User comfort analysis of inkjet-printed electrochromic glass

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Abstract

This thesis investigates the performance of inkjet-printed electrochromic (EC) glass compared to traditional triple glazing with roller shades in an office setting in the Netherlands. The study aims to assess thermal and visual comfort, via a live experiment conducted in a controlled environment. Key performance indicators (KPIs) include thermal sensation & preference, solar heat perception & satisfaction, (day)light adequacy, colour rendering satisfaction, view clarity satisfaction, and glare perception. Results indicate that EC glass outperforms traditional glazing in maintaining thermal comfort, particularly in darker scenarios, although both glazing types keeping room temperatures within a comfortable range. Visual comfort results are mixed; EC glass provided better daylight sufficiency in low-light conditions, while traditional glazing offered better performance in bright conditions. User satisfaction regarding colour rendering and glare did not show significant differences between the two façade types. This study was limited to the winter period of the Dutch climate. Ideally, to obtain a complete picture of the performance between both facades, this experiment should be conducted again during the summer period or in a warmer climate.

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1 Introduction

Buildings are a large consumer of the world's energy. According to the *Tracking Green Energy Progress 2023* report by the International Energy Agency (IEA), buildings operations account for an estimated 30% of the world's energy usage and 26% of global energy-related CO_2 emissions (International Energy Agency, 2023). The report also states that by 2030, to be in line with the Net Zero Emissions by 2050 (NZE) Scenario, global space heating and cooling intensities would have to decrease by 35% and 25% respectively when compared to today (International Energy Agency, 2023).

Due to the large difference in U-value with other façade elements, glazing plays a large role in building energy transmittance losses. For example, for a two-storey residential building of which windows cover 30% of the façade, windows will account for about 60% of total energy losses through the building envelope (Gustavsen et al., 2007). According to the United States Department of Energy, in the US, heat gain and heat losses through glazing are responsible for 25 to 30% of residential heating and cooling energy demand (United States Department of Energy, n.d.). Glazing also plays an important factor in solar heat gain. A higher solar heat gain might be desirable in climates with colder outdoor temperatures, since the amount of energy entering the building envelope through solar radiation could then be saved on building heating energy. The opposite would be true in warmer climates. There, windows with a lower solar heat gain might be desirable as to prevent overheating of indoor spaces and to save on required building cooling energy.

Besides being a big influence for buildings energy levels, glazing plays an essential role in user experience and comfort. For instance, glazing is directly related to thermal and visual comfort and skin health. Glazing also has large influences on vision, air ventilation, and photo-protection, and it also has biopsychological effects (Rezaei et al., 2017) (Cannavale et al., 2020) (Park & Kim, 2015) (Tuchinda et al., 2006).

2 State of the art

2.1 Smart glazing

Developments in materials science during the past few decades have provided many innovations in facade and glazing technologies. One category of those developments is smart glazing. This type of glazing can change its own transparency or tint based on external stimuli or signals (Rashidzadeh & Matin, 2023).

Over the years, a number of smart glazing technologies have been developed, which can be categorized into passive and active systems. Passive systems change their transparency automatically based on external variables, and are thus not controllable. Active systems are controllable, and can change their transparency in a controlled manner, which is mostly done with electrical signals (Krarti, 2022).

Examples of passive technologies are thermochromic and photochromic systems, which adjust the tint of the glass based on changes in temperature and light, respectively (Baetens et al., 2010). Examples of active technologies are gasochromic (GC), electrochromic (EC), suspended particle (SP) and liquid crystal (LC) systems. Gasochromic glass changes tint by pumping particular gases between the glass panels, with the gas reacting with the gasochromic layer on the inside of the glass. Electrochromic glass is transparent at rest, but changes colour upon electrical stimulation, producing an oxidation or reduction reaction that lowers transmittance (Casini, 2018). Suspended particle (SP) glass in a resting state absorbs light due to randomly oriented particles in the glass. In the presence of an electric field, the particles align themselves and the glass becomes transparent. Liquid crystal (LC) glass is similar in function to SP, but differs from SP in that LC windows scatter incoming light diffusely (Rezaei et al., 2017). Most EC and SP technologies are a dark blue colour in their non-transparent state. LC glass is a milky neutral colour in its non-transparent state. Another difference between EC and SP and LC is that EC uses direct current (DC), and SP and LC use alternating current (AC).

2.2 Active glazing systems

Of all these technologies, EC seems the most promising regarding reduction of building energy usage and control of user comfort levels. Unlike the passive systems, EC is controllable, which is beneficial as control strategies can be developed. EC also has a better performance in terms of energy consumption compared to SP and LC, for a similar visual performance to that of SP. EC glass from Sageglass has a Solar Heat Gain Coefficient (SHGC) of 0.46 in the transparent state and 0.06 when fully tinted. The Visual Light Transmission (VLT) varies between 60% and 1%. Changing state consumes 2.5 W/m2. Holding a particular tint consumes less than 0.4 W/m2. The SHGC of SP ranges between 0.57 and 0.06 and the VLT ranges from 65% to 0.5%. Switching state requires 5 W/m2 and holding state requires 0.55 W/m2. The SHGC of LC is between 0.69 at rest and 0.55 fully tinted. The VLT of LC ranges from 75% to 50%. Change of state and its retention both require 5-10 W/m2 (Casini, 2018). In terms of power consumption and range in visual properties, EC largely wins over LC. Compared to SP, EC uses half the power when switching states, and 27% less power when maintaining a given state.

Table 1 Comparison of active electric glazing technologies (Casini, 2018)

Technology	Electrochromic (EC)	Suspended particle (SP)	Liquid crystal (LC)
Clear state – dark state	Off – on	On – off	On – off
Solar heat gain coefficient (clear – dark)	0.46 – 0.06	0.57 – 0.06	0.69 – 0.55
Visual light transmission (clear – dark)	60% – 1%	65% – 0.5%	75% – 50%
Diffuse light scattering	No	No	Yes
Colours	Blue, green, grey	Blue	Clear, bronze, grey, green
State change power requirements	2.5 W/m^2	5 W/m^2	5-10 W/m^2
State maintenance power requirements	0.4 W/m^2	0.55 W/m^2	5-10 W/m^2
Voltage requirements	12 V DC	65 – 110 V AC	65 – 110 V AC
State change speed	5 – 12 min	1 – 3 s	40 ms

Regarding state switching speed, the rate at which EC glass changes tint is relatively slow compared to other technologies. SP glass can switch its transparency to the desired level within a few seconds. LC glass is even faster, being able to change states near instantaneously. For a 10x30 cm sample of EC glass from Sageglass, it takes 5 minutes for the glass to be fully tinted. This slow speed becomes even slower as the glass panels get larger. For a 120x80 cm sample, tinting takes 12 minutes and bleaching takes 8 minutes. Additionally, these times become longer at higher temperatures of the glass. For users, this slow change can be both advantageous and disadvantageous. On the one hand, it allows users to gradually get used to the changes in exposure while not being distracted, but on the other hand the glass is slow at responding to sudden fluctuations in daylight, such as when cloud drifts by on a sunny day (Casini, 2018).

To summarize, SP windows can change transparency faster than EC and are more controllable in terms of transparency level, but use more energy in the process. From the perspective of energy consumption, SP windows are better to use in situations where windows need to be non-transparent more often, such as vehicles parked in the sun, due to the fact that SP windows are opaque at rest (Rezaei et al., 2017) (Casini, 2018). LC glass is also not suitable for the building envelope because LC is opaque at rest, has no intermediate stages between on and off, and scatters light diffusely which obstructs views of the outside environment. In this regard, LC is more suitable as privacy glass for meeting rooms for example (Krarti, 2022) (Casini, 2018).

Gasochromic glass is cheaper to produce compared to EC and can change tint at least 10 times faster, but has a much smaller operating range than EC, with -34% for VLT and -8% for SHGC. Installation of GC glass is also more complicated than that of EC glass, as GC windows require a separate gas line to the window to be able to operate, making GC windows less of an ideal solution when retrofitting glazing in existing buildings (Casini, 2018).

2.3 Energy saving potential of EC glass

Regarding the reduction of energy consumption in buildings, several studies show varying but positive results for EC glass. Mainly since the 2000s, several projects have proven the benefits of active dynamic glass. When compared to static, near-infrared reflecting glazing combined with external shading solutions it has been shown that EC glass can save up to 60% of the energy consumption of artificial light. It can also reduce cooling loads by up to 20% and peak loads by up to 26% (International Energy Agency, 2013). When applied to prototypical buildings at three different locations in the US, EC glass reduced building energy consumption by up to 22% compared to standard ASHRAE 2007 double glazing (Sbar et al., 2012). In office spaces in European cities, EC glass could provide up to 57% reduction in building energy consumption when optimal controls are used, compared to standard requirement static glazing (Favoino et al., 2015). EC glass also performs well in simulations. Compared to static solutions in temperate climates, EC can be responsible for 8 to 10% reduction in energy consumption, depending on the orientation of the façade (Dussault et al., 2012) and in hot, dry climates it can provide a 30% reduction in annual solar gain (Aldawoud, 2013). It also performs well against traditional shading systems such as venetian blinds in continental climates, with a 14.3% reduction in energy consumption for heating, cooling and lighting (Aste et al., 2012). EC glass can provide 11.2% reduction in heating and cooling energy consumption in Mediterranean climates compared to normal two-layer glass, according to simulations, depending on the orientation of the facades (Tavares et al., 2016).

Besides a good performance in terms of energy consumption and energy savings, electrochromic glass also has a good acceptance rate by users because of the reduction in glare, reflections and discomfort near windows (Casini, 2018). Another advantage over traditional solar shading is that the functionality of EC glass does not depend on weather conditions. Strong winds can have a grip on external traditional blinds, affecting light transmission. This can be distracting to the user in terms of visuals, but noise as well. In extremely strong winds, traditional blinds cannot be used. On top of that, external blinds require more maintenance than EC glass.

There are some limitations and downsides to EC glass. For example, in terms of energy performance the effectiveness of EC glass does depend on the climate in which it is used, the orientation of the façade, and whether heating or cooling is dominating. It is most effective in situations where there are larger differences between cooler and warmer periods. This is true for both long- and short-time scales, such as climates with larger differences between summer and winter, and on east and west facades (Casini, 2018).

Another limitation of EC glass is the limited number of available colours. Commercially available EC glass is mostly of dark blue colour. This may form an issue, as users may find the blue colour to be bothersome due to increased eye fatigue from the blue light. One experimental study measuring occupants' response to glare under different coloured glazing shows that participants experience discomfort due to glare more often when exposed to blue glazing compared to neutral-coloured glazing. In their experiment, neutral-coloured glazing has a higher acceptance rate than blue-coloured glazing, despite neutral glazing having higher glare metrics. This suggests that users tolerate glare better in neutral colour conditions rather than blue colour conditions. (Jain et al., 2023)

Control strategies are another important factor in the usefulness of EC glass. Using the right control strategies can bring out the full potential of energy savings and user comfort of EC glass, but on the other hand, its effectiveness can be severely limited if an incorrect control strategy is applied. Research on energy consumption of buildings with EC glass with different control strategies shows that the energy consumption of air-conditioning is 25% lower using the best control strategy compared to the worst control strategy.

2.4 Types of control systems for EC glass

There are multiple different types of control strategies for electrochromic glass. They can be placed into three main categories:

- Rule-based control
- Model Predictive Control (MPC)
- Optimal Control using Genetic Algorithms (GA)

Rule-based control strategies operate based on predefined rules or instructions that change the behaviour of the system in response to specific conditions. Rule-based systems are purely reactionary and do not involve optimization processes. An example of how they work is by changing the transparency of EC glass when a certain threshold for incident solar radiation is reached (Dussault et al., 2016).

MPC strategies operate by using models to predict future responses of the structure. By making these predictions and taking current system variables into account, it then uses an optimization algorithm to decide which control inputs should be manipulated in order to get the desired effect over a short time period. The desired effect being keeping the temperature at a certain level or keeping glare to a minimum, for example. In this regard MPC strategies are more suited for complex systems than rule-based strategies, as they are better able to adapt to immediate situational changes and they can consider future outcomes. MPC systems are also better able to stay within certain constraints such as keeping the temperature within a certain range or not exceeding an energy consumption limit. Rule-based systems suffer from potentially becoming overly complicated as the complexity of the system increases (Dussault et al., 2016).

Genetic algorithms and MPCs are both optimizing control strategies, but they are different in how they operate. GAs generate and evolve different combinations of control system inputs over time, and then evaluates their performance based on a certain objective. The algorithm iteratively checks the fitness of combinations against a predefined objective, selects the best performing ones and mutates and recombines them to find the best settings for a given situation, while taking constraints into account. In case of an office scenario with EC glass, GA could be used to figure out the ideal hourly settings of the system variables to keep building energy consumption to a minimum, while keeping visual comfort in mind. GA and MPC are different in functionality in that GA systems try to find a solution for ideal system settings iteratively over a longer period of time, while MPC systems focus more on real-time decision making (Dussault et al., 2016).

2.5 Production cost of EC glass

Despite some disadvantages, EC glass still has many advantages over other technologies, and it makes sense to try to incorporate EC glass as much as possible in both new and existing buildings. However, that being said, production cost of EC glass is high due to the manufacturing process of sputtering, and is a subject improvement (Cannavale et al., 2020) (Casini, 2018). The cost of EC glass is estimated between 500 and 1000 € per square meter (Syrrakou et al., 2005). This is many times higher than the price of high performance static solar control insulated glass, which is about 80 €/m^2. To get good market penetration for EC glass, the price needs to be reduced by about tenfold, to a price of around 100-150 €/m^2. This is less than the price for low-e IGUs with mechanical blinds systems (Syrrakou et al., 2005).

However, progress has been made in improving the production process. Brite Solar Technologies have developed their own process for producing neutral-tinted EC glass using low-cost inkjet printing, which lowers the production price of the glass to about 100 €/m^2. This new, low-cost production method could be the solution to the low market penetration for EC glass. This glass, made by a new method, must be tested for performance in both energy saving potential and user experience, as it is no guarantee that this glass will perform the same as EC glass made by using other methods.

The aforementioned paragraphs show how important facades and windows are in terms of energy management and user comfort. Active glazing systems, especially EC glass, can drastically improve building energy usage and user comfort compared to traditional static glazing. Researchers are actively trying to improve EC glass performance, eliminate its problems and reduce its production costs.

3 Problem definition and objective

The effect that buildings have on global energy consumption is widely recognized. Studies have shown that EC glass has the potential to make a major impact on global building energy consumption. In addition, simulations by Patrick Kwee (Kwee, 2020) show that EC glass consistently outperforms other window technologies in terms of energy savings and energy consumption in multiple climates, while also scoring well in terms of visual comfort.

As shown in the previous chapter, the energy performance of EC glass has been the subject of a number of different studies. In these studies, energy performance is measured either via simulations or experiments. Of these experimental studies, only a select few have worked with real users to evaluate user comfort of the EC glass system. This is an issue, as the fields of energy performance and user comfort and interaction are intertwined with each other. What is best for one field in a given situation could be in conflict with what is best for the other. User preferences are not always in line with ideal energy saving scenarios, thus causing user dissatisfaction and perhaps even discomfort if users cannot intervene with the automated system.

When assessing the performance of electrochromic glass, or any sort of active dynamic glazing for that matter, a comprehensive approach involves concurrent consideration of both energy efficiency and user comfort and interaction. In short, in literature there is a lack of multi-domain approaches when evaluating performance of EC glass. This study aims to add to the body of knowledge of EC glass performance in a multi-domain approach – these domains being user comfort and preference – in order to pave a way to more energy efficient and user-friendly building envelopes. The focus of this study will specifically be on the new inkjet-printed EC glass developed by Brite Solar Technologies, mentioned in the previous chapter. Due to time and workload limitations the scope of this project is limited to user comfort assessment.

This leads to the following research objective:

A comparison between office spaces using inkjet-printed EC glass and normal triple glazing with traditional shading on the domains of visual and thermal user comfort in the Dutch climate.

4 Research questions

4.1 Research question

The research question is defined as such:

What is the performance of inkjet-printed EC glass compared to normal triple glazing office glass with traditional shading on the domains of visual and thermal user comfort in the Dutch climate?

4.2 Sub-questions

This research question will be supported by several, categorized sub-questions:

- Thermal sub-questions:
  - *How do the physical temperatures in the rooms compare, and what is the thermal sensation of the user?*
    - *What is the user thermal preference in relation to their thermal sensation?*
  - *What is the amount of solar energy entering the rooms, and does the user feel any solar heat?*
    - *What is the user satisfaction regarding solar heat sensation?*
  - *Which factors are of influence on thermal sensation & preference, and solar heat sensation and satisfaction?*
  - *How does the EC glass compare to triple glazing on the domain of thermal comfort?*
- Visual sub-questions:
  - *What is the level of (day)light in the rooms and is it adequate for performing relevant tasks?*
    - *What is the user satisfaction with the amount of daylight entering the rooms?*
  - *What is the colour rendering of the windows, and how satisfied is the user with the colour of the daylight entering the rooms?*
  - *How much light do the windows transmit, and what is the user satisfaction regarding the clarity of the view?*
  - *What is the level of (day)light entering the user's eyes and is it disturbing, in terms of glare?*
  - *Which factors are of influence on (day)light sufficiency & satisfaction, daylight colour, view clarity, and glare sensation?*
  - *How does the EC glass compare to triple glazing on the domain of visual comfort?*
- General sub-questions:
  - *What is the user satisfaction with the state switching speed of the facades?*
  - *What is the user satisfaction regarding the state switching sound of the facades?*

4.3 Method

The method used to answer these questions is through an experiment in a live office environment at The Green Village on the TU Delft campus. In this office there are two nearly identical meeting rooms. One of these rooms will act as a control room, with standard three-layer office glass installed with roller shades. The second room has the new type of inkjet-printed EC glass installed, integrated onto the same triple glazing as in the control room. Both rooms contain an air conditioner and sensors that measure and log temperature, humidity and solar irradiation. Additional sensors measuring black globe temperature, air temperature and vertical and horizontal illuminance at occupant level are used as well. Additionally, room and façade characteristics such as visual transmittance and colour of daylight through the façade are measured before the start of the experiment. This is discussed in chapter 6.

During the 5-6 months run of the experiment, user comfort and preference is measured with the help of test subjects in a live office environment. Each subject is placed in the EC room and in the control room for a set period of time. Here, they are expected to perform normal office work. Each session the volunteers are put through multiple scenarios in which the state of the façade is changed in combination with the outdoor lighting conditions. After each scenario, the volunteers are asked to fill in a questionnaire which includes questions about their experience in the particular room in terms of visual and thermal comfort, as well as other aspects. The EC glass and blinds in the control room are under full manual control of the researcher during the experiment in order to accommodate the different scenarios. After the experiment concludes, user experiences are quantified by linking results from the questionnaires to data from the measurement equipment. Statistical tests are also performed to check for significance of the results. Figure 1 shows a visual representation of the timeline and the main tasks that were performed for this research.

4.4 Deliverables

The deliverables for this study are:

- Graphs presenting questionnaire results with levels of significance between the scenarios and rooms.
- Graphs presenting summarized relevant sensor data.
- A discussion and conclusion on the performance of inkjet-printed EC glass compared to triple glazing with roller shades in terms user comfort and satisfaction.

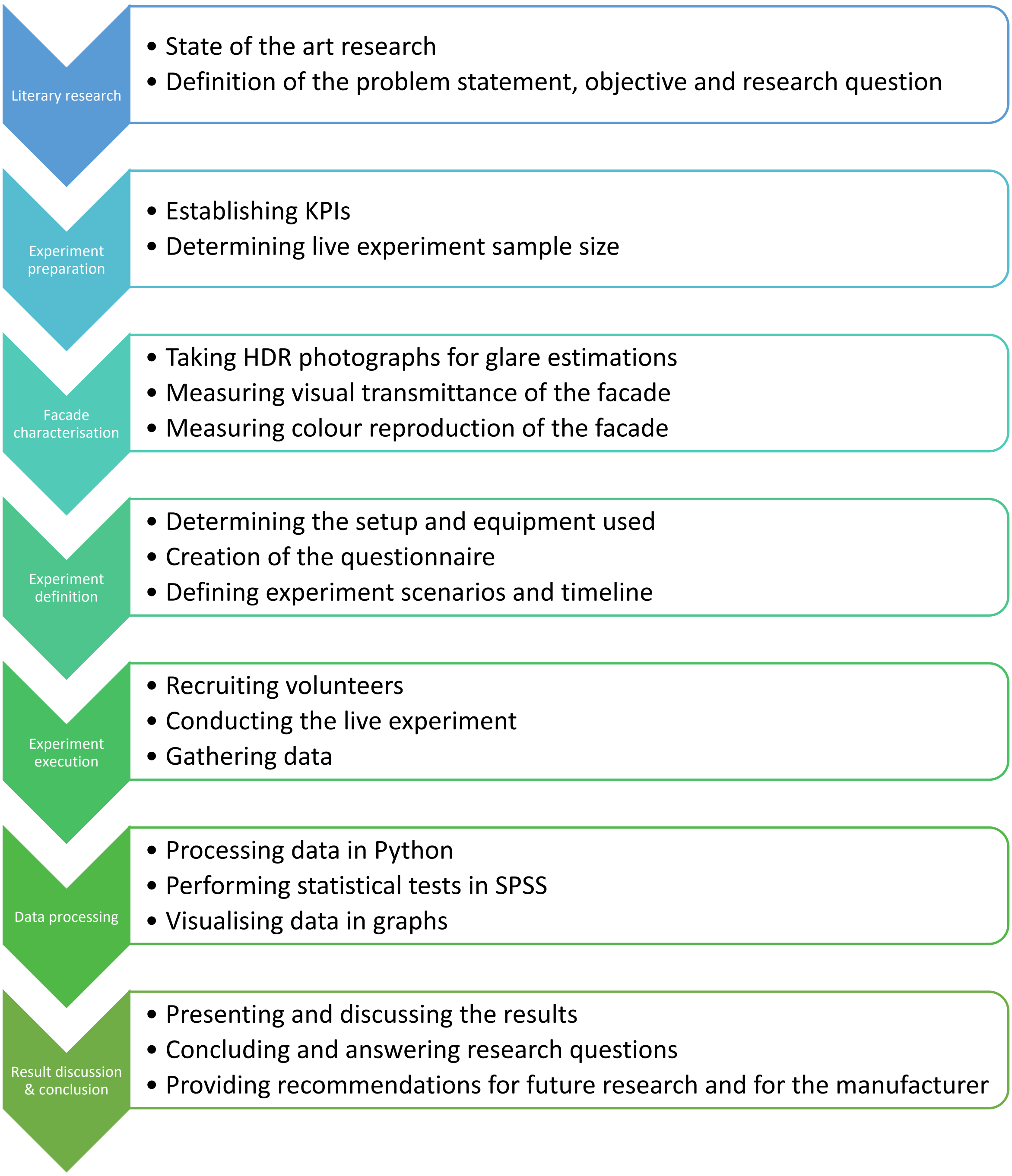

Figure 1 Visual representation of the research timeline

5 Experiment preparation

In preparation for the experiment, it is of importance to first define the metrics by which the different glazing types will be assessed. These key performance indicators (KPIs) are defined in chapter 5.1. Furthermore, due to randomness in the human nature, a population will have a certain standard deviation from the mean in terms of user comfort. In order for this experiment to have adequate statistical power it is necessary to minimize this standard deviation by having a large enough sample size. This sample size is determined in a power analysis which is discussed in chapter 5.2.

5.1 Key performance indicators

This subchapter discusses the KPIs that are chosen for the experiment and how they are quantified and measured. There is no official method in literature for determining KPIs for this type of study. Hence, for this study, the decision was made to select KPIs of a broad nature, aligning with those commonly used in existing literature. This approach ensures comparability with prior studies while also providing robust insights into the assessment of internal environmental quality. The KPIs are divided into two categories: visual and thermal. In chapter 7 an in-depth elaboration of the experiment setup is given, further explaining how the KPIs are measured.

5.1.1 Visual KPIs

For the visual aspect, the following KPIs were found to be the most relevant.

Light and daylight access

In order to comfortably perform a task, an individual must have a well-illuminated work surface without experiencing excessive or insufficient (day)light entering their field of view and causing discomfort. In this case, work plane illuminance is measured by placing an illuminance sensor horizontally on the subject's desk, aimed upwards. This can be used to check whether the subject's work plane is sufficiently illuminated. A second illuminance sensor is placed vertically at the level of the subject's eyes, aimed in the direction of the subject's field of view. This monitors how much light falls into the subject's eyes. Additionally, this sensor is used to estimate glare, which is explained in chapter 6.1x. Subject's opinion on the adequacy of the amount of (day)light and satisfaction with the amount of daylight is assessed via the questionnaire.

Glare

Daylight glare probability is an indication of the percentage of people who would be distracted by glare from a particular viewpoint. The DGP is determined by taking fisheye HDR photographs from the volunteer's point of view and by editing and correcting these photographs in the RADIANCE tool suite according to a specific step-by-step plan created by Pierson et al. (2021), described in chapter 6.1. These photographs would ideally be taken continuously in the exact position and direction of the volunteer's eyes. As this is not practical, reference HDR photos are taken before the start of the experiment. At the same time, vertical illuminance directly at the lens position is measured. DGP derived from the HDR pictures is then linked to the measured vertical illuminance. During live experiment sessions, glare is then estimated via the vertical illuminance which is monitored continuously. The subjective sensation of glare is assessed via the questionnaire.

Colour of daylight

As mentioned in chapter 2.3, colour of the incoming daylight can have an influence on user comfort. In this experiment the colour of the EC glazing does not change continuously over time, and colour characteristics are therefore measured once before the start of the experiment. These measurements are done with an illuminance spectrophotometer. This is discussed in chapter 6.3. Subjects' satisfaction of the colour of incoming daylight is assessed via the questionnaire.

View clarity/access to outside view

View clarity or access to outside view refers to the degree and quality of visibility or connection that a volunteer has with the external environment from within the meeting rooms. Subjects' satisfaction regarding clarity of the view to the outside is assessed via the questionnaire.

5.1.2 Thermal KPIs

For the thermal aspect the following KPIs were regarded as relevant:

Temperature sensation & preference

Temperature sensation and preference relative to current sensation are subjective and are assessed via the questionnaire. When relative humidity, volunteer clothing level and operative temperature are known, Figure 2 (or an online calculator) could be used to deduce whether a subject would theoretically be thermally comfortable. Questionnaire data can be compared to this figure to check if subject responses are within expected ranges. Relative humidity is measured with a humidity sensor and volunteer clothing level is assessed via the questionnaire.

Operative temperature

Using only dry bulb air temperature is not enough for thermal comfort studies. It does not sufficiently consider the effects of radiation or air velocity. Operative temperature, on the other hand, is a comprehensive representation of the effects of air temperature, radiant temperature and air velocity, as it is determined by all three of these factors. Air temperature is measured by placing a thermometer inside a ping-pong ball covered in aluminium foil. This ensures that only air temperature is measured and not both air temperature and radiant temperature on this particular thermometer. Mean radiant temperature can be estimated via black globe temperature. Black globe temperature is measured with a thermometer encased in a ping-pong ball which is coloured black. Air speed is measured with an anemometer, or can be estimated. Air speed is especially important for the operative temperature. If air speed is small, operative temperature is the average of air temperature and mean radiant temperature. In the case of this experiment, it was confirmed that the air speed in the Office Lab meeting rooms is low enough that it no longer plays a role in determining the operative temperature. The mean radiant temperature is then equal to the black globe temperature, as shown in equation 1 and 2. As a result, the operative temperature is the average between air temperature and black globe temperature.

$$MRT = \left[(GT + 273.15)^4 + \frac{1.1 \cdot 10^8 \cdot \upsilon_a^{0.6}}{\varepsilon \cdot D^{0.4}}(GT - T_a)\right]^{\frac{1}{4}} - 273.15 \qquad [1]$$

Where:
MRT is the mean radiant temperature in °C
GT is the globe temperature in °C
υ_a is the air speed at the level of the glove in meters per second
ε is the emissivity of the globe
D is the diameter of the globe in meters
T_a is the air temperature in °C

With a sufficiently low air speed (υ_a = 0) equation 1 simplifies to:

$$MRT = GT \qquad [2]$$

Solar heat sensation & satisfaction

Solar heat sensation and satisfaction are subjective and are assessed via the questionnaire. The aim of these KPIs is to provide insight into the sensation of heat from the sun through the facade on the subject's skin, and whether this is perceived as pleasant or not. Too much or too little solar heat is detrimental to subjects' comfort, health, productivity, and the building's energy usage. Subject's solar heat sensation can be compared to black globe temperature and solar irradiation - measured with indoor and outdoor pyranometers - to check for consistency.

