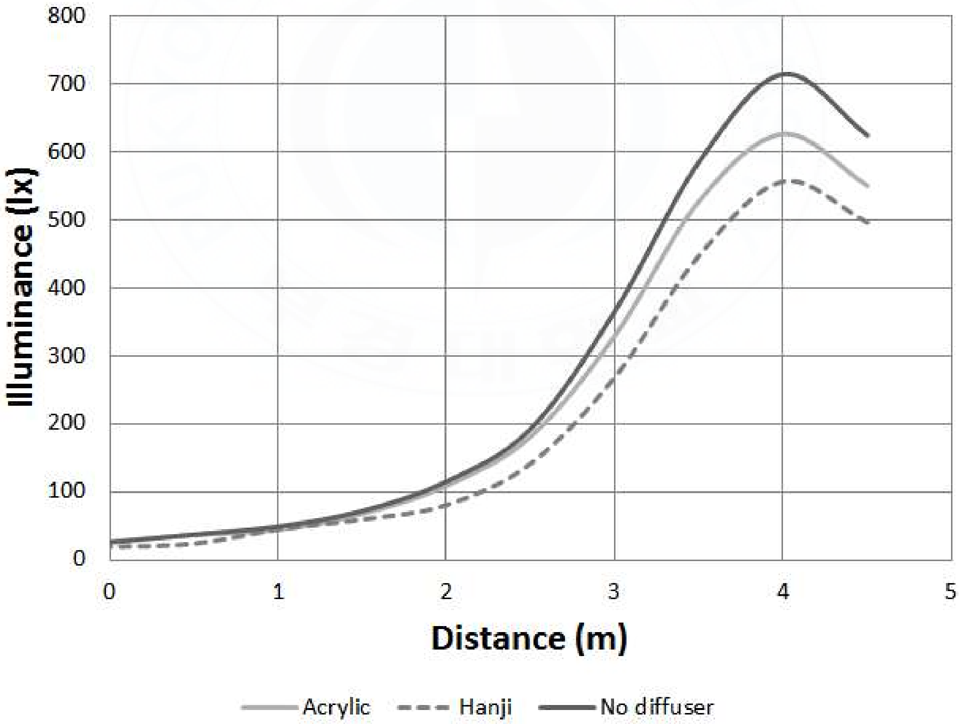

Figure 18. YZ-section for illuminance with one luminaire

Figure 18 shows minor difference in the distribution of the light, since the lines are near-parallel.

The drop in the illuminance levels caused by the added diffuser is visible in the graph. The difference between the measurement values gained from the measurements without a diffuser are less than 100 lux higher compared to the values attained with an acrylic diffuser and over 100 lux when compared to the diffuser made of hanji paper.

The Figure 19 below shows the minimum, maximum and average values for the distribution of the three different lighting settings.

The minimum value of the different experiment settings does not have a remarkable difference. A slight difference in the average value can be detected. The difference in the maximum value is over 100 lux between the hanji diffuser and the result obtained without any diffuser. The difference between the values attained without any diffuser and with an acrylic diffuser is less than 100 lux.

With the opal diffusers, acrylic and especially with the hanji diffuser, the distance between the maximum and the average value and the distance between the minimum and the average value is reduced. This indicates that there are less variation in the illuminance in different places and the attained illuminance levels are more similar than the values attained without any diffuser. The reduced variation indicates softer diffusion which is backed up with the contoured maps shown in Figures 14-16.

