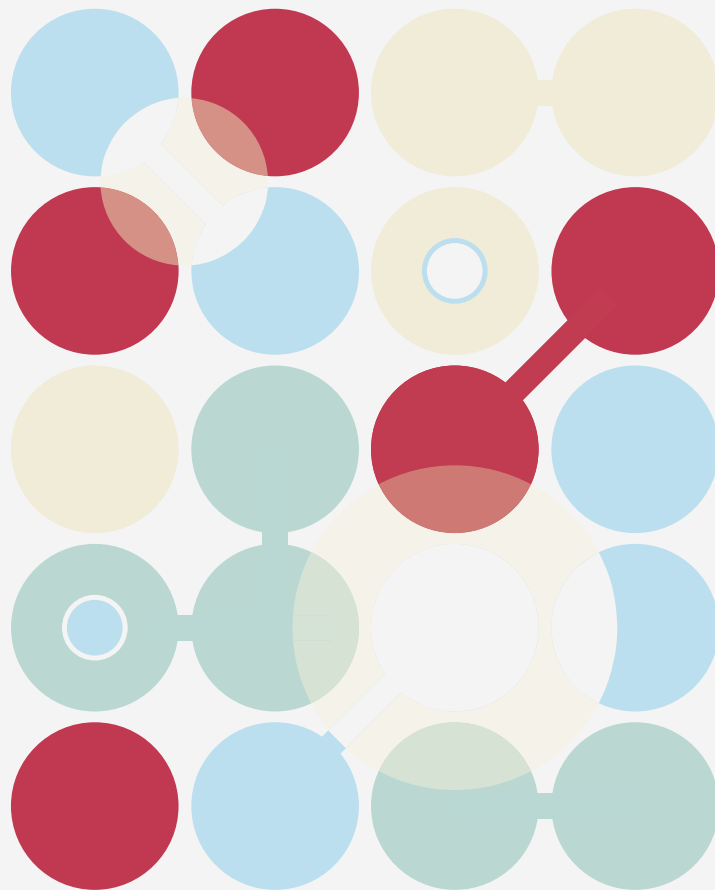




**/Affective window:
a seamless interaction between
switchable glazing and the
occupant**

Christianne Neeltje Luijten

/Acknowledgements

Before choosing a graduation topic, I took several aspects into consideration. Giving a preference for a specific topic was difficult for me, since I am interested in many domains and there is so much to choose from. One thing that I have noticed throughout my whole education, my master, bachelor and even high school, is that I am practical and social. In other words, a hands-on practical project that involves close collaborations with others, is what I was looking for. I talked to different mentors about the projects they offered and after meeting with a very enthusiastic and optimistic Mauro; this one stood out the most. It was challenging, exciting and new for me. The project provided me the opportunity to test my interests. I had not yet encountered such a project before, exploring dynamic and human-centered façades, during my masters degree, but I was eager to add meaningful, new and relevant knowledge to the chosen topic. With Alessandra, Mark and Regina added to the supervisory team I was ready to take on the challenge. The difficulties were yet to show themselves.

Starting out as a rookie in the field of glare, façades and human-centred interaction, learning as much as possible and exploring prior done research was an important basis for my results and ability to interpret them. As a designer, not used to the process a researcher goes through and is familiar with, the explorations performed initially felt like I was stumbling around blindly. Taking the correct measurements and preparing the experiments was a confusing struggle, taking two steps backward with only one forward. Fortunately, I had a great team of experienced experimental researchers to lend me a hand. After a period of trial and error, helpful suggestions from others, I started to get the hang of it. I even felt confident enough to help others with measuring lighting conditions of their experimental set up.

I would like to thank Mauro for always being optimistic, encouraging and pointing me towards the right direction. I would specifically like to thank Mark and Alessandra who motivated me to dig deeper into the data, not to stray, to develop interest in experimental research and interaction between the façade and occupant, through frequent contact. Contact with them was very much appreciated, especially during these times. I want to thank Regina for her critical eye on, among other things, the planning and goals of the project and taking time to go through the research with me.

Finally, my special thanks to all the participants who participated in my experiment. Almost 30 people contributed their time to help me gain the data presented in this study.

To my parents, my brother and sister, thank you for your sympathetic ear during my complaints.

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MSc Architecture, Urbanism and Building Sciences

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/Abstract

New building technologies are developing rapidly, the use of sensors and actuation with it. These technological developments provide opportunities for buildings to react to their environment in real time. Hence, reducing the energy demand of the built environment which is critical in addressing the issue of climate change. However, there is a distinct lack of human-centered interfaces, leading to discomfort among occupants. This not only results in discomfort, such as visual discomfort experienced due to an oversupply of light, but also a reduction in productivity. In this thesis, a novel dynamic building shading technology is discussed, and the occupant is added directly into the control loop, to discover their preferences, and to avoid visual discomfort and glare. Hence, the main posed research question of this graduation project states: “How can an automated system, consisting of switchable glazing and a system that can sense the needs of the occupant, be used to control glare in an effective manner?” An effective manner of controlling the switchable glazing should both minimise glare, the negative sensation associated with the oversupply of light, and, optimise the use of daylight. The occupant’s facial expression and micro-movements and a lux sensor are combined in a new control strategy, to sense visual discomfort in real-time. Previous studies are analysed to create an office-like environment to test this hypothesis, seeing whether it is possible to predict if one is experiencing glare by one’s facial movements. Two experimental studies are conducted, (i) the first experiment to determine the physical characteristics of the experiment room and (ii) the second experiment to test the novel control system. During the second experiment, a benchmark control strategy and the novel control strategy are tested in the office-like environment and the results are compared. The results from the facial movements show that, in particular, eyebrow movements, may be triggered by light. The results express the potential of adding the face to a control strategy for controlling the amount of light transmitted through the glazing. However, after evaluating the effectiveness of the system, its benefits in terms of daylight and improved availability of view are not clear. For now, at least, in its prototype form, the novel system appeared to be no worse than the benchmark.

The desired goal is an interaction between the user and switchable glazing, providing a personal comfortable indoor environment, whilst optimizing the usage of daylight. Such experimental studies, also to study the data with real sunlight, the most common source of glare. To reach this, more data has to be collected, however, the following key improvements are suggested; (i) gathering the occupant’s response regarding the level of discomfort immediately (in real-time), (ii) the matter of how to improve the potential for each individual to have their own system is investigated, (iii) the light should be measured via more sensors in different places (for instance fixed to the wall). It should be measured in real-time to determine which one is most beneficial. Furthermore, relation ought to be considered with the architectural design of the building. (iv) The experimental set up mirrors an actual office building to enhance the correlation of the data gathered during

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/Introduction

“Global climate change is one of the greatest challenges facing humanity in the twenty-first century” said Angela Merkel (Schellnhuber, 2010). Over the years, architecture has been influenced by many different factors, historical, political, economic, but now, due to the climate change concern, sustainability and impact on health and well-being of occupants is top priority in modern-day architecture (Lechner, 2015). The energy consumption of the built environment accounts for 40% of the European Union’s (EU) total energy consumption and 36% of the EU’s total CO₂ emissions, making it essential to reduce the energy utilization to meet the sustainable development goals (European Commission, 2013) (figure 1).

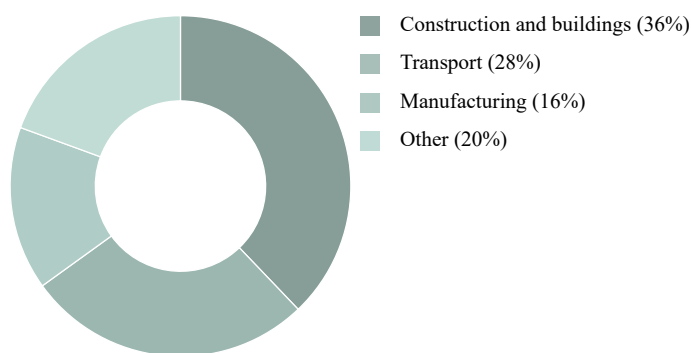


Figure [1]: EU’s total CO₂ emissions (European Commission, 2013)

Research, norms and technologies, are steadily contributing to the development and improvement of the built environment’s energy performance. However, this should not be at the expense of the indoor environment quality. Since, the indoor environment quality has an impact on the buildings’ occupants’ comfort, well-being, health and productivity (Ong, 2013). Well-being is strongly connected to health and productivity (Adams, 2019). Happy and healthy office employees are more productive than office employees with poorer well-being (Hamar, 2015). Consequently, good indoor environment quality might benefit businesses worldwide economically, as 90% of typical business operating costs can be spent on staff (WorldGBC, 2014) (figure 2). Therefore, smart buildings face several challenges. They must be sustainable in the use of resources alongside integrating advantageous evolving building technologies and should react to the occupants need including their health and well-being (Clements-Croome, 2018).

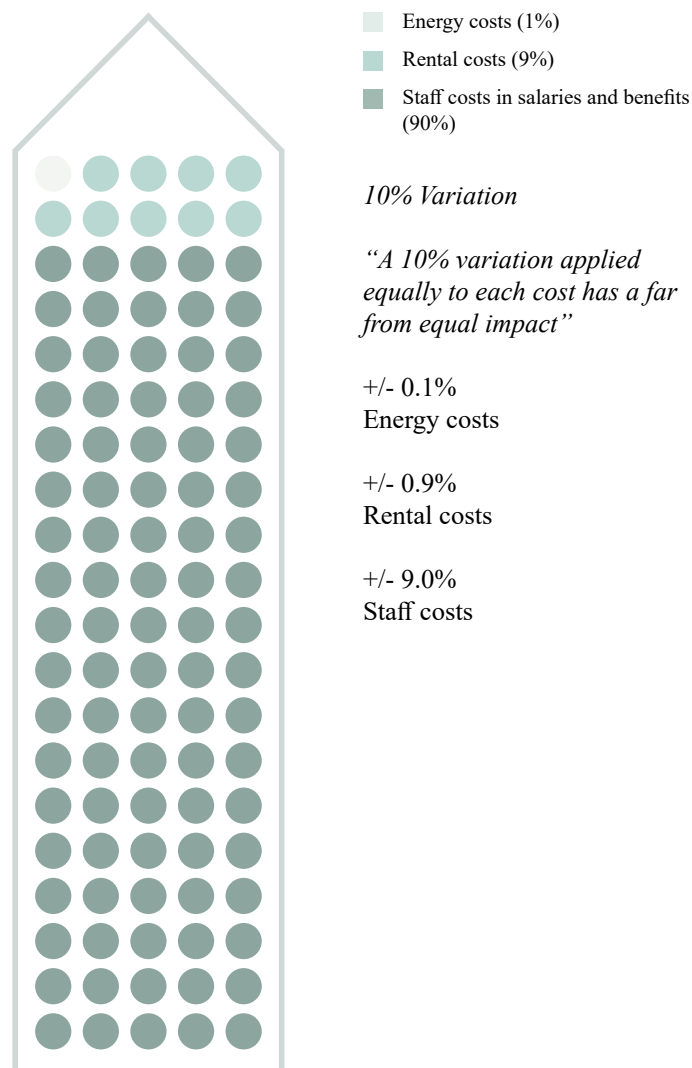


Figure [2]: World Green Building Council report: typical business operating costs (WorldGBC, 2014)

Building efficiency should be reviewed as enhancing the performance of a complex system created to deliver occupants a comfortable, secure, and appealing living and work environment (Quadrennial Technology Review, 2015). This calls for high-end architecture and engineering designs, quality constructed components, and affective operating systems. To enhance the energy performance of a building it is necessary to determine where the greatest amount of energy is attributed to. Different studies over time present that most of the building’s energy utilization in its life cycle is used during the operational phase. In 1997, Adelberth built and studied three dwellings to gain insight into the energy use of buildings. Adelberth found that 84% of the energy used throughout the buildings’ life cycles was in the operational phase (Adelberth, 1997) (figure 3).

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In the paper “Life cycle energy analysis of buildings: An overview” 73 buildings were evaluated, both residential and office, across 13 countries (Ramesh, 2010). The results point out that 80-90% of the buildings’ energy utilization is in the operational phase and 10-20% in the embodied phase (Ramesh, 2010). Thus, reducing the operating energy, through passive and active technologies, can improve the energy performance of a building’s life cycle, even if the embodied energy increases a little (Ramesh, 2010).

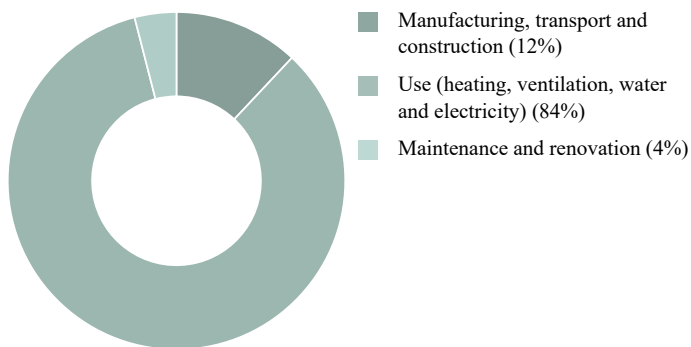


Figure [3]: A building’s energy use during its lifecycle (Adalbert, 1997)

Operating energy use varies per sector (Sisson, 2009). A great deal of the energy used by office buildings is needed for heating, ventilation, air conditioning (HVAC) and lighting (Department of the Environment and Energy, 2012). Figure 4 indicates the approximate distribution of the energy supply for an office building: 39% is used for HVAC, 25% for lighting, 22% for electric equipment (for instance computers), 4% for lifts, 1% for domestic hot water and 9% for other the uses. Modifying and thereby reducing the energy needs of these domains could strongly benefit the energy efficiency of an office building. Glass properties and the use of transparent components can affect the transmitted solar radiation, heat losses and gains, which has an impact on the energy usage for lighting and HVAC. Hence, glazing generally has a large impact on the total energy consumption of an office building (Graiz, 2019). Therefore, an optimal design of glazing and control over the solar radiation transmitted through glass is important to reduce CO₂ emissions of an office building. Not only can glazing increase the usage of daylight, it also provides view. View through a window may benefit the occupants health and well-being, as it may influence the recovery from surgery (Ulrich, 1984).

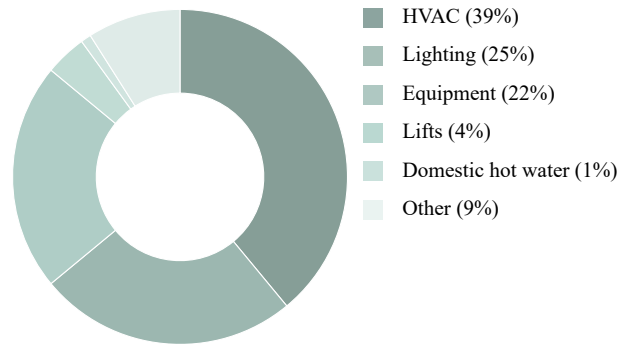


Figure [4]: Typical Energy Consumption Breakdown of an Office Building (Department of the Environment and Energy, 2012)

Building automation is another development that is essential due to the fact that manual operation building technologies (unaware insufficient doing) can increase the energy utilization (Sisson, 2009). Unsustainable energy utilization will continue to grow in all areas due to the growth of the world population (expected to be nearly 50% higher in 2050 than in 2000, an extra 3 billion people) and from increasing energy use per person. User behaviour (positive and negative) can make a substantial difference. Wasteful behaviour could raise the energy use with 33%, while clever energy (the minimum) use could decrease it by 32%. (figure 5). This means that energy use of buildings may be cut by 60%. An example of wasteful behaviour is, when the indoor environment is too bright and the occupant is experiencing visual discomfort, the occupant closes the blinds and turns to artificial energy demanding sources, such as indoor lighting. When highly reflective blinds are completely closed by the occupant, the heat gain may be reduced by approximately 45%. Thus, the occupant could be tempted to turn on the available heating devices, such as the radiator. Eventually, the occupant tends to leave the blinds closed, although, as the position of sun in relation to the façade changes during the day, it would not be needed anymore (Edwards, 2002). A number of studies have already shown that the user does not often adjust the blinds position, almost only when the light from the sun is too bright, the occupant closes the blinds (Escuyer, 2001). When the occupant retracts the blinds or shutters, one does so mostly to increase the amount of daylight, to save energy or to create a view (Galasiu & Veitch, 2006). Unfortunately, the occupant usually does not open the blinds quickly (Meerkbeek, 2014).

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The insufficient use and its consequences led to interest in developing various techniques to reduce the energy demand of buildings via glazing technologies and various automated dynamic shading systems. For this reason, research studies have been carried out in order to better understand the occupant's behaviour. A study found that 88% of occupants opened the blinds when they were closed automatically, they opened the blinds after only 15 minutes (Reinhart and Voss, 2003).

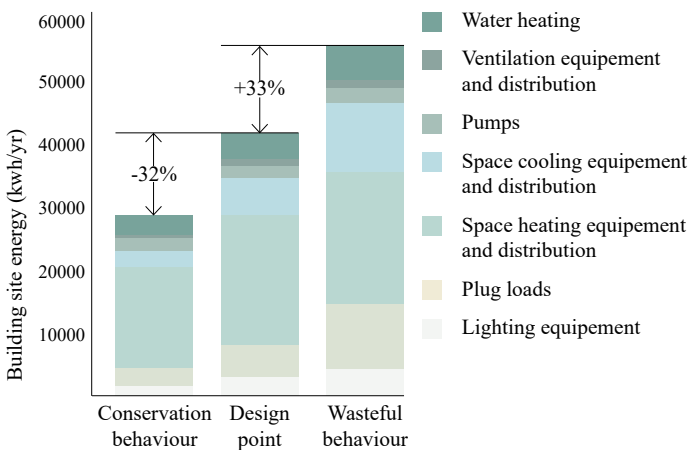


Figure [5]: Effects on the energy performance of a building comparing manual insufficient operating (negative user behaviour) against conservation operation (positive user behaviour) (Sisson, 2009).

Because of the unaware insufficient use of the blinds, due to the visual discomfort of the occupant, the energy performance of the building decreases (Paik, 2006). Building automation is a promising solution to reduce the carbon footprint of the built environment (Favoino, 2015). Nevertheless, the automated control system that reduces the energy demand may still decrease the indoor environment quality. The automated building technologies often react to exterior environmental factors and have little relation with the occupant inside the building. The technologies might lead to occupant visual discomfort and glare. To prevent this the occupant must be considered the control strategy of the building component.