Table 2 summarizes the KPIs, what is measured, and what device they are measured with.

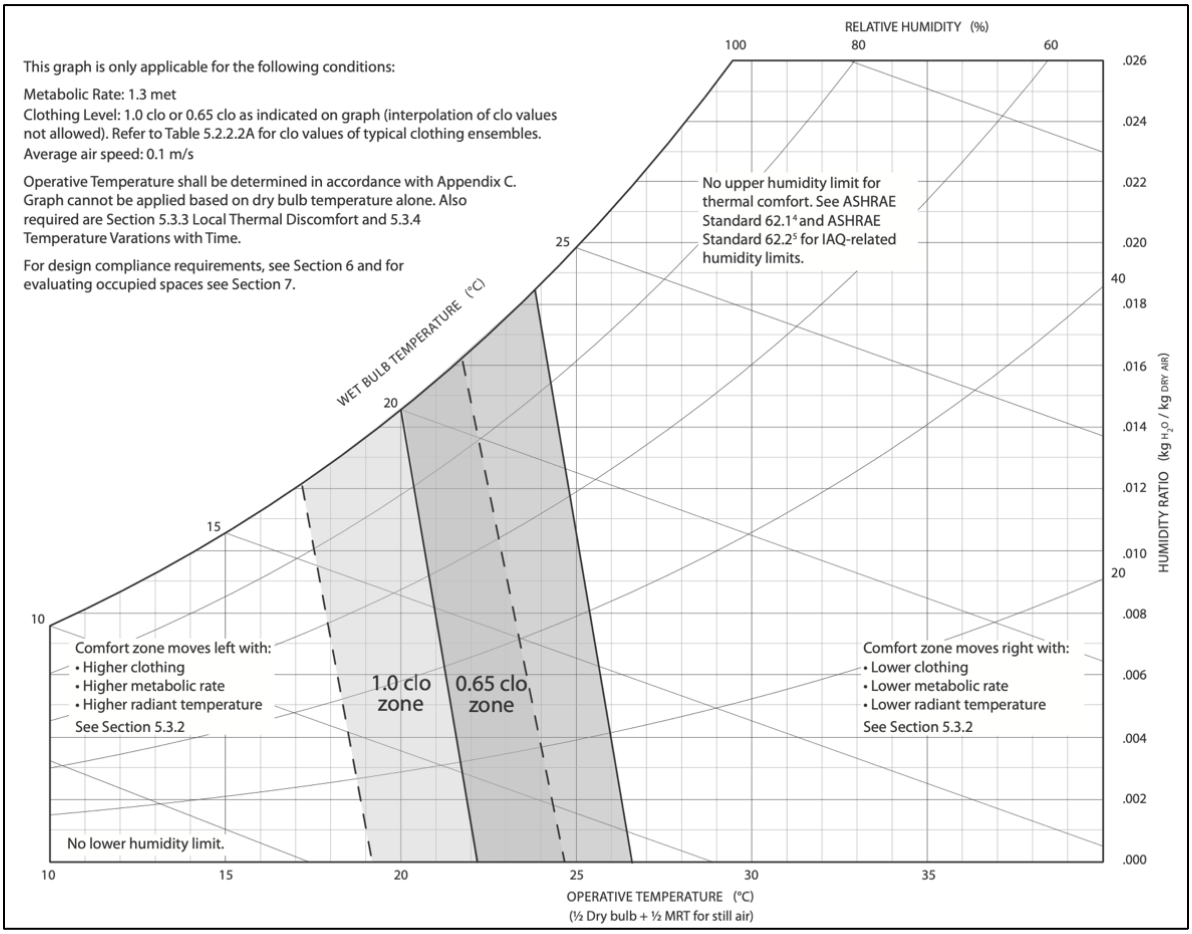

Figure 2 Human comfort zones for different operative temperatures, humidity levels and clothing level (ASHRAE, 2020)

Table 2 Summary of KPIs

Aspect	KPI	What is measured	What is it measured with
Visual	(Day)light access	Illuminance on desk and at eye level, Opinion on (day)light sufficiency and satisfaction	(IoT) lux sensors, Questionnaire
	Glare	DGP estimated via vertical illuminance, Subjective sensation of glare	HDR photographs (before experiment), (IoT) lux sensors (during experiment), Questionnaire
	Colour of daylight	Colour characteristics of the EC glass, Satisfaction of colour of daylight	Illuminance spectrophotometer, Questionnaire
	View clarity	Satisfaction of clarity of view to outside	Questionnaire
Thermal	Thermal sensation and preference	Sensation of (air) temperature and thermal preference relative to current sensation	Questionnaire
	Operative temperature	Air temperature, Black globe temperature, Relative humidity	Dry bulb thermometer, Black globe thermometer, Humidity sensor
	Solar heat sensation and satisfaction	Sensation of solar heat and satisfaction regarding the amount of incoming solar heat, Black globe temperature, Solar irradiation (indoor and outdoor)	Questionnaire, Black globe thermometer, Pyranometers

5.2 Sample size

To get an accurate sample size for the experiment, effect size first needs to be determined in a pilot study. This is out of scope for this research and thus a medium Cohen effect size of f=0.25 is assumed, which is the standard option for ANOVA: repeated measures, within factors in G*Power version 3.1.9.7. This effect size is assumed as it is expected that the volunteers will notice a reasonable difference between scenarios in terms of visual and thermal comfort. All volunteers will experience two rooms (two groups) and three scenarios per room (three measurements). Table 3 shows the different combination of groups and scenarios.

Table 3 Experiment groups and scenarios

	Scenario A	**Scenario B**	**Scenario C**
Group 1: EC glass room	No sun in field of view, EC disabled (bright state)	Sun in field of view, EC enabled (dark state)	Sun in field of view, EC disabled (bright state)
Group 2: Normal glass room	No sun in field of view, Roller shades up (bright state)	Sun in field of view, Roller shades down (dark state)	Sun in field of view, Roller shades up (bright state)

With a within factor repeated measures ANOVA in G*Power the total sample size is then calculated with the following inputs:

- Effect size f = 0.25 (medium effect size, assumption)
- α error probability = 0.05
- Power (1-β error probability) = 0.8
- Number of groups = 2
- Number of measurements = 3
- Correlation among repeated measures = 0.5 (standard setting, assumption)
- Nonsphericity correction ϵ = 1 (standard setting, assumption)

This leads to a total sample size of 28 for an actual power of 81.2%. The minimum number of subjects needed for the experiment is thus 28. However, it is best to take a sample size as large as practically possible to correct for overestimations of effect size and correlation among repeated measures. In addition, a larger sample size is also more beneficial for the power of the experiment. Figure 3 shows the settings used in G*Power to calculate the total sample size.

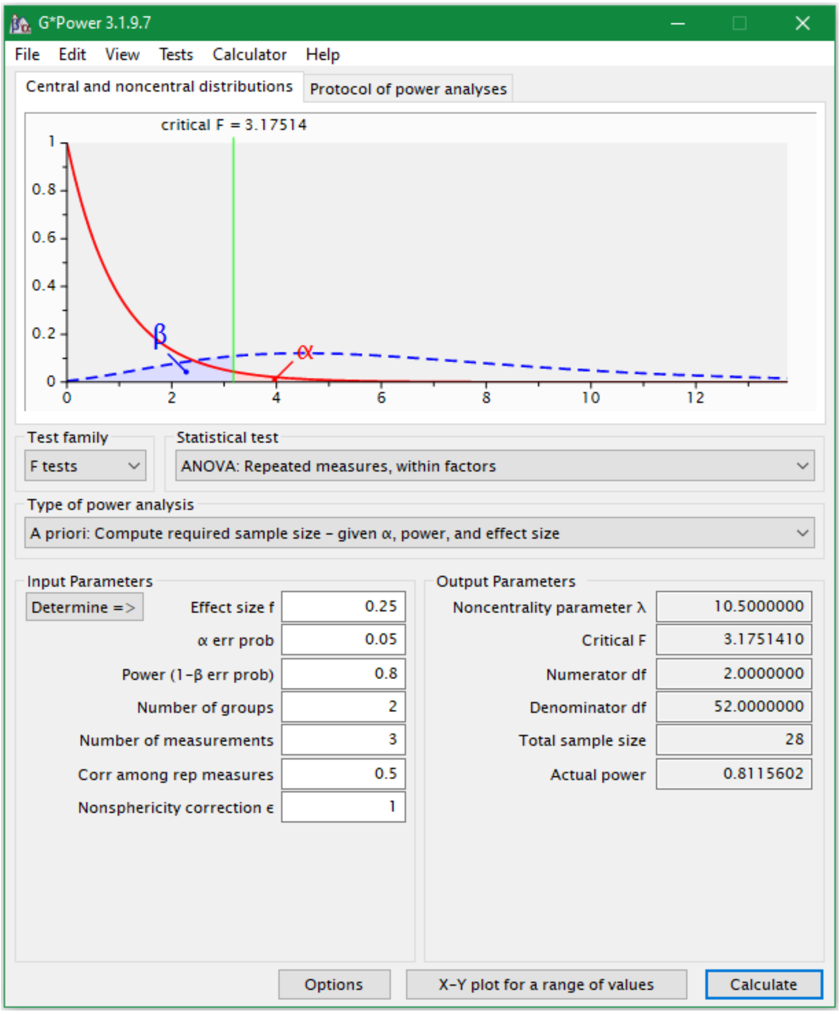

*Figure 3 G*Power settings for sample size calculation with repeated measures, within factors ANOVA*

6 Glass characterization

Before the experiment can officially commence it is necessary to take reference measurements of certain aspects of the glazing types and the rooms. This way, the glass can be characterized and properties supplied by the manufacturer can be verified. In this case, three types of reference measurements were done: 1) HDR photographs for DGP calculation and glare source identification, 2) illuminance measurements to identify the visual transmittance of the window composition in bleached and tinted state, and 3) colour measurements to identify colour characteristics for both states of the glass.

Figure 4 shows the windows of the EC room, photographed from the inside. The EC panels in the left and middle window frames are approximately 40x40 cm in size and are glued to a larger glass plate via the edges of the panels. The glue seams between the panels are visible as bright straight lines on the windows in Figure 4 and Figure 18. This assembly replaces the inner glass pane of the triple-glazed window in the left and middle window frames. The right window frame is actually a door to the outside; however, it remains closed during the experiment and is therefore referred to as a window frame. The EC panels on the right window frame are approximately 45x35 cm in size and are also glued to a larger glass plate via the edges of the panels. However, this assembly replaces the outer glass pane instead of the inner glass pane of the triple glazing. The EC panels were made using a lab printer that could only process limited panel sizes. Thus, the small size of the panels is a limitation of the current experimental production process, and the panels in this experiment (including glue seams) are not fully representative of the final product which are full window frame sized EC panels. Chapter 6.2.2 further elaborates on the composition of the facade.

Figure 4 EC room facade from the inside

6.1 HDR photographs

To calculate the Daylight Glare Probability, the article "Tutorial: Luminance Maps for Daylighting Studies from High Dynamic Range Photography" was followed, written by Pierson et al. (2021) was followed. This tutorial describes how to create HDR photos, how to ascertain things like the response curve of the camera and the vignetting curve of the lens, how to edit and correct the HDR photos with the tools in the RADIANCE suite to calculate the DGP, and how to create glare source and false colour images. An overview of the steps of the tutorial is presented in Figure 5. The entire procedure summarized below. The steps are briefly explained below.

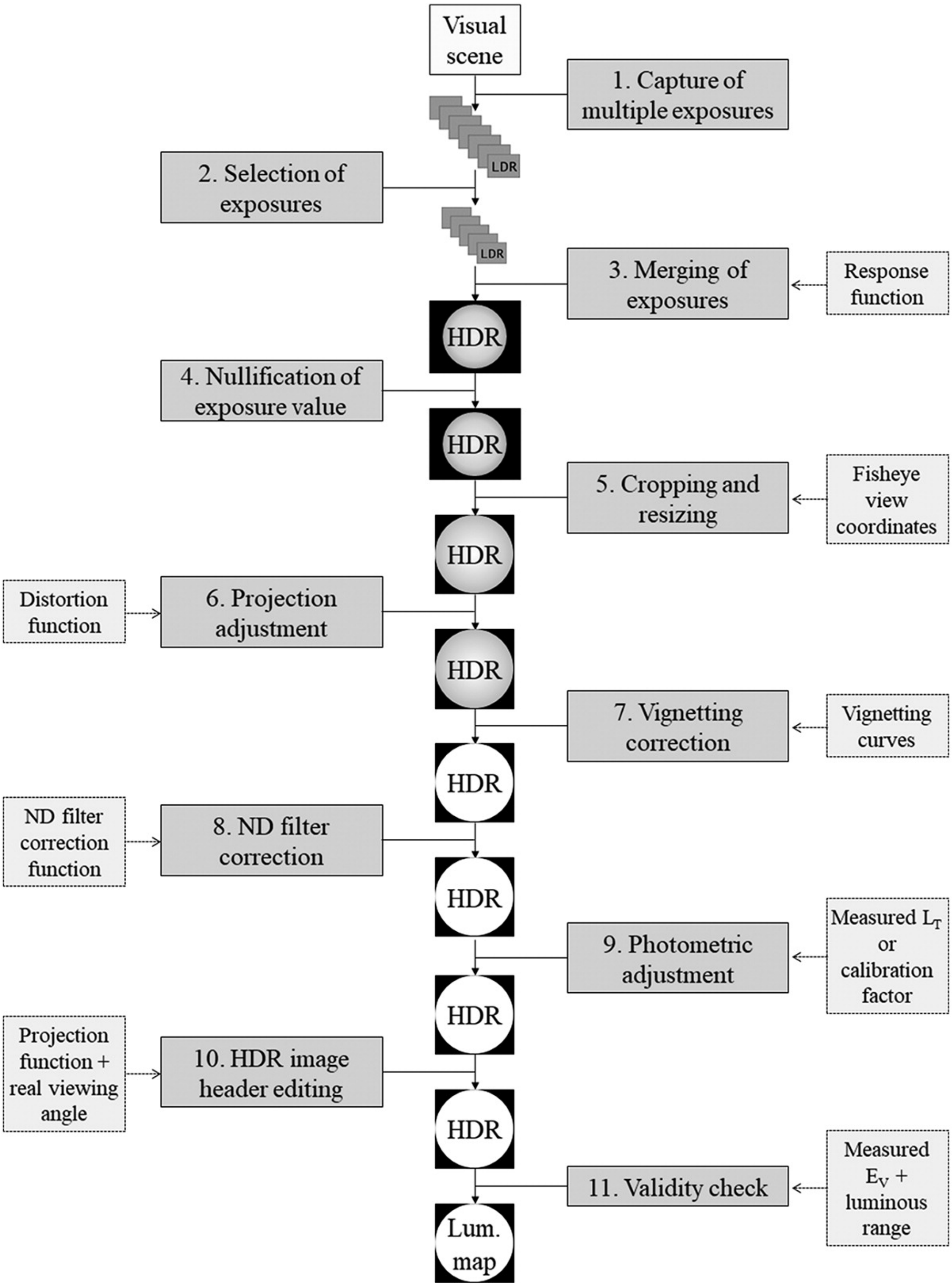

Figure 5 Step by step instructions on how to create luminance maps from LDR pictures for DGP calculations (Pierson et al., 2021)

Step 1: Capture of multiple exposures

The camera and lens used are the Canon EOS 80D with the Sigma 4.5mm f/2.8 EX DC HSM Circular Fisheye lens. The camera is placed on a tripod at a height of about 110-120 cm, in the same position and direction as the subject's eyes and field of view. The camera is controlled remotely via the Canon EOS Utility 3 tool installed on a laptop to ensure stability while taking pictures. Camera settings are as follows:

Table 4 Camera settings for HDR imaging

Colour space	RGB
Colour profile	sRGB IEC61966-2.1
Aperture value	6
Focal length	5 mm
ISO speed	100
Flash	No
F number	f/8
Exposure program	Manual
Metering mode	Pattern
White balance	Manual

For each scenario a series of low dynamic range pictures is taken with exposure times ranging from 1/8000 seconds to 30 seconds. Each successive photo has (roughly) double the exposure time compared to the previous one. This results in a total of 19 pictures taken for each scenario. Apart from exposure time every setting stays the same for each picture. The resulting pictures range from very dark and underexposed, to very bright and overexposed. Pictures are saved in jpeg format as this requires less storage space than raw format while still having adequate quality for the purposes of HDR image generation. At the same time the camera is taking the LDR pictures, the spot luminance of a grey target in the camera's field of view is measured. At the same time vertical illuminance at the tip of the lens is measured as well, with an off-the-shelf illuminance sensor. Both the spot luminance and the vertical illuminance measurements are used for image calibration in later steps.

Step 2: Selection of exposures

According to the tutorial it is recommended to use the widest range of LDR images as possible, but that only images containing useful information should be inputted to accelerate the HDR generation process and to make the process more stable. In this case processing speed and stability are not an issue. Furthermore, virtually every LDR image contains useful information, as the underexposed images contain bright spots and the overexposed images contain dark spots. Therefore, for every scenario, each and every LDR image that is taken is selected for merging.

Step 3: Merging of exposures

Using the tool *hdrgen* from the RADIANCE software package the selected images are merged via an algorithm which linearises pixel values by cancelling out the camera response function. Pixel values of each image are divided by their respective exposure time. Then, each pixel value of each image is weighted according to its value. All pictures are then merged, resulting in an HDR which is the average of all exposures.

Step 4: Nullification of exposure value

Next, to prevent wrong interpretation of the exposure by the software, the exposure value of the picture is stripped from the file completely, and is included directly into the pixel values. This is done with the tool *ra_xyze.*

Step 5: Cropping and resizing

Because the picture at this point still is a circular image in the middle of a black rectangle, it needs to be cropped to the circular image's borders. Due to limitations in the software the image also has to be resized to a resolution of 1500 by 1500 pixels.

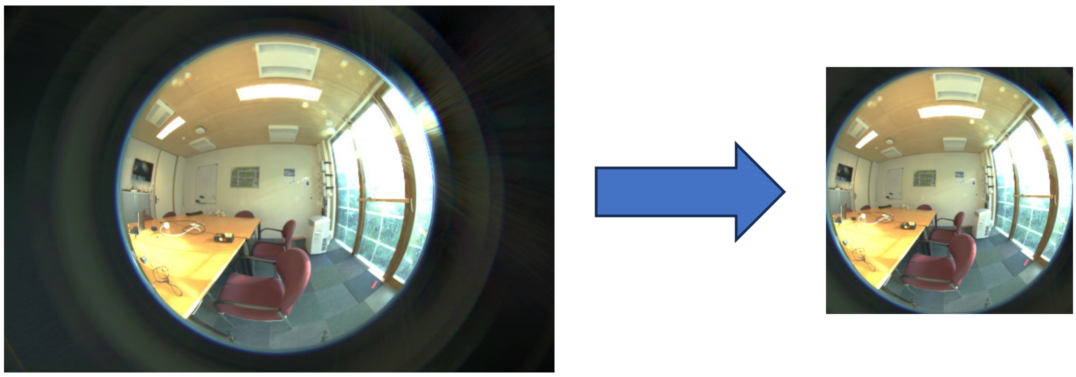

Figure 6 Cropping and resizing of HDR image

Step 6: Projection adjustment

To correct for lens distortion, the projection of the image must be adjusted from equisolid to equidistant projection. This is done with the tool *pcomb*, which also sets the pixel values outside the 180° fisheye view to 0 for all colour channels, which is pure black. The tool uses an external file containing the distortion function of equisolid to equidistant projection to adjust the image.

Step 7: Vignetting correction

Light fall-off along the edge, also known as vignetting, also has to be corrected. Again, the tool *pcomb* is used for this, this time with a file containing the correction function for vignetting for the used lens aperture.

Step 8: ND filter correction

No ND filter was used while taking the LDR pictures, so this step is skipped.

Step 9: Photometric adjustment

At this point the HDR image has only captured relative luminance values, and the image requires photometric adjustment to represent true luminance values. This adjustment involves multiplying pixel luminance by a scaling factor. This scaling factor is derived from spot luminance measurements of a grey target in the field of view. While shooting the LDR pictures, spot luminance measurements were taken with a handheld luminance meter. The ratio between the luminance of the target in the HDR picture and the handheld luminance meter is then used as a correction factor for the tool *pcomb*.

Step 10: HDR image header editing
Correcting HDR image header information is essential for accurate post-analysis as it ensures precise calculations of metrics and average values. This involves erasing existing view information in the metadata of the image and inserting correct details regarding lens projection type and viewing angles. This is done with the *getinfo* tool.

Step 11: Validity check
As a final step the resulting HDR image has to be validated. In this case this is done via illuminance comparisons. Illuminance comparison evaluates the total illuminance in the HDR image – which is calculated with *evalglare* – against the sensor-measured illuminance mentioned in step 1. In case of a large discrepancy (25% error or more), the HDR image is discarded.

6.1.1 Results & discussion

After the entire process, *evalglare* is used to calculate the daylight glare probability for each HDR reference picture. This DGP is then compared to a simplified DGP calculation created by Wienold (2009) which uses the vertical illuminance at eye level (E_v). The formula is as follows:

$$DGP_s = 6.22 \cdot 10^{-5} \cdot E_v + 0.184 \qquad [3]$$

However, this formula is not accurate for illuminances below 320 lux. For these low light cases the following formula is used:

$$DGP_{lowlight} = DGP_s \frac{e^{0.024 \cdot E_v - 4}}{1 + e^{0.024 \cdot E_v - 4}} \qquad [4]$$

The results of the *evalglare* DGP calculation and the simplified calculations are presented in the table below. For each picture, the table shows the *evalglare* calculated E_v, the E_v measured with an off-the-shelf illuminance sensor, the *evalglare* calculated DGP, and the simplified DGP calculation from formula 3 and 4 which uses the measured E_v as input.

Table 5 Vertical illuminance and DGP calculation results

HDR PHOTO NR.	CALCULATED E_v	MEASURED E_v	CALCULATED DGP	SIMPLIFIED DGP
1	619	430	23%	21%
2	1398	640	27%	22%
3	228	310	15%	15%
4	949	630	23%	22%
5	232	224	15%	12%
6	350	335	23%	20%
7	152	254	8%	7%
8	614	543	20%	22%
9	467	410	20%	21%
10	620	560	20%	22%
11	655	560	22%	22%
12	1629	1444	29%	27%

13	**545**	**526**	**23%**	**22%**
14	1286	1050	25%	25%
15	699	507	22%	22%

The average error between the *evalglare* calculated DGP and the simplified DGP is 1.4%. Estimation of DGP via vertical illuminance at eye level is therefore deemed as a valid method to study daylight glare probability within the live experiment.

Apart from calculating and verifying DGP, the HDR pictures are also used to create glare source and false colour images of both meeting rooms. These images are then used to identify potential glare sources and a worst-case viewing angle (in terms of glare) for the live experiment. Three positions and angles are considered: A, B and C, presented in Figure 7. Of these positions, B has the largest potential for creating glare scenarios for inhabitants as the sun and the sky are visible in the afternoon. This is ideal for assessing glare performance between the rooms and therefore this position and viewing angle is chosen as the position for the volunteers in the live experiment.

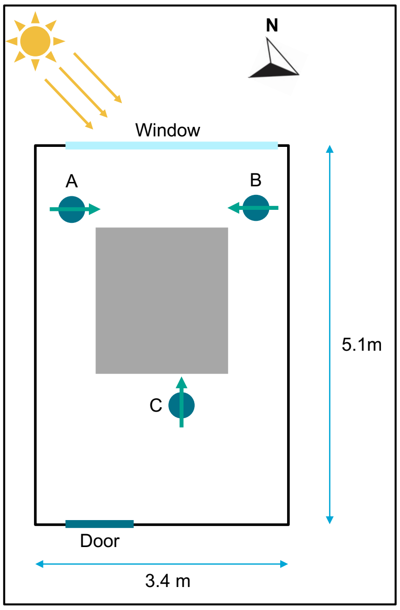

Figure 7 Positions in the room considered for worst-case viewing angle

The post-processed HDR image, the glare sources and the false colour of the EC room for position B are shown in Figure 8, Figure 9 and Figure 10. Of the normal room these are respectively Figure 11, Figure 12 and Figure 13. Pictures of the EC room for positions A and C are presented in Appendix A.