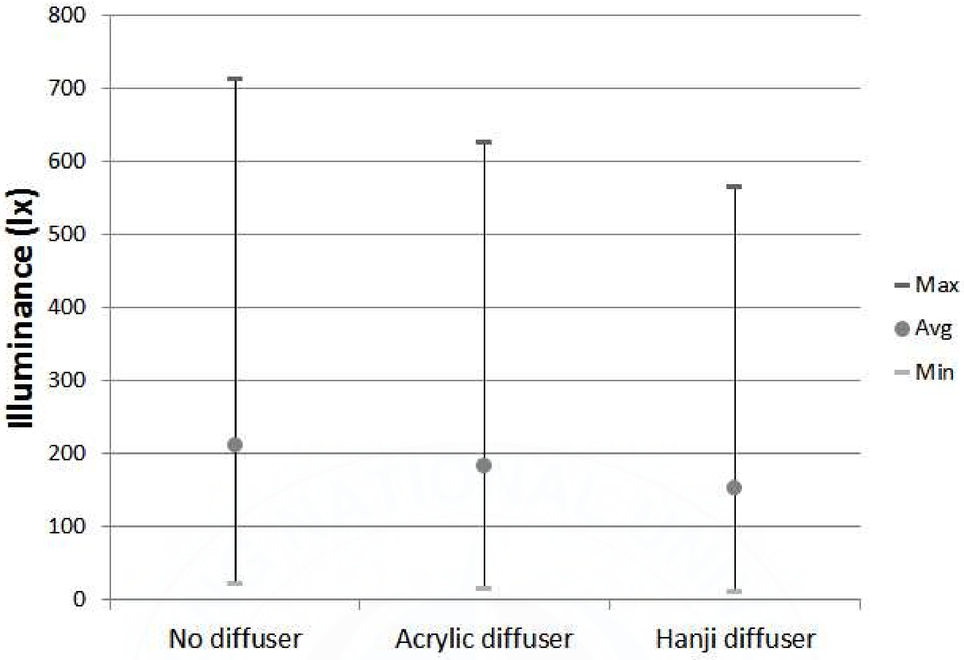

Figure 19. Maximum, average and minimum illuminane for one luminaire

4.2 Uniformity

4.2.1 Experiment on uniformity

The uniformity of lighting was measured to understand how the use of different diffusers alters the uniformity of produced light and if the diffused light is uniform or not. In the case of uniformity, the room was measured with all of the luminaires in the room on.

The space used in the experiment the same office type room with the same LED lighting as used in the previous experiment on distribution of light. For the experiment on uniformity, all three luminaires were used and measured instead of one single luminaire.

The measurement grid for the experiment was the same as in the distribution experiment, calculated with the formulas provided in the Factfile no. 3 “Measurement of illuminance in electrically lit spaces”, provided by The Society of Light and Lighting [15]. The equations are presented in the previous part. As the object of the experiment was not measure the illuminance of the room to check the level of illuminance and it’s sufficiency to office room, the grid was modified from 700mmx700mm to 500mmx500mm, since it would give out a more detailed measurement of the uniformity of the light in the room.

4.2.2 Results

The results achieved in the experiment were analyzed with excel and a contouring and surface modeling program called Surface 13 in order to visualize the uniformity qualities of the light source.

Surface 13 produced contouring maps where the brightly lit areas are lighter and the dimly lit areas are darker. The map shown on Figure 12, the layout of the room, is placed in the background of the contoured map to demonstrate the placing of the furniture and the luminaires in the room.

For excel, the minimum, maximum and average values of the illuminance were analyzed and the sections of illuminance level plotted to XZ- and YZ- planes are presented as well. Figures 20 to 22 present the contoured map produced with Surface 13.

Figure 20 presents the contoured map for the comparable measurements achieved by using all of the three luminaires in the room without any added diffuser. The illuminance level is considerably higher beneath luminaires and presents almost sharp edges when moving towards the walls of the rooms. Without any added diffuser, the light does not disperse properly in the room, leaving the center of the room lit with a very high illuminance level and reducing by 25-45% within a meter of distance towards the walls of the room. The outer perimeter of the room is lit with a dimmer level of lighting compared to the center of the room.

Figure 21 shows the results of illuminance levels attained with a acrylic diffuser attached to the luminaires. As displayed in Figure 21 the added acrylic diffuser lowers the illuminance level and disperses the peak level of light into a larger area. Unlike in the lighting environment achieved without a diffuser, the illuminance level drops only 15-40% in a distance of one meter towards the outer walls. The outer perimeter of the room is more dimly lit compared to the center of the room, but the obvious gap in the illuminance levels perceived in Figure 20 seems to be missing.

The analyzed results of measurements with the diffuser made out of hanji are presented in Figure 22. Alike to the acrylic diffuser, the hanji diffuser does soften the peak level of illuminance in the room. Compared to the previous ones, the diffuser made of hanji drops the level of illuminance 15-30% when moving towards the walls of the room. There aren't a tremendous difference in the illuminance levels perceived in the outer perimeter of the room and the center of the room.