The interest for integrating the occupants' needs, for sake of increasing comfort, satisfaction, health and well-being in the building and its components has grown. This is provoked by the possibility that it could increase productivity and as a result

benefit the business economically. Besides that, consumers are prioritising health and wellness more and more nowadays (Weinswig, 2017). This growing interest is certainly reaching the office buildings, employees and employers, as some businesses offer their employees an hourly Yoga class at the office to reduce stress (Smith, 2007).

WELL and Fitwell are new building standards focussed on the health and well-being of the occupants, well-established building standards such as BREEAM and LEED are also adding components of comfort, health and well-being to the energy and sustainability elements (Ward, 2017). Methods to sense and respond or predict the occupant's needs are studied for the capability of integrating the occupants' comfort, satisfaction, health and well-being influenced by the environment, into building components. Still, progress in the techniques to capture the occupant's needs is limited (Allen, 2019). Namely, the methods may deliver infrequent data and can be disruptive. Thus, this research focuses on a technique to capture the occupants needs in a less intrusive manner alongside providing frequent data.

The occupants' discomfort can be caused by many indoor environmental domains such as thermal environment, visual environment, view, acoustic environment and more (Paik, 2006). This study is mainly focussed on the visual environment, view and glare. The posed problem is that the existing automated systems controlling the solar radiation transmitted through glass, to reduce the energy demand of the building, do not yet correlate with the occupants' comfort. Taking this as a starting point, the following main research question is posed: "how can an automated system, consisting of switchable glazing and a system that can sense the needs of the occupant, be used to control glare in an effective manner?" The aim of this research is to provide a novel system that is capable of effectively controlling the switchable glazing. Ergo, enhancing the energy efficiency of an office building, optimizing the usage of daylight, increasing the availability of view and minimising the occupant's visual discomfort.

For the purpose of achieving this, an introduction to the history of light and architecture is made, where after visual comfort, façade strategies, and methods to sense the occupants' needs will be outlined.

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These literature reviews are essential to understand the following chapters into forming an effective control strategy, able to generate an interaction between the switchable glazing and the occupant. Previously conducted experimental research studies have been reviewed, where the visual environment was unpleasant for the participant. Whereafter a similar experiment setup is built, where data is derived and the control strategy is tested. This study will conclude with a description of how an automated system can be used to effectively control switchable glazing. Lastly, recommendations will be proposed for consecutive research.

1. The history of architecture and light

“The history of architecture is the history of the struggle for light” said Le Corbusier (VELUX, 2006). Le Corbusier explained that light and architecture have always been connected. At the very beginning, daylight was the only light source available for the indoor environment. Buildings were meant to shelter the occupant from exterior weather conditions, such as rain, to provide thermal comfort, but openings were also necessary to provide visual comfort with the aid of natural light (Carmody, et al., 2007). Le Corbusier described the relation between light and architecture as: “Architecture is the masterly, correct and magnificent play of masses brought together in light. Our eyes are made to see forms in light; light and shade reveal these forms; cubes, cones, spheres, cylinders or pyramids are the great primary forms which light reveals to advantage; the image of these is distinct and tangible within us without ambiguity. It is for this reason that these are beautiful forms, the most beautiful forms.” In other words, people interact with architecture and its forms through the means of light. Without light reaching the human eye, one would not be able to see its environment. Lighting effects human surroundings in many ways; light reveals aesthetic and beauty; displays colour and tone; provides the ability to perform visual tasks; navigation and orientation; influences human comfort and behaviour; as well as circadian rhythms and health (Boyce, 2014). In order to generate effective and efficient lighting, it is key to understand how to use light to achieve these ends.

The Pantheon in Rome expresses an effective way of using daylight: as the light source (sun) moves, the natural lighting highlights the interior shapes and creates strong shadows, thus revealing the architectural aesthetics (VELUX, 2006) (figure 6). The Pantheon is an early historical example of a building which demonstrates the value and a skilful utilization of light in architecture. For many years, indoor spaces have been lit, only by daylight. Daylight is dynamic, orientation specific and site-specific. Proven by the Pantheon, soon architecture was designed precisely to embody natural lighting and the amount of sunshine available during the day. Buildings in cooler areas around the world were realised with taller windows whereas buildings in warm areas had small windows to lower the amount of light entering the space indoor.

When darkness appeared at the end of the day, torches and candles provided light where needed. Later, by the hand of technical developments, torches were replaced by artificial forms of light produced by oil lamps, gas lamps and eventually arc lamps. People desired more light for indoor visual tasks. As of today, architecture circles around the two forms of lighting, daylight and artificial light.

Koshino house, a more modern and later realised architectural design by Tadao Ando, exhibits intriguing choreography of daylight (figure 7). The walls wait until the orientation of the sun changes, where light and shadows reveal materials and striking forms. The pursuit of light is a constant characteristic in the creations of the architect Tadao Ando. He plays with the site-specific behaviour of daylight. The building’s visitor’s visual experience changes during the day, since the appearance of the wall transforms. “Light is the origin of all being, light gives with each moment, new form to being and new interrelationships to things, and architecture condenses light to its most concise being. The creation of space in architecture is simply the condensation and purification of the power of light” says Tadao Ando justifying the relation between light and architecture (Nyawara, 2018). The architect uses the power and advantages of daylight in architecture. Both the Pantheon and Koshino house, an old and new architectural design express that natural light influences architecture and the people’s indoor experience very much. Light can bring beauty, reveal shapes, colour and material, create an exciting ambience and more.



Figure [6]: Pantheon in Rome (Painting by Giovanni Paolo Pannini, 1734)



Figure [7]: Koshino House designed by Tadao Ando (Photo by Mine Yilmaz-Ulas)

2. Designing for light

Human beings need light to see their surroundings. Visible light, visible to most human eyes, is a small component of the electromagnetic (EM) spectrum. The EM spectrum contains different parts which are defined by wavelength range (Pritchard, 1995). As light moves through the atmosphere like a wave. When it reaches a physical material it can be absorbed, reflected and transmitted (Michel, 1996). The function of light entering a building is typically offering sight and revealing objects (Pritchard, 1995). One almost always depends on light to perform tasks. Aside from the visual processes in which light plays a large role, it contributes to non-visual processes as well (Hanifin, 2007). Imagine a bright environment, one instantly feels much more alert than in the dark. After a longer period, the biological clock reacts to light and accordingly influences mood and performance during the day. Furthermore, the biological clock also regulates the day-to-day pattern of alertness (Górnicka, 2008). Hence, visual processes revolve around revealing colour, tone, aesthetic, beauty to the viewer, and naturally the ability to perform tasks, aid in navigation and orientation. Non-visual processes can be divided into immediate and long-term effects. The occupant's sensation of comfort and delight as well as the pupil response, melatonin suppression and alertness are immediate effects. Long term effects can result in change of physiological circadian rhythms, alertness pattern and health (Górnicka, 2008). The visual and non-visual effects of light are important to understand to design a space with and for good lighting.

2.1 The context

When designing with and for light the context is essential. How much light is used in various indoor spaces, differs. Where increasingly complex tasks must be done indoor, more light is desired. Where one needs greater luminous power, an artificial light source can be added if not enough daylight is available. Not only the quantity is important, as the quality of light can influence the occupant's mood. A study compares participants working in artificial light to people working in daylight (Boubekri, 2014). The results show that the form of light has effects even beyond the workplace, for instance, the participants with only artificial light sleep an average of 46 minutes less per night.

Research shows that lack of sleep and poor sleep quality have a number of consequences for health and safety. For example, insufficient sleep and reduced sleep quality have been linked to higher cortisol levels in the evening, disrupted glucose metabolism, a heightened appetite due to lower leptin and higher ghrelin values plus a higher body mass index, as well as increased tiredness and decreased performance, alertness and mental concentration, which can lead to an increased error rate and subsequently to an increased risk of injury (Boubekri, 2014). A prior similar study showed that the ranges of vitality, social functioning and mental health scores for those who worked in dark offices were lower than those for those who worked in offices with more lighting (Mills, 2007). In addition, another study aimed at forecasters of burnout among nurses observed that being exposed to at least three hours of daylight per day resulted in reduced stress and increased satisfaction at the job (Alimoglu, 2005). All this strongly suggests that the architectural design of office environments ought to focus on sufficient exposure of daylight for workers to promote the health and well-being of office staff.

2.2 Daylight

Daylight is dynamic, orientation specific and site-specific. Daylight offers benefits in terms of variability, psychology, vision and energy. Natural light also has its disadvantages in terms of variability, glare, overheating, etc. Some of these examples, associated with natural light, are physical factors. More physical factors are temporal and seasonal variations, characteristics of daylight, colour, temperature and lux distribution. Both physical and occupant related factors influenced by light affect the design of the building's envelope. The human matters and the physical factors could benefit the indoor environment for the occupant and could increase the energy performance of the building. For activities related to an office environment, the most important physical requirement is availability of the sufficient and ambient quality of light in the room (Raymond, 1997). The room must provide the occupants a visually comfortable workspace for them to carry out their work. Visual comfort is reliant on factors such as the intensity of the available daylight, the direction of the light from the source, the contrast between environment, surfaces as a reflective

2. Designing for light

source, for say a table, the type of activity to be carried out, the specific occupant, and the reaction of the occupants visual system. Since the viewer, in other words occupant, became involved in the design process for light, architects and light designers have made great strides in the technology for light.

2.3 Visual delight

Lighting designer Richard Kelly explains three principles of light in the article “Lighting as an Integral Part of Architecture, ambient luminescence, focal glow and the play of brilliants” (Kelly, 1952). Kelly argued that visual beauty is perceived by interplay of the three principles. Ambient light produces shadow less illumination (Kelly, 1954). An example of ambience luminance is the light entering through a cloudy sky. Focal glow helps individuals see. It is like the light from a desk lamp that shines on the paper that must be read. The principle play of brilliance is like the light from candle flames. Play of brilliance excites the optic nerves and awakens curiosity. The third principle of light can be distracting, annoying or even dangerous when the attention is drawn to a bright object (relatively to the visual background), which leads to the needed information becoming unavailable. In this case the viewer is certainly experiencing visual discomfort. When the attention is drawn to desirable information, it is sensed as reassuring and satisfying (Lam, 1977). In other words, the space will provide the viewer visual comfort.

2.4 Visual comfort

Visual comfort is generally understood as the quality of a light source that meets several criteria (illuminance, luminance ratios, colour rendition, modelling) (Ganslandt, 1992). Visual comfort means that the occupant’s vision is good, the occupant finds the light in the environment comfortable and does not want to change it. However, occupants may have different preferences, visual comfort is therefore subjective (Guzowski, 2000). The different preferences referring to domains that influence the visual comfort of the occupant are influenced by the personality, culture and the human being’s bioregion (Guzowski, 2000). Nevertheless, Carlucci describes that visual comfort is influenced by the physiology of the

human eye and basically by the physical quantities describing the amount of light and its distribution in space (Carlucci, 2015). Hence, visual comfort can be evaluated using objective values related to lighting. Light in and around a building can give beauty to the building, and also influence the mood and productivity of the occupants in the building, if designed optimally (when it is experienced as comfortable) (Borsuit, 2015). Borsuit describes that the occupants favourite light source is daylight entering the building via an opening or transparent material. On the other hand, direct sunlight can also cause visual discomfort for the occupant and decrease the occupant’s productivity (Hopkinson, 1997). As a result, façade-related visual performance is influenced by a complex interplay between numerous different factors (Reinhart, Wienold, 2011). In terms of natural light, an ideal façade would ensure continuously at least (i) sufficient levels of well-distributed daylight illumination, (ii) the absence of disturbing glare for all occupants, and (iii) full view of the surroundings.

2.5 Visual discomfort

Visual (dis)comfort has different dimensions. Firstly, availability of daylight is important, meaning the task illuminance and its uniformity. Secondly, the view, the visual quality and the visual interest must be experienced pleasantly. In addition, contrast in the field of view, colours and temperature of light can be sensed as unpleasant. Visual discomfort could be a consequence of the third principle described by Kelly, play of brilliance, resulting in the information needed becoming unavailable due to a bright, distracting and annoying lightsource. Common instances where such discomfort is caused are the headlights of approaching vehicles when driving in the dark and direct sunlight through windows during the day (figure 10 & 12). Due to the direct sunlight through the windows during the day, the readability of the computer screen could be affected. Natural light entering the room via the window of the façade may cause glare (figure 8). Glare is known as a primary triggering factor in the use of blinds and shutters (O’Brien, Kapsis, & Athienitis, 2013) (Van Den Wymelenberg, 2012) (figure 9).



Figure [8]: Sun shining directly into the room causing glare



Figure [9]: Shutters closed to minimise the light entering the space

2. Designing for light

2.6 Glare

Glare is a negative sensation of light. One faces glare when there is a great amount of luminance in the visual field, that is much greater than the luminance to which the eyes are adapted (Ganslandt, 1992). This leads to discomfort, reduced visibility or both. Quite simply, glare occurs when too much light enters the human eye and interferes with the eye's ability to manage it. Glare naturally causes an uncomfortable visual environment. Glare can be divided into reflex glare, disability glare, discomfort glare and contrast glare between visual target and surroundings (Ganslandt, 1992).

2.7 Disability glare

Disability glare leads to diminished visual performance, due to too much luminance causing a loss in visibility (figure 10). Probably the most important cause is scattering of light from the glare source in the optical system of the eye. The scattered light travels through the cornea, the eye chamber and the lens to such a degree, that a uniform luminance hindrance is drawn over the retina, the hindrance reduces the apparent contrast and makes it hard to see (figure 11).

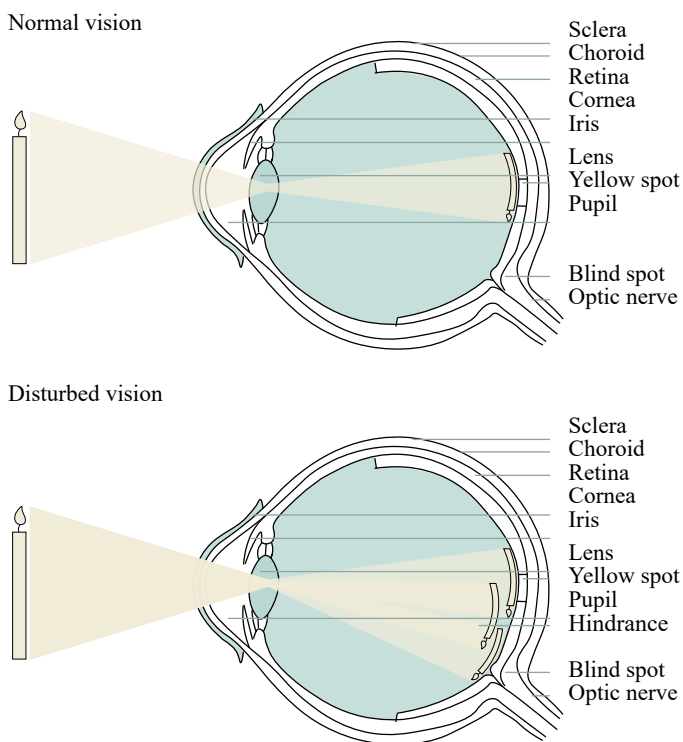


Figure [11]: Sectional view of the eye, representation of the scattering of light (Ganslandt, 1992)

2.8 Discomfort glare

Discomfort glare is a sensation of discomfort or even pain caused by excessive luminance in the field of view (Ganslandt, 1992) (figure 12). An earlier mentioned instance of visual discomfort, annoyance due to the headlights of an oncoming car while driving in the dark, is illustrated in figure 12. Discomfort glare has subjective rating, is in most cases below disability glare and indirect consequences can be headaches and tiresome. These consequences are often not directly measurable. Glare can decrease the productivity of the occupant, even more when the task is visually demanding (Sivak, 1991).

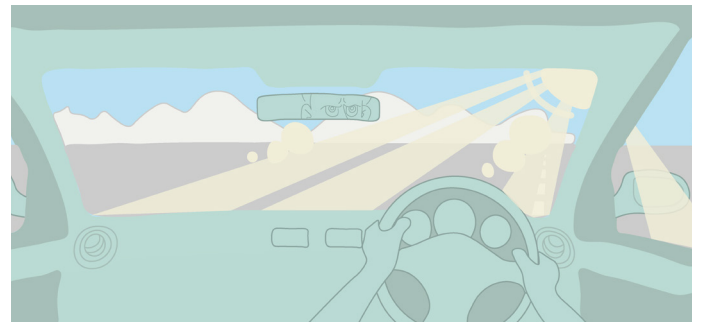


Figure [10]: Disability glare instance where too much light during the day is causing loss of visibility.

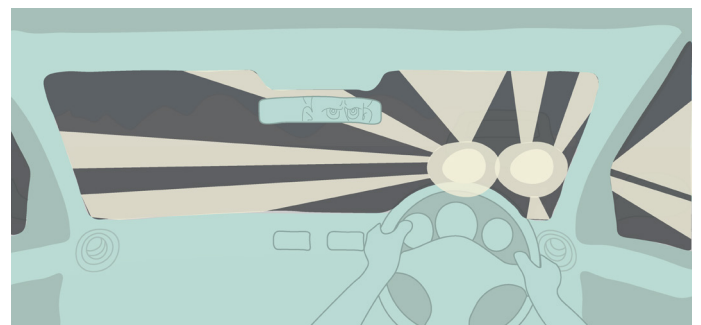


Figure [12]: Discomfort glare instance where the headlights of an approaching vehicle are causing irritation.

2. Designing for light

2.9 Glare parameters and prediction

The physical parameters that determine the degree of discomfort are largely known. The more important parameters are the luminance of the glare source in the direction of the observer. The principal structure of existing complex glare formulas involves; luminance of the glare source; the background luminance; size of the glare and position of the source relative to the viewing direction (Ganslandt, 1992). There is a difference between (i) direct glare and (ii) indirect glare. Direct glare is caused by high luminance from a light source present in the field of view. Reflective glare results from the reflection of high brightness in a polished surface in a field of view for instance reflection of the sun on a mirror can cause discomfort (Ganslandt, 1992). Figure 13 illustrates a situation where glare is experienced and helps to clarify the difference between luminance and illuminance.

2.10 Illuminance

Illuminance assesses the density of luminous flux. Figure 13 explains that illuminance expresses the amount of luminous flux from a light source (light bulb, sun, etc) falling on a surface. At any point it can be measured in a room. In Erco handbook of lighting design is explained: “Illuminance can be determined from the luminous intensity of the light source. Illuminance decreases with the square of the distance from the light source (inverse square law)” (Ganslandt, 1992).