Figure 8 HDR fisheye photo of the EC room, clear glass, view direction parallel to the window

Figure 9 EC room glare sources

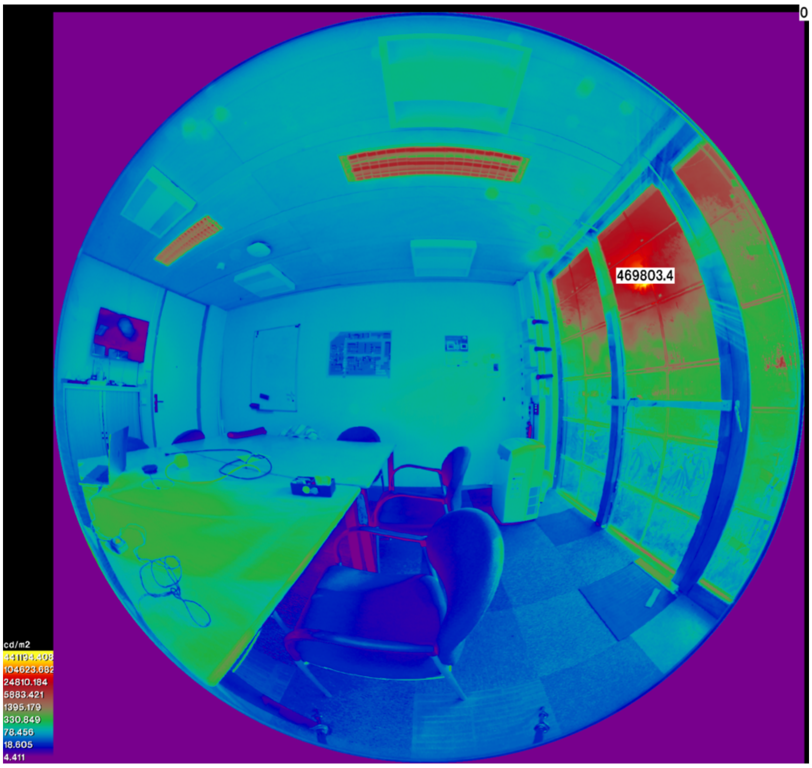

Figure 10 EC room false colour

Figure 11 HDR fisheye photo of the normal room, view direction parallel to the window

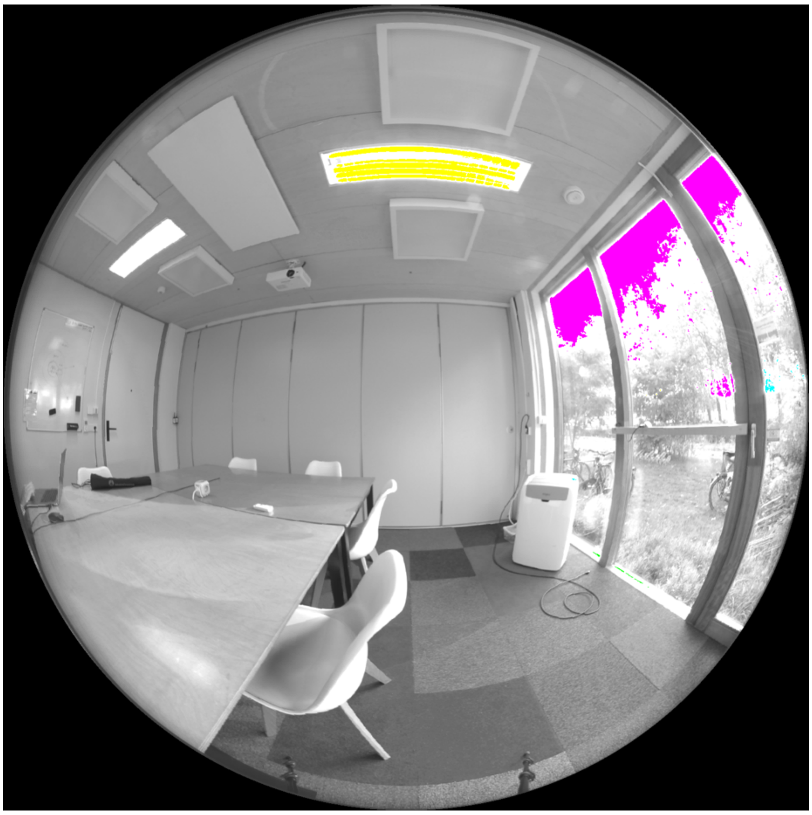

Figure 12 Normal room glare sources

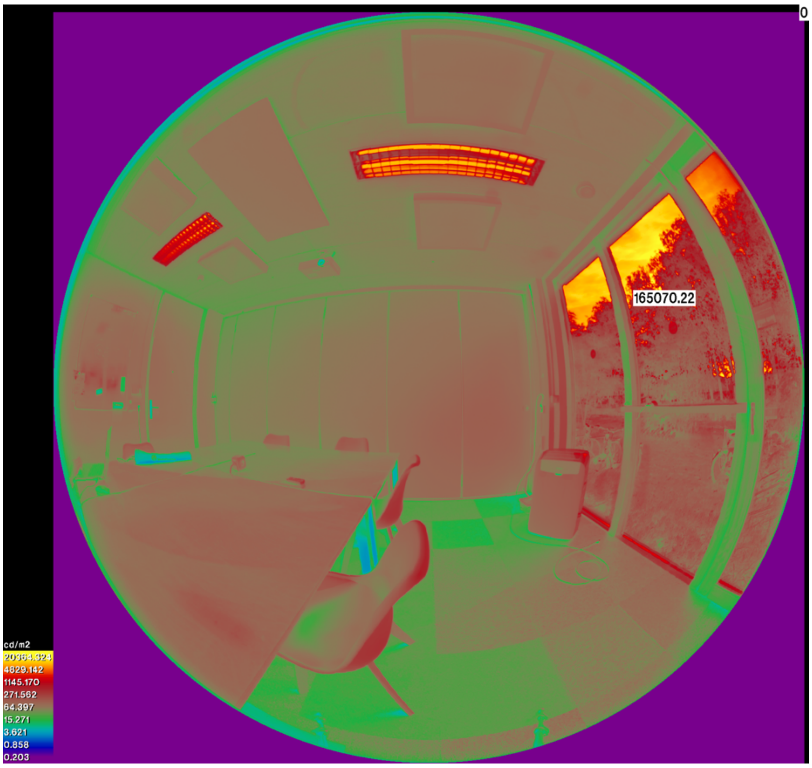

Figure 13 Normal room false colour

From these images, it is clear that in both rooms the sky and sun are both in the field of view from this position and that they are potential sources of glare. In both rooms, the lights in the ceiling are potential sources of glare as well. Something to note is that the glue lines holding the EC panels are potential sources of glare as well, as can be seen in the clear state photo in Figure 9 and especially in the dark state photo in Figure 14. This is perhaps due to the fact that the glue is not as transparent as the glass which may cause light passing through the glue lines to be diffused into the lens more than normally would happen. From a personal point of view, the glue lines are more noticeable on sunny days. There are no pictures from cloudy days available to test this theory, however.

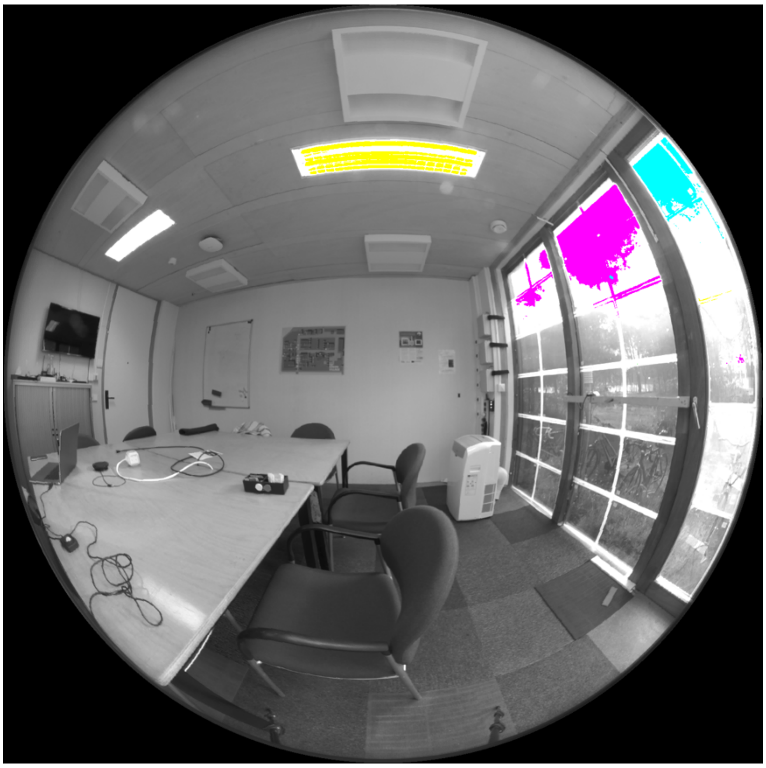

Figure 14 Glare sources in the EC room, dark state

6.2 Visual transmittance

6.2.1 Setup

To measure the visual transmittance of the EC glass, two IoT lux sensors are placed on the interior and exterior of the middle of an EC glass pane, both facing the outside. They are placed in such a way that they have similar view of the outside, with nothing blocking their view of the sun (see Figure 15 and Figure 16). Both sensors are connected to a Raspberry Pi which logs the sensors' values every second the measurements take place. The ratio between the measured values of the interior sensor and the exterior sensor is the visual transmittance, T_{vis}. Measurements took place on two separate occasions; August 28th which was a bright, sunny day, and the second on August 29th which was a cloudy day. The course of measurements was as follows:

1. 20 minutes in bleached state;
2. Tinting of the glass;
3. 20 minutes in dark state;
4. Bleaching of the glass;
5. 20 minutes in bleached state (on the 29th only);
6. Tinting of the glass (on the 29th only);
7. 20 minutes in dark state (on the 29th only).

A state transition is indicated by flashing lights on the control panel, to the left of the window (Figure 17). Each 20-minute countdown began when the indicator lights of the control system stopped flashing.

Figure 15 Transmittance measurements setup interior view

Figure 16 Transmittance measurements setup exterior view

6.2.2 Manufacturer specifications

According to the manufacturer of the EC panels the glass has a transmittance of 65% in clear state and 10% in dark state. In this test setup, for the left and middle window frames (see Figure 17), the EC panels were mounted on the inside of the triple-glazed windows. For the right window frame, the panels were mounted on the outside. The panels are fixed to the windows by adhesive along the edges of the panels (Figure 18). The EC panels are laminated panels made of two layers of 3mm thick glass with the EC layer in between. The composition of the triple glazing is as follows:

1. Stratobel 33.1 (3 mm Planibel Clearlite + 0.38 mm PVB Clear + 3 mm iplus 1.1 pos.2) unhardened;
2. 15 mm Argon 90%;
3. 4 mm Planibel Clearlite unhardened;
4. 15 mm Argon 90%;
5. Stratobel 33.1 (3 mm iplus 1.1 pos.5 + 0.38 mm PVB Clear + 3 mm Planibel Clearlite) unhardened.

The EC panels are smaller than the window frames because they are manufactured with a lab printer. The smaller panels are laminated onto a larger glass plate, which results in seams between the panels, as shown in Figure 18. This glass assembly replaces either the inner layer of the triple-layer glass or the outer layer. The triple glazing has a light transmittance τv of 73%, light reflectance ρv of 15%, internal light reflectance ρvi of 15%, and a colour rendering index Ra of 96%. The theoretical transmittance of the clear EC panes combined with the triple glazing is 47.5%. For darkened EC glass the theoretical transmittance is 7.3%

The type of roller blinds for the standard room façade is Luxaflex, model name Outdoor Screen Beaufort. According to the manufacturer, the fabric is Sergé 3%. This is a fibreglass fabric consisting of 41.5% ± 1.5 glass and 58.5% ± 1.5 PVC. The thickness is 0.83 mm ± 0.5, and the colour is anthracite grey (RAL 7016). The fabric has an openness factor of 3% and has a tex (linear mass, used for measuring the fineness of yarn/fibres) of 165 ± 5. The roller blinds cover the entire façade, and there are no gaps at the sides or bottom where light can come through.

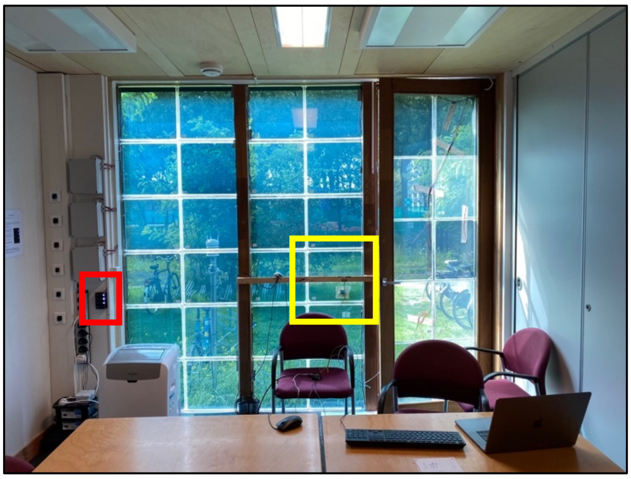

Figure 17 Windows with EC panes installed. Control panel marked in red and panel used for transmittance measurements marked in yellow

Figure 18 An EC glass pane glued to the window

6.2.3 Results & discussion

The results of the measurements are presented in the following graphs.

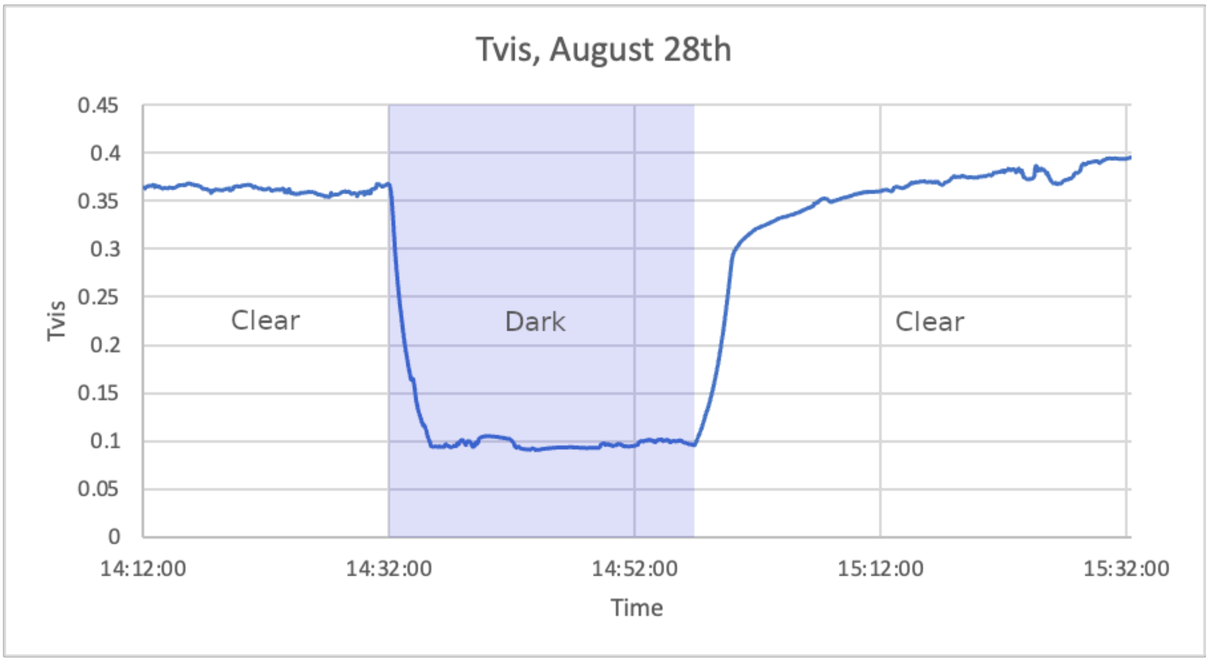

Figure 19 Measured Tvis on August 28th

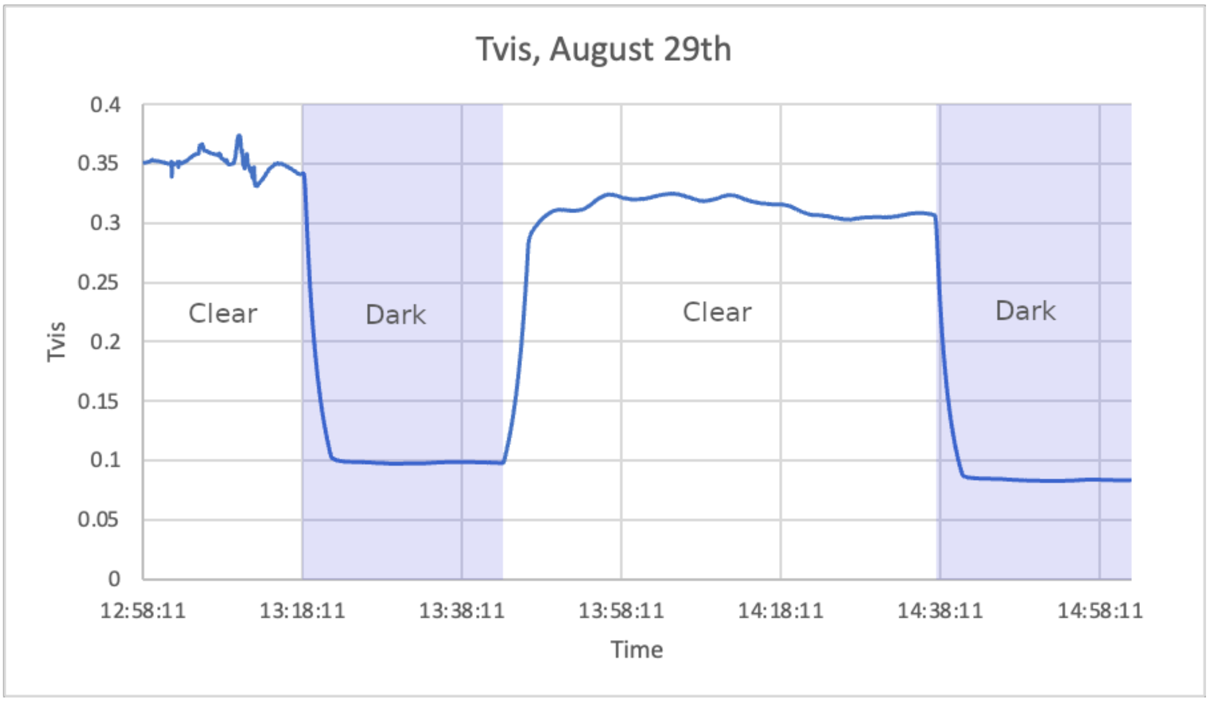

Figure 20 Measured Tvis on August 29th

The graphs show that on both days the T_{vis} starts steady around 0.36 and drops to 0.1 when tinting. Subsequently on bleaching, the T_{vis} rises rapidly to 0.3 before rising more gradually. So far, the shape of the curve in the graph matches the manufacturer's drawing, as shown in Figure 21. After this, however, a discrepancy emerges between the two graphs. On the 28th, T_{vis} continues to rise steadily to a value of 0.4. The measurement is cut off 35 minutes after the start of the bleaching process, so it is unknown whether the rise would continue or not. On the 29th, this was taken into account and the glass was kept at bleached level for longer. However, this time the glass did not turn as transparent as the day before, with a maximum T_{vis} of 0.32. The T_{vis} then seems to stabilise to 0.3. This is a difference of 0.1 from the previous day's maximum T_{vis}. The manufacturer did not specify the expected ranges for T_{vis} in the two states, so whether this behaviour is normal cannot be determined.

It is possible that the glass stabilizes over time to a transmittance of 0.35, since it started at this value on both days, and the glass did not change tint for a while before the measurements started. However, more research would be needed for this. In the dark state, the measured transmittance of 7% to 10% meets the expected theoretical transmittance of 7.3% as mentioned in 6.2.2. In bright state, however, it is a lot lower. Where a transmittance of 47.5% is expected, the measured values fluctuate between 30% and 40%, with a possible stable value of 35%.

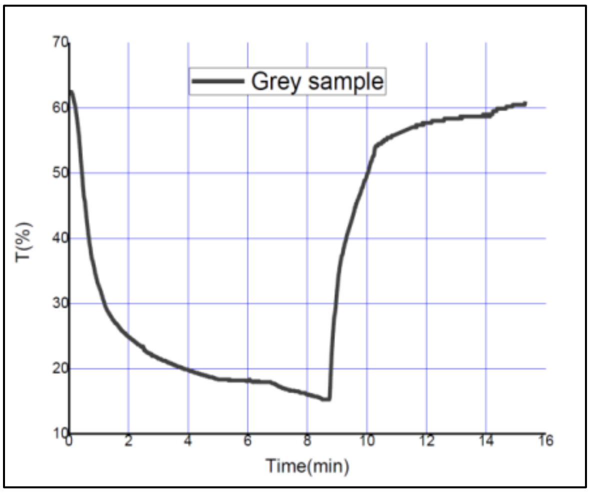

Figure 21 Manufacturer provided graph on Tvis during tinting and bleaching over time

Another thing to note is that the T_{vis} in the second tinted scenario on the 29th at 14:41 is stably lower than the other tinted scenario on the same day and the one the day before. However, this is a 0.02 difference, which could also be caused by measuring error. One more peculiarity is the behaviour of the indicator lights (positioned on the left side of the window) during the bleaching of the glass. The tinting process takes 4-5 minutes and only during this time do the indicator lights flash, which is the expected behaviour. During the bleaching process, however, the lights flash much longer, about 35 minutes. This happens consistently each bleaching process. It is possible that this long blinking time is related to the discrepancies observed in the T_{vis}, perhaps due to a defect in the system, or it could be by design of the manufacturer.

Another theory for the cause of the discrepancy is that the performance of the EC glass depends on temperature of the environment or the glass itself. To test this, the graph seen in Figure 22 was created. In this graph the room temperature and the interior and exterior window surface temperatures are plotted against the T_{vis} from August 29th. The graph does show a lower interior and exterior surface temperature during the period of the discrepancy, but it cannot be said with certainty whether there is a link here.

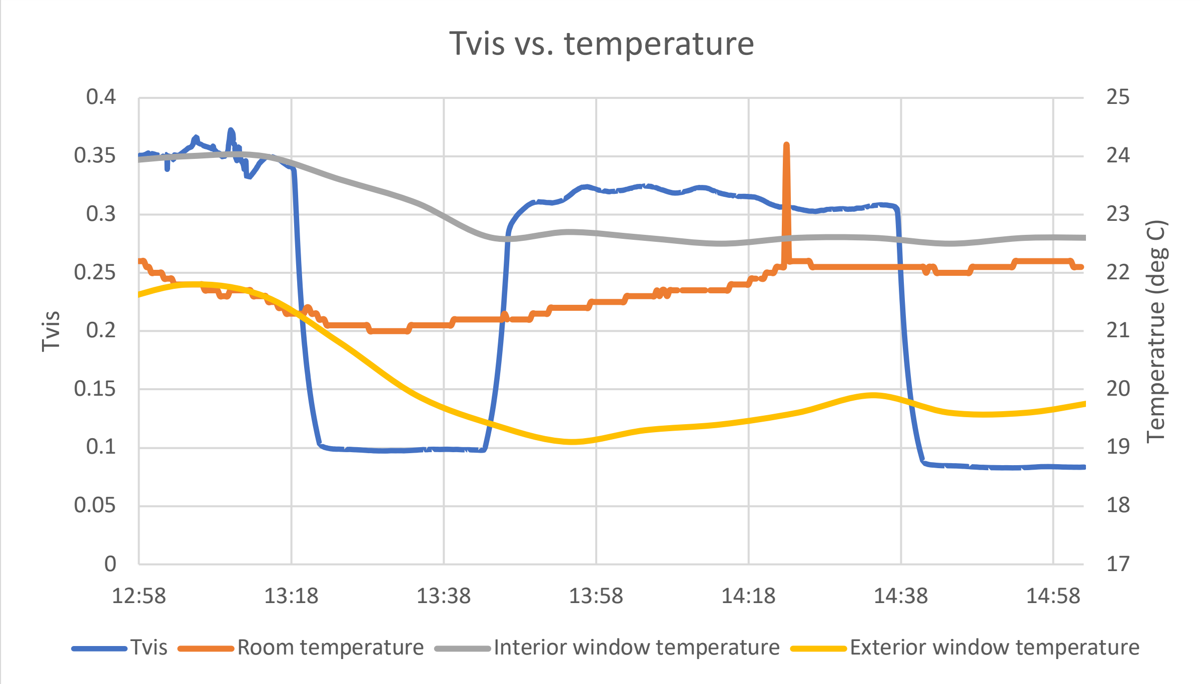

Figure 22 Tvis compared to room temperature, interior window temperature and exterior window temperature

The possible influence of the angle of incidence of sunlight on the windows was also considered. In Figure 23, the T_{vis} is plotted against the solar irradiation (as logged by the external pyranometer) and the solar irradiation scaled by the angle of incidence relative to the normal of the window. However, this graph does not show a clear correlation. In short, it cannot be determined with certainty where the peculiarities in the data come from, nor whether they fall within expectations. This would require additional research, which is out of scope for this project.

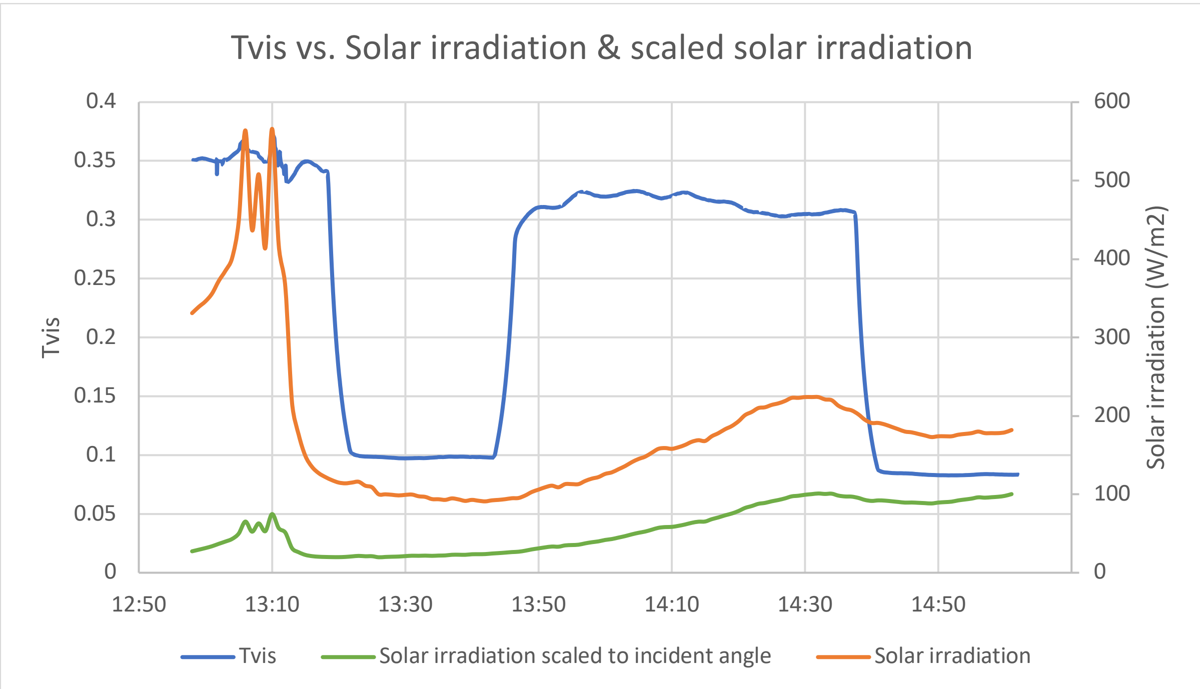

Figure 23 Tvis vs. Solar irradiation & scaled solar irradiation

For full disclosure, the T_{vis} of the normal glass was also measured, with and without shading active. This is presented in Figure 24. As expected, the pattern of the T_{vis} is stable, given that there are no factors that can influence the stable properties of the glass and shading as is the case with the EC glazing. The fluctuations visible in the graph are most likely due to measurement errors or local conditions such as shadow coverage. The average T_{vis} for the glass without shading is 67.8%. With shading, it is 3.5%. This is in line with the openness factor of 3% provided by the manufacturer.

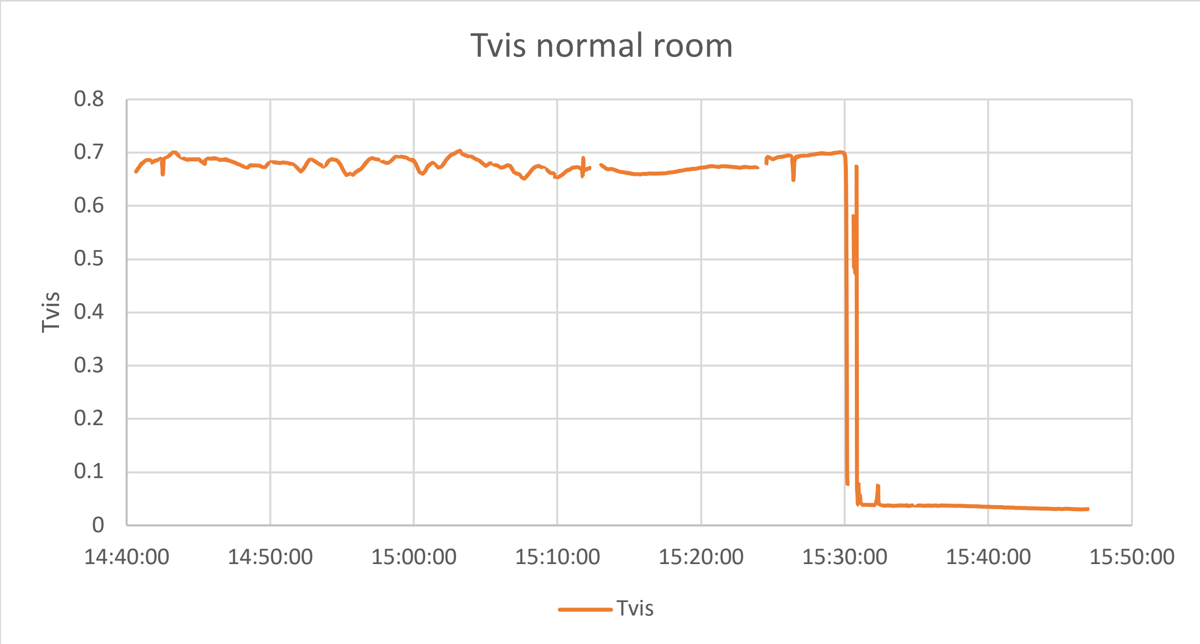

Figure 24 Tvis of the normal glazed room with roller shades

6.3 Colour

6.3.1 Setup

To assess the colour of the EC glass, an illuminance spectrophotometer (ISPM) is used to measure the correlated colour temperature (CCT), peak wavelength and colour rendering index (CRI). The model of the device used is a Konica Minolta CL-500A. The ISPM is placed close to the window facing outside with no obstructions in view (Figure 25). Measurements were made of the bleached glass, tinted glass and of daylight without glass in view.

