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Title:
Enhancing Visual Comfort and Daylight Availability through Polarized Windows

Semester Theme:
Master's Thesis

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Abstract:
This thesis explores the efficacy of polarized filters in reducing indoor glare while maintaining a high degree of light quality when compared to traditional window treatments. The results, which were acquired using experimental setups as well as manual UGR calculations, show that while polarized filters are helpful in reducing glare, other conventional treatments often perform better overall.

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Chapter 1: Idea Generation

1.1 Introduction

Achieving the highest possible visual comfort is a top priority in the field of lighting design since it has a major effect on building occupants' productivity and well-being. Visual comfort refers to a lighting environment where the occupants experience no visual strain or discomfort. This idea includes several elements, including overall light quality, glare reduction, and suitable brightness levels. In addition to these elements, views and access to daylight are crucial for designing areas that are visually pleasing.

"...there is the need to control inward views from outside the building. This is highly dependent on culture and room use and, even in residential buildings, can range from a desire to display to a need for absolute privacy. Next, constraints on window design arise when a view to the outside could cause distraction or glare, particularly where visual tasks may be demanding and the occupants of the room are restricted in position."

(Tregenza and Loe, 2013)

Large windows are frequently used in modern design to optimize the amount of daylight available, but they can also present problems including glare from the sun and reflections from the nearby outside environment. In order to solve these problems, window treatments are applied, in order to strike a balance between the advantages of natural light and visual comfort.

"Unless there is a clear reason why a room should be windowless (in a cinema, for instance) everybody required to remain indoors should have access to a view out."
(Tregenza and Loe, 2013)

This thesis investigates whether polarized filters, might be an alternative to more conventional window treatment options like tinted or glazed glass, and if can be utilized to reduce glare. This study will specifically investigate how polarized filters affect visual comfort, with a focus on glare reduction and improved light quality. Existing treatments, such as tinted glass and various types of glazing, will be examined to compare their performance against polarized filters.

1.2 Visual Comfort

1.2.1 Glare

"Glare is generally associated with a luminance or luminance contrast within the visual field of an observer that is sufficiently greater than that to which the eyes are able to adapt … Discomfort glare is a psychological sensation of discomfort but is not necessarily linked to any measureable changes to visual performance."

(Kent, Fotios and Altomonte, 2018)

Glare can have a substantial impact on one's ability to see comfortably in both artificial and natural lighting settings. A notable brightness ratio between the task (i.e., what is being looked at) and the bright light source is what produces glare. Factors such as the angle between the task and the glare source and ocular adaptation have major impacts on the feeling of glare. This causes irritation, discomfort, or even a decline in the quality of the visual performance. Direct sunlight or reflected light from surfaces within a space can also produce glare. It can lower productivity and lower the well-being of building occupants while interfering with visual tasks.

Disability and discomfort glares are the two main forms of glares that have an impact on visual comfort. Disability glare is the result of an excessive amount of light entering the observer's eyes, which instantly impairs visual performance. When an observer experiences light sensitivity, they usually squint, blink, or turn away from the glare to reduce discomfort.

On the other hand, discomfort glare is more subtle and personal. Because of the extreme contrast between the bright and dark regions of the visual field, it is characterized by a gradual decrease in visual comfort. Premature eye tiredness, discomfort, and even migraines can result from this imbalance.

1.2.2 Light Quality

The quality of light in a space is another important aspect of visual comfort. Numerous studies have found that people prefer natural daylight over artificial illumination, especially in living and working contexts. Daylight has a variety of benefits for occupants, including visual, physiological, psychological, and even economic implications. Natural light is appreciated for a variety of reasons.

1. It improves occupant satisfaction and productivity, particularly in work environments.
2. It enhances visual quality by precisely depicting colors, improving color differentiation activities.
3. Natural light varies in strength, direction, and color throughout the day, connecting people to the outside world.
4. Maximizing daylight can reduce the demand for artificial lighting, resulting in energy savings and decreased electricity use.

However, daylight alone is insufficient to provide visual comfort. While it offers unrivaled benefits, it also adds issues such as excessive glare and shifting lighting levels. Effective daylight management is critical for mitigating these difficulties, which is why various window treatments are used. They control the amount and quality of light that enters indoor rooms.

1.3 Daylight Availability

In a building, daylight availability is the quantity of natural light that can be used. It is affected by things like the size and direction of the windows as well as the existence of obstacles or shading devices. Daylighting technologies are intended to minimize the negative impacts of natural light, such as glare and excessive heat gain, while maximizing its benefits. Using large windows, which let in plenty of natural light, is one popular way to increase the amount of daylight available in a space. Large windows, however, can potentially introduce direct glare or reflected glare, from outside surfaces, if they are not properly treated.

To balance daylight availability with visual comfort, various window treatments are applied. Traditional solutions include tinted glass, which reduces light transmission and solar heat gain; and reflective coatings that minimize glare by reflecting sunlight. However, these treatments can sometimes diminish the overall quality of light.

1.4 Window Treatments: Existing Solutions and Polarized Films

This study will compare the efficacy of polarized filters and several existing window treatments in controlling color temperature, brightness, color rendering and glare. There will be tests and evaluations of several conventional treatments, such as tinted glass, reflective foil, and lower transmittance glass.

By selectively filtering polarized light, polarized films offer a potential improvement over existing treatments by lowering glare and preserving high-quality light transmission. Better visual comfort could result from this without substantially lowering the amount of daylight available overal.

1.5 Research Question

"How does the use of polarized film/filters in building windows affect visual comfort, specifically in terms of glare reduction and light quality, compared to traditional window solutions?"

This question will guide the comparative analysis of the different window treatments, focusing on how polarized films can address the challenges of glare and light quality while maximizing the benefits of natural daylight. The results of this analysis will provide insight into the potential advantages of polarized filters as a solution for enhancing visual comfort in lightning design.

Chapter 2: Theoretical Framework – Polarized Filters and Light

The inspiration for this study came from the way polarized filters work and their potential to totally remove glare under certain circumstances while maintaining the quality of the light. We must first investigate the behavior of light and how polarization impacts its transmission in order to fully understand this.

2.1 Light and the Electromagnetic Spectrum

"Light, like radiant heat, radio waves and X-rays, is a flow of electromagnetic energy, the result of continually changing fields of electricity and magnetism in space. Light is part of the electromagnetic spectrum and is distinguishable from other types of radiation only by its wavelength."

(Tregenza and Loe, 2013)

One way to think of light is as a vibrating rope. The light source is represented by one end of the rope, while the destination, such as the human eye, is represented by the other end. Wavelengths, or waves, are produced when the rope vibrates. Human perception of color varies with the frequency of these vibrations; visible light having wavelengths between about 380 and 750 nm.

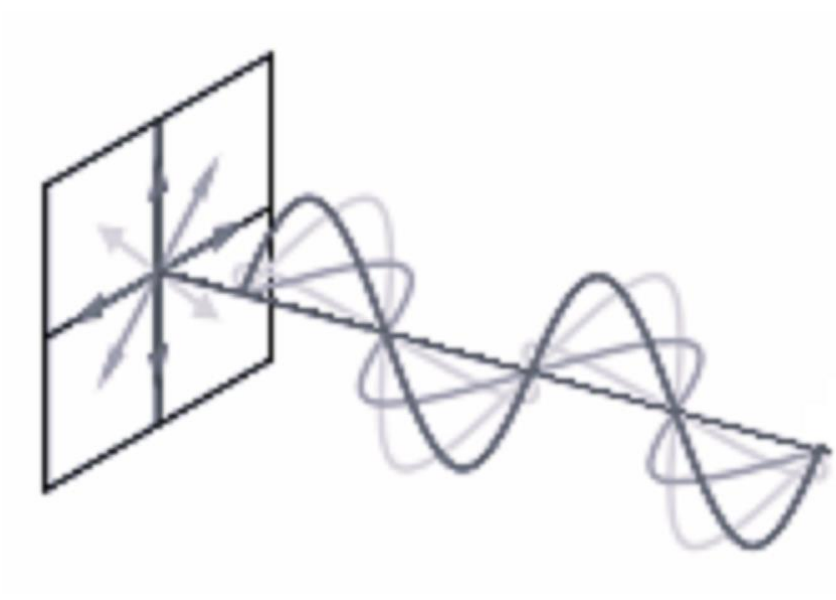


Fig. 1 – Unpolarized light wavelengths

Most natural and electrical light sources emit **unpolarized light**, meaning the light wavelengths vibrate in multiple directions (Fig.1). These waves have a random direction that fluctuates over time, producing light without any specific polarization.

"Most sources of light emit waves whose planes of polarization vary randomly with time. These variations take place suddenly and at intervals of as little as 10^{-9} s. A wave of this type is said to be unpolarized, because over any reasonable interval of time its plane of polarization does not favour any one of the possible directions more than any other."

(Muncaster, 2014)

This unpolarized light is the most common form of light encountered in daily life, it comes from the sun, electric bulbs, and other standard light sources.