2.11 Luminance

“Whereas illuminance indicates the amount of luminous flux falling on a given surface, luminance describes the brightness of an illuminated or luminous surface. Luminance is defined as the ratio of luminous intensity of a surface (cd) to the projected area of this surface (m²)” (Ganslandt, 1992).

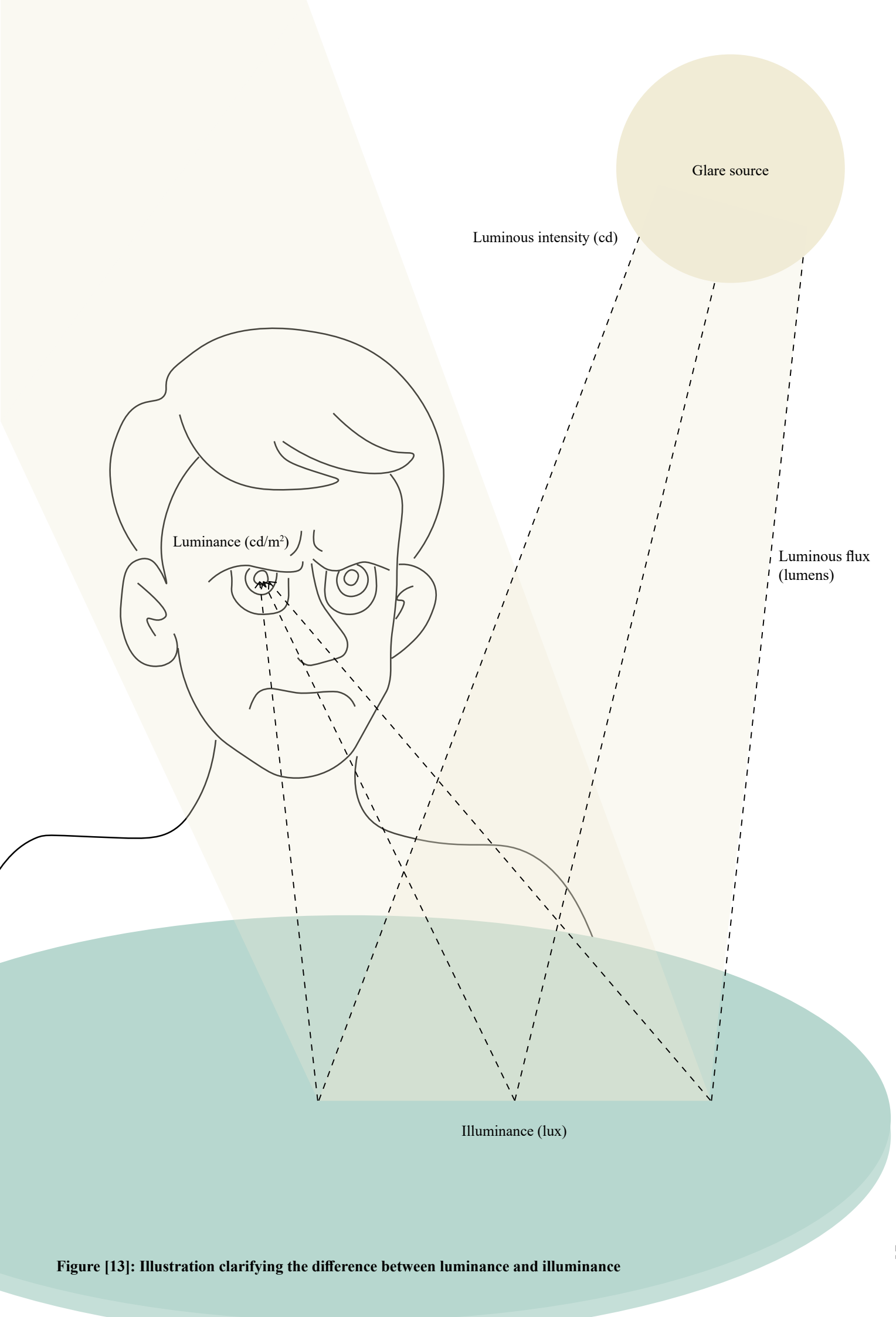


Figure [13]: Illustration clarifying the difference between luminance and illuminance

2. Designing for light

2.12 Daylight glare metrics

Different methods exist to predict when the occupant could experience glare. The principle structure of a glare formula is:

$$G = f \left(\frac{L_s^{a_1} \cdot \omega_s^{a_2}}{L_b^{a_3} \cdot P^{a_4}} \right)$$

L_s : Luminance of source [cd/m²]

ω_s : Solid angle of source [sr]

L_b : Background luminance [cd/m²]

P: Position index [-]

2.13 Daylight Glare Index

In 1972 Hopkins developed the Daylight Glare Index (DGI) (Hopkinson, 1972). The DGI was the first metric which considered large glare sources, such as the sky view through the window. The user polling and testing condition were published. Direct sunlight and reflections typically not accounted for, but they can be.

$$DGI = 10 \log_{10} 0.48 \sum_{i=1}^n \frac{L_s^{1.6} \cdot \Omega_s^{0.8}}{L_b + 0.07 \omega_s^{0.5} L_s}$$

L_s : Luminance of source [cd/m²]

ω_s : Solid angle of source [sr]

L_b : Background luminance [cd/m²]

Ω_s : [ω_s/P] Solid angle subtended of the source

2.14 Daylight Glare Probability

Wienold and Christoffersen introduced The Daylight Glare probability (DGP) method (Wienold, 2006). It is a method to measure glare by taking the vertical luminance, at the position of the occupant's eye, into account and illuminance of the light source (Oh, 2012). Throughout experiments and testing it is proven that the method matches

up (0.94) to the subjective experience of glare by occupants (Wienold, 2006). The DGP is a combination of the vertical eye illuminance with the modified glare index formula. The DGP equation states (Wienold, 2006):

$$DGP = c_1 \cdot E_v + c_2 \cdot \log(1 + \sum_i \frac{L_{s,i}^2 \cdot \omega_{s,i}}{L_v^{a_1} \cdot P_i^2}) + c_3$$

E_v : vertical Eye illuminance [lux]

ω_s : Solid angle of source [sr]

L_s : Luminance of source [cd/m²]

P: Position index [-]

$c_1 = 5.87 \cdot 10^{-5}$

$c_2 = 9.18 \cdot 10^{-2}$

$c_3 = 0.16$

$a_1 = 1.87$

E_v in the equation is the vertical illuminance, $L_{s,i}$ is the luminance of light source, $\omega_{s,i}$ is the solid angle of light source and P_i is the position index of light source (Wienold, 2006).

Wienold created a simplified method: calculating the vertical eye illuminance using the daylight coefficient method (Wienold, 2006).

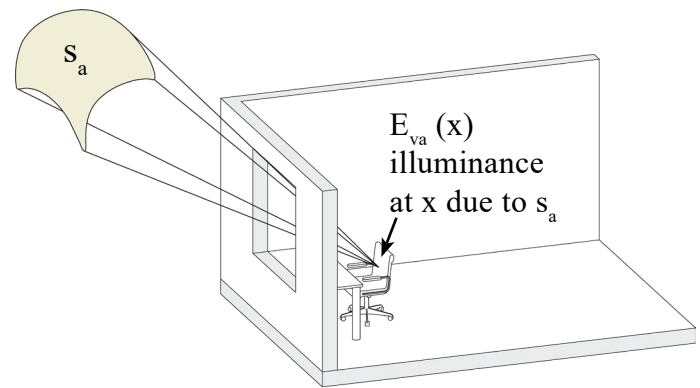


Figure [14]: Illustration expressing the simplified DGP method (Wienold, 2006)

2. Designing for light

The method is possible by using a photographic technique creating high dynamic range images (HDR). A sequence of low dynamic range photos must be taken by a fisheye camera of the room with specific settings to create an HDR image. The fisheye lens is important to use since it must be relatable to the human eye. HDR images are calibrated to create luminance maps. The luminance maps help to study the daylight availability, glare and visual comfort of the space. The DGP comes with a scaling system that expresses what is preferable by the occupant. The scaling has four ratings: (i) imperceptible ($DGP < 0.35$), (ii) perceptible ($0.35 < DGP < 0.40$), (iii) disturbing ($0.40 < DGP < 0.45$), (iiii) intolerable ($DGP > 0.45$).

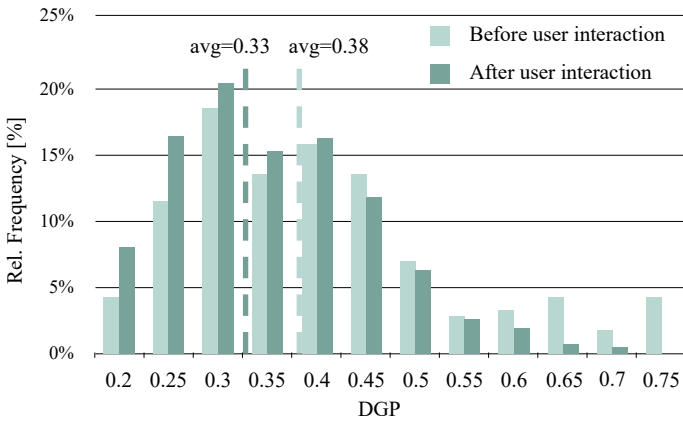


Figure [15]: The acceptance of glare (Wienold, 2009)

2.15 Unified Glare Rating

The CIE established a glare rating procedure for interior lighting, the Unified Glare Rating (UGR). The UGR is an objective measure of glare that is used by lighting designers to help control the risk that occupants of a building will experience glare from the artificial lighting (Mistrick, 1999). UGR values range from 40 (extremely high glare) to 5 (very low glare). In most cases the less glare the better, meaning a low UGR is preferable to a high UGR. International standards such as EN12464 recommend maximum UGR for different situations. $UGR < 19$ is generally advised for many offices and classrooms. UGR is an expression of the relative intensity of light from a light fixture compared to the intensity of light from the surroundings, as perceived by the occupant. The UGR method can only be used for an interior lighting installation. It cannot be calculated for an outdoor installation (such as street lighting), nor can it be calculated for a light fixture on its own.

The formula for calculating the UGR states:

$$UGR = 8 \log_{10} \left(\frac{0.25}{L_b} \sum_{i=1}^n \frac{L_s^2 \cdot \omega_s}{P} \right)$$

L_s : Luminance of source [cd/m^2]

ω_s : Solid angle of source [sr]

L_b : Background luminance [cd/m^2]

P: Position index [-]

Different activities ask for different lighting settings. The following table presents approximate values that apply to several different types of occupation (*).

UGR Value	Application
16	Bedroom & Meeting Rooms
19	Offices & Commercial
22	Industrial work (High)
25	Industrial work (Low)
28	Circulation areas and corridors
>28	Deemed as harsh lighting (not acceptable)

Table [1]: Appropriate UGR value for different types of occupation (*)

2.16 Evalglare

Evalglare is a Radiance-based tool developed by Wienold to evaluate the glare in a scene (Pierson, 2018). Earlier stated is that the DGP can be calculated by taking a sequence of low dynamic range photos with a fisheye lense of the scene and converting these into an HDR image. “Evalglare determines and evaluates glare sources within a 180 degree fisheye HDR image, given in the Radiance image format (.pic or .hdr)” (Wienold, 2016). The output of evalglare is hence a list of uncomfortable glare indices that are calculated from the glare sources identified by the algorithm in the luminance map (Pierson, 2018). Evalglare calculates the DGP, DGI, UGR, VCP, CGI, Lveil. For this study, Evalglare is used to determine the physical settings of the experiment room. The DGP, DGI and UDR outcomes of the various settings will be studied.

3. The perception of light

The world around human beings is perceived through the aid of light. As light continuously shifts caused by exterior processes, the surroundings change and are experienced differently. When people interact with their environment, move around or act in a different way, they find themselves in different states.

3.1 The human visual system

The human visual system is composed of two systems: the eye and a part of the brain. The eyes translate incoming light rays into neural activity. Firstly, the light travels through the cornea, the protective, transparent layer that surrounds the eye. See figure 16 for reference. It then passes through the pupil, an opening behind the cornea and in front of the lens. The iris can contract or release, depending on the amount of light that is transmitted, this is how the iris controls the size of the pupil (figure 17). The light is focused on the retina by the lens and the cornea through refraction. As the cornea is a curved shape, it deflects the light in such a way that the inverted image is projected onto the retina. The photons of light are then captured by the photoreceptors in the retina, which converts the energy of the light into electrical signals. These signals then travel via the optic nerve to the brain, where they are turned around and converted to images that can be perceived.

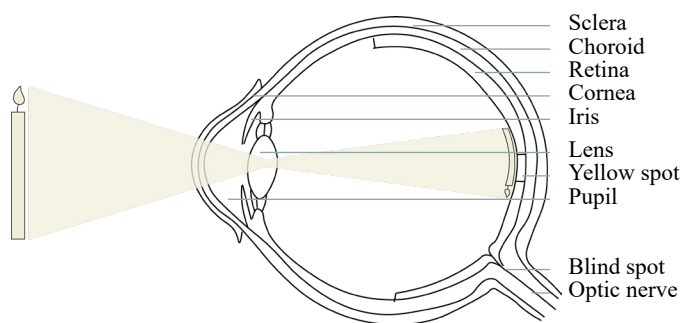


Figure [16]: Sectional view of the eye, representation showing the parts of the eye which are significant in the physiology of vision (Ganslandt, 1992)

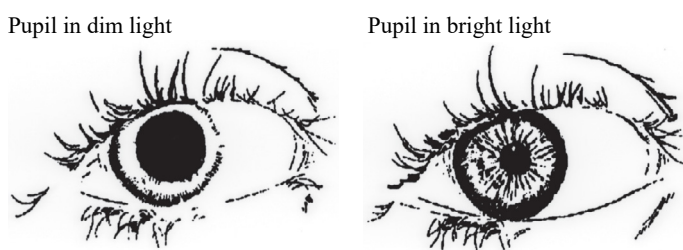


Figure [17]: Contraction or release of the iris (*)

There are three types of photoreceptors: rods, cones and intrinsically photosensitive retinal ganglion cells, which are able to produce chemical signals that transmit information to neurons in the retina and then to the brain. The rods are more light-sensitive than the cones and can aid with sight even in the dark. The rods can be activated by a single photon, and therefore visual experience in very low light is based solely on signals delivered by the rods. When one moves from a well-lit site to a dark area, one initially perceives extreme darkness because the rod pigments are suppressed by the bright light. In addition, the cones are unable to perform at low light intensities. Over a period of time, the rods produce the corresponding protein rhodopsin in the dark, which enables the retina to perceive light again, as this protein breaks down into retinal and scotopsin and then causes the retina to become transparent. This process is called dark adaptation.

The opposite reaction occurs when going from dark to bright light. Because both the rods and cones are triggered, large amounts of photopigment are broken down simultaneously, resulting in an overwhelming sense of signal. The inhibition of rod function and the reduction of retinal sensitivity is called light adaptation. The opposite reaction occurs when going from dark to bright light. Because both the rods and cones are triggered, large amounts of photopigment are broken down simultaneously, resulting in an overwhelming sense of signal. The inhibition of rod function and the reduction of retinal sensitivity is called light adaptation. Dark adaptation can take up to an hour, due to the slow rate of rhodopsin regeneration. Conversely, light adaptation is much faster; within a minute, cones can be activated sufficiently to take over. (Mahroo, 2004). Cones ensure colour vision, and the capability to see contours and edges. While rods have one chemical, cones consist of three to signal colour related information. The spot known as the fovea has the largest concentration of cones. This enables one to see crisp outlines of objects on which one is focused. Prior to reaching the rods and cones, however, light passes through layers of what are known as bipolar, amacrine and ganglion cells (Curcio, 1990).

3. The perception of light

They affect the so-called receptive fields around the ganglion cells. These ganglion cells allow the eye to process local contrasts before they are sent to the brain, so that changes, contrasts and movements can be rapidly identified even before they are sent to the brain. Bipolar cells transmit information from rods and cones to the ganglion cells. They are responsive to an increase or decrease in local light intensity and can thus be switched “on” or “off”. They affect the so-called receptive fields around the ganglion cells. These ganglion cells allow the eye to process local contrasts before they are sent to the brain, so that changes, contrasts and movements can be rapidly identified even before they are sent to the brain. In addition, the ganglion cells play a role in regulating the human circadian rhythm. Via the optic nerve fibres that go to the right and left hemispheres, visual information is transmitted from the thalamus to the back of the brain, the occipital lobe, as can be observed in figure 18 (Bernstein, 2010). This is where clusters of cells called feature detectors, which are responsive to particular features of the visual world, signal the shapes of objects, such as angles, edges and corners. (Hubel & Wiesel, 1979). For the brain to be able to digest the information that enters it, certain systems must be in place. At times these systems demand effort and concentration, yet most sensory input is unconsciously transformed into meaning.

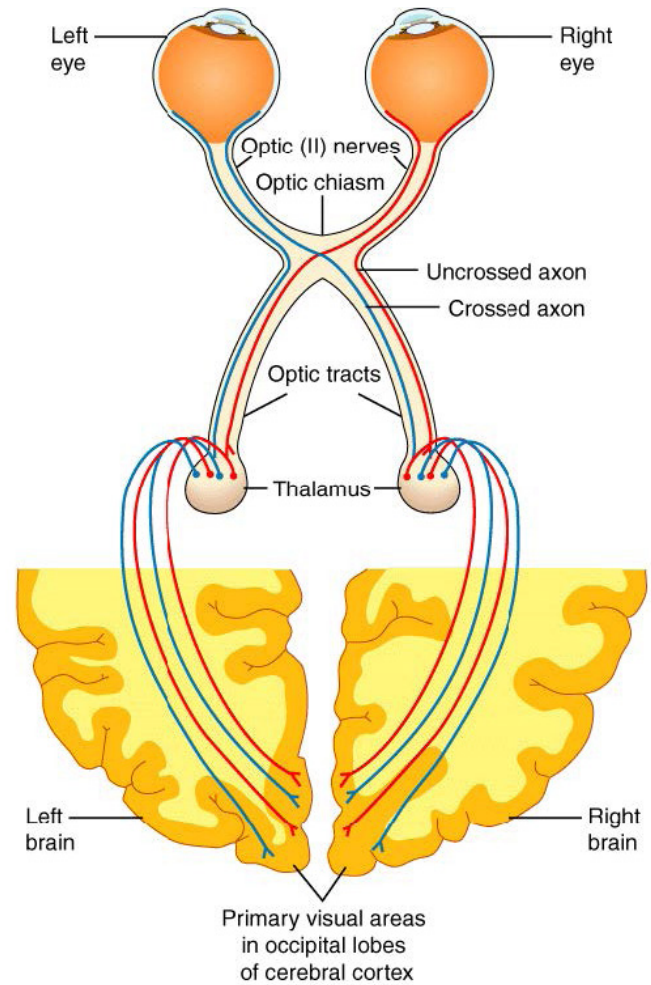


Figure [18]: Visual system (Bernstein, 2010)

4. Designing façades

The façade is the principal skin of a building. It faces the street, park or any other external factor. As earlier described, it is a skin that should protect the occupant from external factors such as rain or wind. Architecture should be designed precisely to use the available light of the day efficiently. The location where a building is realised affects the characteristics of the façades. The design of the building envelope responds to its climatic environment. Before is mentioned that buildings in cooler areas around the world are realised with taller windows, whereas buildings in warm areas, for instance in southern Europe, had small windows to lower the amount of light entering the space indoor. Differences between the façades are notable in traditional architecture as in modern architecture. An example of a building in a cooler area, Delft, with taller windows is presented in figure 19. A relatively old residential building in Italy (figure 20), a warmer area, shows the use of smaller windows in the façades.