Figure 25 Setup of the illuminance spectrophotometer

6.3.2 Results

At the time of writing, only a limited number of parameters are given by the manufacturer on the colour performance of the EC glass. The manufacturer has two versions of the EC glass: a blue and a grey version. Currently, the grey version is installed at the Office Lab in the Green Village, for which the manufacturer has provided these properties:

State of electrochromic device	*CIELAB parameters*	*Colour description*
Bleached	L=86.5, a=-6.5, b=13.3	Pale yellow
Tinted	L=36.7, a=-7.8, b=3.8	Grey

Translating the provided CIELAB values of the tinted grey glass to more intuitive RGB values gives R=75, G=90 and B=80, showing that the glass has more of a green, bluish hue, rather than true grey. In this window composition (EC + triple-pane) the slight shift towards green and blue in can also be seen on the spectral irradiance graph of Figure 26, where the peak moves from 535 nm in bleached state to 497 nm in tinted state. The shift towards colder colours in tinted state is also noticeable in the colour temperatures. The CCT for bleached glass is 5258 K which is slightly warmer than sunlight at 5406 K, while tinted glass is markedly colder at 6609 K. Finally, the CRI of these windows is 85.6% in bleached state and 81.5% in tinted state.

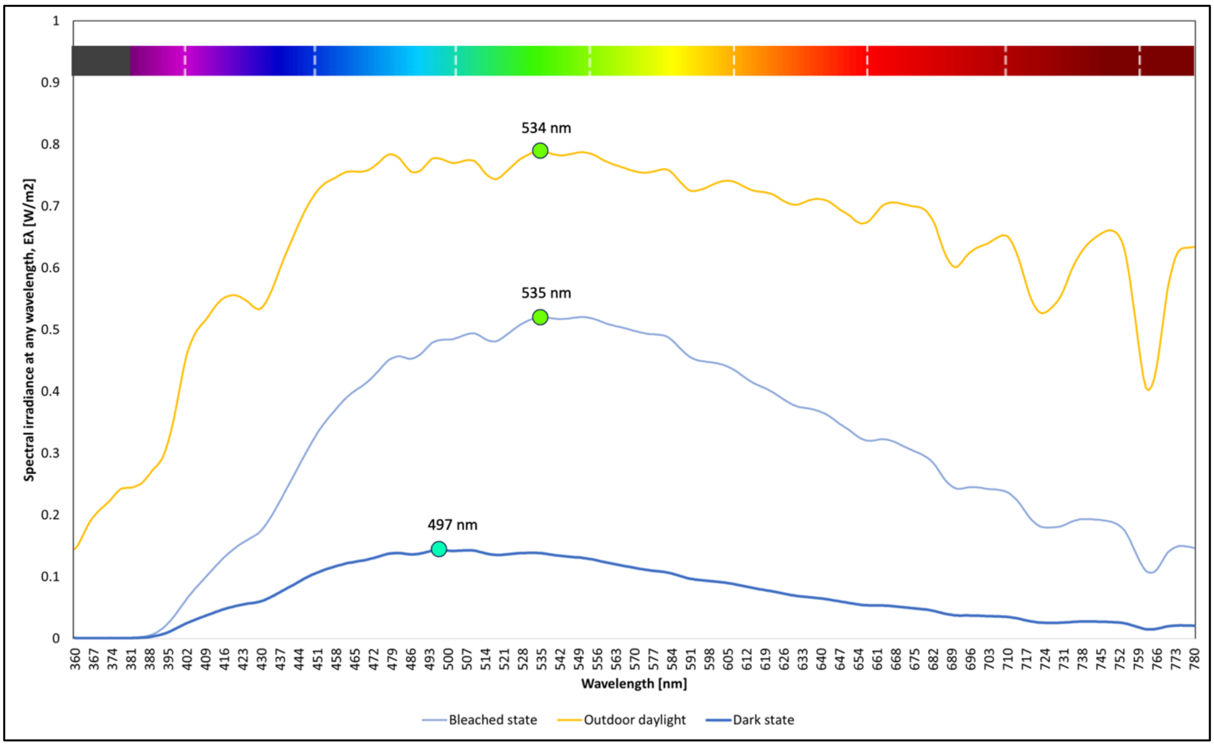

Figure 26 Spectral irradiance of outdoor daylight and EC glass in both states

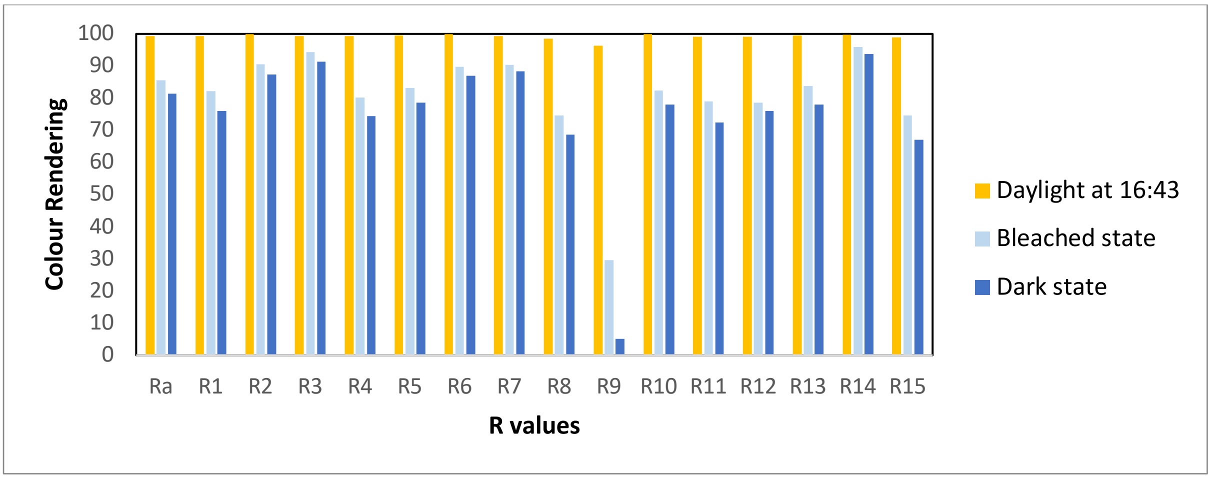

Figure 27 Colour rendering index of daylight and of the EC glass in bleached and dark state

7 Methodology of the experiment

7.1 General description

The experiment takes place in the Office Lab of the Green Village on the TUDelft campus during the months of December through March. Two almost identical meeting rooms are used in the Office Lab: Meeting room Blue with the EC panels installed on the windows, and meeting room Red with normal triple glazing and roller shades. The aim is to place volunteers in these rooms in a simulated office environment, while exposing them to ordinary use case scenarios of the façade shading. Participants' reactions are recorded via questionnaires, and are relativised to physical environmental measurements that take place during their stay.

In a session, volunteers are put in one of the meeting rooms for a certain period of time with the objective of performing work at a computer as they normally would in an office. During their stay in the rooms, they are exposed to different lighting and shading scenarios. At the end of each scenario, the volunteers are prompted to fill in a questionnaire containing queries regarding their opinions and experiences of the scenario under consideration. Volunteers are expected to answer each question fully and truthfully. However, they are told that they are allowed to skip any question if they don't want to. They are also told that they are allowed to leave the experiment at any time should they not want to participate anymore for whatever reason.

Only one session of the experiment takes place per day. All volunteers experience both rooms over the course of two sessions, meaning each participant has to visit the Office Lab twice. The time between these two sessions resolves possible biases or preferences volunteers may have about the rooms. The disadvantage of spreading over two days is that the weather and lighting situations may differ between days. Each volunteer's starting room is chosen randomly, again to balance potential bias participants might have. There are two workstation setups in each room and both rooms can be used simultaneously, for a maximum of four participants in each session. Only one session can occur per day as it is necessary to keep outdoor lighting conditions as a result of sun position as consistent as possible between sessions. Sessions therefore start and end at fixed times. These times were carefully chosen to accommodate the different scenarios.

While recruiting volunteers, they are in short explained what the experiment is about. Then upon expressed interest, they are asked to indicate their availability via a Google Form that lists available dates. The Google Form again briefly explains the experiment. A schedule is then created detailing when each volunteer is expected to visit The Green Village for their participation. To get a representative sample of the population, a wide range of people are asked to participate. The experiment falls under the umbrella of a larger ongoing research project by the TU Delft, Brite Solar Technologies, and the Green Village. Ethical approval was obtained from the TU Delft HREC (application number 3819) for this larger project including this experiment. Participants of the experiment are assigned a numerical ID code only they themselves and the researcher know, which is stored separately.

7.2 Floor plan

Figure 28 shows the floor plan for both meeting rooms during the experiment. The volunteers (orange triangles) are placed at a desk (grey rectangle) facing the south wall with the windows to their right. This position is chosen specifically as it is as close to the windows as possible and the sky and the sun are in the field of view. This is favourable for testing the glare metric. Each volunteer has their own workplace setup with a docking station, monitor, keyboard and mouse. Volunteers are placed approximately 1.2m and 3.2m from the window, close the north wall, with 0.8 – 1m of space between the north wall and the desk.

A tripod equipped with a Raspberry Pi with two Internet of Things illuminance sensors and a HOBO U12-012 data logger with air temperature, relative humidity, illuminance and black globe temperature sensor is positioned at the 'x' mark. One of the Raspberry Pi's IoT illuminance sensors is located at eye height of the volunteers, also facing the south wall. The other IoT illuminance sensor is placed on the desk at the 'o' mark, facing upwards. Ideally the sensors would be placed on the exact spot as the volunteers, but this is not possible the way this experiment is set up. The sensors are placed between the volunteers as this position is deemed as a reasonable middle ground for both. Using two equipment tripods per room is ruled out as this would increase workload, whereas one equipment tripod per room is sufficient.

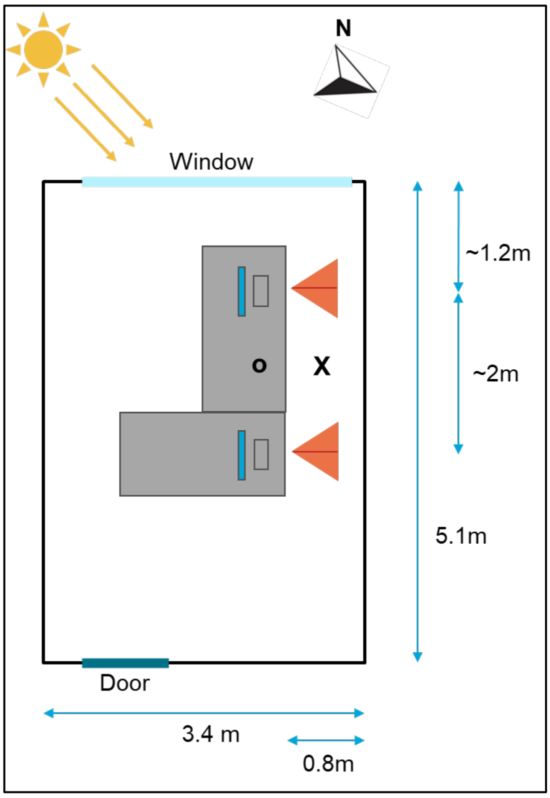

Figure 28 Floor plan for both meeting rooms

7.3 Equipment used

The equipment that is used during the live sessions of the experiment is as follows:

Raspberry Pi with two Internet of Things illuminance sensors (2x)
The Raspberries measure horizontal illuminance at desk level and vertical illuminance at eye level. The devices are mounted to photography tripods placed between the subjects.

HOBO U12-012 Temperature/Relative Humidity/Light/External Channel Data Logger (2x)
The HOBO loggers measure and store data of the air temperature, relative humidity and black globe temperature. The devices are mounted on the tripods as well. The black globe is mounted in such a way that the globe is at the average head height of the participants.

Thies Clima Pyranometer GSM 10.7 (3x)
Pyranometers measure solar irradiance in W/m2. Two are on the inside, one in each meeting room, mounted to the window frames. They face the window, and are about 5 cm away from it. The last one is outside, close to the EC window. All three are mounted at the same height.

Eltek GenII GS-44 data loggers
The data gathered by the pyranometers is recorded by these data loggers. They are placed inside the rooms in the vicinity of the pyranometers.

The table below summarises which instruments were used over the entire duration of the project, as well as how, where and when it was used.

Table 6 Summary of used measuring devices

Device brand and model name	How is the device used?	Where is the device placed?	When is the device used?
Canon EOS 80D with Sigma 4.5mm f/2.8 EX DC HSM Circular Fisheye lens	Creation of HDR photographs used for DGP calculation and estimation with vertical illuminance sensors	At the same position and direction as the volunteer in the workspace closest to the window	Over the course of several days, before the live experiment (chapter 6.1)
Konica Minolta LS-150 handheld spot luminance meter	Spot luminance calibration of HDR photographs	Held in hand	Over the course of several days, before the live experiment (chapter 6.1)
Konica Minolta CL-500A illuminance spectrophotometer	Characterisation of the colour properties of the EC windows	Close to the EC window, facing it	Once, before the live experiment (chapter 6.3)
Raspberry Pi with two IoT illuminance sensors (2x)	1) Characterisation of the transmittance properties of the EC windows 2) Measuring and logging work plane illuminance and vertical illuminance at eye level	1) One sensor attached to the window exterior and the other attached to the interior, both facing outdoors 2) One on the desk, facing upwards and the other at volunteer eye level, facing the room	1) Once before the live experiment (chapter 6.2) 2) Continuously during live experiment sessions

HOBO U12-012 Temperature/Relative Humidity/Light/External Channel Data Logger (2x)	Measuring and logging air temperature, relative humidity and black globe temperature	Attached to a tripod between volunteers, with the black globe sensor mounted at volunteer head level (both rooms)	Continuously during live experiment sessions
Thies Clima Pyranometer GSM 10.7 (3x)	Measuring solar irradiance	Inside close to the window facing outside, mounted to the window frame (both rooms) and outside at the same height in front of the window (only in front of the EC room)	Continuously
Eltek GenII GS-44 data loggers	Logging pyranometer data	In the meeting rooms (position is irrelevant)	Continuously
Generic 21 inch 1080p computer monitor, with keyboard, mouse and USB-c docking station (4x)	Workstation setup for volunteers	On the desks in the meeting rooms	Continuously during live experiment sessions

Figure 29 Pyranometers in the EC room behind the window (pink) and outside in front of the window (orange)

7.4 Questionnaire

The questionnaire consists of five parts: the general questions, part A, B and C, and finally the concluding questions. The full questionnaire can be found in Appendix B. It was created and stored digitally in Qualtrics (Qualtrics.com). During the experiment volunteers access the questionnaire either via scanning a QR code or by typing the link into their web browser, whichever they prefer. The general questions capture various characteristics of the volunteer. In this section the volunteer fills in their participant ID and answers questions about which age group they are part of, if they currently use any corrective eye measures, if they are colourblind, and their level of clothing at the moment.

Part A, B and C are the same in terms of content. Each part is divided into three categories. The first category contains questions regarding the current state of the shading and if the participant wishes to change the state of the shading. If answered yes, the participant can state multiple reasons why they would want to.

The second and third categories are about thermal and visual comfort respectively. Participants respond almost exclusively by means of 3, 4, 5 and 7-point Likert scales. The thermal comfort category contains questions regarding the participant's current temperature sensation, their preference of temperature relative to their current sensation, if they feel heat from the sun through the façade, and if they are satisfied with the solar heat they are feeling.

The visual comfort category consists of questions regarding the adequacy of the amount of electric and daylight combined, the adequacy of exclusively the amount of daylight, and if they are satisfied with the amount of daylight. It also includes questions regarding their satisfaction with the colour of the daylight through the façade and the clarity of the view through the façade. Lastly, this category includes questions regarding sensation of different levels of glare and what those possible glare sources are according to them.

The last part of the questionnaire is related to functional aspects of the façade. It contains questions regarding the participant's satisfaction with the sound of the AC unit (if it turned on at any point during the experiment), satisfaction with the sound of the shading device while it transitions, and lastly their satisfaction with the transition speed of the shading device.

7.5 Scenarios & timeline

As mentioned in section 5.2, the experiment consists of three different scenarios in two rooms. All scenarios depend on the position of the sun relative to the sight lines of the volunteers. In scenario A, the sun is not in the field of view and the sun shading is not used. In scenario B, the sun has entered the field of view and the shading is enabled. In scenario C, the sun is still in the field of view but the shading is turned off. The scenarios are descriptively the same for both rooms, albeit with different shading options in practice. Figure 30 shows a brief explanation of each scenario and where it is positioned on the timeline.

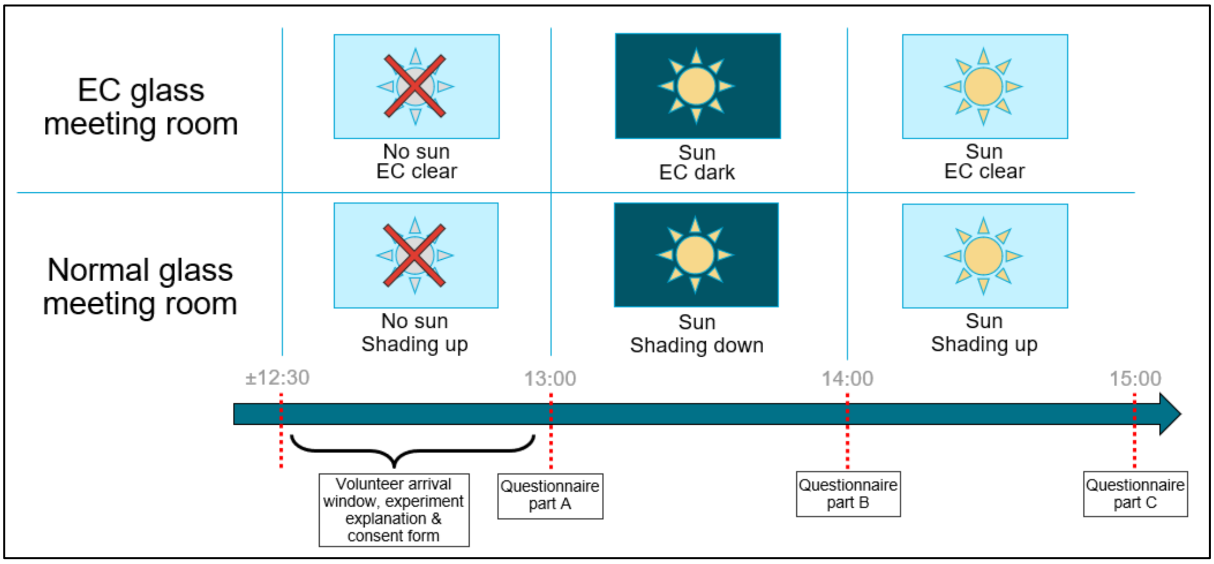

Figure 30 Experiment scenarios and timeline

1. Before each session, all equipment is set up. Desks and chairs are put in place, the workstation setups are installed and the measuring equipment and data loggers are placed and activated.

2. As the scenarios are dependent on the position of the sun, each session starts and ends at similar times. The walk-in of the session starts at 12:30 after which the volunteer promptly takes a seat in one of the available positions in the rooms. This is scenario A: the shading is disabled and the sun is not yet in the field of view. The volunteer acclimates to the room while the experiment is briefed to them. The volunteer is also asked to fill in a consent form (Appendix C). In addition, they are assigned a randomly generated participant ID, which they are required to use for both of their sessions. After that, the volunteer can immediately start working on their task. Around 13:00, the volunteer is prompted to fill in the general questions and part A of the questionnaire.

3. Once the general questions and part A are completed, the shading is enabled. This is the start of scenario B, around 13:10. This is also roughly the time when the sun comes into the field of view. The volunteers work on their tasks until 14:00, after which they are prompted to complete Part B of the questionnaire.

4. When part B is completed, the shading is disabled. This is the start of scenario C, at around 14:10. The volunteers continue their tasks until 15:00, after which they are requested to complete Part C and the final questions. At the end of the session, the sun is relatively low on the horizon. As a reference, on the shortest day of the year, December 22nd, the sun sets at 16:27.

5. Lastly, data from the loggers is extracted, equipment is turned off and the workstation setups are returned to storage.

There is a fourth scenario that is not used in the current design of the experiment, scenario D. The three chosen scenarios were so for a number of practical reasons. In scenario D, the sun is not in the field of view and the shading is enabled. The aim of the experiment is to mimic an actual office situation as accurately as possible. Compared to the other three scenarios, scenario D is probably less likely to occur in practice, which is why it was left out. In addition, the execution of the experiment is more streamlined, as less work needs to be done each session and volunteers do not have to be present for as long.

The order in which volunteers are presented with the scenarios is also of importance. Firstly, scenario A can only take place at the beginning of the session because the sun is not yet in the field of view. Secondly, dark scenario B is sandwiched between two light scenarios to emphasize the difference between scenarios. For a light-dark-light timeline, it is interesting to compare the light scenarios to see whether opinions stay the same. In a light-light-dark timeline, the difference between the light scenarios may develop too gradually to see a clear difference.

8 Results

In this chapter, the results of the experiment are presented. Graphs have been made of the data from each question in the questionnaire and every sensor mentioned in chapter 7.3. First, in chapter 8.1, the general results are presented discussing the distribution of volunteers, data entries and weather, as well as the general questions of the questionnaire. Then in chapter 8.2, the data gathered by the sensors is presented. Afterwards, the results of the questionnaire are presented in chapter 8.3, as well as the statistical analysis of these results. Finally in chapter 8.4 the challenges and difficulties that were encountered during the experiment are discussed. Interpretation and discussion of the data is provided in chapter 9.

8.1 General results

As many people as possible were invited to take part in the experiment, and over the course of ±3 months a total of 38 volunteers have participated. Almost all subjects experienced both rooms and completed three questionnaires per room. Two participants were only able to partake in one of the two sessions, meaning there were a total of 74 individual sessions generating 222 responses for the main part of the questionnaire. For 165 responses the weather was overcast, for 37 it was partly overcast and for the remaining 20 it was clear.

By far the largest age group were the 25- to 40-year-olds, with 27 people. They were followed by the 40- to 60-year-olds with 5 people, and finally the below-25 and above-60 groups with 3 people each (Figure 31). Most individuals did not use eye-correction, though it was not uncommon. People used glasses for 19 sessions, contact lenses for 8 sessions, and people did not use any eye correction for 47 sessions (Figure 32). Lastly, for most of the sessions people were dressed for winter weather as they wore trousers, a t-shirt or long-sleeve shirt plus a long-sleeve sweater for 37 sessions. The next most popular combination was trousers, a t-shirt and a long-sleeve shirt for 14 sessions, followed by 12 sessions by the same combo minus the t-shirt. The full distribution of worn clothing combinations is presented in Figure 34. The full list of answers that volunteers were able to choose from can be seen in Appendix B, question 6.

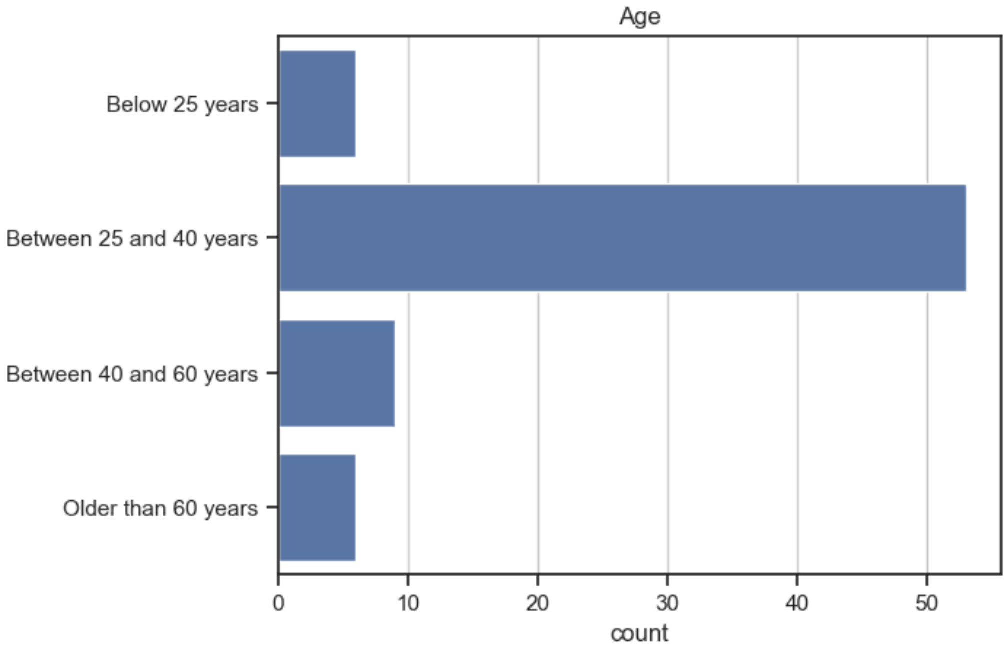

Figure 31 Age distribution of participants

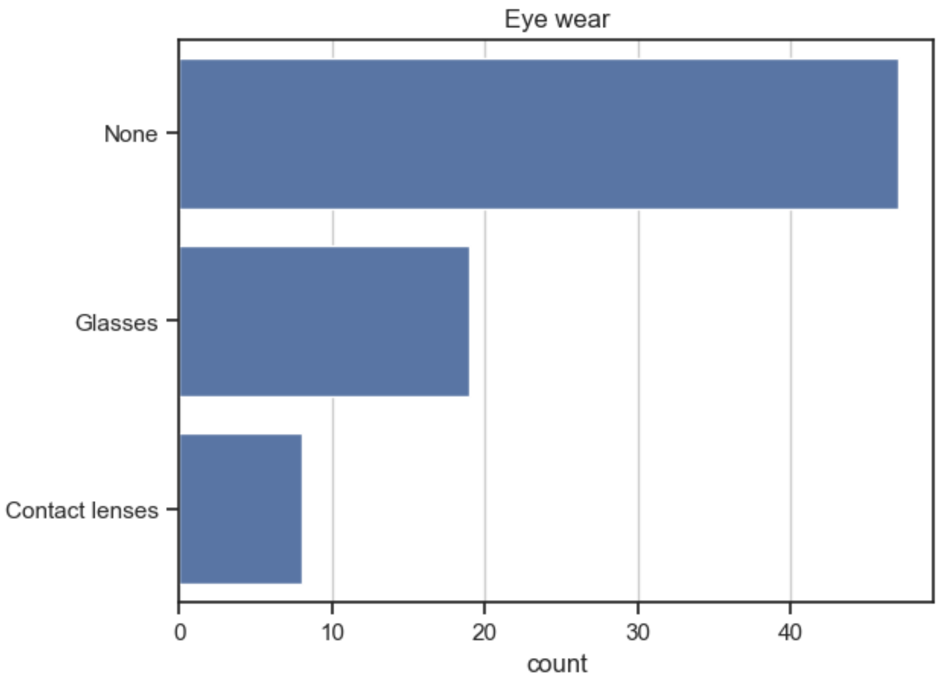

Figure 32 Eyewear used by participants

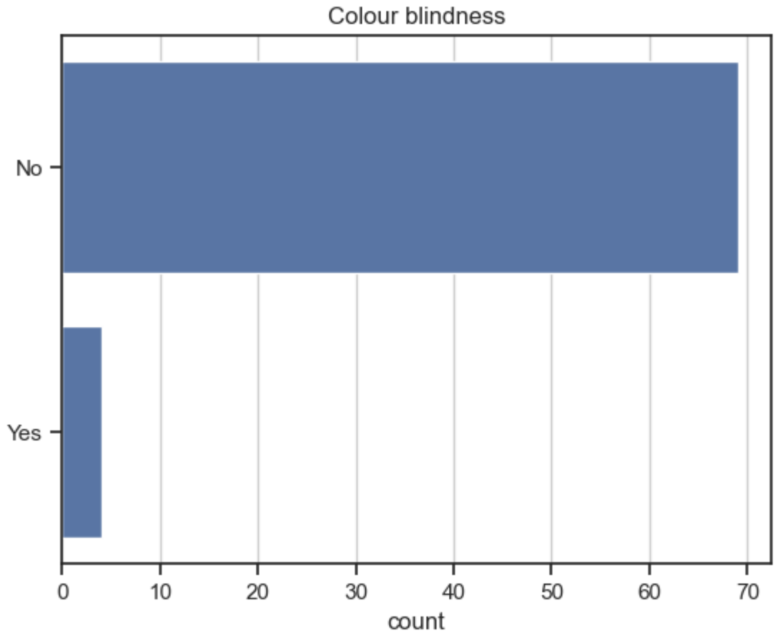

Figure 33 Colour blindness among participants

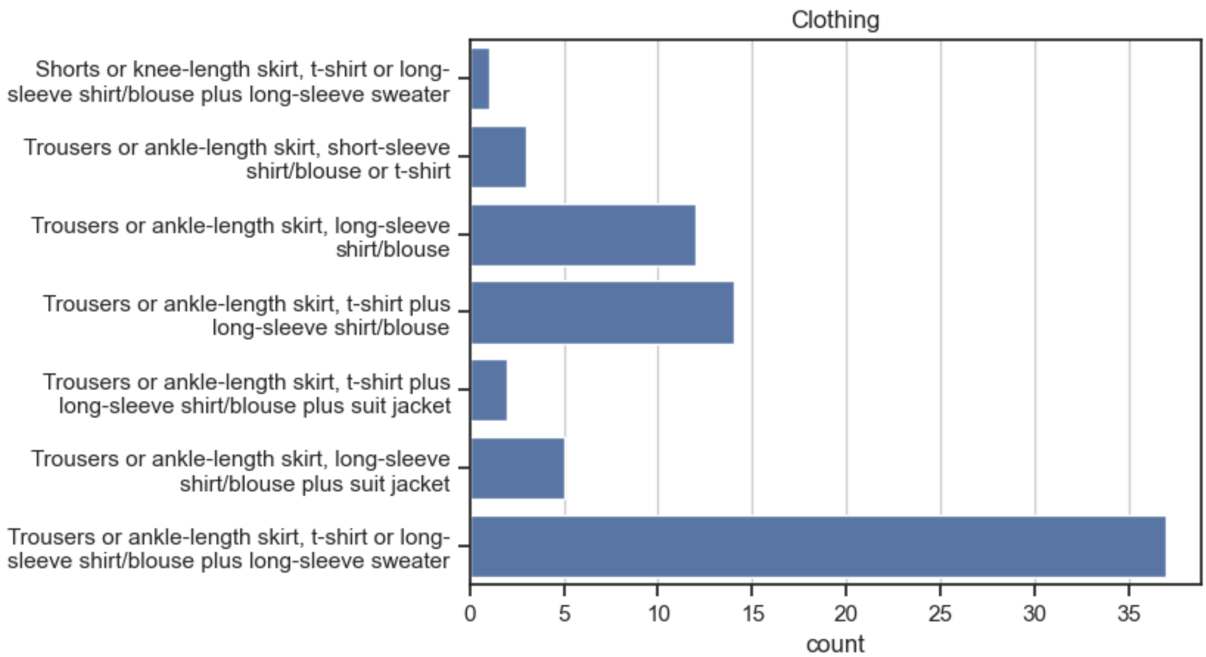

Figure 34 Clothing worn by participants

8.2 Sensor results

From the equipment mentioned in chapter 7.3, a total of eight different metrics were collected. These are:

- Dry bulb air temperature;
- Black globe temperature;
- Operative temperature;
- Relative humidity;
- Horizontal illuminance at desk level;
- Vertical illuminance at eye level;
- Indoor solar irradiance;
- Outdoor solar irradiance.