2.2 How Polarized Filters Work

A polarized filter is intended to alter the behavior of light, selectively allowing only light wavelengths oriented in a specific direction to go through. Typically, the filter is made from a special plastic sheet that contains long chains of polymer molecules, which are randomly arranged during production. When the sheet is stretched in one direction, these molecules are forcefully aligned in that same direction, forming a structure that acts like a fence made from aligned bars (Fig. 2).

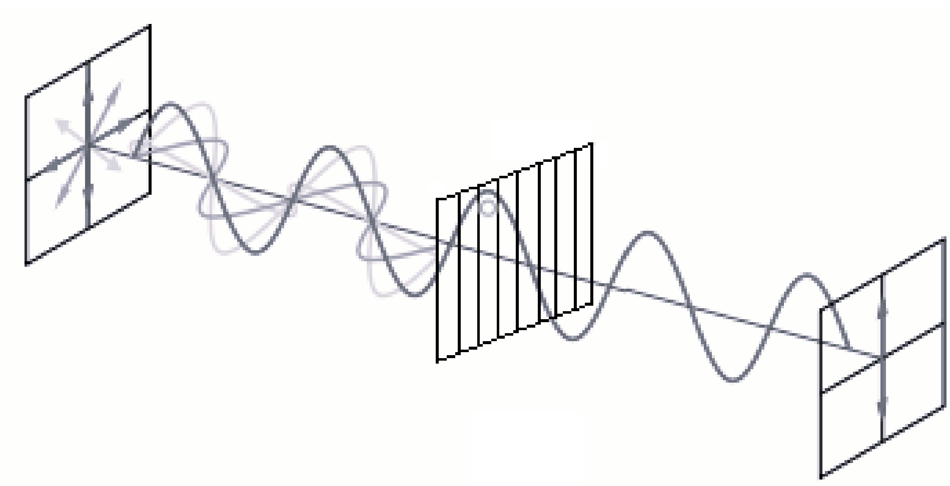


Fig. 2 – Unpolarized to Polarized Light

In this comparison, the "bars of the fence" symbolize the aligned polymer molecules in the filter. Only light wavelengths that are parallel to the orientation of the molecules can travel through this filter when unpolarized light reaches it; all other light wavelengths are blocked. This essentially polarizes the light by restricting its oscillation to a single direction (Fig. 5).

2.3 Brewster's Angle and Polarized Light

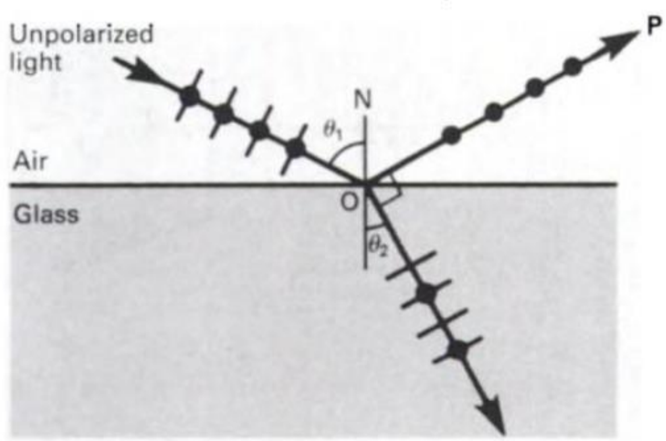


Fig. 3 – Polarization by Reflection (Muncaster, 2014)

Polarization also occurs naturally under certain conditions; an example is the **Brewster's angle theory**.

"When a pencil of light is incident, at an angle whose co-tangent is equal to the index of refraction, the reflected portion will be either wholly polarized, or the quantity of polarized light which it contains will be a maximum."

(Royal Society (London, 1817)

When unpolarized light reaches a transparent or semi-transparent surface at a particular angle (the Brewster angle; Fig. 3), the surface reflects some of the light, which then gets polarized and "vibrates" in waves parallel to the plane of the reflected surface. The remainder of the light travels through the material. Depending on the characteristics of the surface and the observer's position, the reflected light may cause glare.

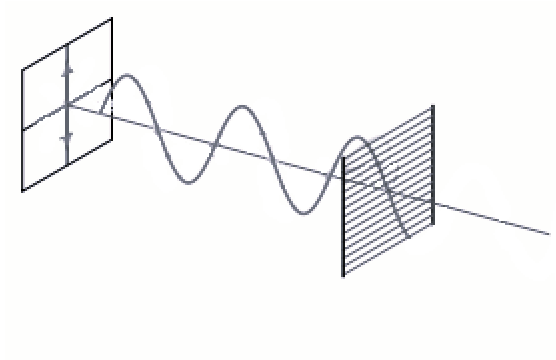


Fig. 4 – Polarized Light Perpendicular to a Polarized Filter

This implies that a polarized filter can totally block this reflected glare if it is positioned with its molecules orientated perpendicular to the polarized reflected light (Fig. 4). This is especially important in situations when the sun is the light source and its rays reflect off different surfaces, such as a body of water or other windows. This could result in specular reflections and indirect glare, which can be minimized or eliminated by properly aligning a polarizing filter to be "perpendicular" to the polarized reflected light (Fig. 5).

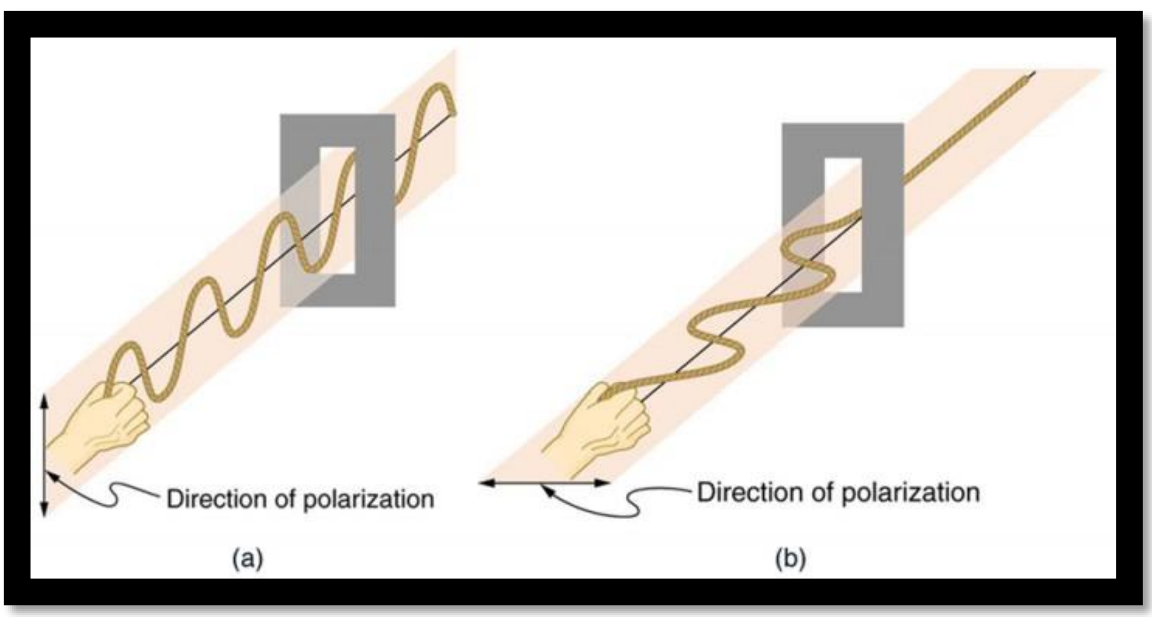


Fig. 5 – Rope representation of Polarized Light and filters

2.4 Hypothesis: Impact of Polarized Filters on Light Quality

One important characteristic of polarized filters is that they let through all visible light wavelengths, without changing the frequency, the light's color. They also don't change the quantity of the wavelengths that are aligned with the filter. This means that by filtering out light waves that are not aligned with the filter's orientation, polarized filters merely reduce the quantity of light without changing the light's spectral distribution. As a result, the filter has no effect on color rendering or color temperature, therefore the quality of light is unaltered.

This leads to the hypothesis:

"Polarized windows/filters do not affect the quality of light, only the quantity."

The reduction in light quantity happens because only light waves aligned with the filter can pass through, while those oscillating in other directions are blocked. Nevertheless, after passing through a polarized filter, the associated color temperature (CCT) and color rendering index (CRI) do not change since the filtered light keeps its original wavelength distribution.

2.5 Literature Review Analysis

Numerous important studies have been carried out in order to create a thorough understanding of how daylight and visual comfort affect human performance. Some of the analyzed literature review is compiled in the table that follows, which includes important research on daylighting, visual comfort, and its effects on occupants well-being.