Figure [19]: Traditional residential building in the Netherlands, Delft



Figure [20]: Traditional residential building in Italy, Sansepolcro

4. Designing façades

4.1 Glass façades

Modern office buildings are often designed with glazed façades (figure 21). Using glass has many reasons. Glass façades can contribute to the beauty and panache of a building. Moreover, glass can be moulded in different shapes and offers the architect exciting forms to integrate in the building envelope. Glass is a translucent material that can transmit a large quantity of solar radiation, which almost no other material can. In 2013 Jin states in the article, “Sensitivity of façade performance on early-stage design variable”, that in (non-adaptive) building envelopes, the transparent component offers the largest probability to benefit the energy demand (Jin, 2014). The glazing thermo-optical properties, the g-value, the U-value (U_g), the visible transmission of the transparent façade (T_{vis}) and the window to wall ratio (WWR) provide the largest potential in energy savings (Jin, 2013). Glazing systems generally have a large impact on the total energy consumption of office buildings (Graiz, Azhari, 2019). Glass properties can affect the transmitted solar radiation, heat losses and gains, which has an impact on the energy usage for lighting and HVAC. Glass does not require a lot of cleaning and maintenance. Furthermore, it can have various appearances in colour as well since it can be laminated.

A prior human related advantage is the aspect that the occupant can enjoy a view (Christoffersen and Johnsen, 2000). Christoffersen and Johnsen concluded that office employees prefer to sit near windows. Christoffersen et al. studied 20 Danish buildings and what the most positive aspects of the window was (Christofferson et al., 1999). They found that the occupants like to be able to check the weather outside and to have the option to open the window (Christofferson et al., 1999). Farley and Veitch (2001) point out via literature, in the paper “A Room with a View: A Review of the Effects of Windows on Work and Well-Being”, that people prefer natural rather than built or urban views from windows. Windows with a view of nature were shown to improve work and well-being in a multitude of ways, including enhancing job satisfaction, job value, perceptions of self-efficacy, perceptions of physical working conditions, life satisfaction, and reducing the intention to quit and the recovery time of surgical patients.

Yet access to a view did not improve student performances or the actual productivity of office workers (Farley, 2001). The research of Hellinga (2013) concludes that the most frequently mentioned benefit of windows was the view to the outside that it provides, followed by access to daylight (Hellinga, 2013). Hellinga confirms the findings of Christoffersen et al. (2000) and Farley and Veitch (2001), namely, that providing a view to the exterior is most appreciated by the building users (Hellinga, 2013). The literature research performed by Hellinga presents that in an office, the window should cover at least 20-25% of the façades area and desirably 30% or even more. The results of both the questionnaire survey and the scale model survey conducted by Hellinga are in line with this result and indicate that a fully glazed façade is generally not appreciated (Hellinga, 2013).

Stated is that the glazed façade transmits solar radiation (light) which has an impact on the energy demand of the building and the indoor environmental quality. However, the solar radiation could result in overheating and visual discomfort (glare) (Allen, 2018). Glare is a severe issue in these office building since it has disadvantages resulting in visual and non-visual consequences. It is annoying when the occupants cannot read their screen due to too much and bright light entering. The traditional way to stop glare in these offices is the use of miniblinds. These miniblinds could firstly only be controlled manually. In some cases, the blinds were mostly always completely closed. The heat gain of the façades decreased instantly due to the solar radiation not being transmitted through the blinds. The scale of the building in figure 17 presents the large number of occupants, how many rooms have to be heated with artificial sources and how many artificial lights are used if the blinds are shut. Consider the impact on the energy performance of the building due to the designed façades. Losing heat gain by natural light is a pity since the glass has the possibility benefit the energy performance of the building.



Figure [21]: Glazed façades (Photo by Maciej Lulko)

4. Designing façades

4.2 Expansion in urbanization

In 2018, 55% of the world's population lived in urban environments (United nation, 2018). In 2030 60% of the population is expected to live in urban areas and in 2050 this may rise to 68% (United Nations, 2018). This draws attention to realising more high-rise buildings in cities in order to accommodate the increasing number of people. Cities all over the world already have high-rise buildings with glazed façades and the idea of even more in the future stresses the importance of improving the building energy performance. Photos of Amsterdam (figure 22) and Rotterdam (figure 23) present existing high-rise glazed façades of the built environment in the Netherlands. Imagine the impact of sustainable, energy efficient, high-rise buildings on the world emissions. Therefore, an optimal design of glazing and control over the solar radiation transmitted through glass is important to reduce CO₂ emissions. This led to demanding better solutions and improvements on shading technology. Nowadays shading systems are more technically developed and offer dynamic and automated products.

4.3 Adaptive façades

Biological scientists define “adaptation” as the evolutionary transaction where an organism changes due to its environment to endure it (Dobzhansky, 1968). A familiar example that occurs in nature may be, that some animals, for instance a cat or dog, have more fur in winter than during summer. Their protective layer, skin, adapts to the climate and temperature of their surroundings. This way the animals lose less heat in winter and more heat in summer when it is warmer if needed. Picture a building that can also adapt its skin to enhance its energy performance. In the context of the building envelope the word “adaptive” is associated with various alike terms (Romano, 2018). Examples of comparable terms are; intelligent (Kroner, 1997; Clements-Croome, 2004; Hayes-Roth, 1995; Velikov, 2013); responsive (Velikov, 2013; Negroponte, 1975; Ferguson, 2007); interactive (Fox, 2018); switchable (Beevor, 2010). Note that there are many more, only these are the ones discussed in this report to explain the idea of an “affective window”, the posed interaction and switchable glazing.

Frei Otto is one of the first who explains the means of adaptable architectural buildings (Möller, 2015). He said that adaptable architecture must provide the opportunity to change its shape, spaciousness, utilization and location (Möller, 2015). For instance, a demountable building.

With adaptive façades, the physical barrier between inside and outside, the skin, can change its characteristics. The façade can react to its surroundings and adapts to improve the building's performance (Loonen, 2015). Loonen (2013) states that the challenges adaptive façades face is adapting during the day due to environmental external factors to increase the energy performance and supporting the comfort level of the occupant. De façade must react to the occupant's needs and preferences (Loonen, 2013). Hence, adaptability may be understood as the capability of a system to provide the required performance, taking into account several criteria under changing conditions, as the design variables change their physical properties over time (Ferguson, 2007).



Figure [22]: Bird's eye view of the Zuidas (photo by ANP)



Figure [20]: Rotterdam (photo by ANP)

4. Designing façades

4.4 Intelligent façades

Kroner (1997) explains that “intelligent” buildings combine active features with passive design strategies (Kroner, 1997). This way, the building should be able to reduce its energy use and optimise the occupant’s comfort. Thus, when the definition “intelligent” is used for the façade it consists of sensing and efficient responsive elements. The intelligent skin can sense the behaviour of its environment, is linked with a reactive design strategy and has components that can change, creating a pleasant indoor environment quality (Clements- Croome, 2004). In robotics, this means sensors, command processors and actuators (Hayes-Roth, 1995). A difference between an “intelligent” and “adaptive” façade is that the so called “intelligent” façade should sense when to modify its components and characteristics optimising the building’s systems in terms of climate, energy balance and human comfort. Meaning the façade should be able to automatically adapt itself without manual occupant interference and also with manual operation. An “adaptive” façade can be controlled manually and desirable automatically, however automatic controlling is not a fixed requirement. Realising an “intelligent” building is often accomplished by building automation and physically adaptive features such as louvers, blinds, controllable ventilation openings or smart material assemblies (Velikov, 2013).

4.5 Responsive façades

Operational responsiveness in modern architecture may be described as the potential of a system to adjust to deliver the intended performance under various conditions through the design variables which alter their physical values (Ferguson et al., 2007). A “responsive” façade fulfils an active role. The façade can initiate modifications, as a reaction to complex or simple calculations, may it be to greater or lesser extent (Negroponte, 1976). A “responsive” façade is quite similar to an “intelligent” façade, it is able to sense real-time data and respond to it by adjusting the performance characteristics. A responsive façade can also learn over time and improve its controlling strategy (Velikov, 2013). An existing example of a responsive façade is the Institute of the Arab world in Paris (figure 24). The façade system counts many light sensitive diaphragms that regulate the amount of light transmitting through

the façade. The changing aperture size of the components, circles, squares and octagonal benefits the aesthetics of the building with its playful dynamic shadows and influence the energy performance since it affects the solar radiation transmitted through the glazing.

4.6 Interactive façades

“Interactive” architecture is another modern developed approach in the built environment where architecture, computer science, behavioural and social studies intersect in the design. Micheal Fox defines the approach as: “Interactive architectural environments are built upon the convergence of embedded computation and a physical counterpart that satisfies adaptation within the framework of interaction. It encompasses both buildings and environments that have been designed to respond, adapt, change, and come to life” (Fox, 2016). The architectural design approach is to be responsive, potential to sense, think and comprehend its occupants, environment, absorb information and behave to the collected information accordingly. There are yet little exciting interactive facades where the façade reacts directly and automatically to the occupant. Examples of realised interactive facades mainly present that the façade communicates with the occupant via its aesthetics. Examples are the GreenPix, Zero Energy Media Wall in Beijing and the SolPix located in New York. The GreenPix transforms the building envelope to a self-sufficient organism, with its photovoltaic system integrated into the glass curtain wall. The façade entertains the viewer with its playful carbon neutral LED display system (figure 25). The SolPix, a later developed façade constantly monitors its own performance through built-in custom software that visually displays the system’s energy balance, it utilises an algorithm to generate moving images and transforms the installation into a responsive environment for entertainment and public engagement.

4.7 Switchable façades

Switchable façades consist of mostly transparent material, switchable glazing, that can change state (figure 26). The changing state regulates the solar radiation transmitted through the glass façades and thereby the energy performance and indoor environment quality (Beevor, 2010).



Figure [24]: Responsive façade by Jean Nouvel, Institute of the Arab World in Paris (1987) (photo derived from Archdaily)



Figure [25]: Interactive façade, GreenPix, Zero Energy Media Wall (2008) (photo derived from GreenPix press kit)



Figure [26]: Switchable façade, Merck Showcase Switchable glazing at BAU 2019 (photo derived from Merck)

4. Designing façades

4.8 Switchable glass

Smart glass or switchable glass is glass where the transparency changes, it could be self-adjusting or this could be dependent on the electrical voltage across the glass (externally activated). This type of glass can offer privacy or darkening if required. The degree of transparency depends on the voltage across the glass. There is also smart glass where the amount of transparency for heat radiation can be varied. There are several different existing technologies for realising such switchable glazing. Self-adjusting examples are; photochromic, thermochromic and thermotropic. A couple of externally activated switchable glazing technologies are further elaborated, namely, Liquid Crystal, Electrochromic and Suspended Particle Devices. After briefly describing various technologies for switchable glazing the industrial partner of this research, Merck, is introduced.

4.8.1 Liquid Crystal

This glass combination is laminated glass. It has at least two translucent or coloured glasses with a liquid crystal layer in between. This crystal layer is enclosed by two plastic layers (polymer-dispersed liquid crystal, PDLC). When these glasses are “off”, i.e. when there is no voltage on the glass, the window will be non-transparent. When there is voltage on the glass, the glass will immediately change state and become clear. The main disadvantage of this composition of the window is that it requires constant voltage to keep the glass transparent.

4.8.2 Electrochromic

This glass is formed by two layers of glass. Various layers of conductive material are vaporised on these glasses. Ion flow modifies the transparency of this material and thus of the glass. The glass is translucent in its resting state and can be activated by applying a voltage across the glass. It is enough to apply the voltage only once to change the state of the glass. It consumes less energy than the previous described type of glass. A disadvantage, however, is that this technique is not stable and that the glass gradually becomes transparent again. Therefore, voltage must be applied at regular intervals to keep the glass dark. Other disadvantages are the slow operation (up to

almost 4 minutes), green or blue discolouration (due to the metal oxides used in the evaporated layers) and that the discolouration is not homogenous: the discolouration occurs from left to right or from top to bottom, but not everywhere at the same time.

4.8.3 Suspended Particle Device

This composition consists of two glasses with a conductive substance in between, somewhat similar to PDLC. This conductive substance contains microscopic particles that absorb light. When there is no voltage on the glass, the glass will absorb the light and thus become dark. Again, a constant voltage is required to keep the glass translucent. This composition does not offer complete obscurity and is therefore not suitable for complete privacy. SPD technology also has the disadvantage of strong blue discolouration.

4.8.4 Merck

An example of a developed existing switchable façade shading technology is switchable glass, provided by Merck, the industrial partner of this project (figure 26). Merck provided glass that is later on used during the experimental phase of this study. As priorly described, switchable glazing is glass that can change state and therefore the amount of light coming through the window and influence the view. The glass consists of multiple layers. The outer layers are the glass panels and in between are liquid crystals and dye molecules. Figure 27 presents a schematic section of the glass and the behaviour of the liquid crystal mixture and dye molecules accustomed for the colour needs, during three various states (bright, intermediate, dark) (licrivision technology). The brochure from Merck explains that the amount of voltage applied influences the parts in the liquid mixture, located in between the two glass sheets. The orientation of the liquid crystals differs when voltage is applied from that when no voltage is applied. Thus, the applied voltage influences the solar radiation transmitted through the glass. When ten volts is applied to the glass it is in a bright state, where the largest amount of solar radiation can be transmitted through. If the applied voltage is low (zero) the glass turns to its darkest state letting less light enter the room. This way the switchable glass regulates the amount of light and heat passing through a window.

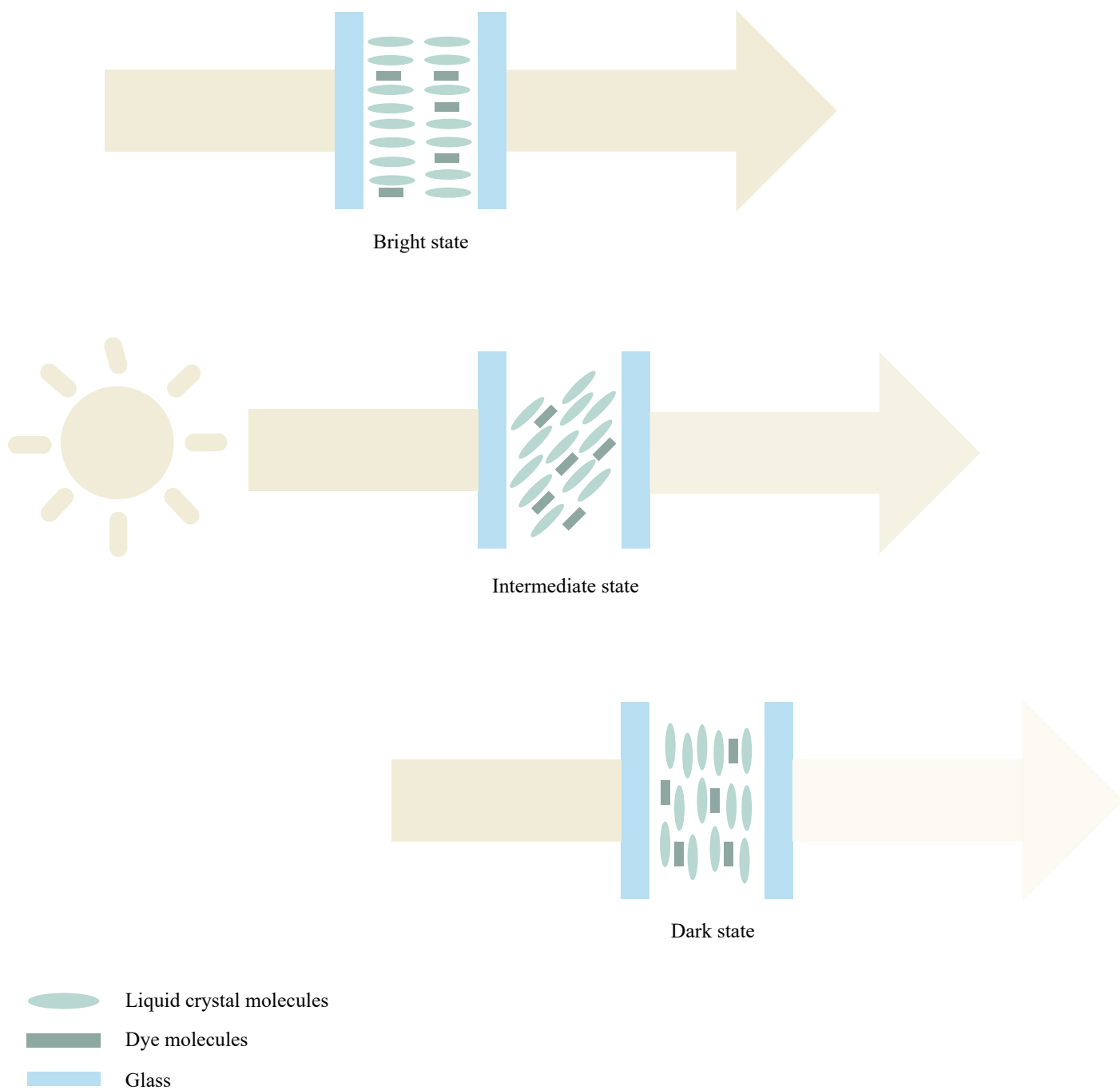


Figure [27]: Illustration expressing the technology of the glass provided by Merck

4. Designing façades

4.9 Affective window

Affective computing is the study and development of systems and devices that can recognize, interpret, process, and simulate human affects/emotions. So, an affective window understands a person's feelings, mood and glare response. During this research the affective window is a window with the properties of the switchable glazing, provided by Merck. The window is responsive and intelligent. Meaning it can react to its environment considering time of the day, orientations and with the aid of a sensor to measure the amount of light entering the room. Furthermore, it is interactive as it gathers data from the occupant with a camera capturing the occupant's facial movements in a non-intrusive manner. This is elaborated on in the following chapter. The state of the glass changes depending on the control system and the gathered data from multiple sensors.