Boxplots were created of each metric, as shown in Figure 35 through Figure 42. In each graph the data is visualized per scenario. The icons on the x-axis represent scenarios A, B and C from left to right. Within each scenario, the data is partitioned by room. Outliers are marked with "x". Each data point is an average of the measured values for a volunteer in a scenario for the metric in question. Since 222 usable sessions were conducted during the experiment, there would ideally be 222 data points for each sensor graph as well. For some graphs, however, there are fewer data points due to equipment failure. This is discussed in chapter 8.4. The title of each graph shows the number of data points. This sub-chapter only aims to present the data in the form of graphs to the reader. The graphs are described, interpreted and discussed in chapter 9.

The data points in the sensor graphs are calculated by taking the average over a time span of 30 minutes. For example: A volunteer opens part A of the questionnaire at 13:12. The air temperature corresponding to this volunteer in this scenario is then the average of the air temperature from 12:52 to 13:22. Thus, this time span runs from 20 minutes before to 10 minutes after opening the relevant part of the questionnaire. This rule applies to each data point of each sensor graph. This time span was specifically chosen because the questions posed in the questionnaire are concerned with how volunteers feel at that specific moment in time. By processing and presenting the data this way, the data points represent a period of data that is most relevant.

Note: The boxplot of the outdoor solar irradiance shows boxes for the EC room and for the normal room. However, there is only one outdoor pyranometer. The data this pyranometer gathers is used for both rooms. The rooms have dissimilar data due to the fact that at times only one room was in use during the experiment.

8.2.1 Sensor graphs

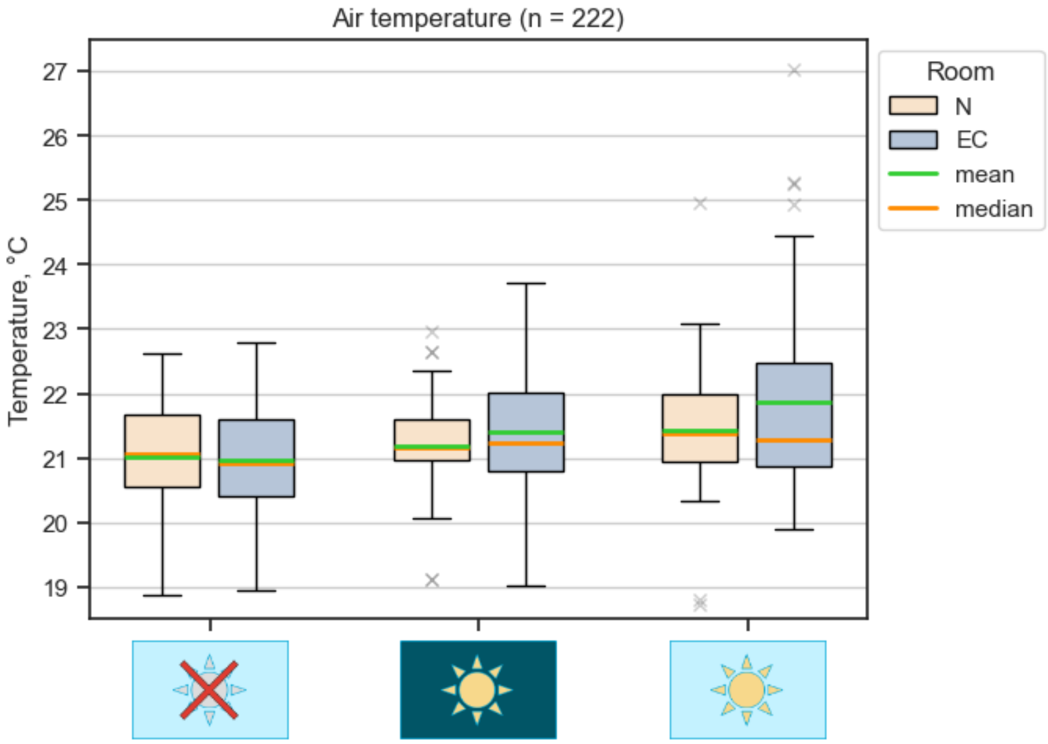

Figure 35 Dry bulb air temperature

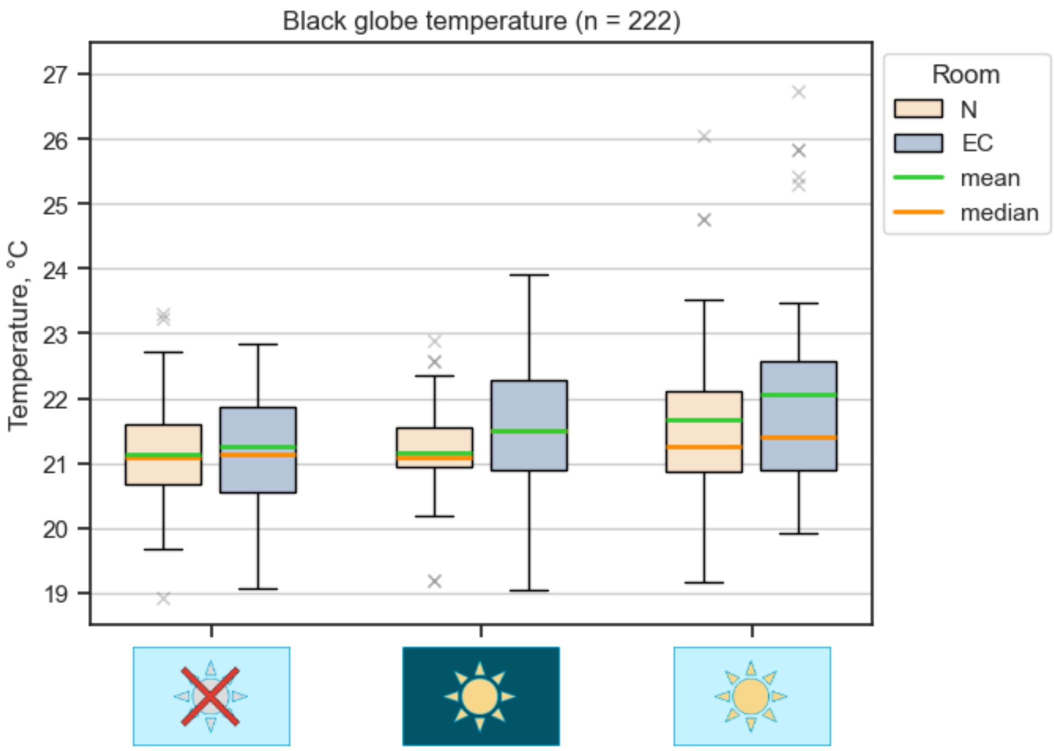

Figure 36 Black globe temperature

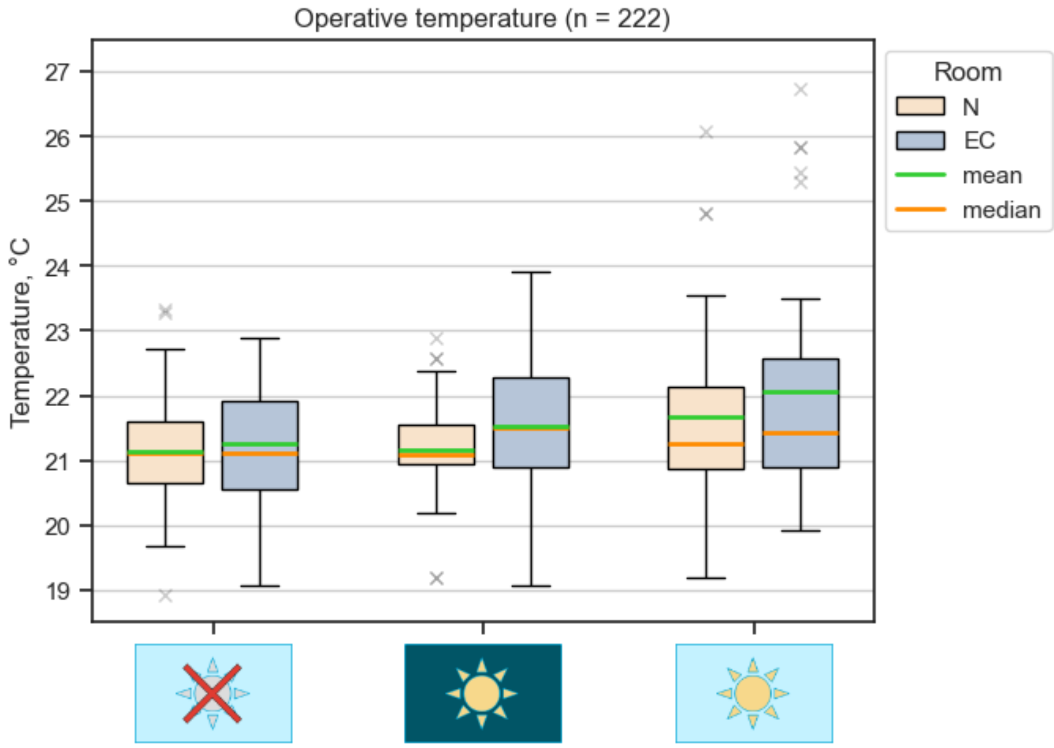

Figure 37 Operative temperature

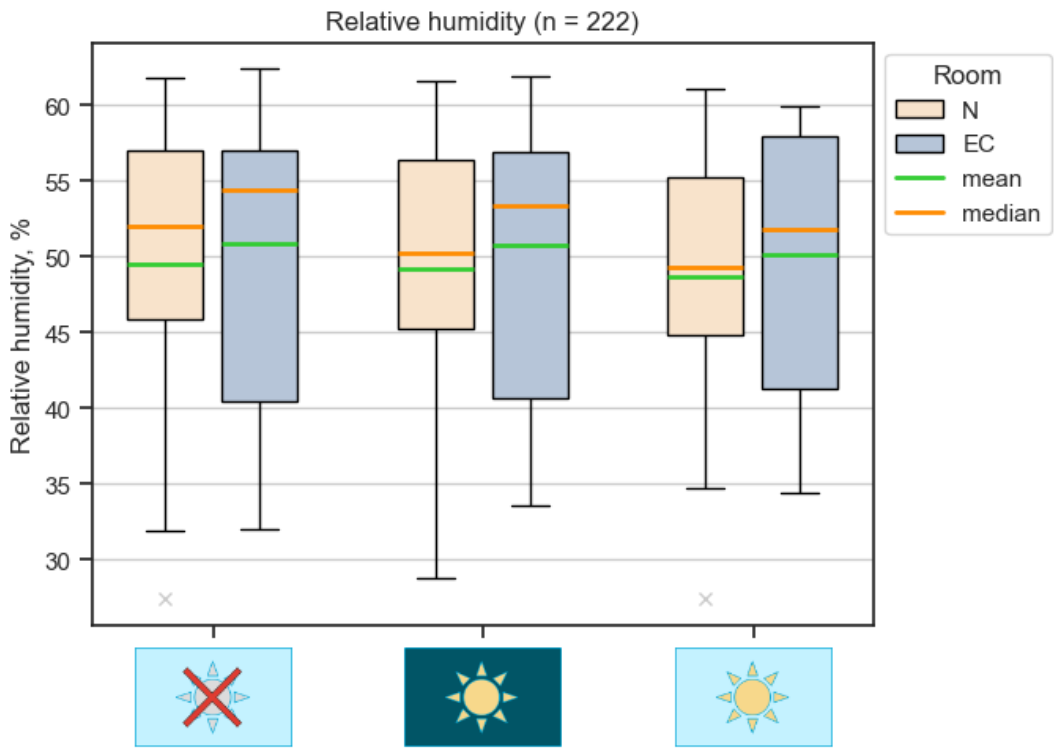

Figure 38 Relative humidity

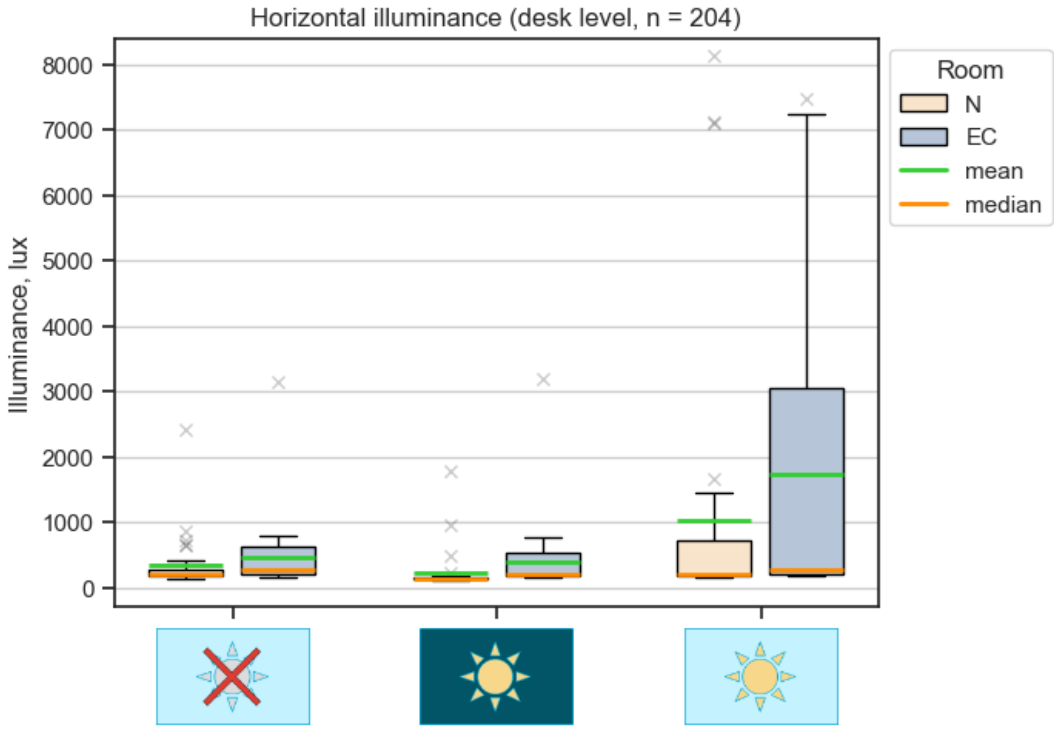

Figure 39 Horizontal illuminance

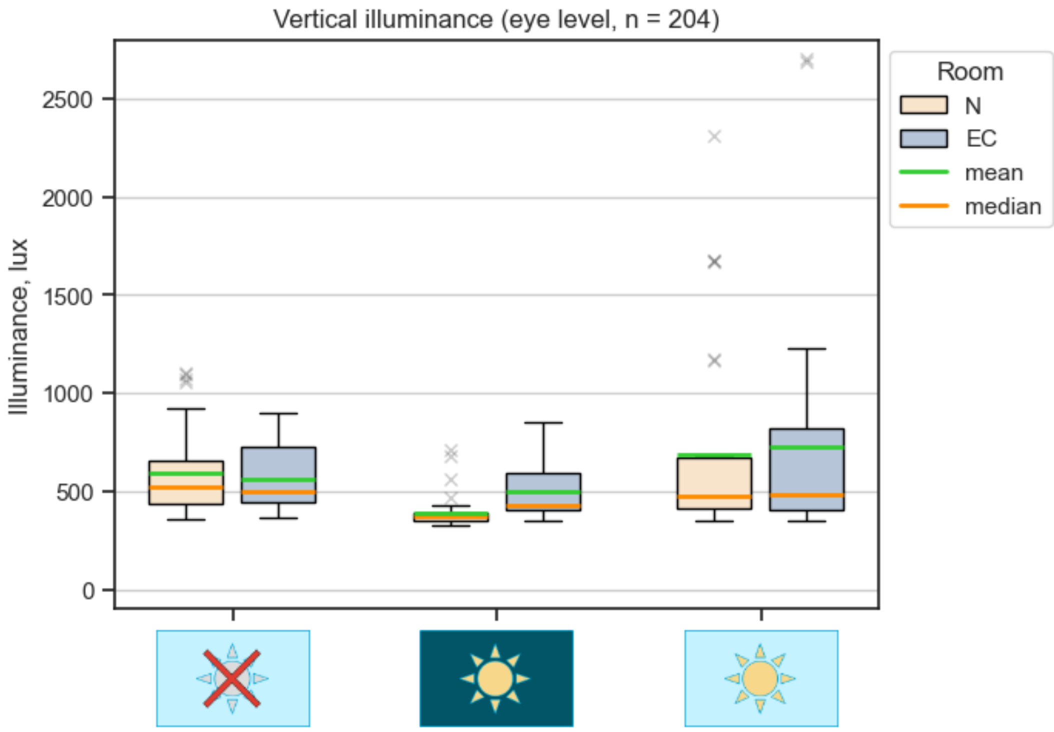

Figure 40 Vertical illuminance

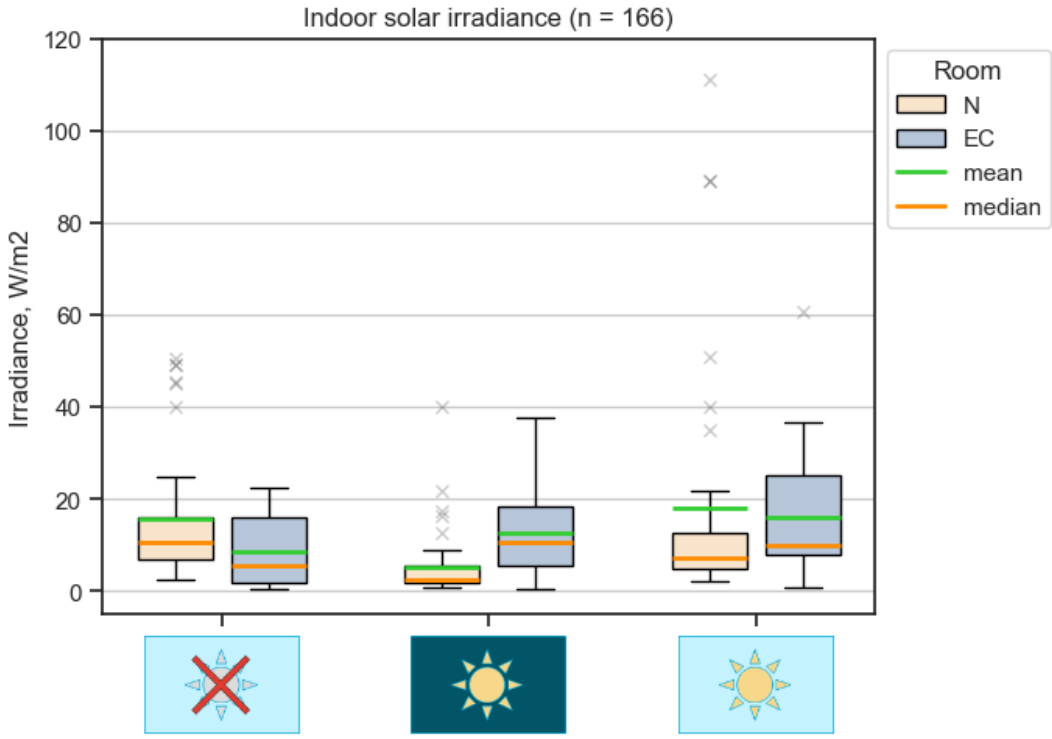

Figure 41 Indoor solar irradiance

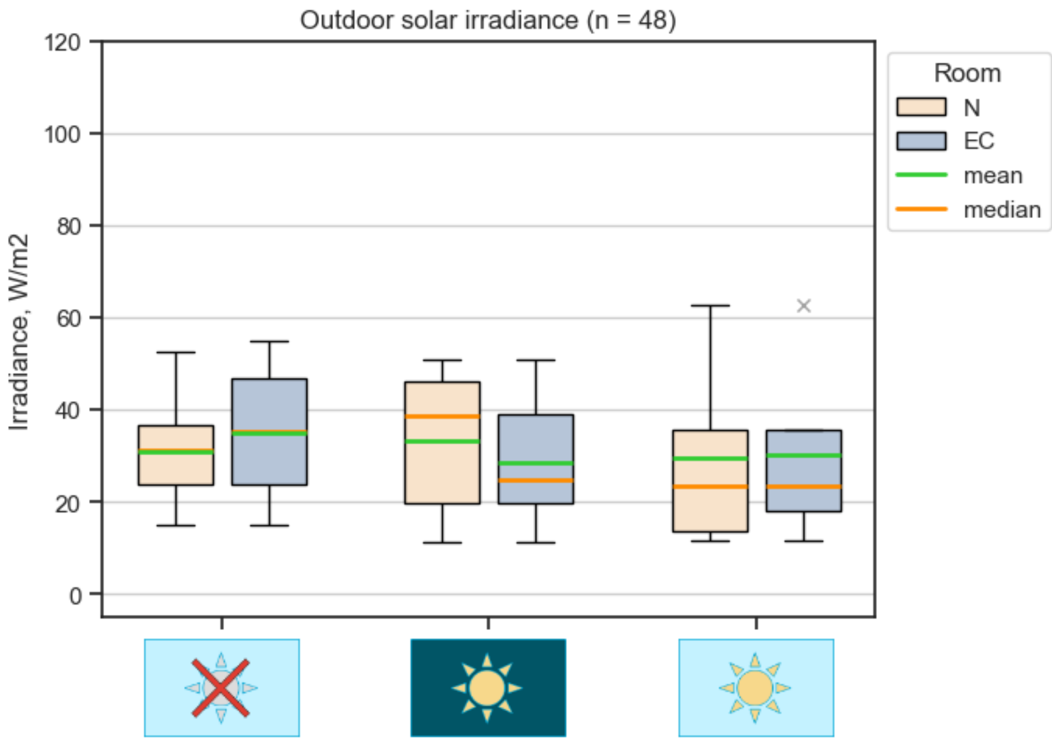

Figure 42 Outdoor solar irradiance

8.3 Questionnaire results

The main part of the questionnaire (parts A, B and C) consists of ten Likert scale questions repeated for each scenario. Table 7 summarises these questions together with their domain, topic, and possible answers given by the volunteers. Similar to the sensor data, boxplots were created for each metric, showing the results of this part of the questionnaire. These graphs are presented in chapter 8.3.1 and 8.3.2. The graphs for the questionnaire data have a similar format to the graphs for the sensors: In each graph the data is visualized per scenario. The icons on the x-axis represent scenarios A, B and C from left to right. Within each scenario, the data is partitioned by room. Outliers are marked with an orange "☐". Each data point is a single response by a volunteer. Darker orange boxes represent multiple datapoints on one spot.

Additions to these graphs are the significance indicators of the data between scenarios and rooms. This is explained in chapter 8.3.4. Levels of significance are displayed as "*" for p <= 0.05, "**" for p <= 0.01, and "***" for p <= 0.001. Boxplots of the final questions are presented in chapter 8.3.3.

The order in which the graphs are presented is the same as the order in which the topics and questions are presented in Table 7. This sub-chapter only aims to present the data in the form of graphs to the reader. The graphs are described, interpreted and discussed in chapter 9.