Author(s)	**Title**	**Objective**	**Methodology**	**Key Findings**
Ceren Tüzer	A Facade Mapping Method to Understand Human Comfort in Buildings with Highly Glazed Facades [1]	To assess the impact of glass curtain walls on user comfort and thermal performance, particularly related to energy consumption in office buildings	Case study of 8 office buildings with glass curtain walls in Ankara; facade mapping and analysis of curtain usage during different seasons	Glass curtain walls negatively impact thermal and visual comfort due to excessive solar heat and glare. Internal blinds are widely used, but external shading is more effective. Solar factors of glazing have less effect than visible light transmission and U-value on comfort levels.

Author(s)	**Title**	**Objective**	**Methodology**	**Key Findings**
Korsavi, S. S., Zomorodian, Z. S., & Tahsildoost, M.	Visual comfort assessment of daylit and sunlit areas: A longitudinal field survey in classrooms in Kashan, Iran [2]	This research aims at testing students' evaluations on visual comfort through questionnaires in daylit and non-daylit areas in classrooms.	Field study using questionnaires and simulations in two classrooms with different orientations in a high school in Kashan, Iran.	Daylit areas provided adequate daylight availability but lacked uniformity. Students reported a wider acceptance of sunlight in sunlit areas than predicted by dynamic metrics. Non-daylit and sunlit areas did not necessarily cause discomfort, and factors like view, space configuration, and region impacted comfort.
Carlucci, S., Causone, F., De Rosa, F., & Pagliano, L.	A review of indices for assessing visual comfort with a view to their use in optimization processes to support building integrated design [3]	To provide an overview of visual comfort indices, categorize them, and discuss their implications for building design optimization.	The paper reviews various visual comfort indices, categorizing them based on their features and discussing their applicability in building design processes.	It concludes that visual comfort is multifaceted, requiring a combination of indices for a comprehensive assessment. While specific indices are useful, none can independently represent the entirety of visual comfort.
Knoop, M., Stefani, O., Bueno, B., Matusiak, B., Hobday, R., Wirz-Justice, A., Martiny, K., Kantermann, T., Aarts, M., Zemmouri, N., Appeltk, S., & Norton, B.	Daylight: What makes the difference? [4]	To provide an overview of the effects of daylight on human physiology, psychology, and overall well-being, highlighting the unique benefits of daylight compared to electric lighting.	The paper synthesizes existing research on daylight's characteristics and their effects on human health, well-being, and performance.	Daylight positively influences visual performance, circadian entrainment, and vitamin D production. While certain responses to daylight are understood, others require further investigation. The study emphasizes the importance of daylight intensity, spectral power distribution, and spatial characteristics.

Table 1 - Literature Review Analysis about visual comfort

The studies summarized in “**Table 1”** demonstrate the critical role that daylight and visual comfort play in enhancing occupant well-being and performance in built environments.

Key Insights

1. **Impact on Comfort**:
   - Tüzer's research highlights how glare and excessive solar heat from glass curtain walls can have a negative impact on visual comfort. This research emphasizes how important it is to incorporate efficient shading techniques, including external shading devices, in order to reduce discomfort in areas with big windows.

2. **Daylight and Visual Perception**:
   - Korsavi et al. find that although daylit locations usually have enough daylight, maintaining homogeneity is still difficult. This implies that although natural light is good for a space, how it is dispersed within it matters just as much to the happiness of its occupants. The results indicate that designers and architects should prioritize both the amount and quality of daylight in their plans

3. **Health and Well-Being**:
   - Knoop et al. emphasize the many psychological and physiological advantages of sunshine, such as its contribution to vitamin D synthesis and circadian entrainment. This is in line with the growing focus on biophilic design principles, which support the use of natural components into architectural processes in order to enhance mental and physical wellness.

2.6 Conclusion

Examining the efficiency of various window treatments, and glazing kinds may help clarify how to maximize daylighting for visual comfort. The studies in “**Table 1”** show how important daylight and visual comfort are for building design and occupant well-being. They highlight the need to manage glare and improve light quality, which ties directly into the goals of this paper.

Chapter 3: Quality Experiment

3.1 Overview of the 1st Experiment (Quality)

The purpose of the 1st experiment was to investigate the hypothesis that polarized filters only alter the quantity of light, not its quality. This experiment evaluated various window materials and compared the outcomes with a control (the clear sky). Various materials, such as reflecting foils, tinted glass, and polarized filters were measured on illuminance, CRI and CCT.

3.2 Equipment and Parameters

For this experiment, a “Sekonic C-800” spectrometer was used to measure the light parameters:

- **Lux Level (Illuminance)**: This measures the quantity of light reaching a surface, expressed in lux.
- **Color Rendering Index (CRI)**: CRI indicates the ability of a light source to reveal the true colors of objects as compared to a natural light source.
- **Spectral Power Distribution (SPD)**: SPD provides a visual representation of the light's spectral distribution, showing the intensity of different wavelengths.
- **Correlated Color Temperature (CCT)**: CCT expresses the color appearance of light, measured in kelvin (K), where lower temperatures suggest a warmer light and higher temperatures indicate a cooler light.

3.3 Tested Materials

The experiment tested several window materials, each representing different types of glazing or treatment:

1. **Control (Clear Sky)**: The reference measurement was taken with the spectrometer facing the clear sky.
2. **Tinted Glass**: Saint-Gobain sapphire blue glass, 1 layer, 5.9mm thick.
3. **Least Treatment Glass**: Saint-Gobain Stadip glass, 2 layers, 12.1mm thick.

4. **Climatop Glass**: Saint-Gobain Climatop glass, 3 layers, 28.6mm thick, with 40% light transmission.
5. **Reflective Foil**: Plexiglas sheet with 2-way mirror foil (d-c-fix® self-adhesive window film Mirror Privacy), applied on a 3mm Plexiglas sheet.
6. **Polarized Film**: A single layer of polarized filter was used to test its impact on light.
7. **Two Layers of Polarized Film**: Two layers of polarized film were placed at a 90-degree angle to each other to block as much light as possible.

3.4 Methodology

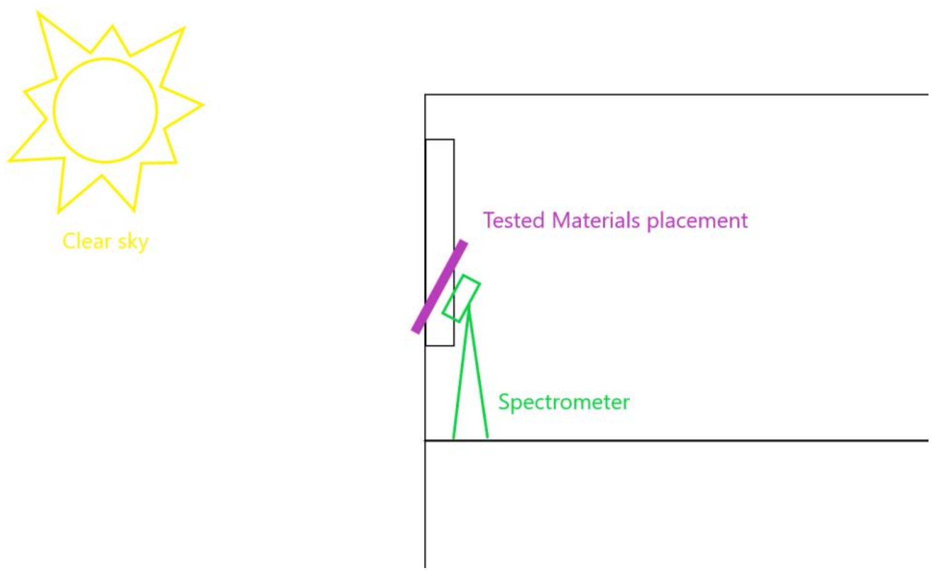


Fig. 6 – Experiment setup

The experiment took place indoors on a sunny day. The spectrometer was positioned to face the sky through an unobstructed large window (Fig. 6), ensuring no interference from buildings or other obstacles. The following procedure was followed:

- For each material, three initial measurements were taken with the spectrometer facing the clear sky.
- Then, the material was placed in front of the spectrometer, and three additional measurements were taken.

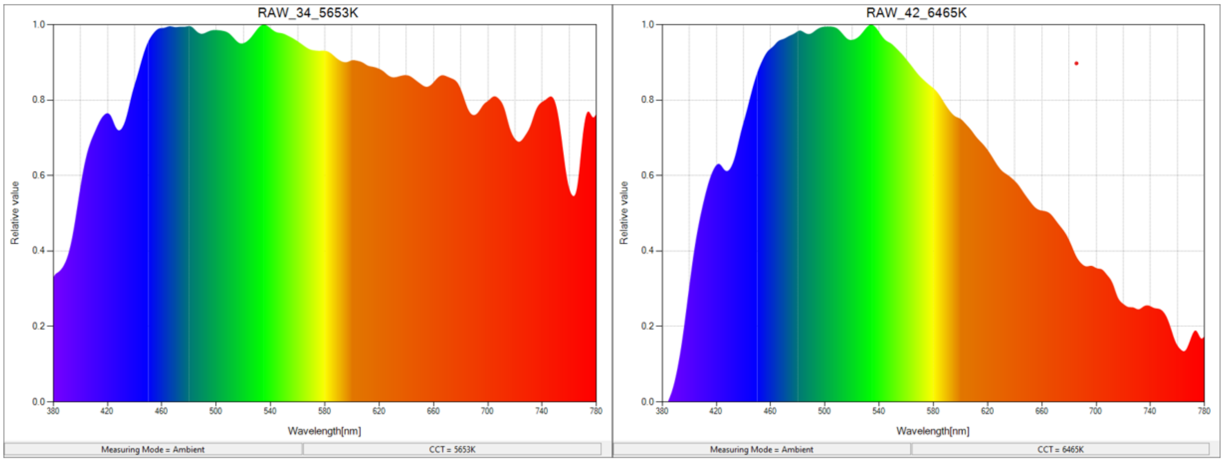
- The process was repeated for each material in quick succession to minimize changes in sunlight conditions.
- The average value of the three measurements was calculated to eliminate potential device errors and anomalies.