An affective window operates automatically and can be overridden by the occupant's manual input. The default setting of the glass should optimize the energy performance of the building. However, is the control logic sensing visual discomfort, glare, considering a high lux value or the occupants face expression, the glass state should change to a darker state. Once it is dark, the glass must switch back to transparent when the lux level has dropped to bring back the desired view for the satisfaction of the occupant. Consequently, the affective window effectively controls the solar radiation transmitted through switchable glazing, optimizing the energy performance and creating a comfortable indoor visual environment for the occupant. To design such a system, various control strategies and the developments are reviewed.

4.10 Façades control strategies

A study done by Konstantzos combines the DGP in an office building and dynamic shading technologies. Konstantzos replicated an office space and did simulations while changing the façade shading component. His study presented the strong correlation between the DGP and vertical illuminance. He explains that development in dynamic shading technologies influence the control of vertical illuminance and thus, visual comfort (Konstantzos, 2015).

In the article: "Occupant-Centred control strategies for adaptive facades: preliminary study of the impact of shortwave solar radiation on thermal comfort" a related study is practiced at the University of Cambridge. The experiments are simulated in the Mobile Adaptive Technologies Experimental Lab (MATELab) (Luna Navarro, 2019). MATELab was used to research the relation between façade control and the thermal and visual comfort of the occupant. It has been established in Cambridge and is still being used primarily to investigate the relationship between the façade control and the thermal and visual comfort of occupants (Luna Navarro, 2019). In the article is written that shortwave radiation influences the thermal comfort, thus implanting pleasant control strategies for solar radiation transmitted through the façade. A wrong use of the shading technology such as switchable glazing could lead to overheating issues (Luna Navarro, 2019). The tests done in the MATELab point out the importance of simulating different positions and angles of the occupants towards the façade, as it affects the indoor environment, to configure a suitable learning control strategy (Luna Navarro, 2019). This work is relevant for the experiments performed for the verification of proposed control strategy for the affective window.

In the article: "Occupant-Façade interaction, a review and classification scheme" is concluded that artificial intelligence and new interfaces potentially could create an interaction between the occupant and smart dynamic façade technologies (Luna Navarro, 2020). The controlling interface would be a loop, with the occupant in it, and therefore able to create human-centred remedies. This leads to research and experiments exploring the possibility of sensing the occupant's emotion. A novel control system is proposed.

5. The novel control system

A novel control system is desired that can control the glass in a human-centred manner. To gain insight in manners how to sense the occupant's need a literature review is done studying previous, somewhat similar, performed research. Namely, previously performed studies have been done investigating facial movements due to glare. Consequently, these studies are reviewed to comprehend how to create a visual uncomfortable environment and also how to analyse facial expressions.

5.1 An objective measure of discomfort glare

Berman (1994) studied the objective measure of glare (Berman, 1994). In his research the participants had to look at a monitor where a large symbol was presented (figure 28).

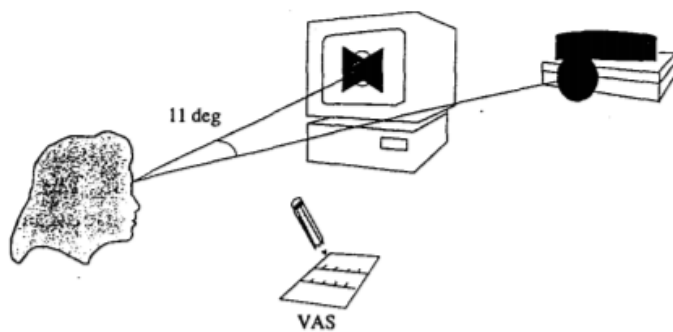


Figure [28]: Experiment set-up (Berman, 1994)

The artificial glare source in his research was a projector. The glare source was 11 degrees to the right of the monitor screen. All subjects were wired for an EMG recording to study the behaviour facial movement due to visual discomfort, glare (figure 29). In contrast to the use of a webcam, this is an obtrusive manner of measuring the facial movements.

Figure 30 shows the EMG records facial movements when glare is introduced to the environment of the participant. Berman's research indicated that activity around the eye is a reasonable option to explore in the search for a measurable response to glare (Berman, 1994).



Figure [29]: Capturing the participant's facial movement (Berman, 1994)

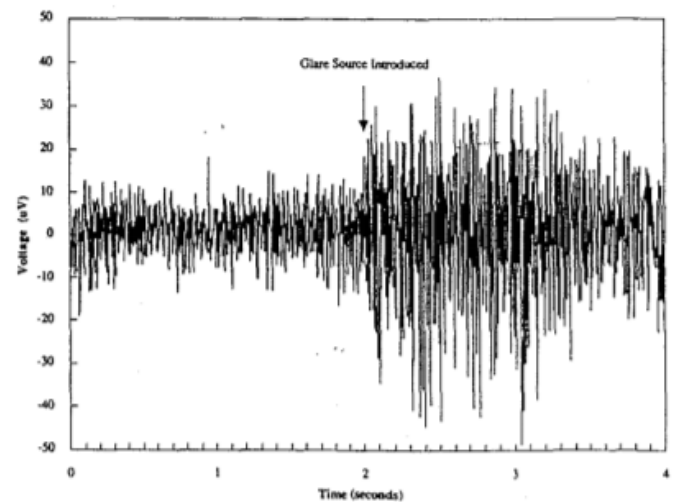


Figure [30]: EMG recording output (Berman, 1994)

5.2 Testing experimental methods for discomfort glare investigations

More recently, another research studies facial expressions in a similar way to Berman (Iodice, 2018) (figure 31 & 32). The study used a point source as an artificial glare source. The light from the source was transmitted through a diffusive sheet.

5. The novel control system

This research stressed that it is recommended to evaluate experiments in various manners. The experimental set up of both researches, performed by Berman and Iodice, were taken into account when constructing the research room for the novel control strategy.



Figure [31]: Simulated image of the experimental room (Iodice, 2018)



Figure [32]: Subject equipped with EMG, EEG and ECG (left) and with an eye tracker ECG (right) (Iodice, 2018)

5.3 User-centred control of automated shading for intelligent glass façades

“User-centred control of automated shading for intelligent glass façades” is the most recent similar study that is done with a webcam and OpenFace to identify whether it is possible

to predict if the occupant is experiencing glare or visual discomfort (figure 33 & 34). On the contrary to the other experiments, the occupants’ needs are captured in a non-intrusive manner. Due to the camera there is no need for wires taped to a participant’s face to analyse the human’s facial expressions. In this research the following action units were studied; AU02 (Outer Brow Raiser), AU04 (Brow Lowerer), AU06 (Cheek raiser), AU09 (Nose wrinkle) and AU10 (Upper lip raiser) (Allen et al, 2019). Four participants showed a reaction in the intensity of AU02 (Outer brow raiser) and AU04 (Brow lowerer). Three participants showed a reaction in the intensity of AU10 (Upper lip raiser). 1 participant showed a reaction in the intensity of AU06 (Nose wrinkle) and AU09 (Cheek raiser). This research has shown that there is a notable reaction in one’s facial expression due to high luminance.



Figure [33]: Photo of experimental setup (Allen et al, 2019)

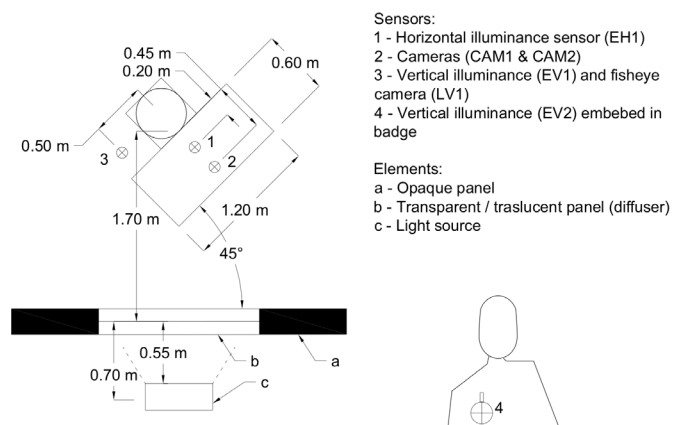


Figure [34]: Plan of experimental setup (Allen et al, 2019)

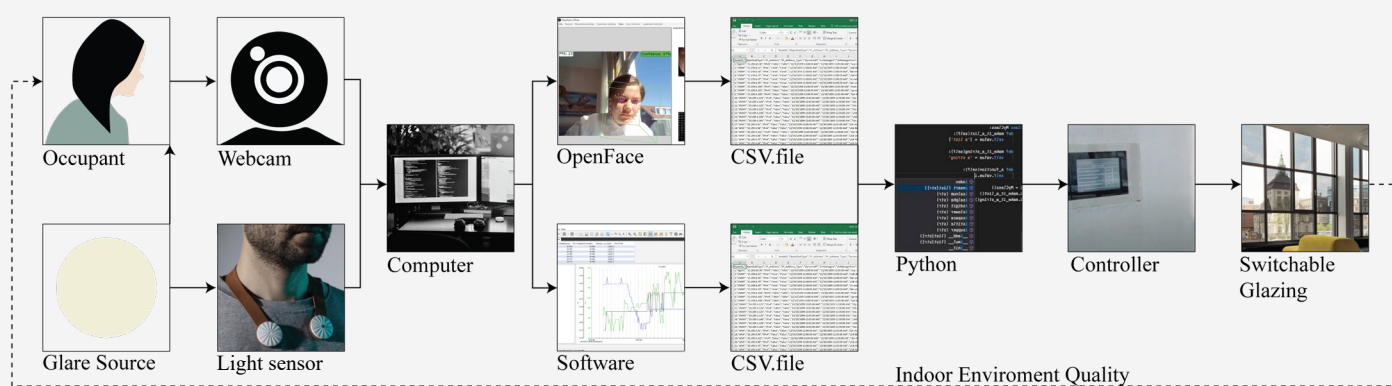


Figure [35]: The novel control system components illustrated in an elevation and a scheme

5. The novel control system

5.4 The components of the novel system

A novel control system is proposed. Figure 35 presents the systems components and roughly how they are connected to each other in an elevation view and a schematic scheme helps to comprehend the connections of the different parts. The control system contains the following hardware components; the occupant; webcam, capturing occupants' facial movements; a wearable lux sensor, measuring lux levels; computer, receiving data and sending signals to the driver of the switchable glazing; the driver of/ and the switchable glazing, changing state to influence light transmitted through the glass and glare. The important software programs used for the control algorithm are; OpenFace, processes the facial action movements; Python, hosting control algorithm; HOBOWare, gathering lux readings. A schematic simplified illustration presents the main components in the control strategy (figure 35). To illustrate an idea of what the novel system could look like in the future a 3D impression is presented (figure 36).

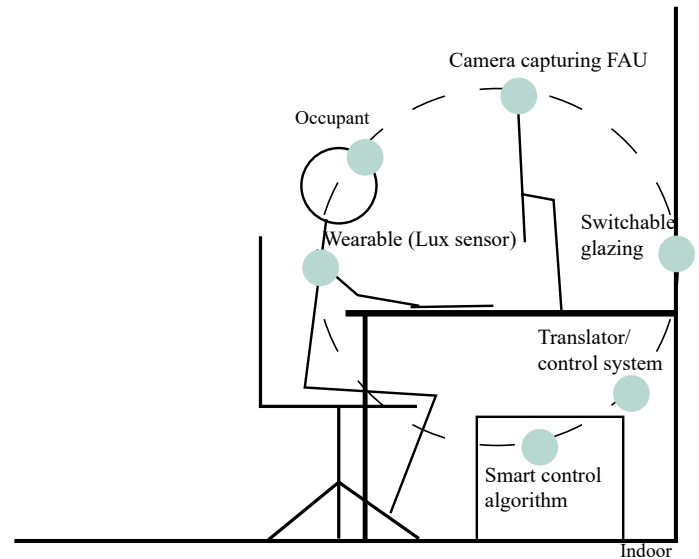
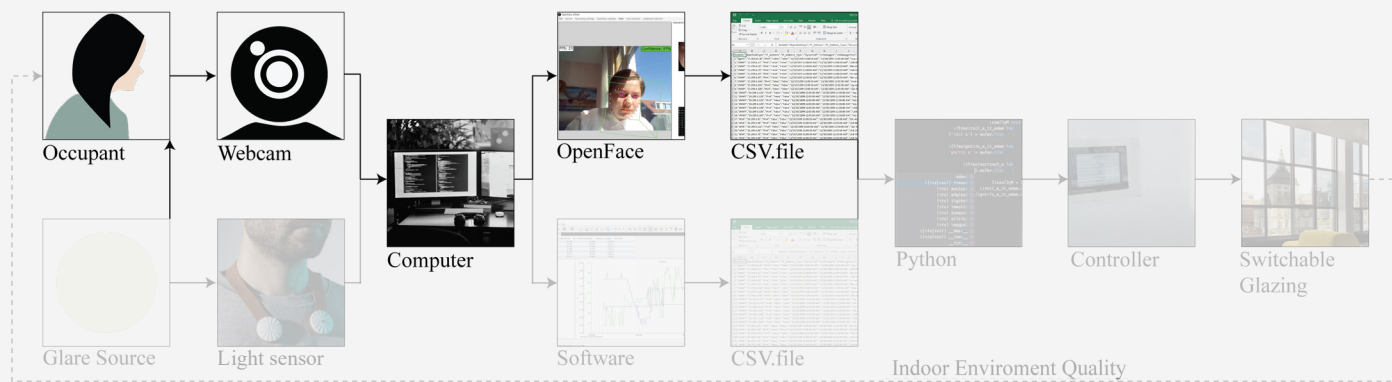
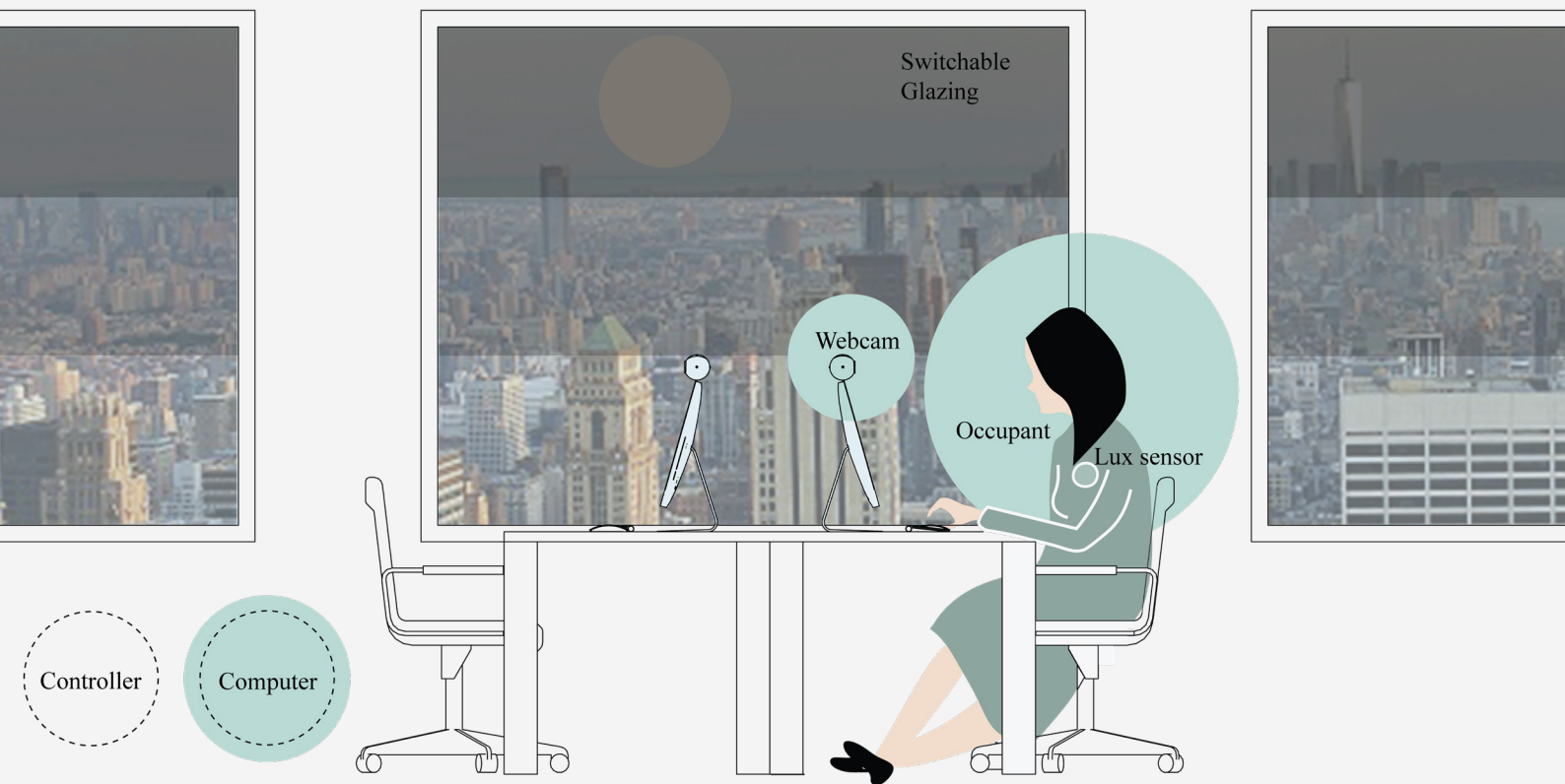


Figure [36]: Schematic simplified sketch of the novel system and the integrated components

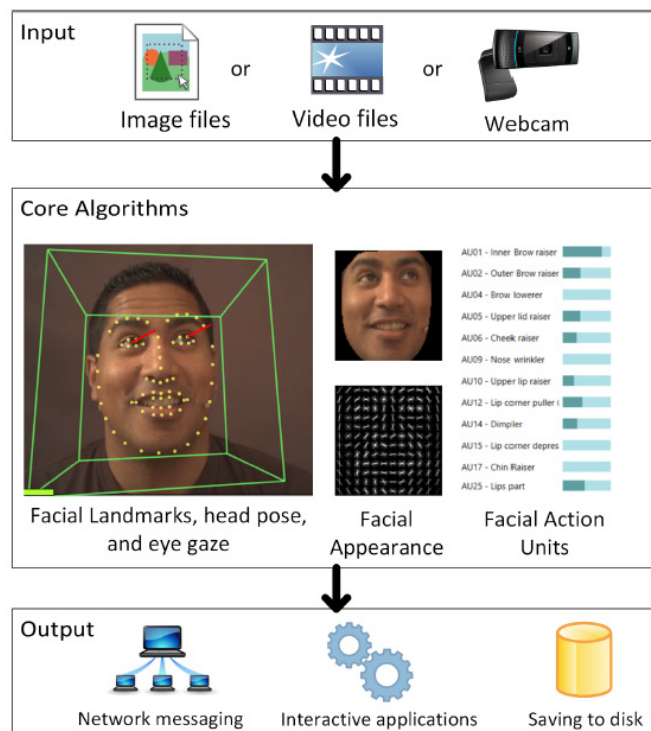


5. The novel control system

5.4.1 OpenFace

OpenFace is a software program capable of facial landmark position, facial landmark detection, head pose estimation, facial action unit recognition, and eye-gaze estimation (Baltrušaitis, 2016). OpenFace was originally developed by Tadas Baltrušaitis in collaboration with CMU MultiComp Lab led by Prof. Louis-Philippe Morency. Some of the original algorithms were developed while working at the Rainbow Group, Cambridge University. OpenFace is able to recognize a subset of action units, specifically: 1, 2, 4, 5, 6, 7, 9, 10, 12, 14, 15, 17, 20, 23, 25, 26, 28, and 45 (Ekman, 1976) (figure 37). Facial action units are used to retrieve the images with a similar facial expression.