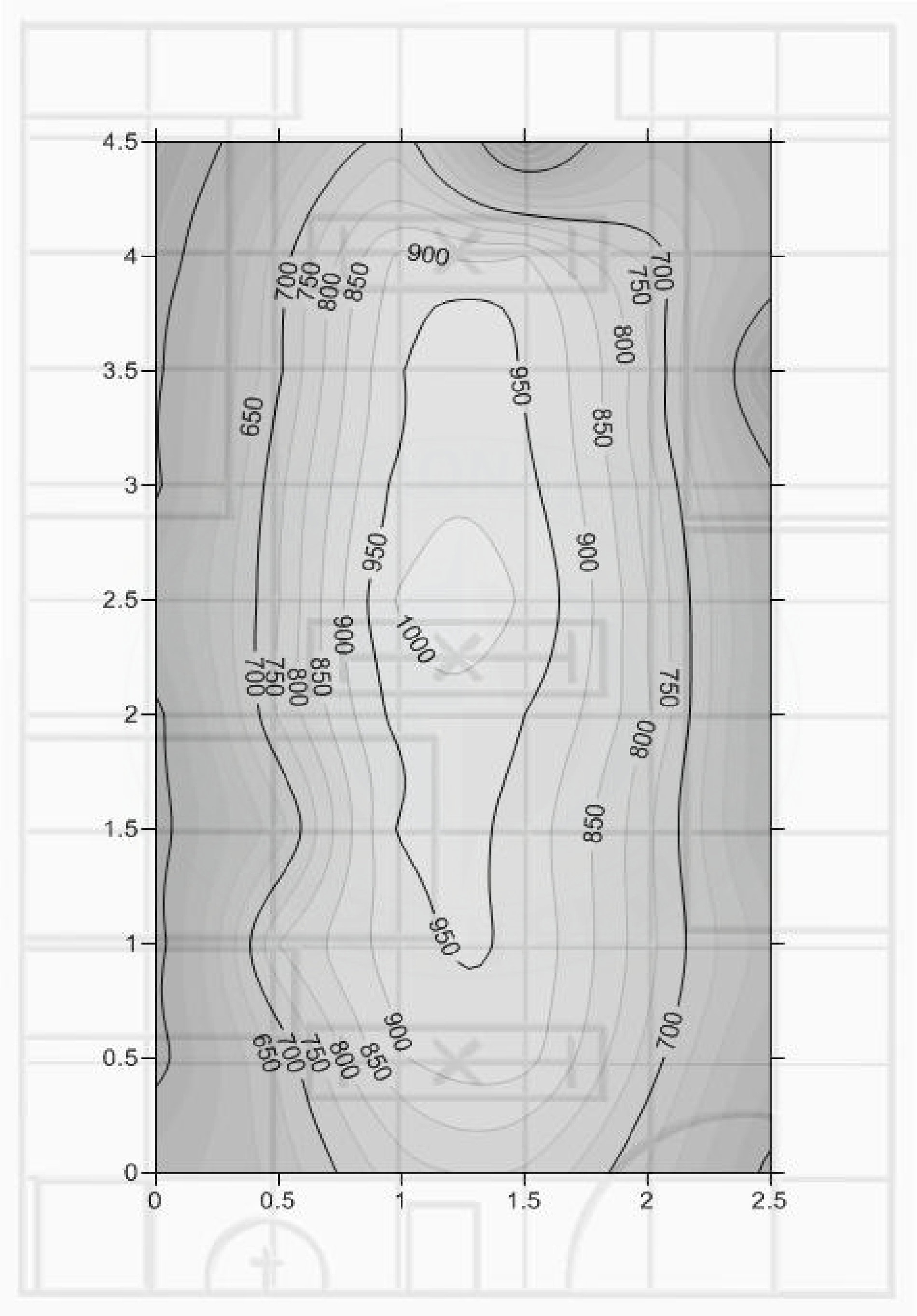

Figure 20. Illuminance distribution for 3 luminaires without a diffuser

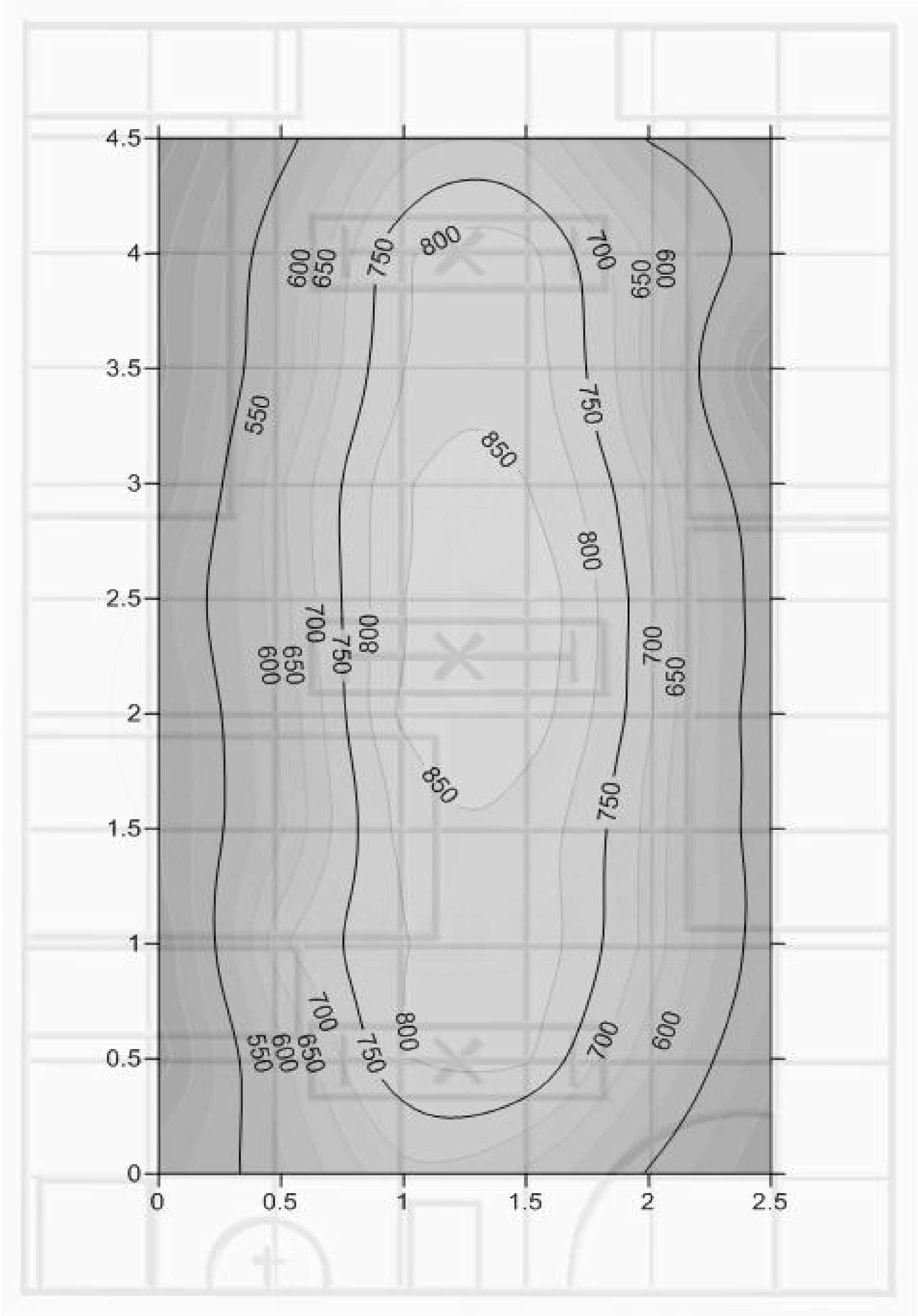