Fig. 7 – Experiment setup

3.5 Results and Analysis

3.5.1 Tinted Glass (Sapphire Blue)

Fig. 8 – Control vs. Tinted Glass



Illuminance [lx]: 4460
CRI Ra: 99.7
CCT [K]: 5653

Illuminance [lx]: 4400
CRI Ra: 89.4
CCT [K]: 6465

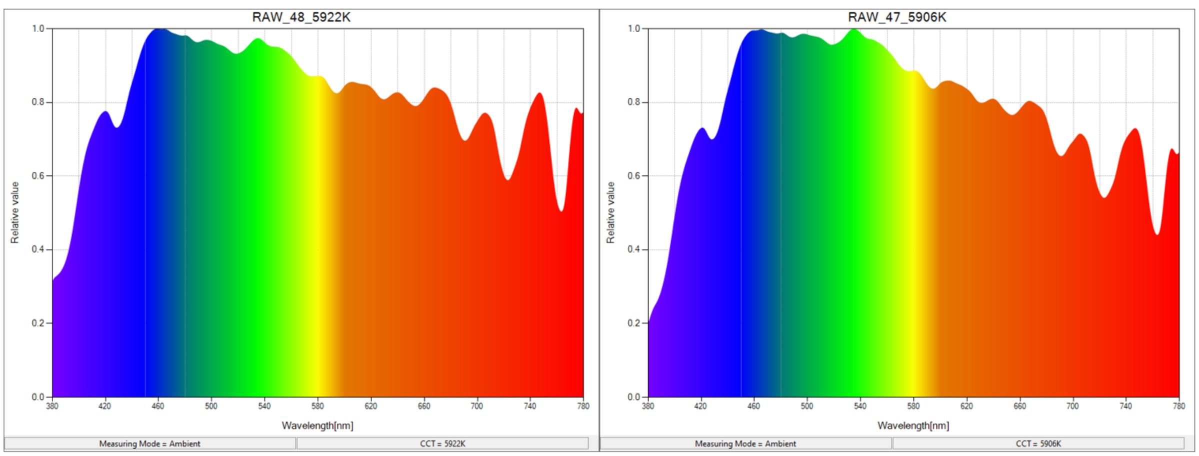
Fig. 9 – SPD: Control vs. Tinted Glass

- **Illuminance**: Dropped from 4460 lux to 4400 lux (a 1.35% drop).
- **CRI**: Dropped from 99.7 to 89.4, indicating a significant reduction in color rendering quality.
- **SPD**: The red wavelengths levels dropped significantly.
- **CCT**: Shifted from 5653K to 6465K, resulting in a cooler light.

Analysis: The light transmission remained high, with only a slight drop in illuminance. However, the tinted glass significantly reduced the quality of light, particularly in the red spectrum, which negatively impacted the overall CRI. The shift to a cooler color temperature could lead to discomfort for occupants.

3.5.2 Least Treatment Glass (Stadip)

Fig. 10 – Control vs. Least Treatment Glass



Illuminance [lx]:	5160	Illuminance [lx]:	4850
CRI Ra:	99.7	CRI Ra:	98.7
CCT [K]:	5922	CCT [K]:	5906

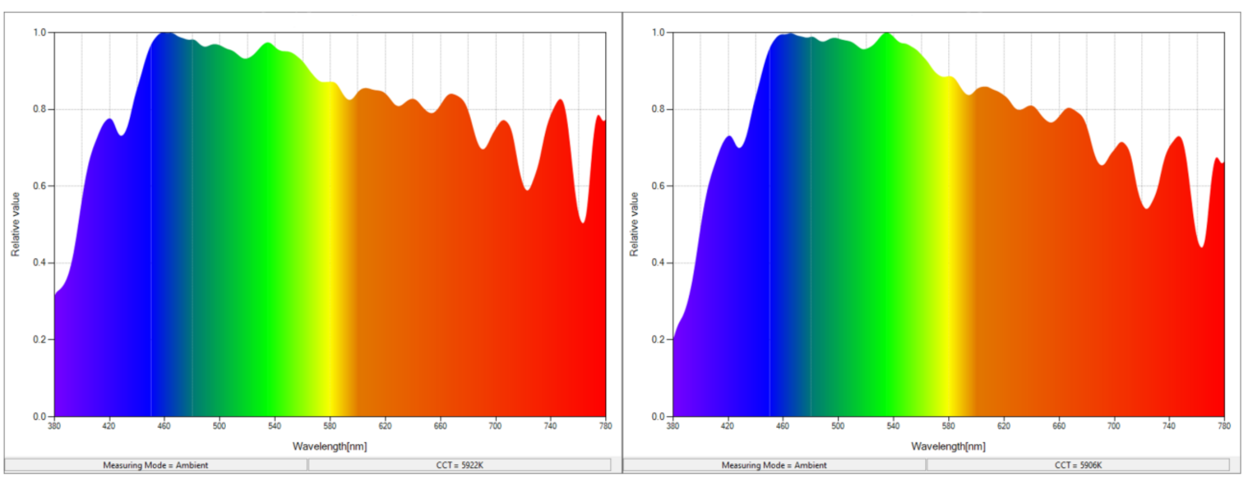
Fig. 11 – SPD: Control vs. Least Treatment Glass

- **Illuminance**: Dropped from 5160 lux to 4850 lux (a 6% drop).
- **CRI**: Slightly decreased from 99.7 to 98.7.
- **SPD**: The spectral distribution remained almost identical to the control.
- **CCT**: Remained stable, from 5922K to 5906K.

Analysis: The Least Treatment Glass provided the best balance between light transmittance and quality. The CRI remained high, ensuring good color rendering, and the CCT remained stable, maintaining the natural daylight characteristics. This glass would be ideal for allowing natural transitions of daylight throughout the day.

3.5.3 40% Transmittance Glass

Fig. 12 – Control vs. 40% Transmittance Glass



Illuminance [lx]:	5142	Illuminance [lx]:	2156
CRI Ra:	99.7	CRI Ra:	98.6
CCT [K]:	5913	CCT [K]:	5942

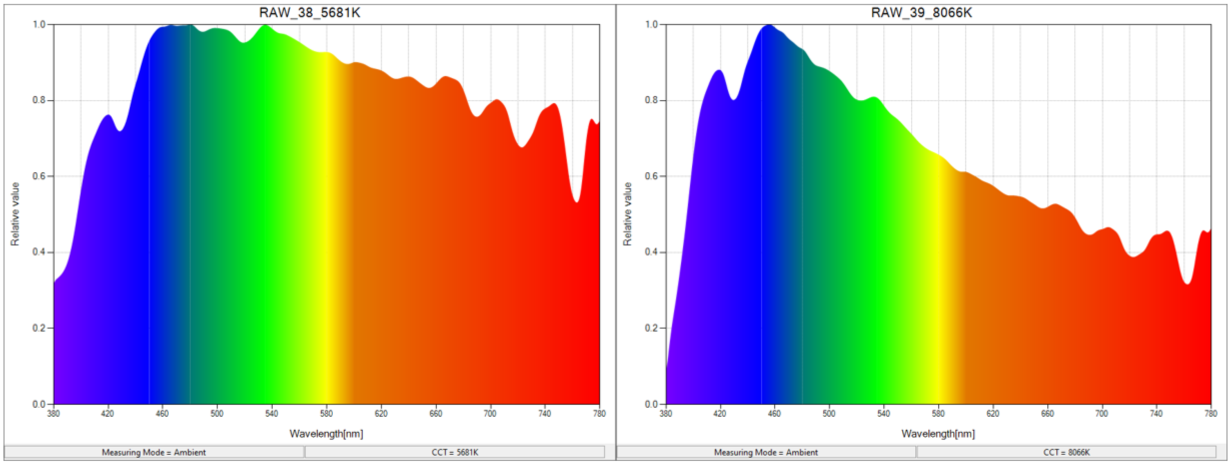
Fig. 13 – SPD: Control vs. 40% Transmittance Glass

- **Illuminance**: Dropped from 5142 lux to 2156 lux (a 42% drop).
- **CRI**: Slightly dropped from 99.7 to 98.6.
- **SPD**: The spectral power distribution (SPD) levels remained almost identical to the control, with no significant changes.
- **CCT**: Remained stable, with only a slight shift from 5913K to 5942K.