The program is capable of capturing real-time data from the occupants and is able to run from a simple webcam. Although, the better the camera, the more accurate data. The output can directly be stored in a csv. file (figure 38). The paper “Can a Building read your mind? Results from a small trial in action unit detection” expresses that there is a potential in using Facial Action Units (FAU) for creating an interaction between the occupant and the building via a controlling system (Allen, 2019). By analyzing and investigating people’s facial expressions, head pose and gaze angle, one has the potential to sense how people feel, what their interests are and their thoughts.



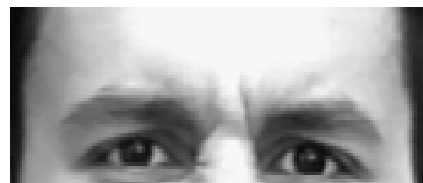
Figure[38]:OpenFaceFramework(Baltrušaitis,2016).



AU01
Inner Brow Raiser



AU02
Outer Brow Raiser



AU04
Brow Lowerer



AU05
Upper Lid Raiser



AU06
Cheek Raiser



AU07
Lid Tightener



AU09
Nose Wrinkler



AU10
Upper Lip Raiser



AU12
Lip Corner Puller



AU12
Dimpler



AU15
Lip Corner Depressor



AU17
Chin Raiser



AU20
Lip stretcher



AU23
Lip Tightener



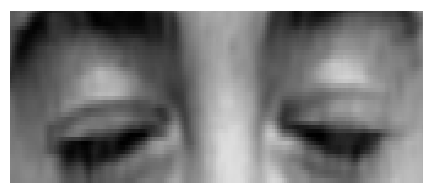
AU23
Lips part



AU26
Jaw drop

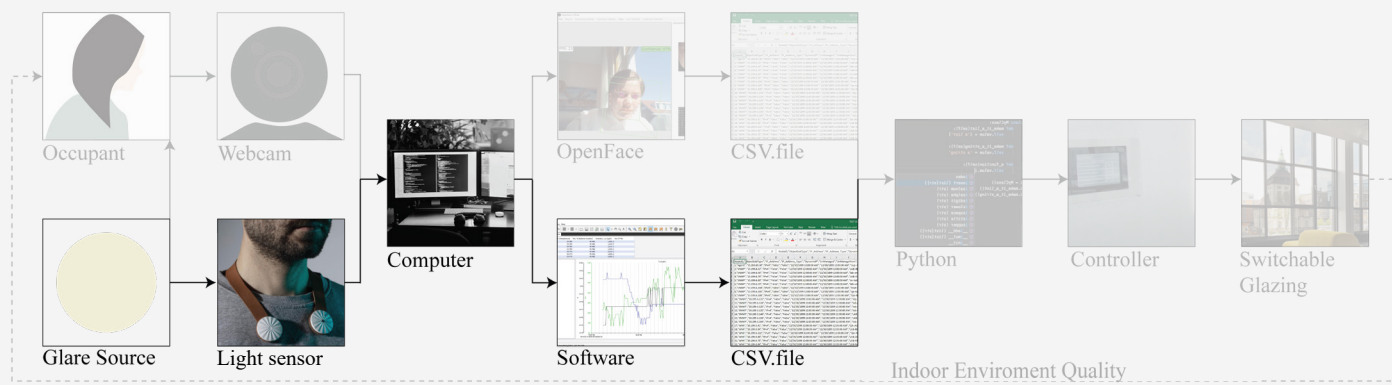


AU28
Lip Suck



AU45
Blink

Figure [37]:Facial Action Coding System



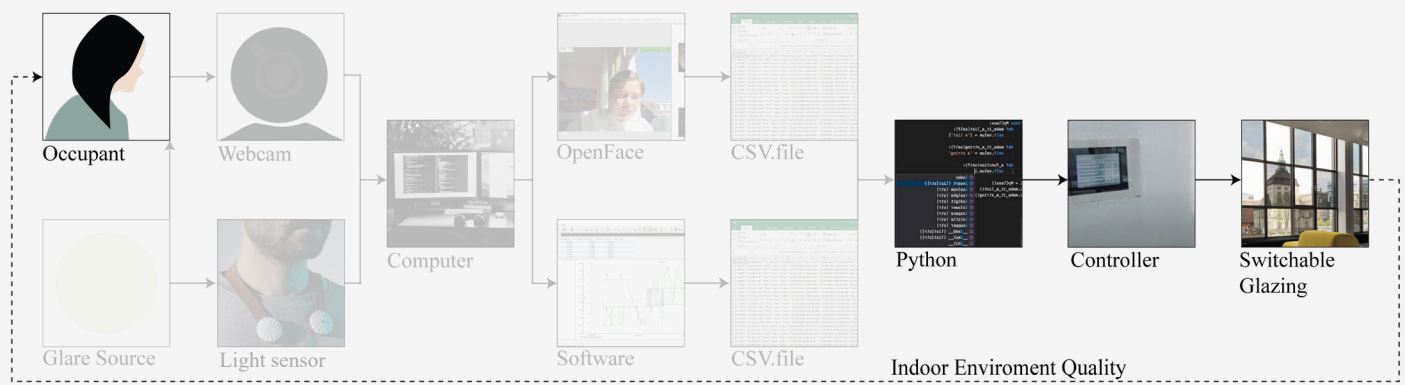
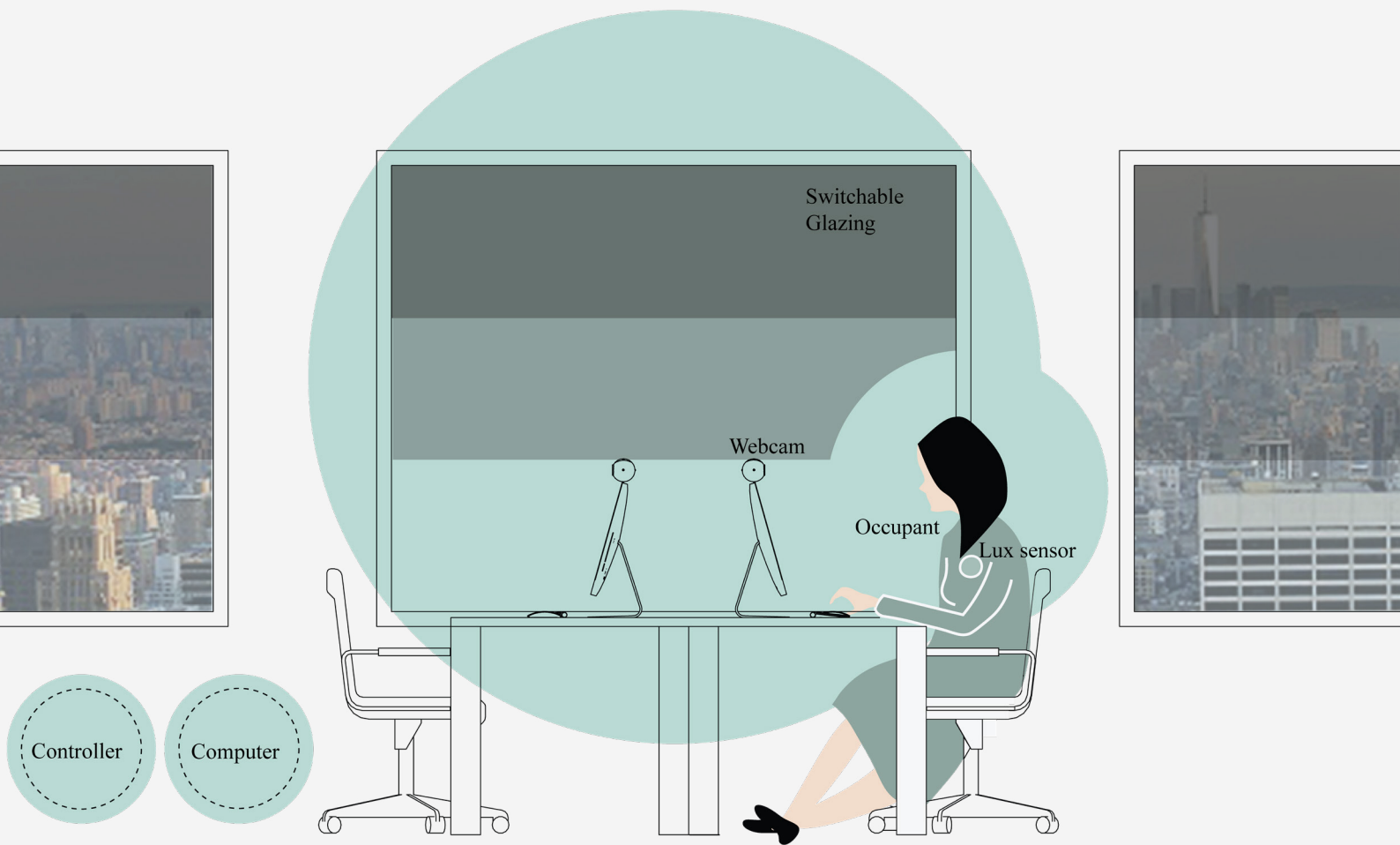
5. The novel control system

5.4.2 Wearable lux sensor

To verify if one is experiencing glare it is desirable to measure the lux level closest to the eyes of the occupant. Since a lux sensor fixed to one's face would be intrusive the wearable is placed onto the chest. In this research a HOBO sensor and the HOBOWare (software) is used for the lux measurements. The HOBO is fixed to the chest with two magnets to the occupant and is able to run real-time lux measurements. The HOBOWare provides a csv. file with lux readings per second.

5.4.3 Switchable glass

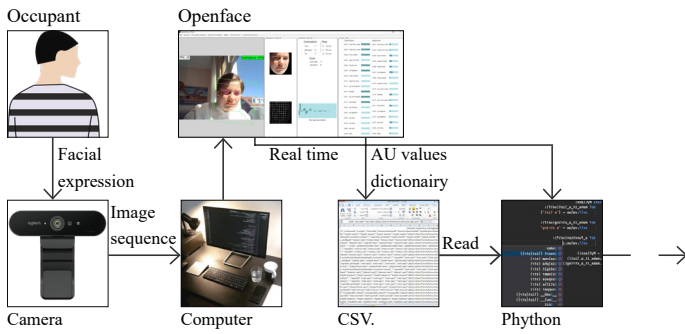
Switchable glass is the façade component that can change state and thus influence, among other things, solar radiation transmitted through the window, usage of daylight and view. The switchable glazing provided by the industrial partner, Merck, comes with a driver that emits voltage to the glass for it to adapt its transparency, For example shift from bright state to intermediate state. The state of the glass by default is set to bright state and may be influenced by the readings of the lux sensor and the facial action units, to switch to a darker state. The glass component provided by Merck and used during this project is a square (dimensions 410 millimetres by 410 millimetres). It is integrated into the artificial façade in the experiment. The brightest state of the glass has a transmission value of 45% and the darkest state a value of 9% ($T_v(\text{bright}) = 0,45$, $T_v(\text{dark}) = 0,09$).



5. The novel control system

5.5 The strategy of the novel system

A control strategy for the novel system and its components is proposed. First, the Action Units that are used are explained, then functions of the HOBO values are clarified and then the methods to control the glass are described.



5.5.1 OpenFace

As a result of an earlier study, AU02, AU04, AU06 and AU10 are considered in the novel control strategy (Allen, 2019). If the intensity of those AU's shows that the occupant could be experiencing glare (and when the HOBO measures a high lux level) the glass darkens.



Figure [38]: AU02 - Outer Brow Raiser

AU02 is incorporated into the control strategy. When the csv.file created by OpenFace gives an output value lower than 0.2 for at least 10 seconds the glass shifts to intermediate state (5 volt). If the AU then still has a value of less than 0.2 the glass state changes to its darkest state (0 volt). The reason that it must react after 10 seconds is due to the fact that the output fluctuates and this way it is more certain that it is due to the amount of light in the room.

Simplified code:

```

Glare_Prediction
If AU02_r < 0,2:
    Glass_state = 0.5
If AU02_r < 0,2:
    Glass_state = 1
Else:
    Glass_state = 0
  
```

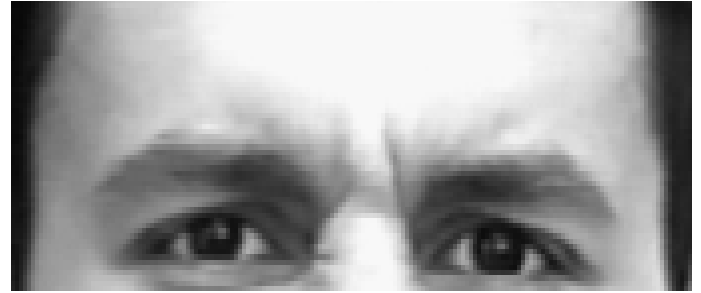


Figure [39]: AU04 - Brow Lowerer

AU04 is also incorporated into the control strategy. For AU04 the same applies. When the csv.file created by OpenFace gives an output value lower than 0.2 for at least 10 seconds the glass shifts to intermediate state (5 volt). If the AU then still has a value of less than 0.2 the glass state changes to its darkest state (0 volt).

Simplified code:

```

Glare_Prediction
If AU04_r < 0,2:
    Glass_state = 0.5
If AU04_r < 0,2:
    Glass_state = 1
Else:
    Glass_state = 0
  
```



Figure [40]: AU06 - Cheek Raiser

5. The novel control system

AU06 is also integrated into the control system, however these values must stay for at least 60 seconds to be absolutely sure it is due to the oversupply of light. Since only one participant showed a reaction with this AU in a prior research, the AU is less dominant.

Simplified code:

```
Glare_Prediction
If AU06_r < 0,2:
    Glass_state = 0.5
If AU06_r < 0,2:
    Glass_state = 1
Else:
    Glass_state = 0
```

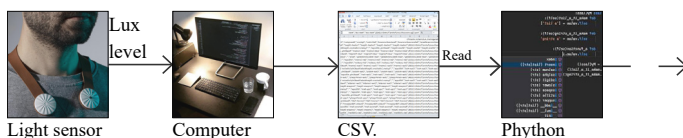


Figure [41]: AU10 - Upper Lip Raiser

Just as AU06, AU10 had a less significant reaction related to the increasing amount of light. Thus, the glass only reacts if the value of this AU is lower than 0.4 for at least 60 seconds.

Simplified code:

```
Glare_Prediction
If AU010_r < 0.4:
    Glass_state = 0.5
If AU010_r < 0.4:
    Glass_state = 1
Else:
    Glass_state = 0
```



5.5.2 Wearable lux sensor

The lux sensor has hierarchy over the output from the facial action units.

When the HOBO measures too much lux the switchable glazing will turn to a darker state. If the sensor does not sense light but the actions units read that the occupant may be experiencing glare the glass will not change state. The threshold values are determined after experiment i.

Thus, the logic on sensing occupant discomfort proposed, simplified, consists of:

```
Glare_Prediction
If AU02_r < 0.2 (and lux value > threshold lux value (A)):
    Glass_state = 0.5
If AU02_r < 0.2 (and lux value > higher threshold lux value (B)):
    Glass_state = 1
Else:
    Glass_state = 0
```

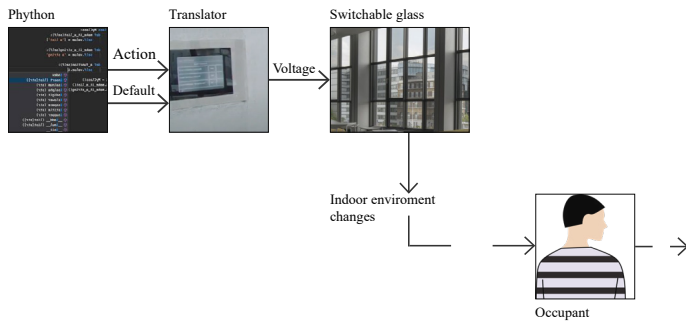
```
Glare_Prediction
If AU04_r < 0.2 (and lux value > threshold lux value (A)):
    Glass_state = 0.5
If AU04_r < 0.2 (and lux value > higher threshold lux value (B)):
    Glass_state = 1
Else:
    Glass_state = 0
```

```
Glare_Prediction
If AU06_r < 0.2 (and lux value > threshold lux value (A)):
    Glass_state = 0.5
If AU06_r < 0.2 (and lux value > higher threshold lux value (B)):
    Glass_state = 1
Else:
    Glass_state = 0
```

```
Glare_Prediction
If AU010_r < 0.4 (and lux value > threshold lux value (A)):
    Glass_state = 0.5
If AU010_r < 0.4 (and lux value > higher threshold lux value (B)):
    Glass_state = 1
Else:
    Glass_state = 0
```

```
Glare_Prediction
If lux value > even higher threshold lux value (C):
    Glass_state = 0.5
If lux value > highest threshold lux value (D):
    Glass_state = 1
Else:
    Glass_state = 0
```

5. The novel control system



5.5.3 Switchable glass

The glass can be controlled in two manners for the experiment. It can either be controlled manually with an application for a mobile phone or automatically via a computer (or Raspberry pi) that is connected via Bluetooth with the driver, or via a cable. A schematic scheme aids to explain the principle of how to connect the driver to the computer (figure 42). The computer hosts the control strategy algorithm in Nodered or Python. The control strategy in either program sends a signal to the microcontroller Arduino with Firmata. The Arduino should be connected to a microcontroller signal amplified to 0-10 Volts. Since the Arduino can only cope with 5 Volts the glass would only be able to switch from dark state to intermediate state. This is the reason the connection needs an amplifier. The microcontroller is then connected to the eyrise driver and controls the glass.