Table 7 Questionnaire main part Likert scale questions

Domain	*Topic*	*Question*	*Possible answers*
Thermal	Temperature sensation	"At present I feel…"	1. Much too cold 2. Too cold 3. Comfortably cool 4. Comfortable 5. Comfortably warm 6. Too warm 7. Much too warm
	Temperature preference	"I would prefer to be…"	1. Much cooler 2. A bit cooler 3. No change 4. A bit warmer 5. Much warmer
	Solar heat sensation	"At present I feel…"	1. No heat from the sun through the façade 2. A bit of heat from the sun through the façade 3. Much heat from the sun through the facade
	Solar heat satisfaction	"Regarding the amount of incoming heat through the façade, I am…"	1. Very unsatisfied 2. Slightly unsatisfied 3. Neutral 4. Slightly satisfied 5. Very satisfied

Visual	Light sufficiency	"Regarding the amount of light (daylight and electric light) to perform my task in the room, at present I feel the room is…"	1. Very dark 2. Dark 3. Slightly dark 4. Adequate amount of light 5. Slightly bright 6. Bright 7. Very bright
	Daylight sufficiency	"Regarding the amount of daylight to perform my task in the room, at present I feel the room is…"	1. Very dark 2. Dark 3. Slightly dark 4. Adequate amount of light 5. Slightly bright 6. Bright 7. Very bright
	Daylight satisfaction	"Regarding the amount of daylight entering the room, at present I am…"	1. Very unsatisfied 2. Slightly unsatisfied 3. Neutral 4. Slightly satisfied 5. Very satisfied
	Daylight colour satisfaction	"Regarding the colour of the daylight through the window, at present I am…"	1. Very unsatisfied 2. Slightly unsatisfied 3. Neutral 4. Slightly satisfied 5. Very satisfied
	View clarity satisfaction	"With regards to the clarity of the view to the outside, at present I am…"	1. Very unsatisfied 2. Slightly unsatisfied 3. Neutral 4. Slightly satisfied 5. Very satisfied
	Glare sensation	"At present I feel a level of glare which is…"	1. Imperceptible (I do not feel any discomfort, I could work under these conditions for any period of time) 2. Noticeable (I could work for approximately one day under these conditions, but it would bother me to work under these conditions every day) 3. Disturbing (I could tolerate these conditions for 15 to 30 minutes, but would require a change in the conditions for any longer period of time) 4. Intolerable (I could not tolerate working in these conditions)

8.3.1 Main questions graphs – thermal domain

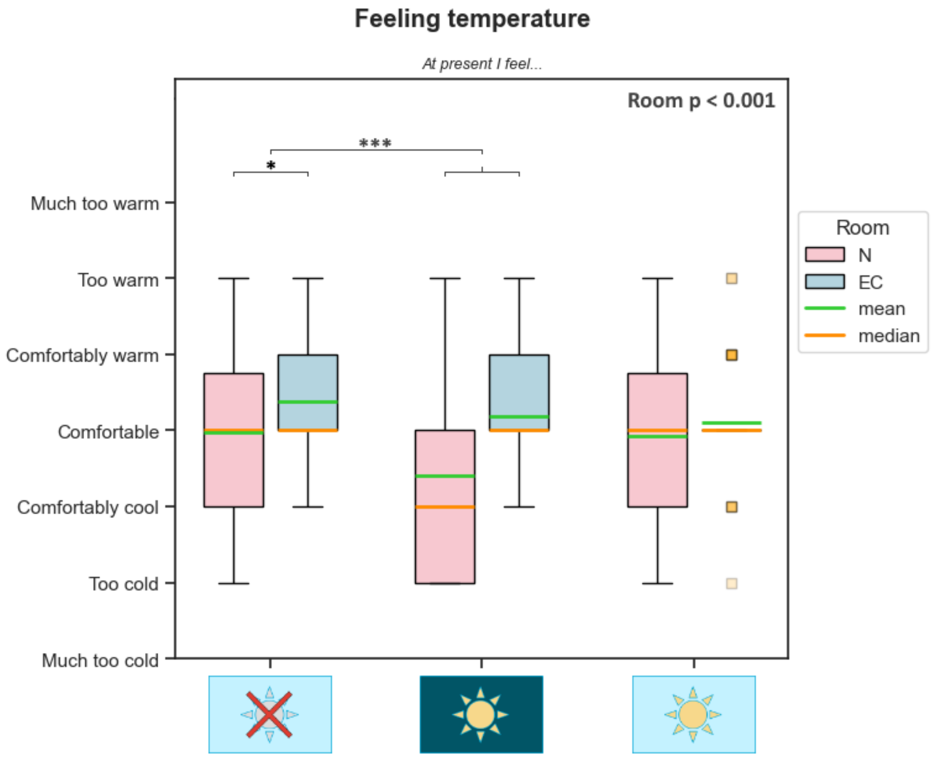

Figure 43 Temperature sensation

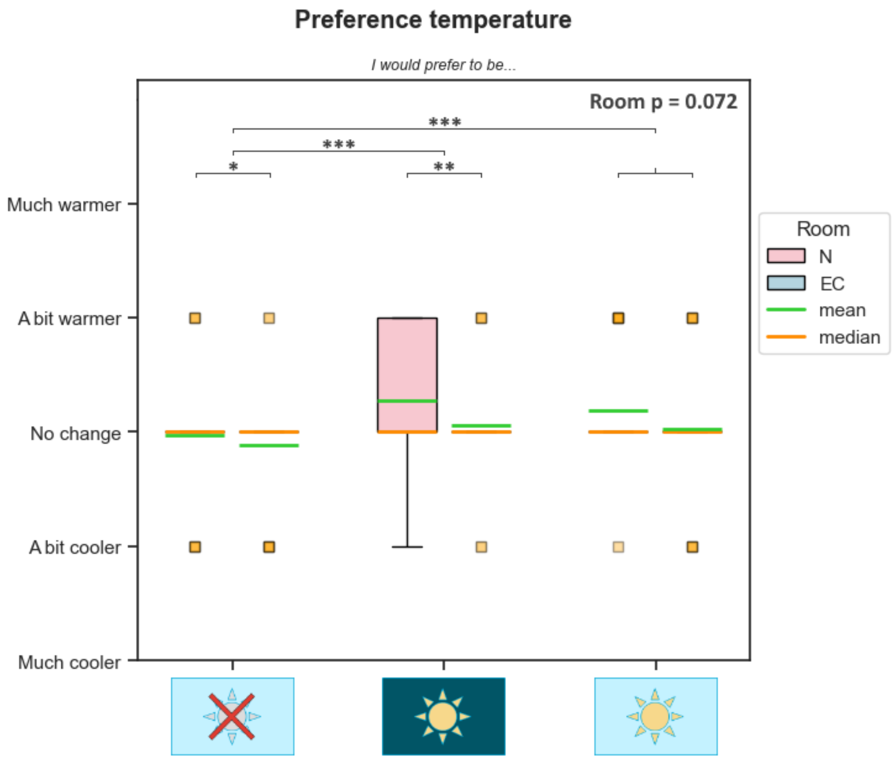

Figure 44 Temperature preference

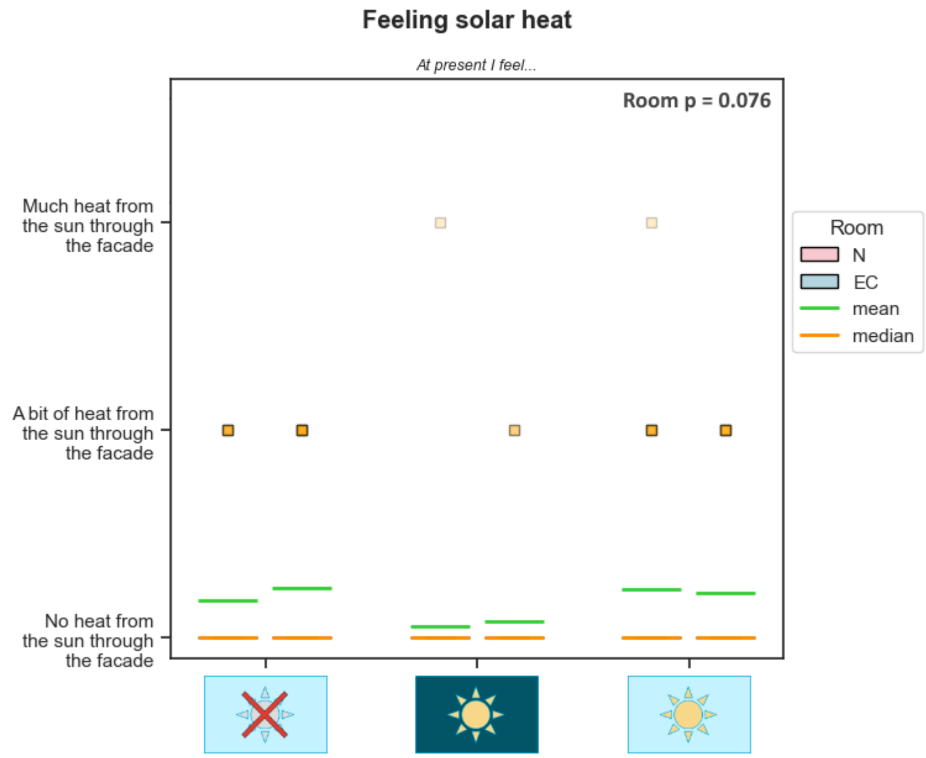

Figure 45 Solar heat sensation

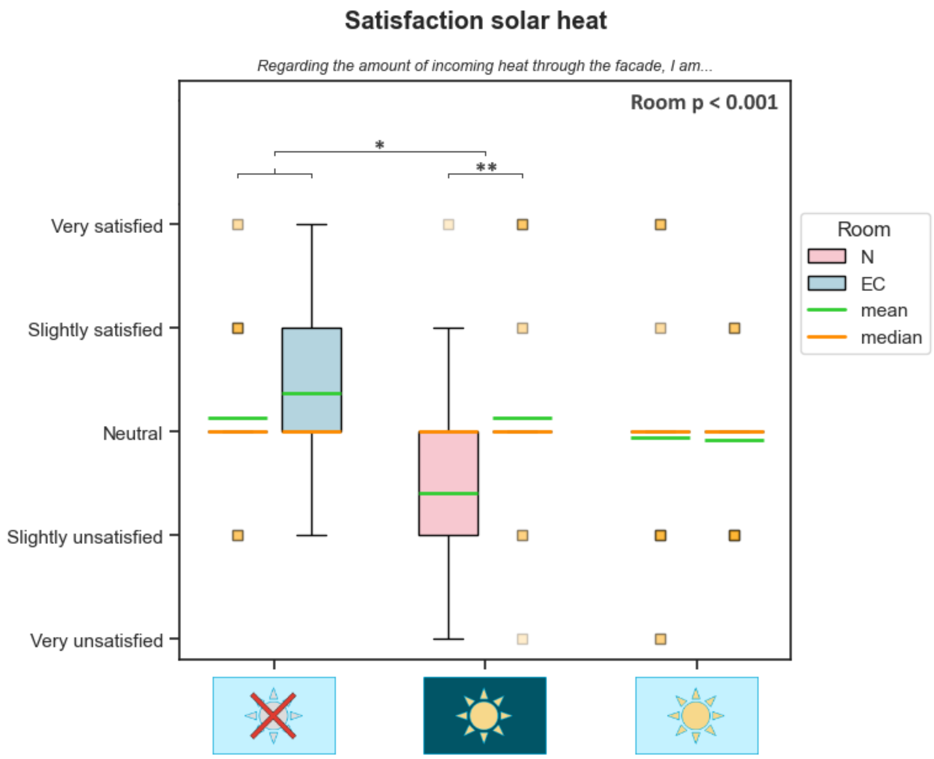

Figure 46 Solar heat satisfaction

8.3.2 Main questions graphs – visual domain

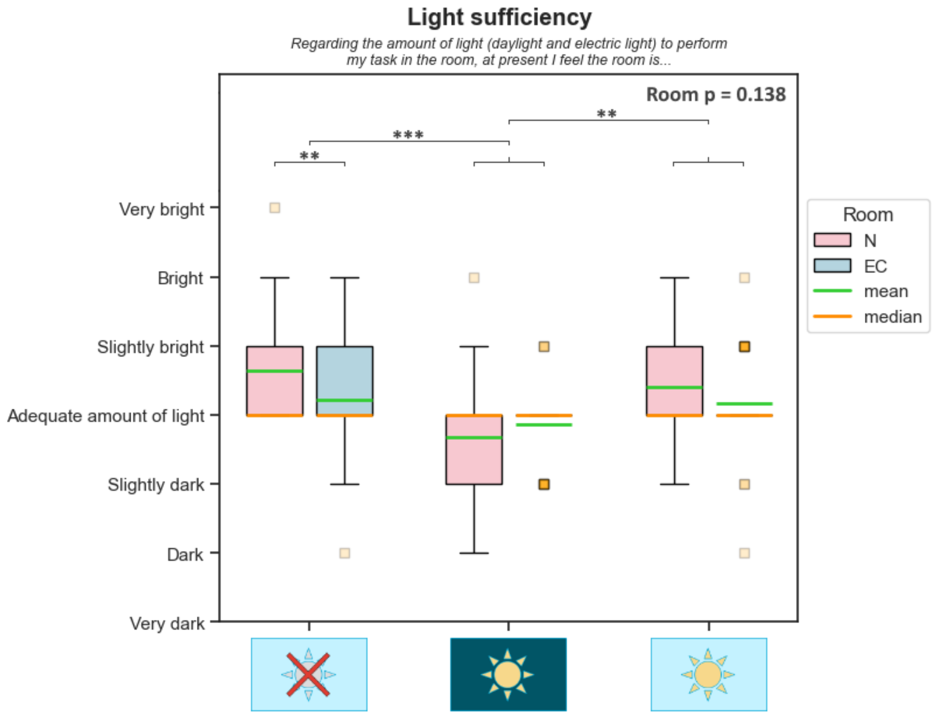

Figure 47 Light sufficiency

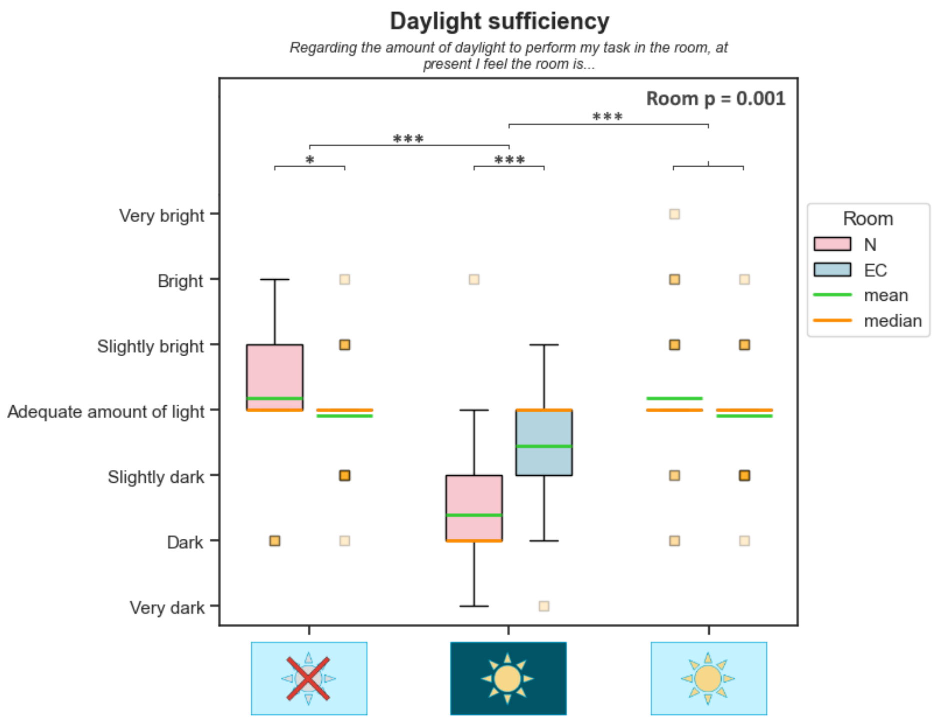

Figure 48 Daylight sufficiency

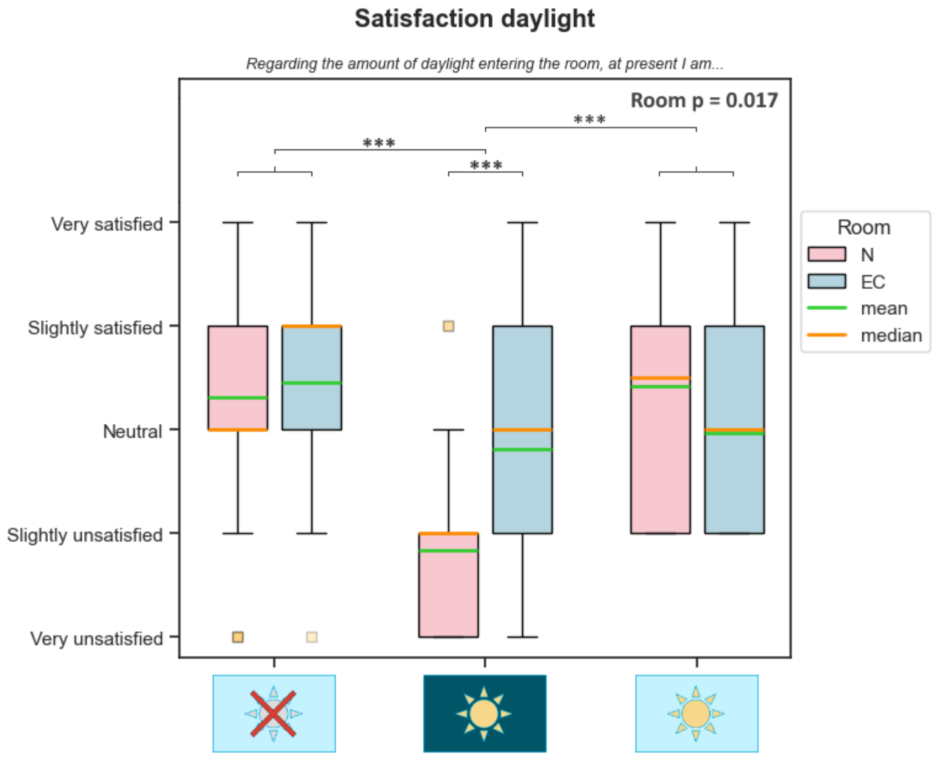

Figure 49 Daylight satisfaction

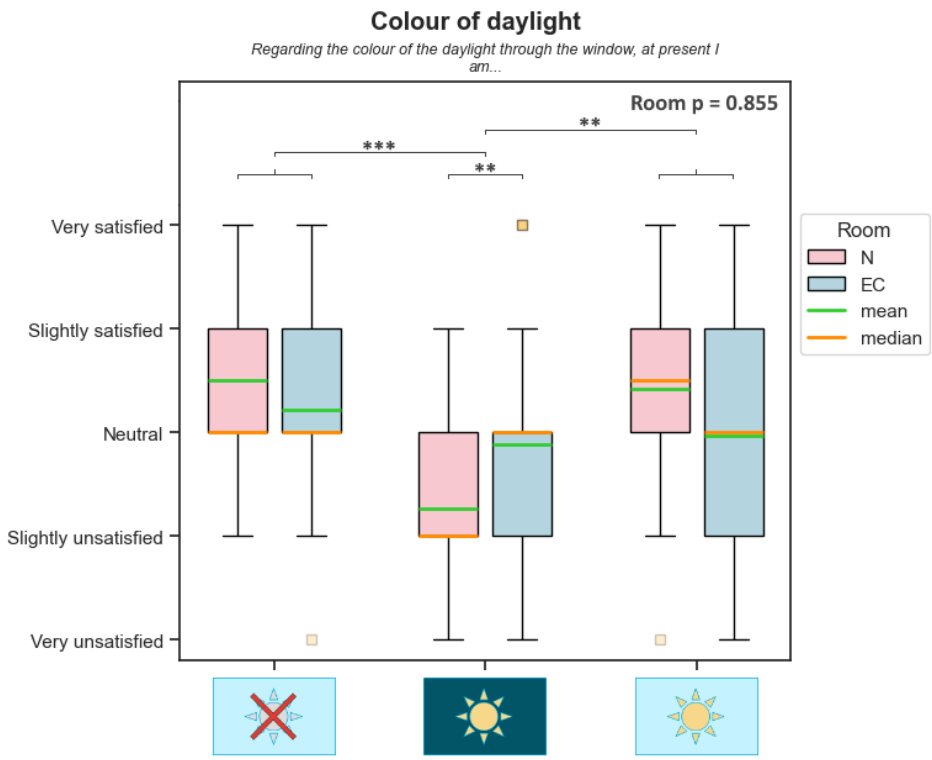

Figure 50 Daylight colour satisfaction

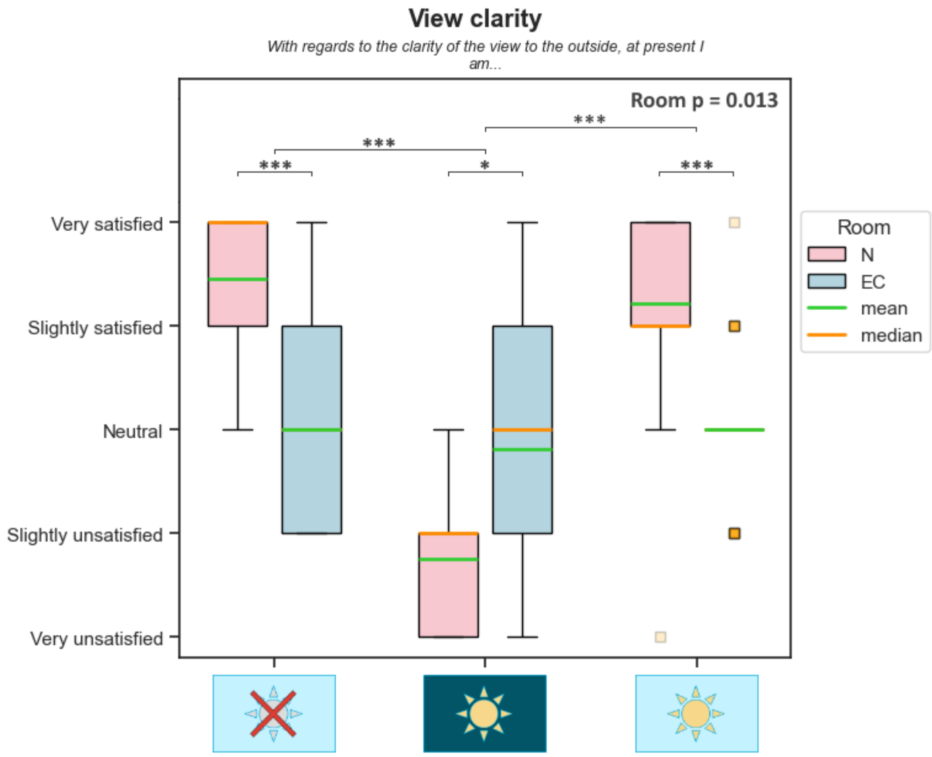

Figure 51 View clarity satisfaction

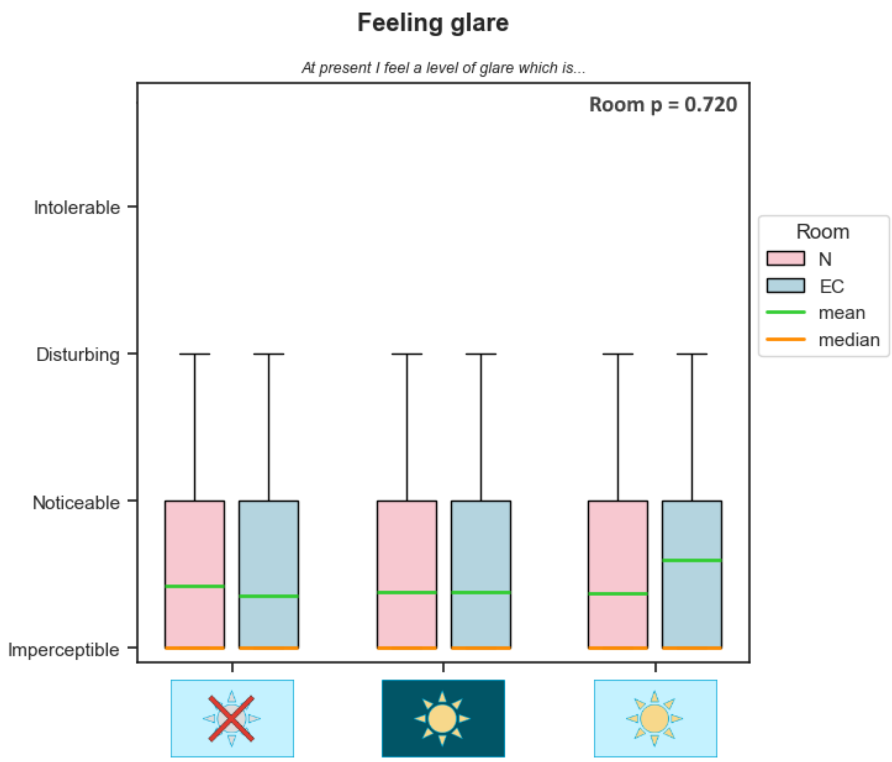

Figure 52 Glare sensation

8.3.3 Final questions

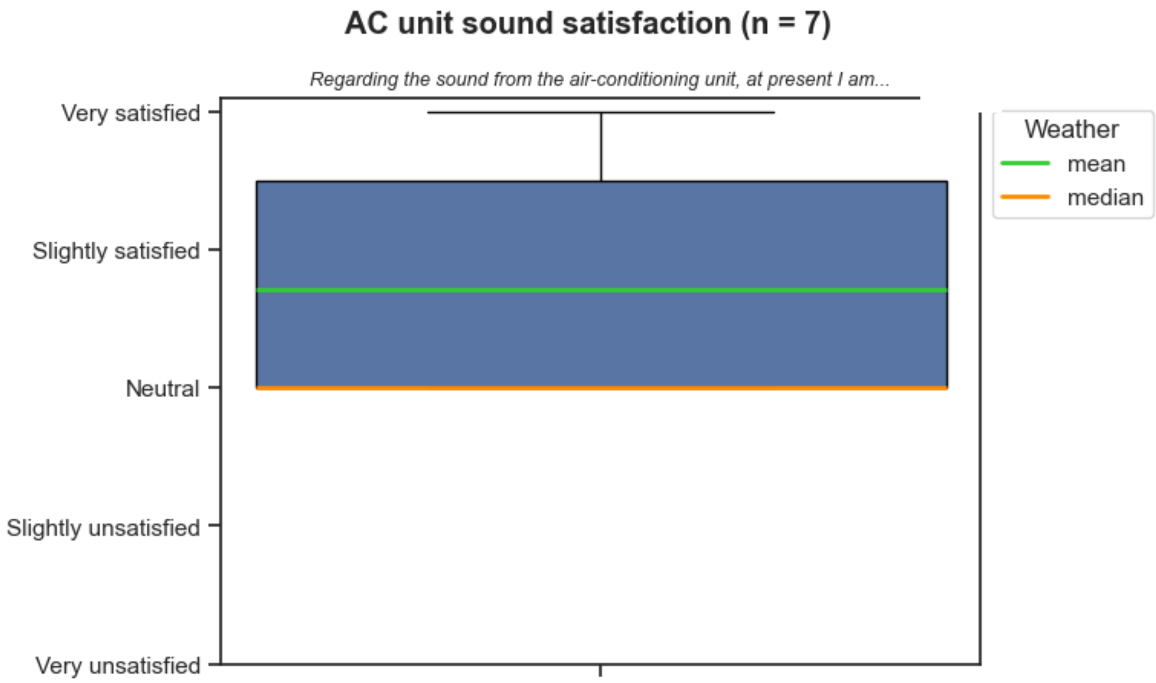

Figure 53 AC unit sound satisfaction

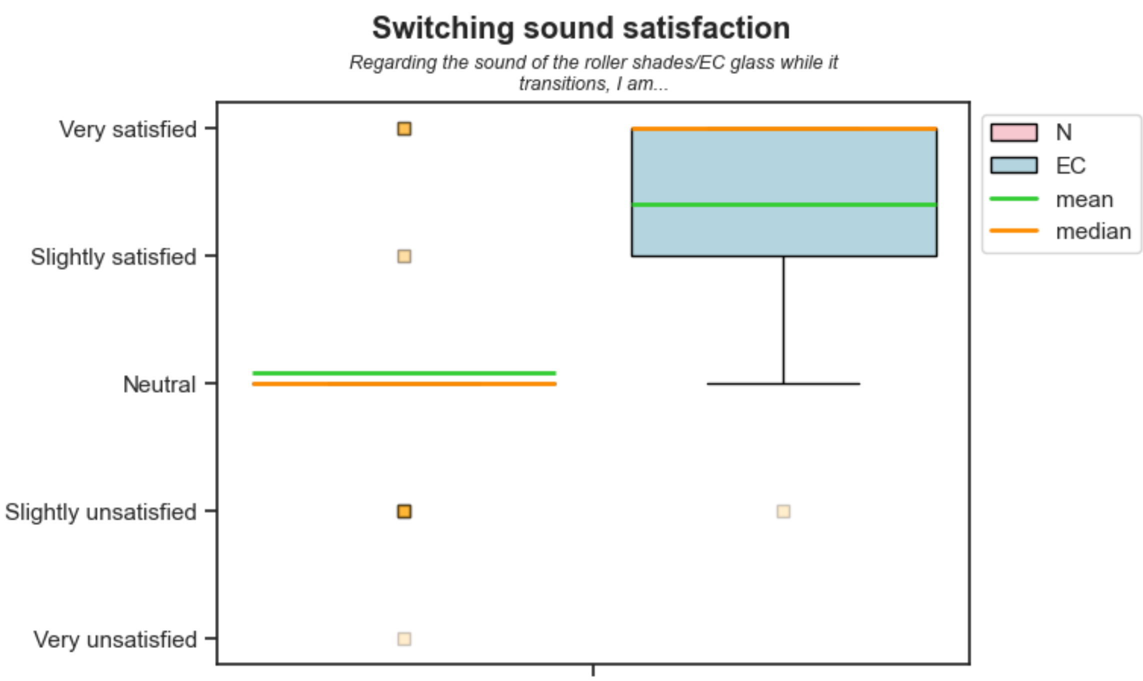

Figure 54 Facade switching sound satisfaction

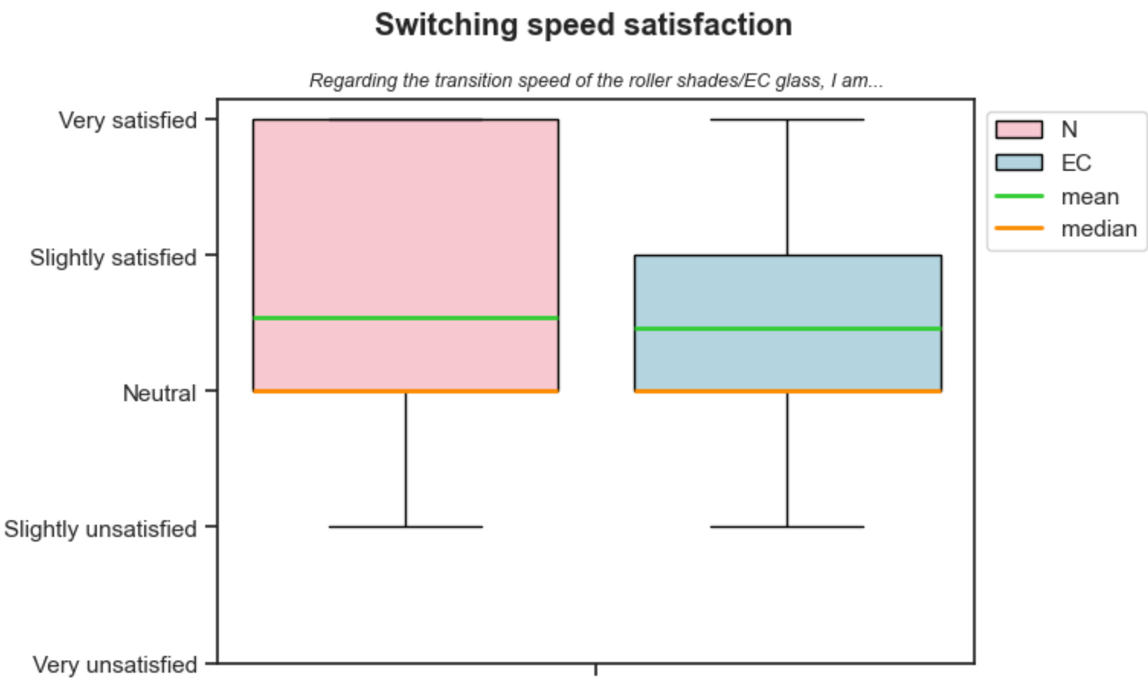

Figure 55 Facade switching speed satisfaction

8.3.4 Statistical significance

Linear mixed models were designed in SPSS for the main part questions to identify significance between the rooms and scenarios. Results of the analysis are presented via significance identifiers in the graphs of chapter 8.3.1 and 8.3.2. The article “Daylight affects human thermal perception” written by Chinazzo, Wienold & Andersen (2019) was used as an example for the statistical analysis, as the experiment setup and subject of the article are similar to this report’s experiment.