Analysis: The 40% transmittance glass performed well in terms of maintaining light quality, as seen in the minimal changes to both CRI and SPD. The color temperature (CCT) also remained stable, which is important for preserving the natural transitions of daylight throughout the day, contributing to occupant comfort. The expected drop in light transmittance (42%) aligns with the material's specifications, providing effective control over the amount of light entering the space while retaining high-quality light characteristics.

3.5.4 Reflective Foil

Fig. 14 –Control vs. Reflective Foil



Illuminance [lx]:	5343	Illuminance [lx]:	358
CRI Ra:	99.7	CRI Ra:	98.7
CCT [K]:	5681	CCT [K]:	8066

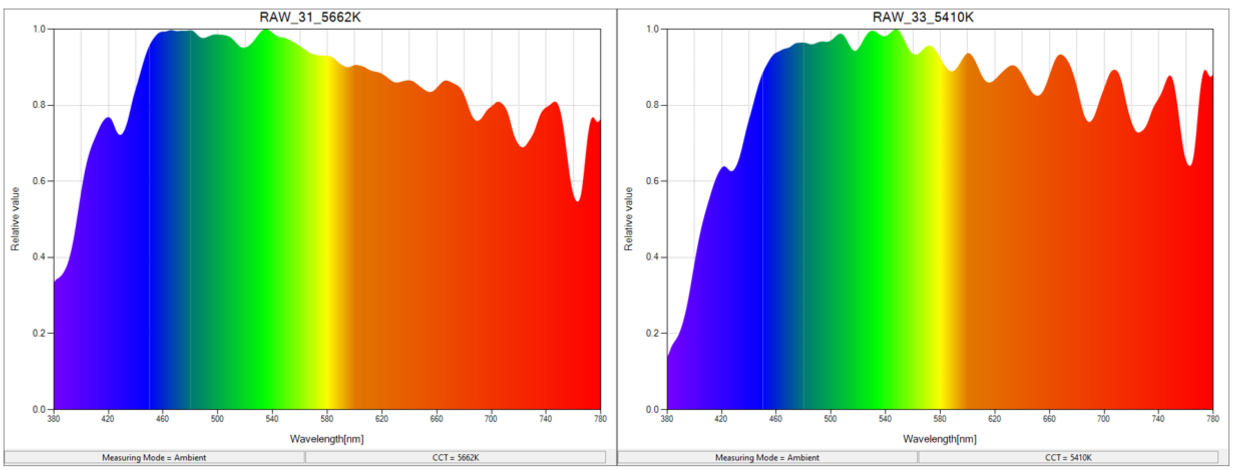
Fig. 15 – SPD: Control vs. Reflective Foil

- **Illuminance**: Dropped dramatically from 5343 lux to 358 lux (a 93.3% drop).
- **CRI**: Remained high at 98.7, a slight drop from 99.7.
- **SPD**: Red, green, and yellow wavelengths dropped significantly.
- **CCT**: Shifted from 5681K to 8066K, resulting in much cooler light.

Analysis: The reflective foil effectively reduced light transmittance by over 90%, acting as a mirror to reflect light. While the CRI remained high, the shift in CCT toward a colder temperature and the reduction in red, green, and yellow wavelengths could negatively affect occupant comfort, especially in environments where natural light is preferred.

3.5.5 Polarized Film

Fig. 16 – SPD: Control vs. Polarized Filter (1-layer)



Illuminance [lx]:	5653		Illuminance [lx]:	2374
CRI Ra:	99.7		CRI Ra:	98.9
CCT [K]:	5662		CCT [K]:	5410

Fig. 17 – SPD: Control vs. Polarized Filter (1-layer)

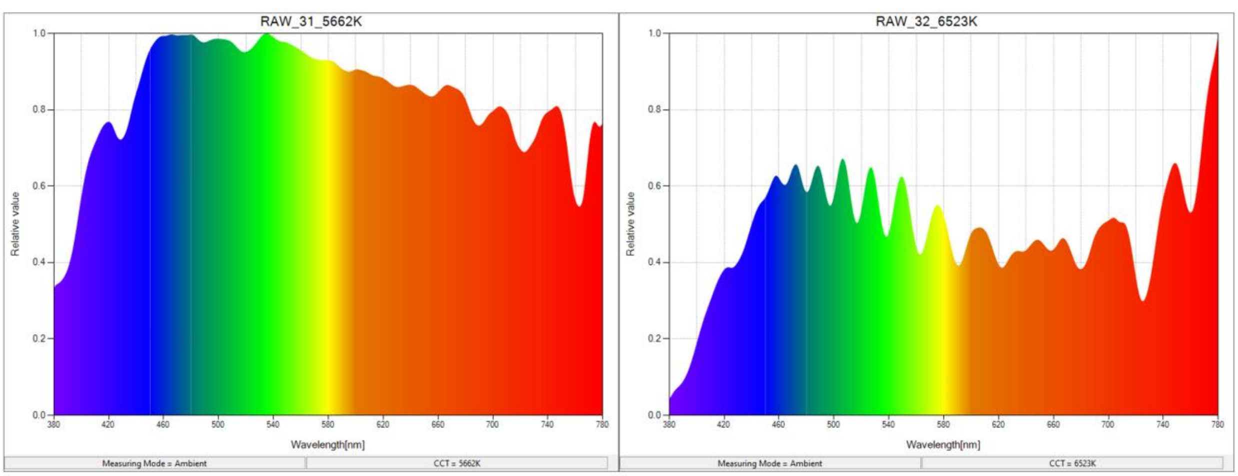
- **Illuminance**: Dropped from 5653 lux to 2374 lux (a 42% drop).
- **CRI**: Slightly dropped from 99.7 to 98.9.
- **SPD**: Red levels remained stable, and the overall spectral distribution was not significantly altered.

- **CCT**: Remained relatively stable, changing from 5662K to 5410K.

Analysis: The polarized film performed exceptionally well, maintaining high CRI and stable SPD while reducing the quantity of light by 42%. The color temperature was not significantly affected, confirming the hypothesis that the polarized film impacts the quantity of light rather than its quality. This suggests polarized films could be a superior solution for reducing glare without compromising the visual comfort of occupants.

3.5.6 Two Layers of Polarized Film (90-Degree Rotation)

Fig. 18 – SPD: Control vs. Polarized Filter (2-layer)



Illuminance [lx]:	5231	Illuminance [lx]:	152
CRI Ra:	99.7	CRI Ra:	97.7
CCT [K]:	5662	CCT [K]:	4523

Fig. 19 – SPD: Control vs. Polarized Filter (2-layer)

- **Illuminance**: Dropped drastically from 5231 lux to 152 lux (a 97.1% drop).
- **CRI**: Dropped from 99.7 to 97.7.
- **SPD**: Significant reductions across all wavelengths, especially in the blue spectrum.
- **CCT**: Shifted from 5662K to 4523K, indicating a warmer light.

Analysis: With two layers of polarized film placed at 90 degrees, light transmission was nearly blocked. Although the quality of light remained high with only a slight drop in CRI, the spectral distribution changed, leading to a warmer color temperature. This suggests that while polarized films can reduce light quantity drastically, they may also slightly alter the color balance when used in combination.

3.6 Conclusion

The results of the experiment confirm the hypothesis that polarized filters affect the quantity of light, not the quality. While the polarized film reduced the light intensity by 42%, it had minimal impact on CRI, SPD, and CCT, preserving the natural light quality. Other materials, such as tinted glass and reflective foils, had more substantial effects on light quality, particularly in reducing CRI and altering CCT.

Chapter 4: Experiment on Glare Reduction

Fig. 20 – 2nd experiment, Spectrometer point of view

The second experiment was conducted in a controlled environment to evaluate how each material affects outside glare, both direct (Fig. 20) and reflected. The primary goal was to determine the effectiveness of various window materials in reducing glare while considering their light transmission properties.