Figure 21. Illuminance distribution for 3 luminaires with an acrylic diffuser

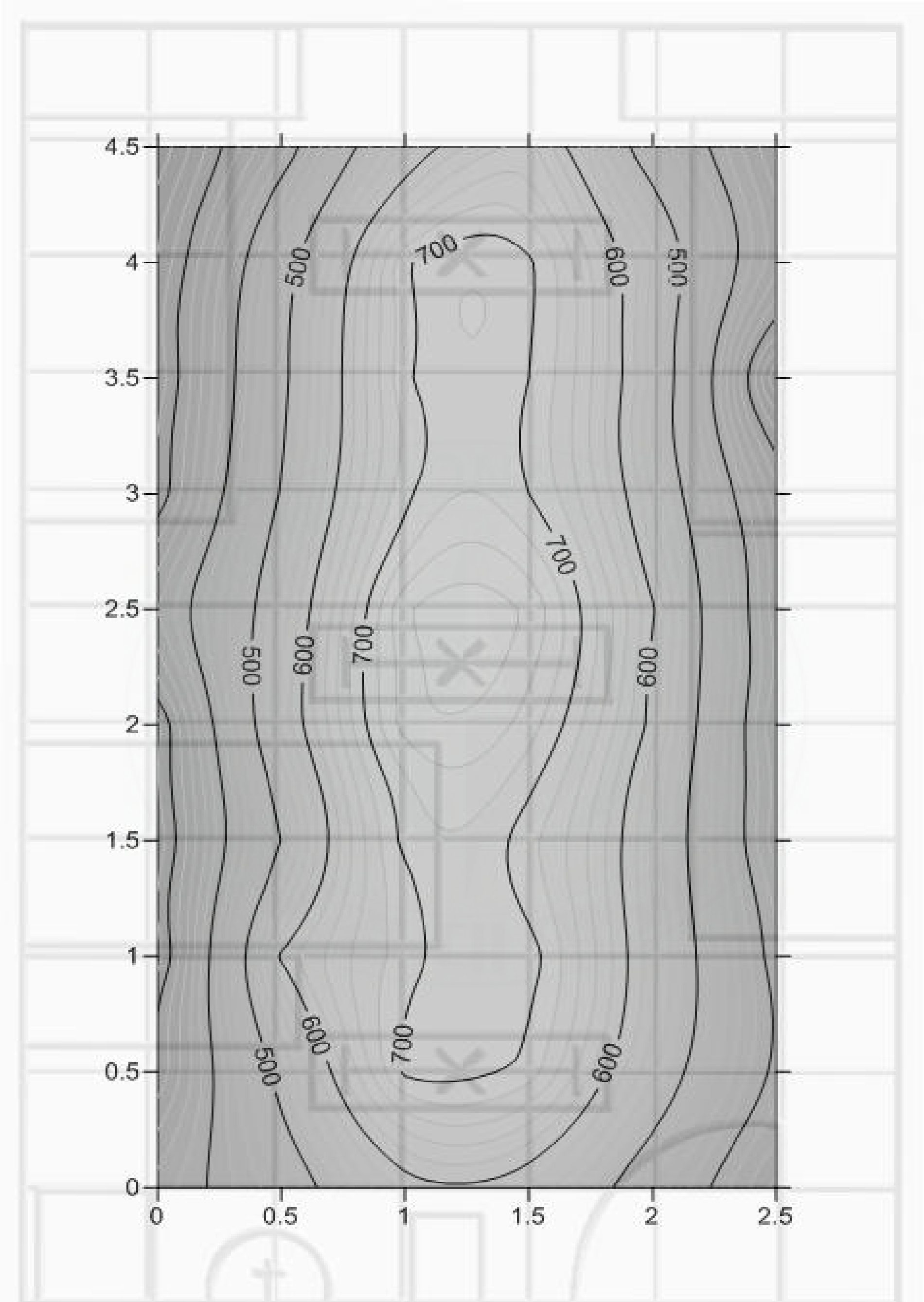

Figure 22. Illuminance distribution for 3 luminaires with a hanji diffuser

Figures 23 and 24 show the distribution on XZ- and YZ-planes. The XZ-section is taken from the middle of the room, from the window-side of the luminaire in the middle.