For the analysis the rooms and scenarios were modelled as fixed effects. Participant ID codes were modelled as random effects, with random intercept. The following metrics were modelled as covariates:

- Age group;
- Eye wear;
- Colour blindness;
- Worn clothing;
- Weather;
- Operative temperature;
- Relative humidity;
- Horizontal illuminance;
- Vertical illuminance;
- Indoor solar irradiance.

Fixed effects were compared pairwise with a Least Significant Difference confidence interval adjustment. The calculated significances are based on estimated marginal means. Shown in the graphs are three categories of pairwise comparisons. First is the significance between rooms per scenario, meaning scenario A in the EC room compared with scenario A in the normal room, and so forth. Second is the significance between scenarios overall, for example scenario A for both rooms compared to scenario B for both rooms, etcetera. Lastly, in the top right of each graph the significance between the rooms in general is presented. Levels of significance are displayed as “*” for p <= 0.05, “**” for p <= 0.01, and “***” for p <= 0.001. Table 8 shows the results of the type III tests for fixed effects. The table is colour coded: cells with a significant value are coloured yellow and based on the strength of significance, the colour is darker.

Table 9 shows the significances of the pairwise comparisons. These are based on the estimated marginal means. There are three categories of pairwise comparisons. The first category is at room level. This only compares rooms with each other, without taking scenarios into account. The second category is at scenario level. This compares each scenario against each other without including the rooms. In the last category, the EC room and the normal room are compared with each other within each scenario.

Table 8 Type III tests of fixed effects

		Fixed effects		Covariates									
		Room	Part	Age group	Eye wear	Colour blindness	Clothing	Weather	Operative temperature	Relative humidity	Horizontal illuminance	Vertical illuminance	Indoor solar irradiance
Temperature sensation	**F**	11.361	8.696	3.467	0.835	0.434	0.950	2.303	63.672	2.030	13.279	0.191	4.226
	Sig.	0.001	0.000	0.064	0.362	0.511	0.331	0.131	0.000	0.156	0.000	0.663	0.041
Temperature preference	**F**	3.278	8.814	1.124	0.033	0.140	1.746	0.006	28.722	1.709	0.119	0.420	0.645
	Sig.	0.072	0.000	0.291	0.855	0.709	0.188	0.941	0.000	0.193	0.730	0.518	0.423
Solar heat sensation	**F**	3.177	1.434	0.075	1.578	0.667	1.106	5.713	2.839	2.285	0.261	9.007	11.472
	Sig.	0.076	0.241	0.784	0.211	0.415	0.294	0.018	0.094	0.132	0.610	0.003	0.001
Solar heat satisfaction	**F**	25.273	3.523	0.011	0.378	2.014	0.926	7.910	0.197	1.167	2.660	0.046	24.037
	Sig.	0.000	0.032	0.916	0.539	0.158	0.337	0.005	0.658	0.282	0.105	0.831	0.000
Light sufficiency	**F**	2.219	7.973	0.307	1.237	0.025	0.365	2.602	0.112	3.981	1.182	11.487	0.162
	Sig.	0.138	0.000	0.581	0.268	0.875	0.547	0.109	0.738	0.048	0.279	0.001	0.688
Daylight sufficiency	**F**	11.022	28.100	0.002	0.163	0.447	1.207	1.357	0.082	0.022	2.454	1.956	8.943
	Sig.	0.001	0.000	0.964	0.687	0.505	0.273	0.246	0.774	0.882	0.119	0.164	0.003
Daylight satisfaction	**F**	5.775	16.566	12.920	0.728	1.187	0.122	5.493	0.012	1.825	5.696	0.384	0.783
	Sig.	0.017	0.000	0.000	0.395	0.278	0.728	0.020	0.912	0.178	0.018	0.536	0.377
Daylight colour	**F**	0.034	8.667	0.003	1.059	1.278	0.876	0.484	1.496	0.060	4.776	2.494	0.567
	Sig.	0.855	0.000	0.958	0.305	0.260	0.351	0.488	0.223	0.807	0.030	0.116	0.452
View clarity	**F**	6.265	34.207	0.156	0.037	1.524	1.228	0.643	0.340	0.028	5.125	1.901	2.975
	Sig.	0.013	0.000	0.693	0.847	0.219	0.269	0.424	0.560	0.868	0.025	0.170	0.086
Glare sensation	**F**	0.129	0.481	0.003	3.692	0.840	0.001	1.705	3.363	3.249	4.196	0.692	0.168
	Sig.	0.720	0.619	0.954	0.056	0.361	0.979	0.193	0.068	0.073	0.042	0.407	0.683

Table 9 Significances of multiple categories of pairwise comparisons, based on estimated marginal means

	Category 1: Between rooms in general	Category 2: Between scenarios			Category 3: Between rooms within a scenario		
	EC ↔ Normal	**A ↔ B**	**B ↔ C**	**A ↔ C**	**A: EC ↔ Normal**	**B: EC ↔ Normal**	**C: EC ↔ Normal**
Temperature sensation	0.001	0.000	0.059	0.051	0.020	0.044	0.708
Temperature preference	0.072	0.001	0.525	0.000	0.013	0.003	0.831
Solar heat sensation	0.076	0.099	0.280	0.642	0.271	0.418	0.314
Solar heat satisfaction	0.000	0.013	0.688	0.055	0.020	0.044	0.708
Light sufficiency	0.138	0.000	0.005	0.472	0.003	0.649	0.283
Daylight sufficiency	0.001	0.000	0.000	0.419	0.021	0.000	0.656
Daylight satisfaction	0.017	0.000	0.000	0.699	0.626	0.000	0.137
Daylight colour	0.855	0.000	0.002	0.592	0.341	0.010	0.027
View clarity	0.013	0.000	0.000	0.730	0.000	0.013	0.000
Glare sensation	0.720	0.762	0.336	0.490	0.402	0.225	0.222

A few metrics were not included in the statistical analysis. These are outdoor solar irradiation, air temperature and black globe temperature. Outdoor solar irradiation was not included due to too many missing data points. If the data were to be used, any analyses done would be potentially unreliable. Air temperature and black globe temperature are also not included because the operative temperature is made up of these two metrics and thus represents them. When air temperature and black globe temperature were used in analyses in SPSS, they were dismissed as being redundant.

8.4 Challenges surrounding the experiment & limitations

There were some minor issues around the execution of the experiment. The air-conditioning did not work in most situations where it was needed. As can be seen in Figure 53, there are seven data points for ‘satisfaction with AC unit sound’, meaning the AC unit was on for only seven of the 222 sessions. The operative temperature graph (Figure 37) shows that some outliers have temperatures much higher than the averages. These scenarios with abnormally high temperatures would have been avoidable had the AC been functioning. The AC likely didn't always work due to an obstruction between the air conditioning unit and the thermostat. The thermostat sends instructions to the air conditioning unit via infrared signals. If something blocks these infrared signals, the air conditioning unit won't function. The non-functioning AC led to a second issue. One participant opted not to partake in the second session due to a migraine after their first session, likely caused by high temperatures and too much sunlight in the eyes.

There are also a few incomplete datasets. Apart from the missing data from the volunteer discussed in the previous paragraph, there were minor issues in collecting the data from two other volunteers. One of them was too preoccupied with other matters during their second session so many answers were missing and the quality of answers was low. Data from this second session was therefore rejected. For the other volunteer, data from scenario B of the normal room is missing. This is because during the run, it was decided to skip scenario B, as the office shading was removed at that time due to a renovation at the Office Lab.

Additionally, the EC glass itself and the control system also caused minor problems. As mentioned earlier in chapter 6.2, during bleaching, the indicator lights of the control keep flashing longer than the bleaching time specified by the manufacturer. It is unknown if this was designed that way or if this is a fault in the system. However, it had no impact on the performance of the live experiment. There were also issues with the EC glass itself. Over the course of the experiment, the panels in all three window frames were degrading, but the panels on the right window frame (from the inside point of view) degraded the fastest. During the run of the experiment, the EC panels on this window progressively broke down one by one until none of them worked any more. The degradation of the panels can also be observed visually, and is shown in Figure 56. These panels were the only ones mounted on the outside of the window, so this degradation was most likely caused by weather conditions.

The interior panels also had issues. At rare occasions, when tinting or bleaching, some panels would not transition and were stuck in their old state. Figure 57 are photos taken during a live session. The left photo shows how the panels outlined in red are not tinted when they should be. Then, after bleaching, exactly these panels changed to their dark state while the rest are bleached. This phenomenon happened perhaps three times at most over the entire course of the experiment.

Apart from these challenges, there were several limitations to the experiment. Firstly, the experiment was confined to the winter season in the Dutch climate, meaning the results may not reflect variations in user comfort and façade performance across different seasons. For instance, aspects such as glare could not be assessed between the two technologies due to the absence of bright, sunny days. Additionally, the accuracy and calibration of the sensors and equipment used to measure environmental parameters could impact data quality, with any discrepancies in these measurements potentially leading to errors in interpreting the results. Furthermore, the reliability of the EC panels, control system, and sensors posed another limitation, as sporadic issues with these technologies could undermine the credibility of the findings.

One final limitation was the size and diversity of the sample population. As this study was a one-person operation and was time-constrained, the number of volunteers that could be processed was limited. The relatively small sample size and lack of diversity in terms of age groups could have made it harder to detect significant effects or generalize the findings to a larger population.

Figure 56 Exterior EC panel degradation

Figure 57 Abnormal EC glass behaviour during live session

9 Discussion

In this chapter the results presented in chapter 8 are discussed. First, any particularities in the sensor data are described and explained if possible. Next, the questionnaire data is interpreted and discussed for each question, along with the related statistical analyses. The references to significances in this chapter pertain to the significances found in Table 9 and Table 10. Concise conclusions regarding the results discussed in this chapter are provided in chapter 10.

Dry bulb air temperature, black globe temperature and operative temperature

The analysis of the air temperature, black globe temperature, and operative temperature (Figure 35, Figure 36 & Figure 37) reveals a noticeable increase in the average temperatures for both rooms over the duration of the sessions. In the normal room, this increase is approximately half a degree, whereas in the EC room, it is about one degree. This trend can likely be attributed to the influence of solar radiation, particularly when the sun starts to impact the windows at the beginning of scenario B. Additionally, the EC room consistently exhibits higher temperatures compared to the normal room, except during scenario A, where the temperatures are nearly identical. This temperature discrepancy might be due to the differing positions of the rooms within the building; the normal room is located on a corner and thus may lose more heat than the EC room, which is situated between the normal room and another office.

Another potential reason for the higher temperature and more rapid temperature increase in the EC room is the energy absorption characteristics of the EC glass. The EC glass has a lower transmittance, allowing it to absorb more solar energy. Given that the EC glass is mounted on the interior side of two of the three window frames, it presents a significant surface area that can radiate or convect heat into the room. This effectively turns the window into a radiator. Empirical observations suggest that bleached EC panels become relatively warm when exposed to sunlight, while dark EC panels can become extremely hot, nearing the pain threshold when touched.

Relative humidity

The data indicates a decreasing trend in relative humidity (Figure 38) for both rooms as the sessions progress. This decline, which is less than five percentage points, could partly be explained by the corresponding increase in operative temperature. Interestingly, the average relative humidity levels in the EC room are consistently higher than those in the normal room. Moreover, the EC room exhibits greater variance in air temperature, black globe temperature, operative temperature, and relative humidity across all scenarios. However, this increased variance does not appear to affect the thermal perception variance, as evidenced by the data presented in Figure 43.

Horizontal and vertical illuminance

For scenarios A and B, the vertical and horizontal illuminance results (Figure 39 & Figure 40) are similar. In scenario A, both rooms perform equally well. In scenario B, the normal room's illuminance is significantly lower than the EC room's due to the roller shades blocking more light than the EC glass. In scenario C, vertical illuminance levels meet expectations, with slightly higher means than in scenario A. However, the horizontal illuminances in scenario C are reasonably high compared to the vertical illuminances. This could be due to the lower position of the sensors, which might capture more sky than the higher vertical illuminance sensors. The treeline, about 40 meters away, might also block light near the horizon, but its impact is uncertain as the trees had no leaves during the experiment.

The much higher horizontal illuminance in the EC room during scenario C may be due to the haziness of the EC glass, as shown in Figure 58. Normal glass transmits light rays with minimal diffusion, so when direct light is blocked, such as by a computer screen, the horizontal illuminance sensor in the normal room receives less light. Conversely, the EC glass diffuses light more effectively, allowing the sensor in the EC room to receive more light even when direct light is obstructed. This discrepancy in horizontal illuminance is not attributed to varying weather conditions, as data analysis confirms similar weather for both rooms.

The haziness effect is also illustrated in Figure 10, Figure 13, and Figure 58. In Figure 13, the normal room's false colour photo clearly shows tree contours against the sky, while in the EC room's photo, these contours are blurred because the window diffuses light, acting as a light source. It is important to note that these observations are based on HDR photos taken at different times, so factors like local cloud cover and sun position could have influenced the lighting. A dedicated study on the haziness effect is recommended for more precise conclusions.

Figure 58 Haziness of the EC glass during sunny conditions (clear state)

Solar irradiance

Boxplots for indoor solar irradiances (Figure 41) are comparable, though the normal room shows less variance but more frequent and larger outliers. The indoor irradiance patterns for scenarios B and C mirror the horizontal and vertical illuminance patterns. In scenario A, the average indoor irradiance in the EC room appears lower, but the large overlap between the boxes indicates that definitive conclusions about differences cannot be made. Outdoor solar irradiance (Figure 42) was not analysed due to insufficient data points, rendering it an unreliable metric.

Thermal sensation

In terms of temperature sensation (Figure 43), there is a noticeable difference between the rooms. For scenarios A and B, the EC room feels warmer than the normal room, with certainty only for scenario A. When considering both rooms overall, the comparison shows high significance ($p < 0.001$) under the given configuration of fixed effects and covariates. While most opinions fall within the "comfort zone", the EC room is perceived as slightly warmer. Significant factors affecting temperature sensation include operative temperature, horizontal illuminance, and indoor solar irradiance. This is logical, as increased sunlight makes the room both warmer and brighter.

Interestingly, in scenario B, the normal room is perceived as colder than in scenario A, despite similar temperature and relative humidity levels. However, the horizontal illuminance in the normal room decreased from an average of 340 lux in scenario A to 215 lux in scenario B. This suggests that light levels significantly impact the perception of temperature.

Thermal preference

For temperature preference (Figure 44), there is little difference between the rooms in scenarios A and B. Most responses indicate a desire for no change in temperature. Notably, in scenario B, occupants of the normal room are slightly more likely to prefer a slightly warmer temperature. This aligns with temperature perception findings, where most responses fell within the comfortable range, but the normal room in scenario B was perceived as colder.

Solar heat sensation

There is little to report regarding solar heat sensation (Figure 45). Most responses indicate no sensation of heat from the sun, and pairwise comparisons show no significant differences. Weather, vertical illuminance and indoor solar irradiance all have a significant effect on solar heat sensation, however. The responses are logical given that 165 of the responses had cloudy weather, 37 were partly cloudy and only 20 were sunny.

Solar heat satisfaction

For the solar heat satisfaction (Figure 46), it can be said that satisfaction with the solar heat for the normal room in B is lower than the EC room. This is the effect of the roller shades, also given the high significance of weather and indoor solar irradiance. A clear connection can be observed between this graph and the indoor solar irradiance graph (Figure 41), as indoor solar irradiance for the EC room stays relatively the same and for the normal room dips slightly in scenario B. This pattern is similar to the pattern in the solar heat satisfaction graph. The roller shades are more effective in blocking solar heat than the EC glass. In this case, in mostly cloudy weather, it makes sense that people would be dissatisfied with the roller shades if they take away what little solar heat there is during the session.

Light sufficiency

The boxplots for light sufficiency (Figure 47) align with expectations. In the light scenarios, the normal room is generally perceived as lighter than the EC room, while in the dark scenario, the EC room is perceived as lighter. However, this difference in perception is only confirmed for scenario A. This pattern is explained by the transmittance characteristics of the EC glass: its minimum transmittance is higher than that of the normal glass with shading, and its maximum transmittance is lower than that of the normal glass with shading. These transmittance ranges are detailed in the measurements in chapter 6.2. Additionally, vertical illuminance has a high significant effect on light sufficiency.

Daylight sufficiency

The daylight sufficiency graph (Figure 49) closely mirrors that of light sufficiency, albeit with all means shifted downward due to the influence of electric lighting. Minor differences are observed between scenarios A and C, whereas scenario B exhibits large, statistically significant differences. Comparisons between scenarios A and B, as well as B and C, show high levels of significance. The key observation is that in bright scenarios, users generally find daylight sufficiency in both scenarios to be adequate. However, in darker scenarios, the normal room is perceived as significantly darker compared to the EC room.

Daylight satisfaction

Opinions on daylight satisfaction (Figure 49) appear to be similar between the rooms within scenario A and C, though there is no significance to confirm this. Within scenario C the normal room does seemingly have a higher satisfaction according to the averages. Within scenario B the difference in opinion is very clear. People are reasonably unsatisfied with the amount of daylight entering the normal room. What is interesting is that opinions on the EC room for B and C are similar, though they do have a large variance. Age group, weather and horizontal illuminance all have a high significance. Interestingly, age group is the only variable of the general questions group that is significant, and it is only significant for daylight satisfaction. Eye wear, colour blindness and clothing are all three not significant for any dependent variable.

Upon analyzing the data, the high significance of age group may be coincidental. Table 10 shows that the group aged 25 and younger experienced more sunlight (horizontal illuminance) on average, while the 60+ group had much less. This disparity in sunlight exposure is coincidental and likely contributes to the respective satisfaction ratings. The actual amount of daylight entering the rooms appears to be the main factor influencing satisfaction, potentially creating a false correlation with age group. To determine if age group truly affects daylight satisfaction, a new study with a more balanced pool of subjects and more sessions would be necessary.

Table 10 Distribution of daylight satisfaction and horizontal illuminance by age group

	Daylight satisfaction			**Horizontal illuminance**		
Age	**Count**	**Mean**	**Median**	**Count**	**Mean**	**Median**
Below 25 years	18	3.33	3	14	771.4	574.4
Between 25 and 40 years	158	3.03	3	146	747.1	209.5
Between 40 and 60 years	27	2.96	3	26	621.8	193.7
Older than 60 years	18	2.17	2	18	179.7	175.3

Daylight colour satisfaction

Overall, subjects reported lower daylight colour satisfaction (Figure 50) for the EC room in scenarios A and C compared to the normal room. Satisfaction particularly drops when the sun is in the field of view in scenario C. This observation is supported by the significant effect of horizontal illuminance on daylight colour satisfaction. In scenario B, people seem dissatisfied with the performance of both rooms, though the averages for the EC room are better than those for the normal room, as indicated by the significance within scenario B. When considering averages, people tend to be more neutral towards the EC glass, while opinions on the normal room vary across the different scenarios.

View clarity satisfaction

Perhaps the most interesting graph is the one for view clarity satisfaction (Figure 51). Similar to the daylight colour satisfaction graph, the averages of the EC room tend to hover around a 'neutral' opinion. The interesting part however is the greatly varying view clarity satisfaction of the normal room. For scenarios A and C the levels of satisfaction are very high, while it dips very low in scenario B. These strong differences of opinion are supported by high significances between the groups.

Horizontal illuminance has a significant effect on view clarity satisfaction, though its practical implications are unclear. As the brightness and sunlight increase for the EC room, the window becomes hazier (see Figure 58 and Figure 59), theoretically reducing view clarity. However, this dissatisfaction for the EC room in bright conditions is not evident in the graph. This discrepancy may be due to the rarity of sunny days during the experiment. In predominantly cloudy conditions, which were most common, the haziness of the glass is less noticeable.

The significant effect of horizontal illuminance appears to be a coincidental pattern match. Comparing the medians of horizontal illuminance and the means of the view clarity satisfaction graph shows a "high-low-high" pattern for both graphs. Practically, the normal room scores high for scenarios without shading (A and C) and low for the scenario with shading (B) because people could see clearly outside in A and C, but not in B. Similarly, for the EC room, people could see outside in all scenarios, but the clarity of the view is lower compared to normal glass.

Figure 59 Haziness of the EC glass during sunny conditions (dark state)

Glare sensation

It is difficult to draw conclusions about the glare sensation of the chambers. The results of both chambers are very similar, implying that the performance of both chambers is similar, however, there is no significance between the groups. This would likely require a larger sample size. Again, horizontal illuminance has a significant effect. This makes sense, since glare sensation is dependent on light falling into the eyes. What is remarkable, however, is that vertical illuminance does not appear to have a significant effect here. In a data analysis, the glare sensation indicated by the subject seems to have little relationship with the simplified DGP calculated via the vertical illuminance. In total, 143 responses indicated 'imperceptible', 64 indicated 'noticeable' and 14 indicated 'disturbing'. The average calculated simplified DGPs corresponding to these responses are 21.5%, 22.8% and 23.8%, respectively. The first two columns of Table 11 shows how often subjects gave a particular response. The rest of the columns present the distribution of the calculated simplified DGP for each response category. As can be seen in the columns, the means of the calculated DGP do not match the DGP associated with the different glare sensation levels. According to theory, glare should be imperceptible at a DGP below 35%. Only above 35% should it be noticeable. What caused these discrepancies is not known for certain, but could have multiple causes. One possible explanation is that the vertical illuminance sensor was consistently misaligned, and thus recorded data incorrectly. Another possibility is that volunteers misunderstood what glare actually means.

Table 11 Simplified DGP calculation distribution

		Simplified DGP distribution				
Glare sensation	**Responses**	**Mean**	**Std. deviation**	**Minimum**	**Median**	**Maximum**
Imperceptible	143	0.215	0.010	0.205	0.211	0.257
Noticeable	64	0.228	0.028	0.204	0.221	0.352
Disturbing	14	0.238	0.046	0.206	0.218	0.351

Air conditioning unit sound, façade switching sound & façade switching speed satisfaction

Lastly, the satisfaction with AC sound, facade switching sound and facade switching speed. People seem to be quite satisfied with the AC sound. However, because of malfunctions, the air conditioners collectively were only active seven times and therefore only seven responses were gathered. The results for the other factors show no meaningful differences between the seven times the air conditioning was on and the times when the air conditioning was off. Seven data points is too few to provide a solid assessment, however.

For the switching sound and speed, the sample size is larger, with 74 responses. These questions are asked at the end of the questionnaire, separate from scenarios A, B, and C. Generally, people are more satisfied with the switching sound of the EC glass compared to the roller shades of the normal glass, with most participants either unbothered or indifferent to the roller shades' sound.

Regarding switching speed, satisfaction levels for the two shading technologies are more similar. People are generally satisfied with both, but the faster, more immediate roller shades are preferred, as they receive higher satisfaction ratings compared to the slower, more gradual EC glass.

10 Conclusion

This study set out to evaluate the performance of inkjet-printed electrochromic (EC) glass compared to traditional triple glazing with roller shades in terms of visual and thermal user comfort in a Dutch office setting. The research was driven by a main question, supplemented by several sub-questions addressing specific aspects of thermal and visual comfort, which are recapped below. By conducting a comprehensive experiment in a controlled office environment, extensive data was gathered on user experiences and environmental conditions, which is discussed in chapter 9. This chapter aims to answer the sub-questions using the data and discussions presented earlier, to then ultimately answer the main research question and compare the facades overall. The main research question and the sub-questions are as follows:

What is the performance of inkjet-printed EC glass compared to normal triple glazing office glass with traditional shading on the domains of visual and thermal user comfort in the Dutch climate?