Fig. 21 – 2nd experiment preparation

4.1 2nd Experiment Setup

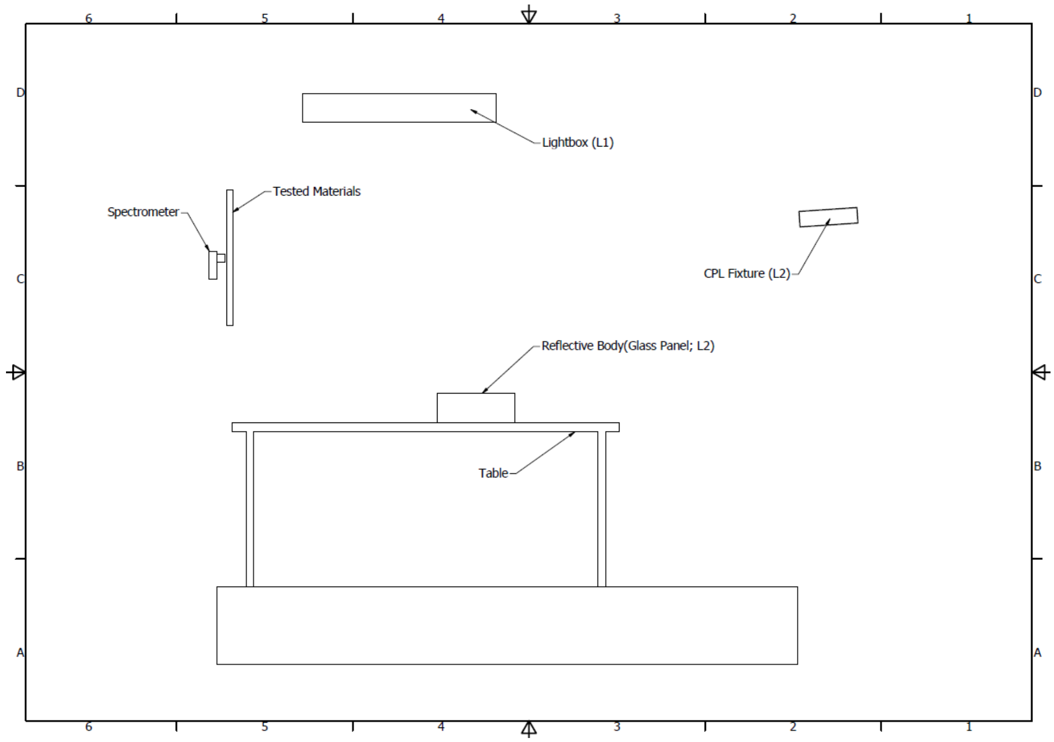


Fig. 22 – 2nd experiment setup, side view

This experiment utilized the **Unified Glare Rating (UGR)** formula to manually calculate the glare reduction for each material. Although software solutions such as Aftab Alpha were initially considered, they proved inconsistent and prone to errors, so manual calculations were chosen for greater accuracy. The necessary measurements were made with a **Sekonic C-800 spectrometer**, ensuring consistency with the data from the first experiment.

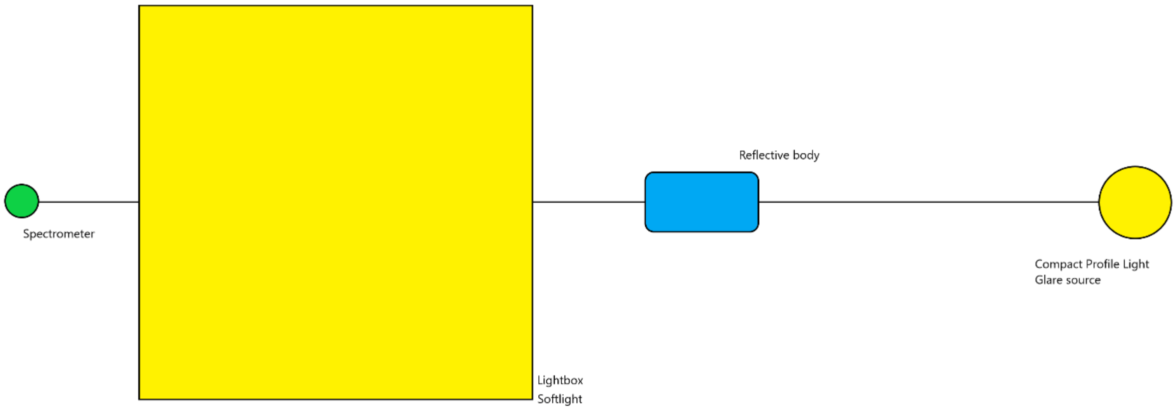


Fig. 23 – 2nd experiment setup, top view

- **Spectrometer Placement**: Positioned at a height of 1.7 meters to replicate typical eye level.
- **Fixtures**:

Fig. 24 – BB&S Lightbox

1. **BB&S Lightbox** (Fig. 24):
   - Used for general ambient light.
   - Dimensions: 1000x1000mm.
   - Placed at a height of 2.4 meters and 0.9 meters in front of the spectrometer.
   - Output: 18,500 lumens, 5600K, 180° beam angle.

Fig. 25 – BB&S Compact Profile Light

2. **BB&S Compact Profile Light (CPL)** (Fig. 25):
   - Used to create a direct glare effect.
   - Circular light source with a diameter of 8cm.
   - Positioned at a height of 1.9 meters and 2.97 meters from the spectrometer.
   - Output: 1,260 lumens, 6000K, 31° beam angle.

4.2 Methodology

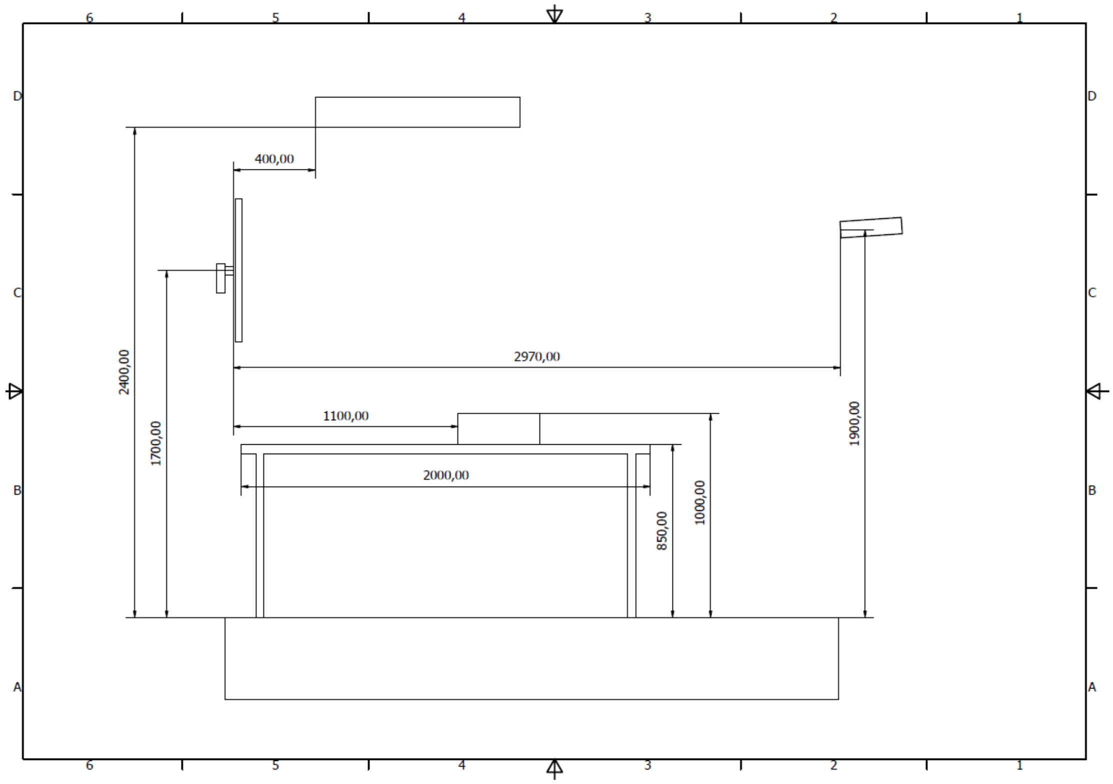


Fig. 26 – 2nd experiment's distances

For the **reflected glare source**, a **Saint-Gobain Climatop glass panel** (28.6mm thick, 70% light transmission) was placed at an angle to reflect light from the CPL into the spectrometer, trying to replicate the "Brewster's Angle". The experiment consisted of measuring direct and reflected glare for each material in comparison to a control (with no material).

- **Control and Materials Tested**:
  - **Tinted Glass**: Saint-Gobain sapphire blue glass, 1 layer, 5.9mm thick.
  - **Least Treatment Glass**: Saint-Gobain Stadip glass, 2 layers, 12.1mm thick.
  - **Climatop Glass**: Saint-Gobain Climatop glass, 3 layers, 28.6mm thick, with 40% light transmission.
  - **Reflective Foil**: Plexiglas sheet with 2-way mirror foil (d-c-fix® self-adhesive window film Mirror Privacy), applied on a 3mm Plexiglas sheet.

- **Polarized Film**: A single layer of polarized filter used in two orientations: normal and 90° rotation.