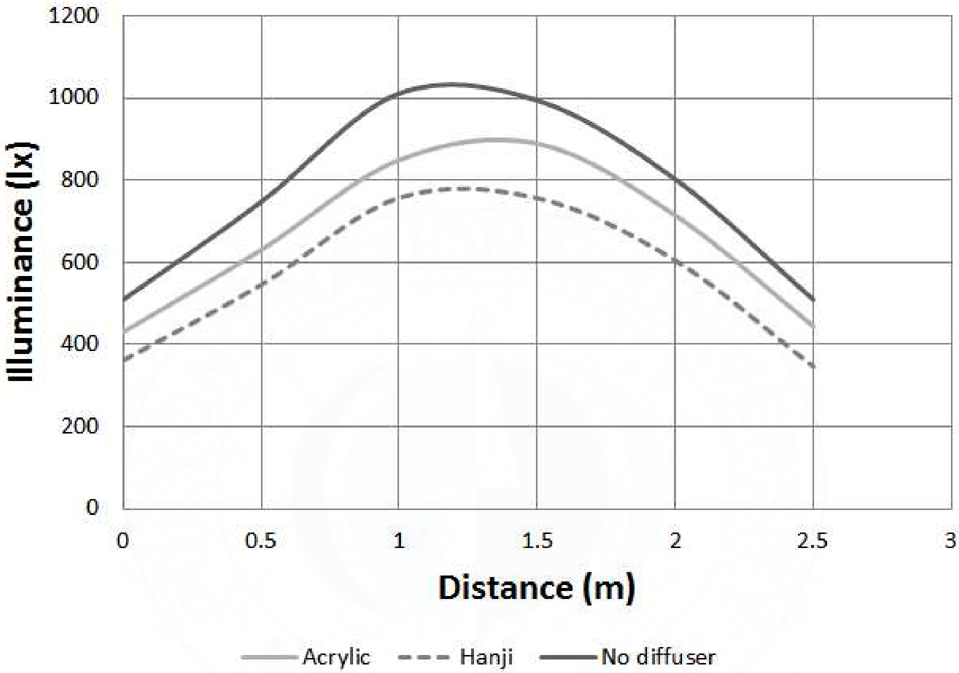

Figure 23. XZ-section for illuminance with three luminaires

Figure 23 shows the minor difference in the distribution of the light, since the curves of the lines are near-parallel. A slight difference between the distribution of light without any diffuser and with diffusers can be detected. The symmetry of the light distribution can be perceived as very similar to each other with each of the lighting environments.

The drop in the illuminance levels caused by the added diffuser is visible in the graph. As for the IESNA requirements for office environment, from the Figure 23 it can be perceived that the illuminance levels are rather insufficient near the walls. The working planes in this office room are on the perimeter of the room, where the illuminance level is lower.

The YZ-section is taken from the middle, approximately 1.5m from left-hand side wall.

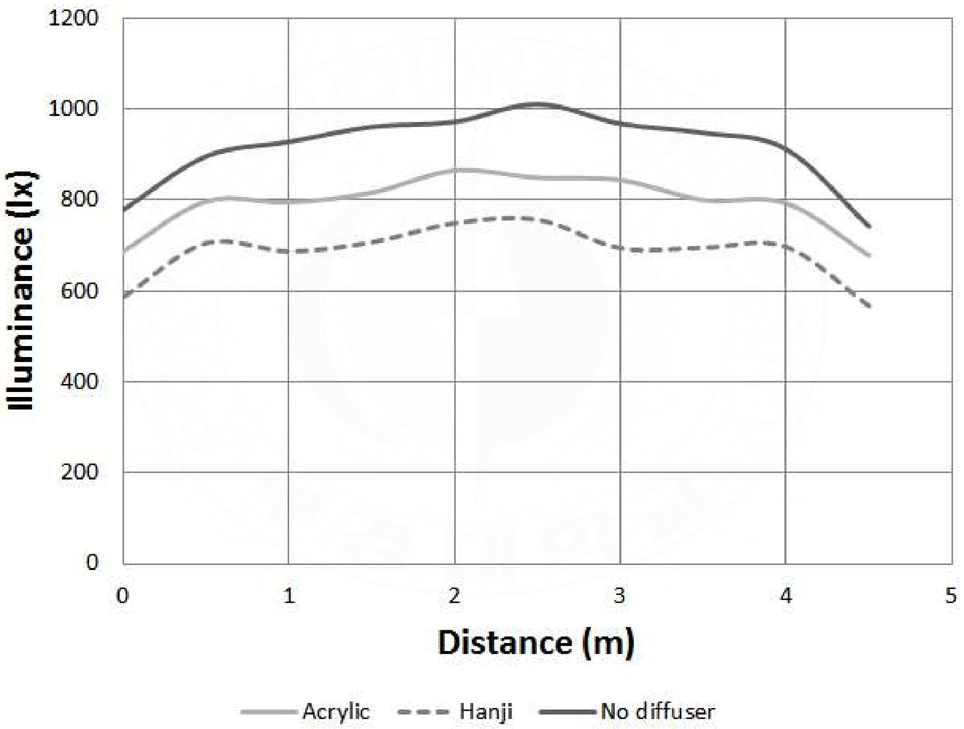

Figure 24. YZ-section for illuminance with three luminaires

Figure 24 shows minor difference in the distribution of the light, since the lines are near-parallel. As for the uniformity of the light, all of the lighting environments seem to have similar results. Some slight dents are visible in places where a luminaire is not present, but overall the uniformity of the illuminance levels in the middle of the room is satisfactory. In Figure 23 it's clearly visible how all of the cases fulfill the IESNA office lighting environment requirements of 500 lux.