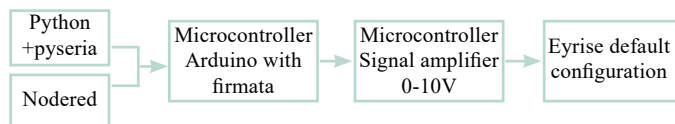


Figure [42]: Schematic control system via a computer

6. Designing the experimental space

An experiment room is created to test the control strategy and gain more data. The experiment room should be a replicate of an office environment. It is necessary to create visual discomfort in the experiment room to have the ability to test the novel system.

6.1 Literature reference

Various similar field studies were reviewed to create an experimental room for this research, including “an experimental study on the effect of visual tasks on discomfort due to peripheral glare” by Kent (2019) (figure 43 & 44). This article presents an experimental study that compared evaluations of discomfort using two visual orientated situations, (i) one where the participant had to stare at a circle projected onto the sheets, (the participant had to a visual fixation point, the circle on the sheet, between the projector and the participant) and (ii), a pseudo-text reading task, where the participant had to read a row of pseudo-text, for instance, bajfic02j5jf9020. The pseudo-text consisted of a row of 16 randomly chosen alphanumeric numbers or letters, displayed with 14-point Calibri font. Participants were instructed to read the row of letters and numbers aloud, from left to right, and were informed that both speed and accuracy were important. The accuracy was checked by recording the responses. Kent (2019) used two different experimental procedures, (i) luminance adjustment, here the luminance of the artificial glare source was adjusted while the background luminance was kept the same, (ii) category rating, where a series of scenes are evaluated, evaluations of visual discomfort were given, which differ in magnitude of luminance, due to the different settings of the artificial glare source. At the start of each luminance adjustment setting, a trial of four scenarios (one for each glare experience, imperceptible, perceptible, disturbing, intolerable), the glare source was set to a standard luminance corresponding to a glare index of 18.5. This is borderline between comfort and discomfort. The glare source was then adjusted by the experimenter after the participant ordered it to increase, decrease, or keep the brightness of the artificial glare source the same. In another paper Kent (2017) explains that luminances set according to adjustment tasks could likely be affected by anchors, the opening setting of the luminance in the experiment room at

the outset of each adjustment, and hence also the order in which the four discomfort scenarios were set. Therefore, after the initial luminance setting (18.5), the four different sensations were evaluated in a random order. This procedure differs slightly from Hopkinson’s multiple-criterion technique (Hopkinson, 1960), which originally instructed observers to make glare settings in a strict ascending sequence (here the participants started in a scenarios that could be experienced as imperceptible and from there the luminance increased to higher levels of discomfort). The order may also affect the outcome of the experiment (Kent, 2020). In the category rating procedure, the magnitude of discomfort due to glare was evaluated at four different levels of glare source luminance in a random order. During an experiment conducted by Iwata et al. (1992), the participant was asked to read text from a textbook on the desk and after two minutes the participant had to describe their level of discomfort. Kent (2019) did this differently, the participants were requested to provide their evaluation of discomfort after 10 seconds in the setting during the projection of the circle, and during the tasks where the participants had to read a pseudo-text, they had to provide their evaluation of discomfort directly after reading the 16 characters aloud.

This experimental design of Kent is the main reference used for the experimental design for this research. One of the reasons why this setup is used is that the design is realistic to build at the Faculty of Architecture in Delft. By adding hinges to the structure the set up could be somewhat flexible and adapted. It is very beneficial if the structure can be adapted, since the glass is not so big, the height of the glass may need to increase or decrease to get the correct position. Furthermore, it can be constructed in a manner that is demountable and if the faculty would close due to COVID-19 restrictions the setup is able to relocate. Moreover, Kent uses a projector as an artificial light source to produce visual discomfort. Since a projector is available for this graduation project, a similar setting is used to potentially create a visually uncomfortable environment in the experimental setup.

6. Designing the experimental space

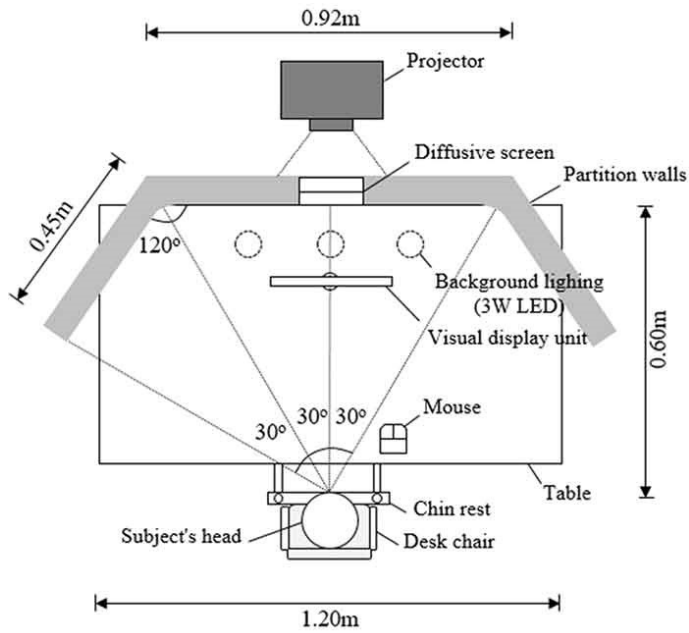


Figure [43]: Plan experimental setup (Kent, 2019)



Figure [44]: Photo of experimental setup (Kent, 2019)

6.2 The experimental space design

Different options for the experiment set ups are evaluated to eventually build the experiment room. A few basic points were set, namely (i) it must be flexible, so easy to adapt, (ii) the arrangement must be able to be dismantled so that it can be moved in case of emergency, (iii) the arrangement must be able to carry the glass, (iiii) the arrangement must be able to stand on its own, (iiiiii) it must resemble an office/workplace. To create such a space some sketches and 3D models of the experiment room are made in Sketch up (figure 45).

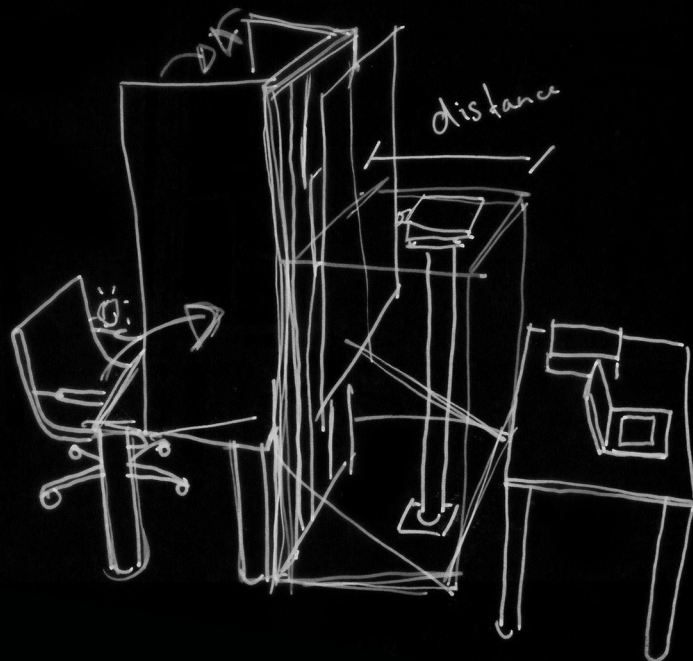
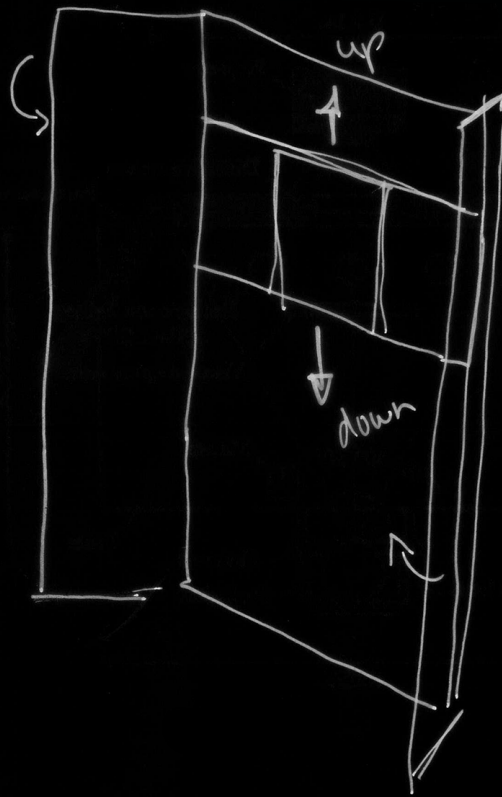
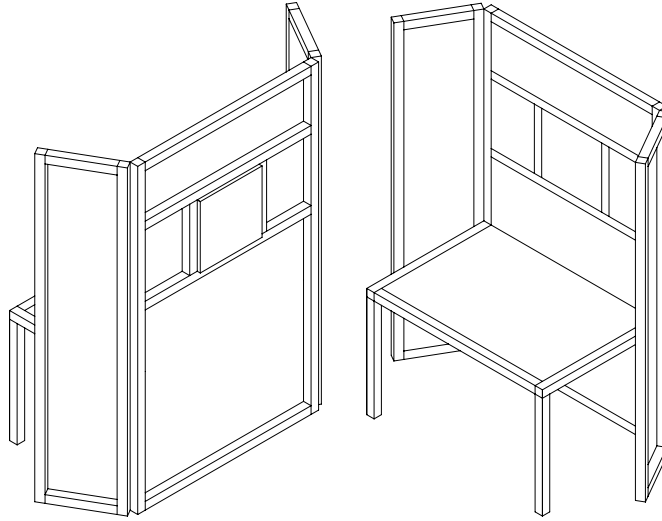
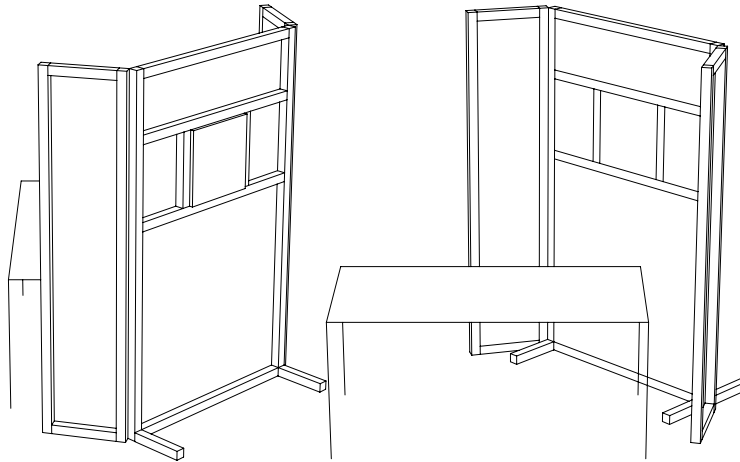


Figure [45]: Sketches experiment set up

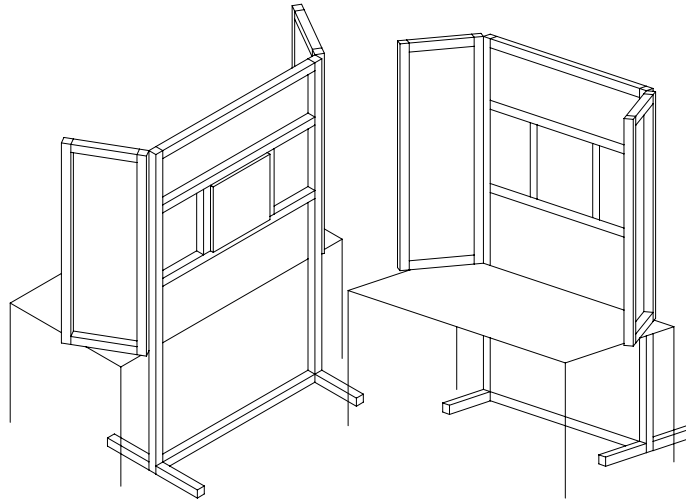
1



2



3



4

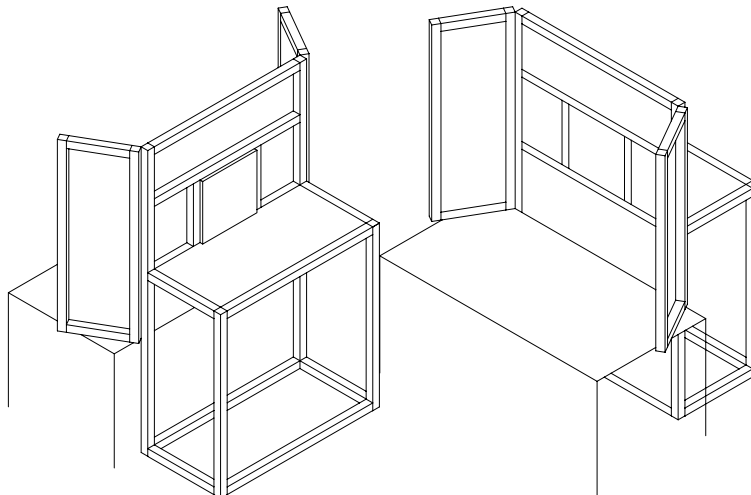


Figure [46]: Options set up

6. Designing the experimental space

Four different variants were prepared and the advantages and disadvantages evaluated, for reference see figure 46. The first option is a set up where the desk is fixed to the artificial façade, thereby it works as standard and keeps the structure from falling. By adding hinges it could be foldable to a smaller size, which would make it easier to move. A disadvantage is that the participant would always face the window, while it is interesting to do experiments with the participants faced in a 45 degree angle towards the window. Nowadays desks in offices are often not placed facing the window. However, the light artificial glare source is quite a small point source (projector), which may not create visual discomfort when one is not facing it. The second option is an example with a standard. The desk drawn is an existing table that is already located in the room where the experiments are done. An advantage here is that the participants could be seated in different angles and positions towards the switchable glazing. An aspect to be aware of is that if the table in the room is slightly too big for the set up, it may not be able to place the participant straight in front of the window. The third option looks like the second one, only here the desk could be placed against the wall even if the dimensions are wider than the artificial façade. A negative aspect could be that a lot of light could appear from underneath the desk. This could however be relatively easy to fix by placing cardboard in front of the areas the unwanted light would come from. The fourth option is one where the set up is kept stable by a component on the ‘exterior’ side of the artificial façade. This component would carry the load of the switchable glass, the projector (artificial glare source) and keep the structure stable. This means that this option does not require an extra foot. Advantages here is that the extra component could carry the glass, projector and controller, a disadvantage is that it could form an obstacle for a diffuse sheet, placed between the projector and the glass, where the light is transmitted through. The desk is not fixed here, so if needed and if there is time, the participant could be placed in different angles and positions towards the window. It was decided to proceed with the fourth option because it is an efficient arrangement and offers the most advantages.

Figure 47 presents a plan view of the experimental setup. The setup is located in the Faculty of Architecture and the Built Environment in Delft. The participant will be seated in the chair in front of the laptop hosting the onscreen tasks. The HOBOT will be attached to the chest of the participant functioning as a wearable light source. A webcam is placed above the laptop screen recording the participant. The projector behind the switchable glazing is the artificial glare source. The light from the projector travels through a diffuse sheet before it is transmitted through the glass.