Each material was measured three times, averaged, and the UGR was calculated using the following formula:

$$\mathrm{UGR} = 8\log_{10}\left(\frac{0.25}{L_b}\sum_{i=1}^{2}\frac{L_i^2 \cdot \omega_i}{p_i^2}\right)$$

Where:

$$L_b = (E_b \cdot p)/\pi$$

E_b – is background luminance (measured with the spectrometer; lux)

p – average reflectance of the environment (which is 0.5)

$$L_i = E_s/w_i$$

$$w_i = 2\pi\big(1 - cos(\alpha/2)\big)$$

E_s – illuminance from each specific light to the spectrometer (measured with the spectrometer; lux)

w_i – solid angle (calculated; steradians)

α – angle made by light source from the point of view of the spectrometer

$$p_i = \frac{1 + (\theta/2)}{\theta/2}$$

Θ – angle formed by the location of the light source relative to the line of sight

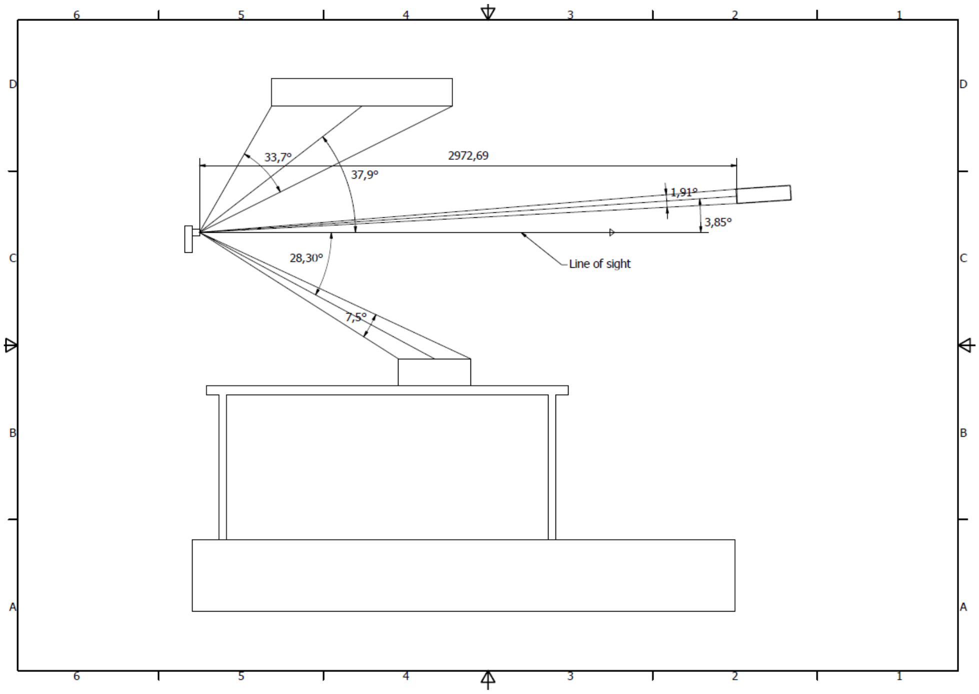


Fig. 27 – 2nd experiment's angles

4.3 Results and Analysis

4.3.1 Direct Glare

Following the UGR formula the following result

Material	UGR	Glare Reduction (%)	Light Reduction (%)	Glare Reduction vs. Light Reduction (%)
Control	29.18	0	0	-
Least Treatment Glass	28.85	1.14	6	19
Blue Tint	25.10	13.96	1.35	1034.08
40% Glass	22.87	21.61	60	36.02
Reflective Foil	9.87	66.16	95	69.65
Polarizer	23.3	20.14	42	47.96

Table 2 – Direct glare results

4.3.2 Direct Glare Analysis:

- The **Blue Tint Glass** had the best overall performance in glare reduction (13.96%) with minimal light reduction (1.35%), achieving a high efficiency of 1034%.
- The **Reflective Foil** performed well in reducing glare (66%) but at a significant cost to light transmission (95% reduction), and an efficiency of 70% making it ideal for environments where glare control is more important than light availability.
- **Polarized Filters** achieved comparable glare reduction (20%) with a moderate light reduction (42%), offering a balanced solution with an efficiency of 48%.

4.3.3 Reflected Glare

Material	UGR	Glare Reduction (%)	Light Reduction (%)	Glare Reduction vs. Light Reduction (%)
Control	27.2	0	0	-
Least Treatment Glass	26.4	2.97	6	49.5
Blue Tint	22.35	17.95	1.35	1329.63
40% Glass	19.33	28.89	60	48.15
Reflective Foil	7.74	71.54	95	75.30
Polarizer (normal)	20.03	26.36	42	62.76
Polarizer (90°)	21.42	21.25	42	50.6

Table 3 – Reflected glare results

4.3.4 Reflected Glare Analysis:

- **Blue Tint Glass** had an exceptional glare reduction performance (17.95%) considering it has almost no light transmission loss (1.35%).
- **Reflective Foil** also proved to be effective at controlling reflected glare (71.54%), but at the cost of a steep reduction in light transmission (95%).

- The **Polarized Filters** reduced reflected glare by up to 26.36% when properly aligned with the polarized light. When rotated 90°, they achieved a lesser glare reduction (21.25%), suggesting that polarization angles play a critical role in performance.

4.4 Conclusion and Insights

Based on the results, each material offers distinct advantages and drawbacks for glare control and light transmission:

- **Blue Tint Glass** was the best performer for balancing **glare reduction** and **light transmission**, but it significantly affects the **CRI** and **CCT**, which could be uncomfortable for occupants.
- **Reflective Foil** is highly effective at **glare reduction**, especially in **hot climates** where it could be used to control both heat and glare. However, its extreme reduction in light transmission and drastic impact on **CCT** make it less ideal for environments where daylight is preferred.
- **40% Transmittance Glass** strikes a good balance, reducing glare by a considerable amount (21.62%) while keeping the **CRI** and **CCT** relatively unaffected. It offers a good compromise between light transmission and glare control.
- **Polarized Filters** showed a strong performance, particularly for reflected glare, confirming their effectiveness as a solution for glare management without significantly affecting light quality.

In summary, the **polarized filters** and **40% transmittance glass** present some of the most balanced solutions for environments that need to prioritize both glare control and light quality. The **reflective foil** is a specialized solution best suited for hot climates or environments where light transmission is less important than glare reduction.

Chapter 5: Design Concepts and Conclusions

5.1 Polarized Filter Design Concepts

The idea of using polarized filters in window design has potential but presents significant design challenges:

1. **Two-Layer Polarizer with Adjustable Rotation**:
    - **Design**: This concept involves two layers of polarized filters, with one layer being adjustable in rotation. By rotating the second layer, the amount of light that enters through the window can be controlled.
    - **Advantages**:
        - Allows dynamic control of light transmission.
        - Offers a variable reduction in glare and brightness.
    - **Disadvantages**:
        - **Redesign of Window Structure**: For the system to work optimally, **round windows** would be needed. The rotation of the second layer is mechanically simpler in round frames, but most buildings use square or rectangular windows.
        - **Initial Light Reduction**: Even in the most open setting (with polarization layers aligned), the light transmission would still be reduced by **at least 50%**.
        - **Control Mechanism**: Adjusting the second layer's rotation would require a motorized or manual mechanism, which would be **costly** and **complex** to integrate into current building designs.
        - **Application Limitation**: Retrofitting this system into existing structures with standard square windows would be challenging and expensive.

2. **Polarized Filters that Activate on Command**:
    - **Design**: In this concept, the window uses a filter that becomes polarized only when necessary, switching between high transparency and polarized modes.
    - **Advantages**:
        - High transparency when polarization is inactive.
        - Instant light and glare reduction when needed.
    - **Disadvantages**:
        - **No Significant Innovation**: This design does not offer any new capabilities beyond existing technologies like **external shades** or **curtains**, which already provide cost-effective light control.
        - **Higher Cost and Complexity**: The complexity and cost of implementing command-activated polarization make it less viable compared to simpler, traditional solutions like **curtains** or **blinds**, which can be installed on existing windows.

5.2 Analysis of Experimental Results

The experimental data indicates that while polarized filters offer some benefits, they fall short compared to other materials tested:

- **Glare Reduction**: Polarized filters performed well in reducing **reflected glare** due to their ability to block polarized light. However, their performance in **direct glare** was not superior to materials like **low-transmittance glass**.
- **Complexity and Limitations**:
    - Polarized filters are limited by their dependence on specific orientations of light. While they can reduce glare from a single direction, they are not effective in handling the more complex **reflected light** in real-world environments, where reflections come from many directions and surfaces.
    - **Brewster's Law** governs the polarization of reflected light, meaning that filters are only effective for certain angles of reflection. This limitation means they cannot address all reflected glare situations.

- **Alternative Solutions**:
    - **Low-Transmittance Glass**: The **40% transmittance glass** performed comparably to polarized filters in both **direct glare** and **light quality retention**. It offers a simpler solution that is easier to implement, as it doesn't require new window designs or complex control mechanisms.
    - **Reflective Foil**: Though less transparent, reflective foil achieved the highest glare reduction in both direct and reflected glare. However, it reduced light transmission significantly, which may make it more suitable for specific applications such as **hot climates**, where reducing heat and light is a priority.