As for the effect of a diffuser, a clear drop in illuminance can be noticed in the graph. From the graph a drop of around 100lux between the acrylic diffuser and the level without a diffuser can be observed. As for the levels attained with a diffuser made out of hanji paper and the levels attained without any diffuser, the drop can be up to 200 lux in the same point of measurement.

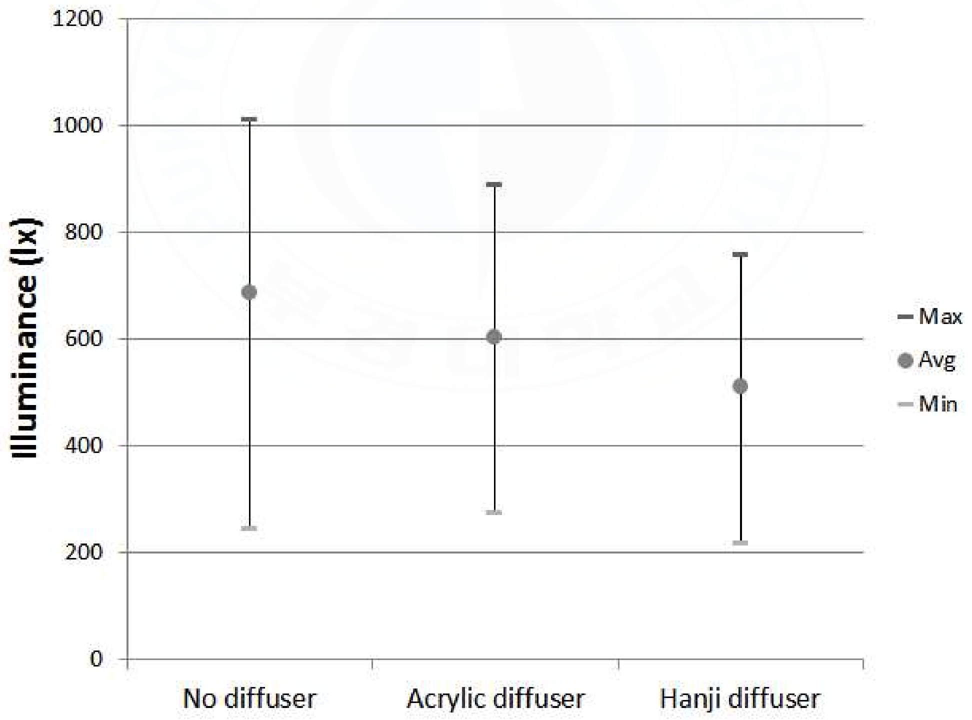

Figure 25. Maximum, average and minimum illuminance for three luminaires

Figure 25 shows the minimum, maximum and average values for the distribution of the three different lighting settings.

The minimum value of the different experiment settings does not have a remarkable difference in the case of the three luminaires. A difference of over 200 lux in the average value can be detected. The difference in the maximum value is over 200 lux between the hanji diffuser and the result obtained without any diffuser.

With the opal diffusers, acrylic and especially with the hanji diffuser, the distance between the maximum and the average value and the distance between the minimum and the average value is reduced. This indicates that there are less variation in the illuminance in different places and the overall illuminance is more even than the values attained without a diffuser. Even overall illuminance can be read as more uniform and invariable lighting.

4.3 Summary

The experiment of diffusion of a light source without and with an added diffuser was conducted by measuring the illuminance level produced by one luminaire in a room.

The results show a diffuser will soften the peak of illuminance levels and help the light travel further in the room. The acrylic diffuser reduces the difference from the peak in one meter difference from over 50% to 20-45%. The diffuser made out of hanji paper reduces the difference from the peak in one meter difference from the 50% acquired without any diffuser to around 20%. The diffusers reduce slightly the difference between the minimum and average values as well as the maximum and average values. This can be recognized as a more diffused light compared to the lighting achieved without a diffuser.