- Thermal sub-questions:
  - *How do the physical temperatures in the rooms compare, and what is the thermal sensation of the user?*
    - *What is the user thermal preference in relation to their thermal sensation?*
  - *What is the amount of solar energy entering the rooms, and does the user feel any solar heat?*
    - *What is the user satisfaction regarding solar heat sensation?*
  - *Which factors are of influence on thermal sensation & preference, and solar heat sensation and satisfaction?*
  - *How does the EC glass compare to triple glazing on the domain of thermal comfort?*
- Visual sub-questions:
  - *What is the level of (day)light in the rooms and is it adequate for performing relevant tasks?*
    - *What is the user satisfaction with the amount of daylight entering the rooms?*
  - *What is the colour rendering of the windows, and how satisfied is the user with the colour of the daylight entering the rooms?*
  - *How much light do the windows transmit, and what is the user satisfaction regarding the clarity of the view?*
  - *What is the level of (day)light entering the user's eyes and is it disturbing, in terms of glare?*
  - *Which factors are of influence on (day)light sufficiency & satisfaction, daylight colour, view clarity, and glare sensation?*
  - *How does the EC glass compare to triple glazing on the domain of visual comfort?*

- General sub-questions:
  - *What is the user satisfaction with the state switching speed of the facades?*
  - *What is the user satisfaction regarding the state switching sound of the facades?*

Thermal comfort

The thermal performance of the two façade types was evaluated by comparing the physical temperatures in the rooms and the thermal and solar heat sensation and satisfaction of users. Throughout the sessions the temperature in the EC room increased more rapidly than in the normal room, but both rooms managed to remain within the comfortable range. Temperature sensation and preference remained neutral for both rooms, except for the dark scenario for the normal room. Because of the lower indoor solar irradiance in this case, temperature sensation went down. Dissatisfaction with this is reflected in the temperature preference and the solar heat satisfaction. For the light scenarios, the performance of the rooms is similar.

Overall, regarding thermal comfort, it appears the EC façade performed better than the normal façade in this study, mainly due to the negative opinions on the normal room when the roller shades are down. However, it should be noted that this experiment took place during the winter period of 2023/2024. The roller shades block more solar heat than the EC glass, and practically speaking, one would not use the solar heat blocking shades on cold, cloudy days - which occurred most often during the experiment. It is logical that in such a situation, people would feel colder and express themselves negatively about the shades. It is possible that the normal glass with roller shades did not reach its full potential, or was disadvantaged by how and when this experiment was conducted. Ideally, this experiment should also be conducted during the summer period. Then it could be the case that the EC room becomes too warm - even in the dark state - and that the blocking effect of the roller shades is actually welcomed.

Visual comfort

The visual performance of the two façade types was evaluated by comparing the levels of electric light and daylight in the rooms, user satisfaction with the amount of daylight, the colour of daylight, view clarity, and user perceptions of glare. Regarding light and daylight sufficiency and satisfaction, both façades performed very similarly in bright scenarios. In both rooms, there was enough light to perform relevant tasks, and users were generally neutral about their satisfaction with daylight in these situations. However, in darker scenarios, it became clear that the EC façade outperformed the normal façade in terms of daylight sufficiency. The normal façade might have performed better if it had a greater openness factor, which was only 3% for this particular model of roller shades.

When it comes to daylight colour and view clarity, drawing a conclusion is more challenging. In summary, opinions about the normal façade were quite divided, with both positive and negative opinions. In contrast, opinions about the EC façade remained consistently neutral. The normal façade performed better in bright situations, while the EC façade performed better in darker situations. Unfortunately, no clear conclusion could be drawn regarding glare sensation. Opinions about both façades were very similar, and there was no statistical significance to support the results. This may require a new study to explore further.

Overall, it is not immediately clear which of the two façades performs better in terms of visual comfort. As with thermal comfort, it depends on the usage situation. In a region like Southern Europe, where the sun shines intensely, and shading is regularly needed, it might be better to use EC façades, given that opinions in this experiment remained neutral for EC façade while opinions about normal façade were negative. In a region like the Netherlands, where the sun does not shine as intensely, it might be better to use normal glass with shading. This way, you can take advantage of the benefits of clear normal glass for most of the year.

General comfort

Regarding switching speed and switching sound, the façades are evenly matched. Users are very satisfied with the (lack of) sound of the EC glass, while their opinions about the sound of the roller shades are more neutral. Conversely, people are more positive about the speed of the roller shades compared to the speed of the EC glass, although the average scores for both façades are very close. Purely considering the average scores and adding them up, the EC glass performs better overall, given that opinions about the speed of the roller shades are "only" neutral.

Overall performance comparison

Within the context of this experiment, reasoned from the results obtained, the EC façade is the better performer. Opinions on EC façade remain consistently neutral. Opinions on the normal façade with shading are also often neutral, however, the normal glass often loses in dark scenarios. Occasionally, the normal façade wins in light scenarios. In practice, however, outside the context of the experiment, the effectiveness of both types of facades most likely depends on climate. In warmer climates where shading is often required, it is better to use EC glass instead of traditional shading, given the neutral opinions of the EC façade in dark condition compared to the negative opinions of the normal façade with roller shades. In the Dutch climate, it is better to use normal glass with shading, as the shades need to be used relatively little during the year. The main reason why the normal façade with the roller shades underperformed compared to the EC façade was due the blocking effect of the roller shades. If the shades had a higher openness factor, results could have turned to the normal façade’s favour.

10.1 Recommendations for the manufacturer

Keeping in mind that the manufacturing process of these inkjet-printed electrochromic panels is relatively new and still in the testing phase, a few recommendations for the manufacturer to improve the product have been listed below.

- Make the EC glass behaviour more consistent, both in operation, looks and functionality. The problems with the panels and the control system are mentioned in chapter 8.4. When using the EC system, occasionally some panels happened to react badly or not at all to the control system signals. Also, the panels deteriorated during the run of the experiment. For example, air bubbles formed due to apparent delamination of the panels. The uniformity between panels also varied. For instance, there were panels that were consistently darker than others.
- Haziness of the panels in direct sunny conditions is also a point of attention. This is mentioned in chapter 9. The haziness in sunny conditions detracted a reasonable amount from the viewing experience. During the execution of the experiment, this was mentioned verbally multiple times by some volunteers.

10.2 Potential follow-up research

To conclude, some ideas for possible follow-up studies are presented here:

- This study was conducted entirely during the winter season. To get a complete and fair picture of the performance of both facades, this experiment should be conducted again in the summer period. Whereas now EC glass performs better, this may not be the case during sunnier, warmer periods. Also, aspects such as glare sensation and solar heat sensation could not be properly tested in winter due to lack of sunshine. A larger sample size would also have helped to highlight the small differences that exist between facades. Ideally, in a follow-up experiment, there would also be a better balance in the selection of volunteers regarding age group, sex, etc.
- For the same reasons as above, it is interesting to test the EC glass in warmer climates than the Dutch. Ideally, multi-domain and with volunteers.
- Finally, it is interesting to use the findings of this experiment to design automatic control systems for both EC systems and tradional shading systems.

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12 Appendices

12.1 Appendix A: HDR and false colour images from alternative positions and angles

Chapter 6.1.1 discusses the chosen position for the HDR photographs (and thus for the volunteers as well) from the options presented in Figure 60. Chapter 6.1.1 presents the images for the chosen position, B. For completeness, this appendix shows the HDR photos and false colour images from the positions A and C. Note that in order to present the HDR photos in this report, the HDR photos had to be converted from .hdr files to .png files. The .png file format cannot carry as much information as the .hdr file format, and therefore, some details in the photos have been lost, especially in the bright areas.

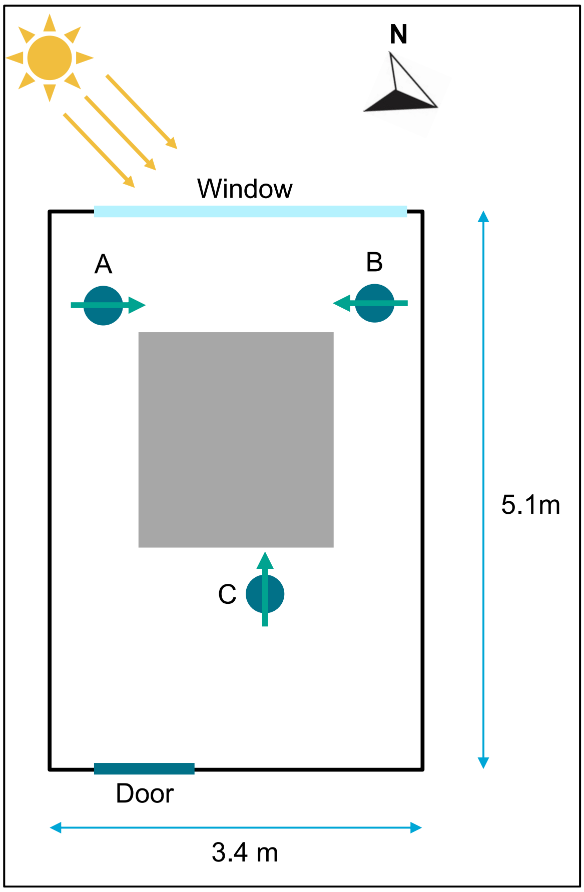

Figure 60 Positions in the room considered for worst-case viewing angle

Figure 61 Position A, HDR photograph

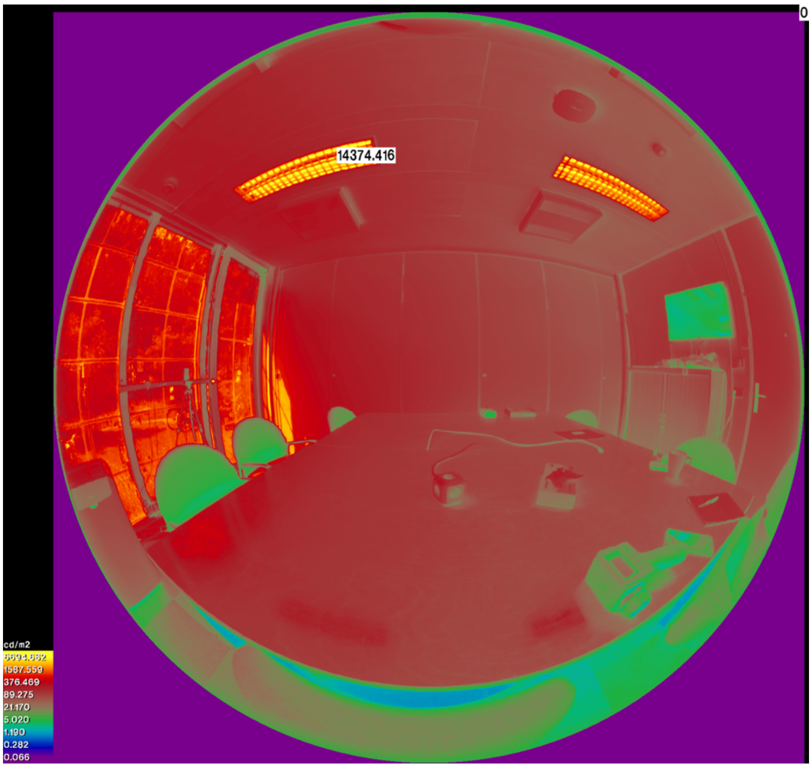

Figure 62 Position A, false colour image

Figure 63 Position C, HDR photograph

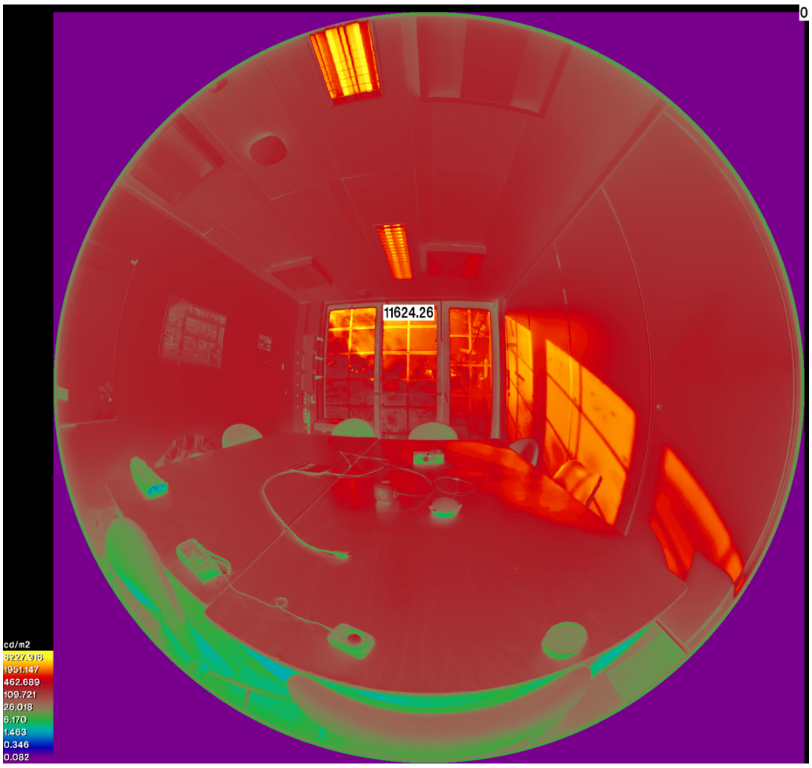

Figure 64 Position C, false colour image

12.2 Appendix B: Full Qualtrics questionnaire

This appendix showcases the complete online questionnaire from the experiment as it was presented to volunteers in Qualtrics. Some questions were only shown depending on the volunteer's answers from previous questions. The rules that decide if questions are shown are presented between {curly brackets}. A condensed version of the questionnaire is shown in chapter 1.1, Table 7. If a question is multiple choice, the available options are shown in bullet points. The questions from parts A, B, and C are identical and are shown only once in this appendix for convenience (questions 7 through 20). Please note however that these questions are presented to the volunteers a total of three times, each time at the corresponding time interval.

Introduction. You are being invited to participate in a research study titled Windows to the Future. This part of the study is being done by Dr. Martin Tenpierik, Dr. Alessandra Luna-Navarro, Dr. Eleonora Brembilla, Dr. Zara Huijbregts and Robert Verbeek from the TU Delft together with Brite Solar, Si-X glass and The Green Village.

This online survey is part of the larger project. The larger project investigates a novel type of electrochromic glass as a means of sun-shading for a building, its manufacturing up-scaling, its energy performance (impact on cooling and heating demand) and the impact of the glass and its colouring on thermal comfort, visual comfort and user experience. Completing this survey is part of the experiment and needs to be done in steps. Each block of the survey will take you less than 5 minutes. The data will be used for understanding which control strategy (controlling the transition from transparent to opaque coloured) is preferred by the users, and how users perceive the colour and visual and thermal comfort behind the EC glass. These results will help us to find the balance between minimising the cooling demand of spaces using EC glass and thermal and visual comfort and will help us identify the ideal control strategy.

Your participation in this study is entirely voluntary and you can withdraw at any time. You are free to omit any question.

We believe there are no known risks associated with this research study; however, as with any online related activity the risk of a breach is always possible. To the best of our ability your answers in this study will remain confidential. We will minimize any risks by storing all data on SurfDrive and ProjectStorage which is a GDPR proof environment and by not asking and storing any personal data in this questionnaire.

By clicking on the next button to start this questionnaire, you give consent to participate in this experiment.

For more information, please contact Martin Tenpierik (m.j.tenpierik@tudelft.nl).

The questionnaire involves general questions, questions regarding thermal comfort and questions regarding visual comfort. Please complete the questionnaire based on your current experience.

Start. You will now first answer a few general questions.

Question 1
PNumber. What is your participant number?
[open text box]

Question 2
Room. In which room are you currently?
- Meeting room red (normal glass)
- Meeting room blue (EC glass)

Question 3
Age. What is your age?
- Below 25 years
- Between 25 and 40 years
- Between 40 and 60 years
- Older than 60 years

Question 4
Eye wear. Do you currently make use of eye correction?
- Yes, I am using glasses
- Yes, I am wearing contact lenses
- No

Question 5
Colour Blindness. Are you colour blind?
- Yes
- No

Question 6
Clothing. Please tick as appropriate
- Shorts or knee-length skirt, short-sleeve shirt/blouse or T-shirt
- Shorts or knee-length skirt, long-sleeve shirt/blouse
- Shorts or knee-length skirt, T-shirt plus long-sleeve shirt/blouse
- Shorts or knee-length skirt, long-sleeve shirt/blouse plus suit jacket
- Shorts or knee-length skirt, T-shirt plus long-sleeve shirt/blouse plus suit jacket
- Shorts or knee-length skirt, T-shirt or long-sleeve shirt/blouse plus long-sleeve sweater
- Trousers or ankle-length skirt, short-sleeve shirt/blouse or T-shirt
- Trousers or ankle-length skirt, long-sleeve shirt/blouse
- Trousers or ankle-length skirt, T-shirt plus long-sleeve shirt/blouse
- Trousers or ankle-length skirt, long-sleeve shirt/blouse plus suit jacket
- Trousers or ankle-length skirt, T-shirt plus long-sleeve shirt/blouse plus suit jacket
- Trousers or ankle-length skirt, T-shirt or long-sleeve shirt/blouse plus long-sleeve sweater

Start of Session A/B/C. Start of Session A/B/C
The following questions need to be answered at the end of session A/B/C. Please do not answer them right now but wait until Robert tells you when to complete this part.

Question 7
Controls. Currently in the room the ...
Lights are [A: on; B: off]
- A
- B

Portable air conditioner is [A: on; B: off]
- A
- B

Question 8a {shown if the answer from question 2 was 'Meeting room red (normal glass)'}
State Sun-Shades. Currently in the room the sun-shades are ...
- Up
- Down

Question 8b {shown if the answer from question 2 was 'Meeting room blue (EC glass)'}
State EC glass. Currently in the room the electrochromic glass is ...
- Clear
- Tinted

Question 9a {shown if the answer from question 2 was 'Meeting room red (normal glass)'}
Change Sun-Shades. Do you currently wish to change the state (up versus down) of the sun-shading?
- Yes
- No

Question 9b {shown if the answer from question 2 was 'Meeting room blue (EC glass)'}
Change EC glass. Do you currently wish to change the state (clear versus tinted) of the electrochromic glass?
- Yes
- No

Question 10a {shown if the answer from question 2 was 'Meeting room red (normal glass)'}
Change Sun-Shades. What is the main reason for wanting so?
- Glare or too much light
- Too much heat from the sun coming in
- Too dark
- Other (specify) [open text box]

Question 10b {shown if the answer from question 2 was 'Meeting room blue (EC glass)'}
Change EC glass. What is the main reason for wanting so?

- Glare or too much light
- Too much heat from the sun coming in
- Too dark
- Other (specify) [open text box]

Question 11
Feeling Temperature. At present I feel

- Much too cold
- Too cold
- Comfortably cool
- Comfortable
- Comfortably warm
- Too warm
- Much too warm

Question 12
Preference Temp. I would prefer to be

- Much cooler
- A bit cooler
- No change
- A bit warmer
- Much warmer

Question 13
Feeling Solar Heat. At present I feel

- No heat from the sun through the façade
- A bit of heat from the sun through the façade
- Much heat from the sun through the façade

Question 14
Satisfaction SolHeat. Regarding the amount of incoming heat from the sun through the facade, I am

- Very unsatisfied
- Slightly unsatisfied
- Neutral
- Slightly satisfied
- Very satisfied

Question 15
Light Sufficiency. Regarding the amount of light (daylight and electric light) to perform my task in the room, at present I feel the room is

- Very dark
- Dark
- Slightly dark
- Adequate amount of light
- Slightly bright
- Bright
- Very bright

Question 16
Daylight Sufficiency. Regarding the amount of daylight to perform my task in the room, at present I feel the room is

- Very dark
- Dark
- Slightly dark
- Adequate amount of light
- Slightly bright
- Bright
- Very bright

Question 17
SatisfactionDaylight. Regarding the amount of daylight entering the room, at present I am

- Very unsatisfied
- Slightly unsatisfied
- Neutral
- Slightly satisfied
- Very satisfied

Question 18
Colour of Daylight. Regarding the colour of the daylight through the window, at present I am

- Very unsatisfied
- Slightly unsatisfied
- Neutral
- Slightly satisfied
- Very satisfied

Question 19
View Clarity. With regards to the clarity of the view to the outside, at present I am

- Very unsatisfied
- Slightly unsatisfied
- Neutral
- Slightly satisfied

Very satisfied

Question 20a
Feeling Glare. Glare is discomfort due to the brightness of the room surfaces, brightness of the window or light contrast.

At present I feel a level of glare – discomfort due to high brightness of the sun, of electric lights or of a surface, or large contrast – which is

- Imperceptible (I do not feel any discomfort, I could work under these conditions for any period of time)
- Noticeable (I could work approximately one day under these conditions, but it would bother me to work under these conditions every day)
- Disturbing (I could tolerate these conditions for 15 to 30 minutes, but would require a change in the conditions for any longer period of time
- Intolerable (I could not tolerate working in these conditions

Question 20b {shown if the answer from question 20a was anything other than 'Imperceptible'}
Sources of Glare. Please state what was the source of glare (multiple answers possible).

- The sun through the window
- The entire window
- A wall
- The desk
- Objects visible through the window
- The electric lighting

Demonstration. Some final questions will follow.

Question 21a {shown if the answer from question 2 was 'Meeting room red (normal glass)'}
Switching speed sha . Regarding the transition speed of the roller blinds, I am

- Very unsatisfied
- Slightly unsatisfied
- Neutral
- Slightly satisfied
- Very satisfied

Question 21b {shown if the answer from question 2 was 'Meeting room blue (EC glass)'}
Switching speed EC. Regarding the transition speed of the facade (EC glass or sun-shades), I am

- Very unsatisfied
- Slightly unsatisfied
- Neutral
- Slightly satisfied
- Very satisfied

Question 22a {shown if the answer from question 2 was 'Meeting room red (normal glass)'}
Sound Transition Sha. Regarding the sound of the sun-shading while it transitions, I am

- Very unsatisfied
- Slightly unsatisfied
- Neutral
- Slightly satisfied
- Very satisfied

Question 22b {shown if the answer from question 2 was 'Meeting room blue (EC glass)'}
Sound Transition EC. Regarding the sound of the façade (EC glass) while it transitions, I am

- Very unsatisfied
- Slightly unsatisfied
- Neutral
- Slightly satisfied
- Very satisfied

Question 23 {shown if the answer from question 7 for any of the parts was 'A: on' for the portable air conditioner}
Sound AC Unit. Regarding the sound from the air-conditioning unit, at present I am

- Very unsatisfied
- Slightly unsatisfied
- Neutral
- Slightly satisfied
- Very satisfied

Question 24
Anything Else. Please use the text box below to add any remark regarding your experience with the installed EC glass/normal glass and roller shades.
[open text box]

12.3 Appendix C: Information sheet and consent form

This appendix shows the information sheet and consent form as they were presented to the volunteers prior to their participation in the experiment. Volunteers were only allowed to continue participating in the experiment if they had answered ‘yes’ to every question and had signed the document. The experiment falls under the umbrella of a larger ongoing research project by the TU Delft, Brite Solar Technologies, and the Green Village. Ethical approval was obtained from the TU Delft HREC (application number 3819) for this larger project including this experiment. Participants of the experiment are assigned a numerical ID code only they themselves and the researcher know, and is stored separately. The information sheet and consent form are presented in the following two pages.

Information Sheet Windows to the Future project

You are being invited to participate in a research study titled Windows to the Future. This study is being done by Dr.ir. Martin Tenpierik, Dr.-Ing. Thaleia Konstantinou, Dr. Marco Ortiz Sanchez MSc, Dr. Eleonora Brembilla MSc, Dr. Alessandra Luna-Navarro MSc, Dr.ir. Zara Huijbregts, Juan Azcarate Aguerre MSc, Prof.dr.ir. Philomena Bluyssen and Prof.dr.-ing. Tillmann Klein and MSc student Robert Verbeek from the TU Delft together with Brite Solar, Si-X glass and The Green Village.

Rising temperatures result in an increased demand for air-conditioning, even in The Netherlands. One option for keeping the sun (heat and glare) out of buildings is to apply sun shading measures. The major disadvantages of these are the limited control on the amount of solar radiation entering the room, and the loss of contact of the user with the outside world that can lead to a feeling of "containment". A possible solution is to use electrochromic (EC) glass, where the optical properties of the glass (tinting) change upon the application of an electric potential in order to realise HVAC energy savings and improve user comfort. This would accommodate permanent contact with the outside world, as well as precise control of solar heat gain and glare in a space.

This project investigates a novel type of electrochromic glass as a means of sun-shading for a building, its manufacturing up-scaling, its energy performance (impact on cooling and heating demand) while installed in a real building, the impact of the glass and its colouring on thermal and visual comfort, the experiences of users, and the viability of the business case for the end users.

Participating in this research involves being present inside a room of which the normal glass has been replaced with grey-tinted electrochromic glass or inside a room with normal triple glass and normal sunshading, being allowed to use the manual control of the glass/sun-shades to change their state and taking part in an (online) survey questionnaire completed by the participant. Furthermore, the operation of doors, windows and the EC glass will be monitored through sensors and environmental variables inside the rooms will be monitored or measured as well (temperature, humidity, solar radiation, use of artificial lights, amount of ventilation, temperature of incoming ventilation flow, illuminance, luminance, and energy use of air conditioning units).

The data collected in the OfficeLab and the questionnaires will be used for understanding the impact of the EC glass on the heating and cooling energy demand of the OfficeLab specifically and buildings more generally, which control strategy (controlling the transition from transparent to opaque coloured) is preferred by the users, how and when users interact with the manual override of the system and how users perceive the colour and visual and thermal comfort behind the EC glass. These results will help us find the balance between minimising the cooling demand of spaces using EC glass and thermal and visual comfort, and will help us identify good control strategies.

Your participation as an individual in this study is entirely voluntary and you can withdraw at any time. You are free to omit any question in the questionnaires or free to not make use of the rooms in which the EC glass and equipment are installed.

We believe there are no known risks associated with this research study. No personal data or data that may identify a person will be collected with the questionnaires. The link used for distributing the questionnaires will be the same for everyone and does not contain any traceable information. Furthermore, no info on who is filling out the questionnaire will be collected. Furthermore, under the circumstances of this research, data from the sensors cannot be linked to a person by the research team. However, concerning the questionnaires, as with any online related activity, the risk of a breach is always possible. To the best of our ability your answers in this study will remain confidential. We will minimize any risks by storing all data on SurfDrive and ProjectStorage which is a GDPR proof environment and by not asking and storing any personal data in this questionnaire. At the end of this research project, aggregated (thus anonymised) data will be stored in the 4TU.research data archive. Finally, no risks are foreseen concerning the use of the EC glass, except for maybe minor discomfort due to the colouring of the light.

Contact details concerning research project: Dr.ir. M.J. Tenpierik, M.J.Tenpierik@tudelft.nl, 0152784411
Contact details data steward: Janine Strandberg, datasteward-BK@tudelft.nl

Consent Form for Windows to the Future project

Please tick the appropriate boxes	**Yes**	**No**
Taking part in the study		
I have read and understood the study information on the first page of this paper, or it has been read to me. I have been able to ask questions about the study and my questions have been answered to my satisfaction.	○	○
I consent voluntarily to be a participant in this study and understand that I can refuse to answer questions and I can withdraw from the study at any time, without having to give a reason.	○	○
I understand that taking part in the study involves being present inside a room of which the normal glass has been replaced by grey-tinted electrochromic glass and taking part in an (online) survey questionnaire completed by the participant.	○	○
Risks associated with participating in the study		
I understand that taking part in the study involves the following risks: minor visual discomfort due to the colouring of the light passing through the electrochromic glass in its opaque state.	○	○
Use of the information in the study		
I understand that information I provide will be used for a report and journal and conference publications. Within the context of The Green Village, monitoring data of physical and environmental variables might be made available to other users of the Green Village. This latter data does not contain any personal information.	○	○
I understand that personal information collected about me that can identify me, such as [my name and email address], will not be shared beyond the study team.	○	○
Future use and reuse of the information by others		
I give permission for the questionnaire data that I provide to be archived in the 4TU.research data archive so it can be used for future research and learning. The deposited data will be in form of an anonymised survey database from which all personal or traceable data has been removed. No use or access restrictions will apply to this archived data.	○	○

Contact details for further info: Dr.ir. M.J. Tenpierik, m.j.tenpierik@tudelft.nl, 0152784411

Signatures

______________________ ______________________ ________

Name of participant [printed] Signature Date

The researcher has accurately explained the research to the potential participant and, to the best of his ability, ensured that the participant understands to what they are freely consenting.

______________________ ______________________ ________

Researcher name [printed] Signature Date