5.3 Conclusion

After the analysis of the data from both the direct glare and reflected glare experiments, it is clear that polarized filters are not the most practical solution for modern window technologies. Several factors make them less desirable for use in building design:

- **Performance Limitations**: Polarized filters, while effective for reflected glare, are not as versatile as other materials. They perform similarly to low-transmittance glass for direct glare, which is simpler and more cost-effective to implement.
- **Complexity and Cost**: The implementation of polarized filters requires additional mechanical systems to control the orientation of the layers, adding to the complexity and cost of the system. In contrast, standard window treatments like low-transmittance glass are widely used, easy to install, and offer the same benefits without the need for mechanical control.
- **Market Viability**: Polarized filters do not offer a significant improvement over existing technologies like blinds, curtains, or low-transmittance glass. These alternatives are already cost-effective, simpler to install, and compatible with current window designs.

In conclusion, while polarized filters show potential in light control and glare reduction, they are not the most practical solution with current technology. Low-transmittance glass is a more suitable and cost-effective option for both new buildings and retrofits, offering a good balance between glare control and light quality without the need for extensive window redesigns or complex control mechanisms.

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Appendix

Direct glare	UGR	L_b(cd/m2)	L1	w1	p1	L2	w2	p2
Control	29.17583115	6.687898089	1870.212497	0.218691727	4.02505756	278564.1358	0.000872331	30.77913806
Least Treat Glass	28.84461319	6.687898089	1755.89633	0.218691727	4.02505756	268246.9456	0.000872331	30.77913806
Blue Tint	25.10253279	6.687898089	969.4010988	0.218691727	4.02505756	161635.9801	0.000872331	30.77913806
40%	22.87033883	6.687898089	731.6234708	0.218691727	4.02505756	114635.4468	0.000872331	30.77913806
Reflective foil	9.872058446	6.687898089	137.1794008	0.218691727	4.02505756	14902.60809	0.000872331	30.77913806
Polarizer	23.29920835	6.687898089	850.5122848	0.218691727	4.02505756	114635.4468	0.000872331	30.77913806
Reflected glare								
Control	27.1973043	6.687898089	1842.776617	0.218691727	4.02505756	6881.269967	0.011480439	5.051225496
Least Treat Glass	26.39059151	6.687898089	1417.732938	0.268033555	4.02505756	6663.508259	0.011480439	5.051225496
Blue Tint	22.31429855	6.687898089	783.4839918	0.268033555	4.02505756	3745.501374	0.011480439	5.051225496
40%	19.33951059	6.687898089	473.8212712	0.268033555	4.02505756	2700.245177	0.011480439	5.051225496
Reflective foil	7.740907153	6.687898089	108.1954084	0.268033555	4.02505756	348.4187325	0.011480439	5.051225496
Polarizer	20.02829678	6.687898089	664.095955	0.268033555	4.02505756	1654.988979	0.011480439	5.051225496
Polarizer 90	21.41783193	6.687898089	559.6314227	0.268033555	4.02505756	4093.920107	0.011480439	5.051225496

Table 4 – UGR formula

UGR – is the UGR result after all data was input

L_b – L_b calculated from the formula:

$$L_b = (E_b \cdot p)/\pi$$

L1,L2 – the results of L_i of the 2 fixtures used, “Lightbox” and “CPL”, in the formula

$$L_i = E_s/w_i$$

w1, w2 - the results of w_i (solid angle) of the 2 fixtures used, “Lightbox” and “CPL”, in the formula

$$w_i = 2\pi\left(1 - cos(\alpha/2)\right)$$

α – angle made by light source from the point of view of the spectrometer

p1, p2 - the results of p_i of the 2 fixtures used, “Lightbox” and “CPL”, in the formula

$$p_i = \frac{1 + (\theta/2)}{\theta/2}$$

Ɵ – angle formed by the location of the light source relative to the line of sight

L_b(cd/m2)	E_b	p(avg refl)	Pi
6.687898089	42	0.5	3.14
6.687898089	42	0.5	3.14
6.687898089	42	0.5	3.14
6.687898089	42	0.5	3.14
6.687898089	42	0.5	3.14
6.687898089	42	0.5	3.14
6.687898089	42	0.5	3.14
6.687898089	42	0.5	3.14
6.687898089	42	0.5	3.14
6.687898089	42	0.5	3.14
6.687898089	42	0.5	3.14
6.687898089	42	0.5	3.14
6.687898089	42	0.5	3.14

Table 5 – L_b formula from the UGR table

E_b – average background illuminance (measured)

P - average reflectance of the suroundings

L1	E_s	w1
1870.212	409	0.218692
1755.896	384	0.218692
969.4011	212	0.218692
731.6235	160	0.218692
137.1794	30	0.218692
850.5123	186	0.218692
1842.777	403	0.218692
1417.733	380	0.268034
783.484	210	0.268034
473.8213	127	0.268034
108.1954	29	0.268034
664.096	178	0.268034
559.6314	150	0.268034

w1	cos(alpha1)	alpha1/2	Pi
0.218692	0.965176477	16.85	3.14
0.218692	0.965176477	16.85	3.14
0.218692	0.965176477	16.85	3.14
0.218692	0.965176477	16.85	3.14
0.218692	0.965176477	16.85	3.14
0.218692	0.965176477	16.85	3.14
0.218692	0.965176477	16.85	3.14
0.268034	0.957319498	16.85	3.14
0.268034	0.957319498	16.85	3.14
0.268034	0.957319498	16.85	3.14
0.268034	0.957319498	16.85	3.14
0.268034	0.957319498	16.85	3.14
0.268034	0.957319498	16.85	3.14

Tables 6,7 – L1 and w1 from the UGR table

E_s – illuminance from the "Lightbox" to the spectrometer (measured with the spectrometer; lux)

w1 - the results of w_i (solid angle) of the "Lightbox" in the formula

$$w_i = 2\pi\big(1 - cos(\alpha/2)\big)$$

alpha1 – angle made by "Lightbox" from the point of view of the spectrometer

Pi – the average taken for the constant π

p1	theta1(radians)	theta1degrees)	Pi
4.025058	0.661144444	37.9	3.14
4.025058	0.661144444	37.9	3.14
4.025058	0.661144444	37.9	3.14
4.025058	0.661144444	37.9	3.14
4.025058	0.661144444	37.9	3.14
4.025058	0.661144444	37.9	3.14
4.025058	0.661144444	37.9	3.14
4.025058	0.661144444	37.9	3.14
4.025058	0.661144444	37.9	3.14
4.025058	0.661144444	37.9	3.14
4.025058	0.661144444	37.9	3.14
4.025058	0.661144444	37.9	3.14
4.025058	0.661144444	37.9	3.14

Table 8 – p2 from the UGR table

theta1 – Ɵ, angle formed by the location of the "Lightbox" relative to the line of sight

L2	E_s	w2
278564.1	243	0.000872
268246.9	234	0.000872
161636	141	0.000872
114635.4	100	0.000872
14902.61	13	0.000872
114635.4	100	0.000872
6881.27	79	0.01148
6663.508	76.5	0.01148
3745.501	43	0.01148
2700.245	31	0.01148
348.4187	4	0.01148
1654.989	19	0.01148
4093.92	47	0.01148

w2	cos(alpha2)	alpha2/2	Pi
0.000872	0.999861094	0.955	3.14
0.000872	0.999861094	0.955	3.14
0.000872	0.999861094	0.955	3.14
0.000872	0.999861094	0.955	3.14
0.000872	0.999861094	0.955	3.14
0.000872	0.999861094	0.955	3.14
0.01148	0.998171905	3.85	3.14
0.01148	0.998171905	3.85	3.14
0.01148	0.998171905	3.85	3.14
0.01148	0.998171905	3.85	3.14
0.01148	0.998171905	3.85	3.14
0.01148	0.998171905	3.85	3.14
0.01148	0.998171905	3.85	3.14

Tables 9,10 – L2 and w2 from the UGR table

E_s – illuminance from the "CPL" to the spectrometer (measured with the spectrometer; lux)

w2 - the results of w_i (solid angle) of the "CPL" in the formula

$$w_i = 2\pi\left(1 - cos(\alpha/2)\right)$$

Alpha2 – angle made by "CPL" from the point of view of the spectrometer

p2	theta2(radians)	theta2(degrees)	Pi
30.77914	0.067161111	3.85	3.14
30.77914	0.067161111	3.85	3.14
30.77914	0.067161111	3.85	3.14
30.77914	0.067161111	3.85	3.14
30.77914	0.067161111	3.85	3.14
30.77914	0.067161111	3.85	3.14
5.051225	0.493677778	28.3	3.14
5.051225	0.493677778	28.3	3.14
5.051225	0.493677778	28.3	3.14
5.051225	0.493677778	28.3	3.14
5.051225	0.493677778	28.3	3.14
5.051225	0.493677778	28.3	3.14
5.051225	0.493677778	28.3	3.14

Table 11 – p2 from the UGR table

theta2 – Ө, angle formed by the location of the "Lightbox" relative to the line of sight