For the uniformity of the light, the results for the illuminance measured without any diffuser show a difference of 25-45% in a distance of one meter from the highest level of illuminance under the luminaires towards the walls of the rooms. The acrylic diffuser drops the difference to 15-45%, but the most uniform result is acquired by using the diffuser made out of hanji. The hanji diffuser reduces the difference to 15-30% in a distance of one meter from the point of highest level of illuminance under the luminaires towards the walls of the room. The diffusers reduce the difference between the minimum and average values as well as the maximum and average values. The diffuser made of hanji paper has the greatest reduction between these values. The reduction can be recognized as a more diffused and uniform light compared to the lighting achieved without a diffuser.

V. Conclusion

5.1 Lighting characteristics

The hypothesis before starting this experiment was that the added diffuser would change the lighting characteristics of light source made of LEDs. The main focus was the use of hanji as a light diffusing material. After conducting the experiment with three types of diffusers, including white hanji paper and a conventional opal acrylic diffuser, the following conclusion can be established.

The diffusers do affect significantly the lighting characteristics of a LED light source when illuminance, luminance and irradiance are considered. The diffuser made of hanji paper drops the illuminance level by over 70%, luminance level by over 80% and irradiance by 70-74%, compared to LED light sources without any diffusers. However, the use of diffuser hardly alters the spectrum of the light generated by the LED light source. The only variation can be found in the blue LEDs, but the blue wavelength of white LED light sources does not show a similar change.

5.2 Distribution and uniformity of lighting

The experiment of diffusion of a light source without and with an added diffuser was conducted by measuring the illuminance level produced by one luminaire in a room.

The results show a diffuser will soften the peak of illuminance levels and help the light travel further in the room. The acrylic diffuser reduces the difference from the peak in one meter difference from over 50% to 20-45%. The diffuser made out of hanji paper reduces the difference from the peak in one meter difference from the 50% acquired without any diffuser to around 20%.

For the uniformity of the light, an experiment was conducted with the full lighting on in the room. Even with all three luminaires lit, the results for the illuminance measured without any diffuser show a difference of 25-45% in a distance of one meter from the highest level of illuminance under the luminaires towards the walls of the rooms. The acrylic diffuser drops the difference to 15-45%, but the most uniform result is acquired by using the diffuser made out of hanji. The hanji diffuser reduces the difference to 15-30% in a distance of one meter from the point of highest level of illuminance under the luminaires towards the walls of the room.

When examining the XZ- and YZ-sections of the room with the full lighting on, it can be noted that the illuminance levels are lacking near the walls of the room. The room layout shows that the working places are located on the perimeter of the room, thus being in the more dimmer spots of the room. The IESNA recommendation for office-like spaces is 500 lux. This is nearly fulfilled without a diffuser and around 100 lux lack from the measurements achieved with a diffuser.

In conclusion it can be stated that the diffuser is crucial for smooth diffusion of light and to gain a uniform lighting in a room. The conventional acrylic diffuser is a good option as a diffuser, but the diffuser made of hanji papers proves to be a slightly more diffusive material. The downside of the hanji paper as a diffuser is the reduced level of illuminance, thus making it harder to work with when less efficient luminaires are considered.

5.3 Further research possibilities

This research covered the objective studies of lighting properties of one single type of hanji paper. As hanji has different manufacturing methods and numerous color variations, future reseach on different hanji types paired with LED lighting is a research path to be considered.

Another important aspect of research is the subjective studies on hanji as a diffuser in LED lighting. The objective studies show the suitability in theory, but the subjective studies will determinate the suitability in a real life situation, where subjects are exposed to the hanji diffused light.

Besides the subjective studies and studies on a wider range of hanji types, an experiment on a larger room can be considered when viewing future research possibilities. The rooms used in this research, i.e. the environmental chamber and the office type room, were of smaller scale in size and would hold only one to three luminaires at a time. Open-office layouts are a popular option in this day and age and the lighting executed is in a far bigger scale. Executing the lighting in a larger room brings out the manufacturing aspect as well. The diffusers that used hanji in this research were hand-made which is not the most efficient way of production. A more productive method of manufacturing is a concern in the use of hanji in light diffusion.

These future research possibilities on the use of the traditional Korean paper, hanji, concludes this research.

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