6. Designing the experimental space

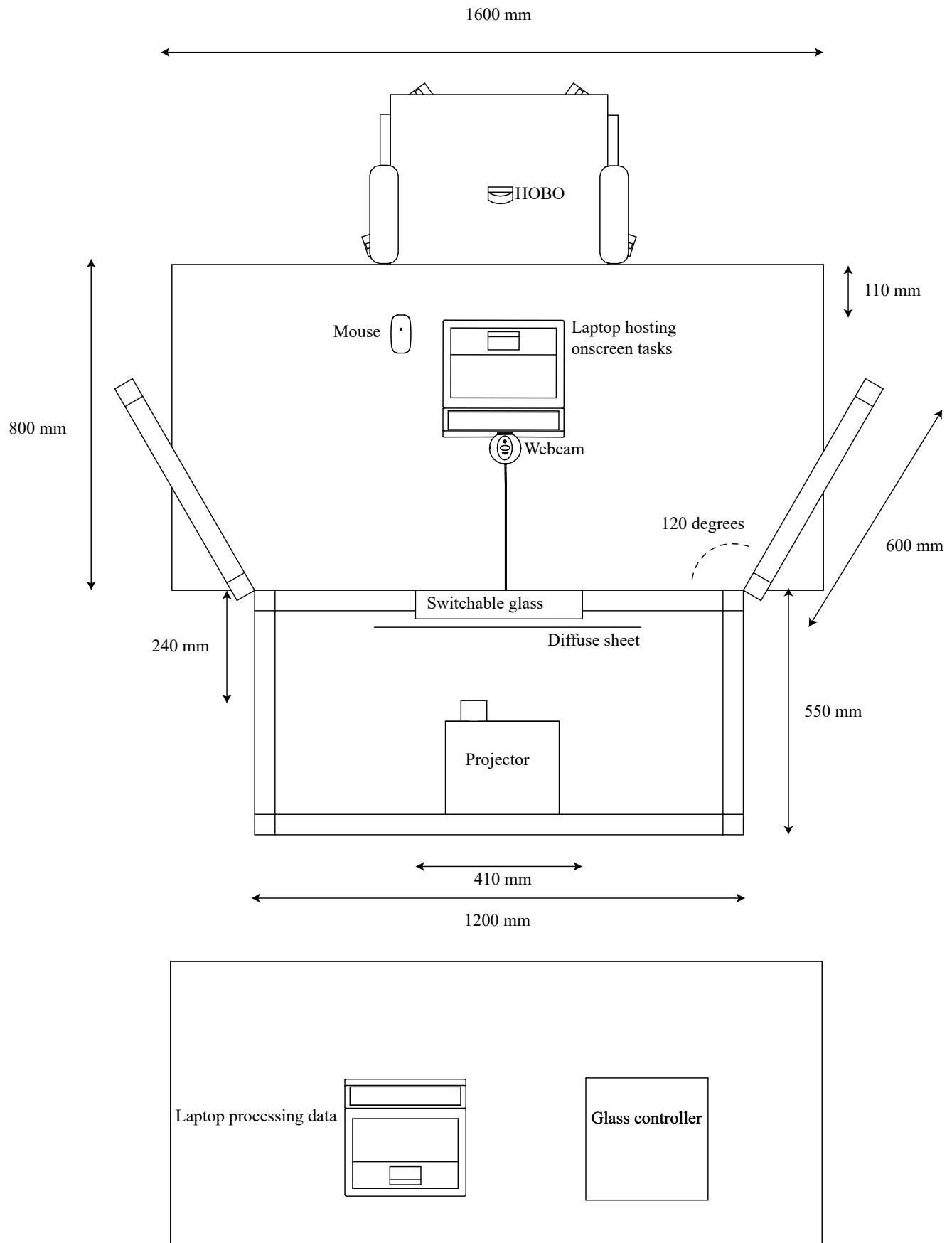


Figure [47]: Plan experimental setup

6. Designing the experimental space

6.3 Possible discussion points

Foitos and Kent (2020) review methods used for subjective evaluation of the discomfort from glare. There are four basic psychophysical manners of evaluating the discomfort from glare, (i) adjustment, (ii) matching, (iii) discrimination and (iiii) category rating. Adjustment and category rating are commonly used for evaluating the discomfort from glare. However some aspects of the experimental area could lead to biased results (Foitos, 2020). An example of such an aspect is the range luminance of the glare source (stimulus range bias). Discrimination and matching could be less commonly used since here to simultaneously viewed scenario's have to be evaluated by the participant. This may be more difficult to set up. For the procedure during adjustment and category rating, the participants decide their choice (evaluating the glare) based on a memory. During these procedures, one scene is shown to the participant and the participant compares it to a reference of a different scene (internal memory) to choose whether the presented scene is comfortable or uncomfortable due to glare.

During an adjustment procedure the participant can control the luminance by changing the source themselves or by requesting the experimenter to adjust the glare source to a higher or lower brightness. The luminance of the glare source is adjusted until it reaches a particular outcome (for instance, intolerable) (Foitos, 2020). Biases that can occur during an adjustment procedure are: (i) stimulus range bias, (ii) anchor effects, (iii) order effects, (iiii) direct versus indirect control and (iiiii) the visual tasks (Foitos, 2020). Stimulus range bias: in the case of the adjustment procedure regarding glare, the luminance range refers to the minimum and maximum luminance levels that can be created by the artificial glare source. The condition before the adjustment is the anchor point. The anchor point affects the feeling and experience of the occupant, a lower anchor point might result in less people finding the glare condition disturbing, while a higher anchor might lead to more people being disturbed by the conditions (Fotios, 2020). The order of the scenes, from high luminance to low, the other way around or randomly might affect the evaluations of the discomfort experienced.

Direct versus indirect control refers to the options the participant has to adjust the setting. Participants seem to have different opinions when they could alter the glare source themselves, instead of changing the luminance by requesting the experimenter to do so. Lastly, the visual task the participant is instructed to do, influences the outcome of the experiment. In chapter 5.1, an experiment conducted by Berman (1994) is described, where the visual task of the participant was to fixate on a large symbol on a monitor (Berman, 1994). Wienold and Christoferson (2006) instructed their participants to do tasks that represented normal working. During the experiment discussed in the paper "User-centred control of automated shading for intelligent glass façades", the participants were instructed to work on crossword puzzles. Visual tasks such as these may influence the data during an adjustment procedure, due to the difference in degree of cognitive attention needed to perform the tasks. An example of an instance where a difference was found in the evaluations of glare by the participants, between the tasks, is the previously discussed one performed by Kent (2019). The participants were more tolerant to glare when they had to read the 16 characters (pseudo-text), then when they were requested to fixate on a projected circle.

Category rating is usually a single interval task, where the participant is asked to evaluate the glare experienced during the scene the participant is in, and categorize it, for instance describe the glare as intolerable. A single interval task is one where only one visual scene is observed. A two interval task is one where two visual scenes are presented, a scene is being judged and compared here. The results of a category rating procedure could be influenced by: (i) stimulus range bias, (ii) order effect, (iii) pre-trial demonstration, (iiii) response scale design, (iiiii) statistical analysis of rating data (Foitos, 2020). Pre-trial demonstration can be compared with anchor effects that have an impact on the results of an adjustment procedure. The difference between these is that the anchor point during the category rating is unclear and may vary per participant. During the category rating the anchor is the visual and memory references held before the first trial, hence the name pre-trial demonstration.

6. Designing the experimental space

The response scale design can be different in many ways. The number of response categories could differ, the category labels and the common understanding of label (terms) could differ per person. Therefore, it is important to state clearly what is meant with the labels used for the category. Regarding the statistical analysis of rating data, it has been suggested that response scales with at least five categories may be analyzed as though they are parametric data and scales with four or less options to choose from, should not (Foitos, 2020).

These discussion points are important to comprehend to be able to find where the results of the experiments conducted during this research may be biased and uncertain.



Figure [48]: Photo of experimental setup



Figure [49]: Photo of experimental setup glare assesment

7. Glare assessment

```
C:\Users\chris\Desktop\HDR>getinfo -d Square90percentbrightstate.pic
Square90percentbrightstate.pic: -Y 1834 +X 2748
```

Figure [50]: Check the dimensions

```
C:\Users\chris\Desktop\HDR>pfilt -x /5.5 -y /5.5 Square90percentbrightstate.pic > Square90percentbrightstatesmall.pic
C:\Users\chris\Desktop\HDR>getinfo -d Square90percentbrightstatesmall.pic
Square90percentbrightstatesmall.pic: -Y 333 +X 500
```

Figure [51]: Change the dimensions

```
C:\Users\chris\Desktop\HDR>evalglare Square90percentbrightstatesmall.pic
Notice: Low brightness scene. Vertical illuminance less than 380 lux! dgp might underestimate glare sources
dgp,dgi,ugr,vcp,cgi,lveil: 0.272906 23.428850 27.302858 2.544089 29.324831 46.669983
```

Figure [52]: Run Evalglare

7. Glare assessment

7.1 Goal

In the literature research (chapter 2.16) the Radiance-based tool Evalglare is explained. To determine what the projector must display and what the settings of the projector should be, a sequence of low dynamic range images is taken of varying conditions. A circular or rectangular form is projected, both white with different opacities. The diameter of the circle projected onto the diffuse sheet is 130 millimeters. The rectangle is 130 millimeters x 155 millimeters. During the glare assessment the indoor ceiling lights are always turned on and kept the same.

7.2 Method

A fisheye camera (Canon EOS 70D) was used to capture a sequence of five low dynamic range images. The aperture used was 4 and the iso value was always set to 100. The exposure times were: 0.006024 s, 0.04819 s, 0.3856 s, 3.221 s and 24.68 s. LMK LabSoft, a software by Technoteam Vision, is used to convert the low dynamic range image to an high dynamic range image and to generate a luminance map of the particular setting. While the low dynamic range photos were taken, the Konica Minolta luminance metre was also used. The Konica Minolta was used to measure the luminance level on the white surfaces approximately in the middle of the photo.

The white surfaces are pieces of paper on the laptop, this is visible in figure 49. The value of these measurements should be almost the same as the value on the generated luminance map. The luminance value may be slightly different due to, for example, the angle the photos are taken from and the measurements with the Konica Minolta luminance metre. Afterwards a pf.file is saved and converted to a pic.file in RadianceConverter. Command Prompt is then opened to calculate the DGP, DGI and UGR through Evalglare, the Radiance-based tool.

Firstly, important is to check the dimensions of the image to be analyzed via the getinfo command (figure 50). The image must be smaller than 800 x 800 pixels for the Evalglare software to work.

Secondly, if the image is too big (bigger than 800 x 800 pixels) change the size of the image using the pfilt command. Divide the x and y pixels by the same factor (in this case the factor 5.5 is used for x and y) to maintain the proportion of the photo (figure 51). Square90percentbrightstatesmall.pic is now the resized photo.

Finally, run Evalglare to establish the Daylight Glare Probability (DGP) of the image. In this case it is 27% (figure 52). Evalglare provides the established Daylight Glare Probability, Daylight Glare Index, Unified Glare Rating, Visual Comfort Probability and CIE Glare Index.

7. Glare assessment

7.3 Results

The diameter of the circle projected onto the diffuse sheet is 130 millimeters. The rectangle is 130 millimeters x 155 millimeters. During the glare assessment the indoor ceiling lights are always turned on and kept the same.

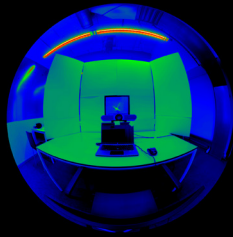
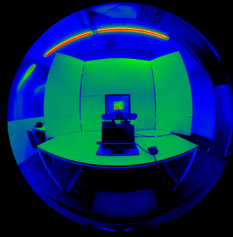
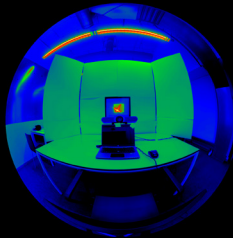
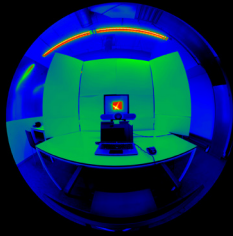
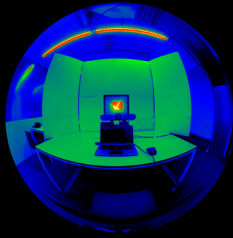
Rectangular form, projector settings, brightness:0	Glass state	Luminance map	Evalglare output		
			DGP	DGI	UGR
Opacity 10%	Bright		0.171	8.28	14
Opacity 30%	Bright		0.172	9.46	14
Opacity 50%	Bright		0.185	13.96	17
Opacity 70%	Bright		0.214	17.70	21
Opacity 90%	Bright		0.273	23.43	27

Table [2]: Calculated DGP, DGI and UGR values: rectangular form projected

7. Glare assessment

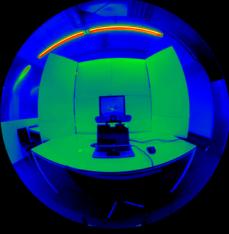
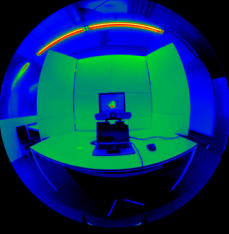
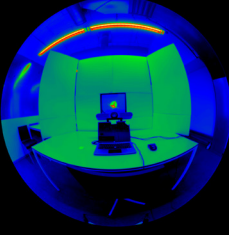
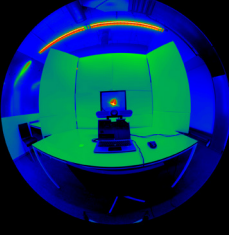
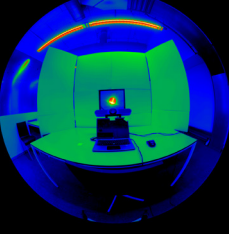
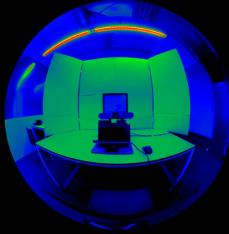
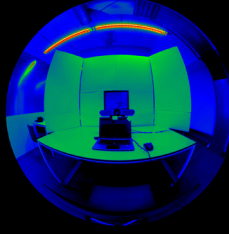
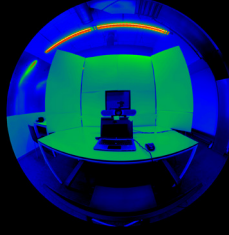
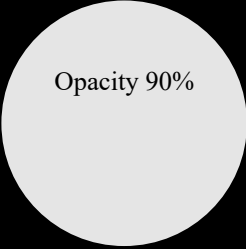
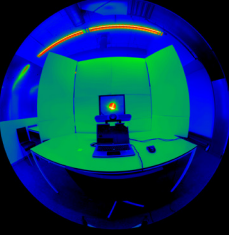
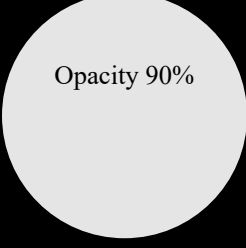
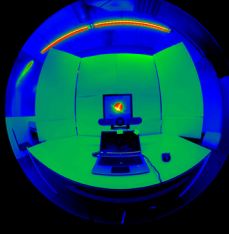
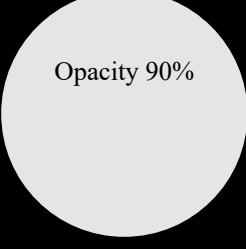
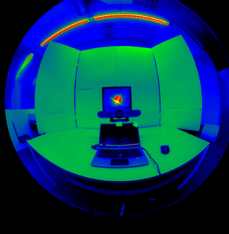
Circular form, projector settings, brightness:0	Glass state	Luminance map	Evalglare output		
			DGP	DGI	UGR
Opacity 10%	Bright		0.184	9.16	15
Opacity 30%	Bright		0.182	8.83	15
Opacity 50%	Bright		0.183	10.10	15
Opacity 70%	Bright		0.200	15.56	19
Opacity 90%	Bright		0.257	22.37	26

Table [3]: Calculated DGP, DGI and UGR values: circular form projected

7. Glare assessment

Circular form, projector settings, brightness:0	Glass state	Luminance map	Evalglare output		
			DGP	DGI	UGR
Cardboard, no light projected	Bright		0.174	8.73	15
Cardboard, no light projected	Intermediate		0.173	8.71	15
Cardboard, no light projected	Dark		0.171	8.72	15
	Bright		0.257	22.37	26
	Intermediate		0.228	19.57	23
	Dark		0.193	15.80	19

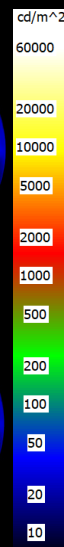


Table [4]: Calculated DGP, DGI and UGR values: evaluation of no exposure artificial glare source and exposure to potential artificial glare source, combined with the different states of the switchable glazing

7. Glare assessment

7.4 Discussion

The DGP values are low due to the fact that there is no daylight entering the experiment room. The windows are completely covered by cardboard while the photos were taken. However, the relative differences between the DGP values is interesting to investigate. Figure 53 shows that the DGP value only slightly increased from 10% to 50%, especially for the circle. The DGP value increases the most from 70% to 90%. Interestingly, when comparing figures 53 and figure 54, the results from the DGP formula show almost no difference between the circle and rectangle with an opacity of 50%, while the DGI indicates that the discomfort due to glare provided by the rectangular form is larger than the circle. All three charts show that the rectangle scores lower with lower transparency, but as transparency of the white surfaces projected onto the diffuse sheet increases, the rectangle scores higher than the circle. This could be due to the difference in contrast.

The UGR value is the most interesting to evaluate since it refers to artificial interior lighting which is the only available light source in the space. Earlier stated in the literature review (chapter 2) is that an UGR value of approximately 19 is wanted in offices. More specific, the European standard BSEN 12464: 2002 specifies the ideal UGR values for typical environments, e.g:

UGR <16 Technical drawing

UGR <19 Reading, writing, training, meetings, PC work.

A UGR of <10 will cause minimal glare and will be virtually unnoticeable, while a UGR higher than 30 would severely impair vision. The number 30 is never reached, 27 is the highest UGR value measured during the glare assessment (figure 55). This is eight numbers higher than the desired maximum UGR value for an office setting. This could result in a visual uncomfortable environment for the participants. Which is desired to be capable of testing the control strategy. Furthermore, the literature review (chapter 2) also expressed that a value of 28 is mostly used for circulation areas and corridors, areas where one passes through.

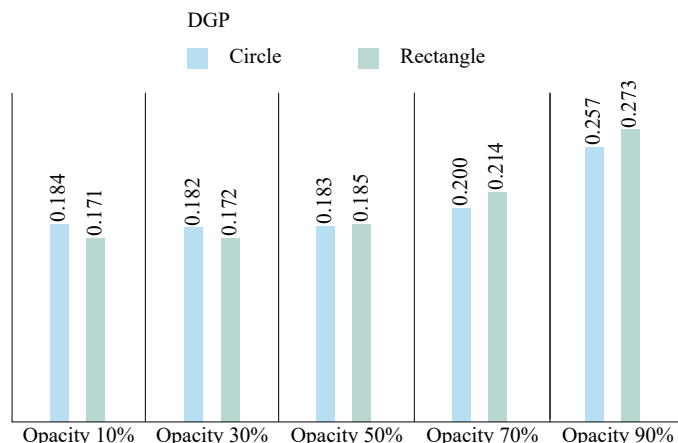


Figure [53]: Differences between circle and rectangle, DGP

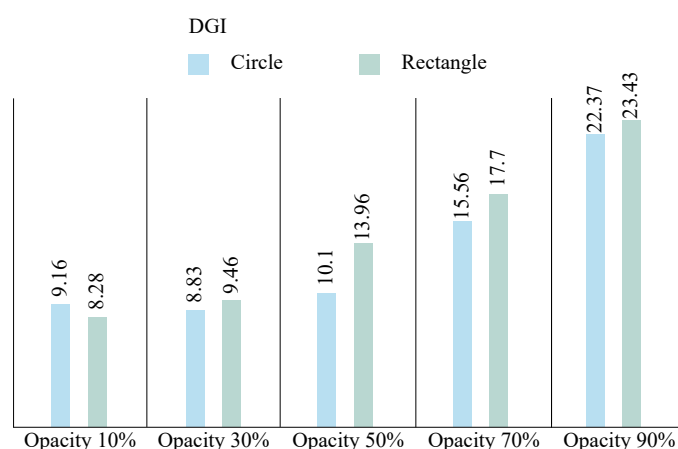


Figure [54]: Differences between circle and rectangle, DGI

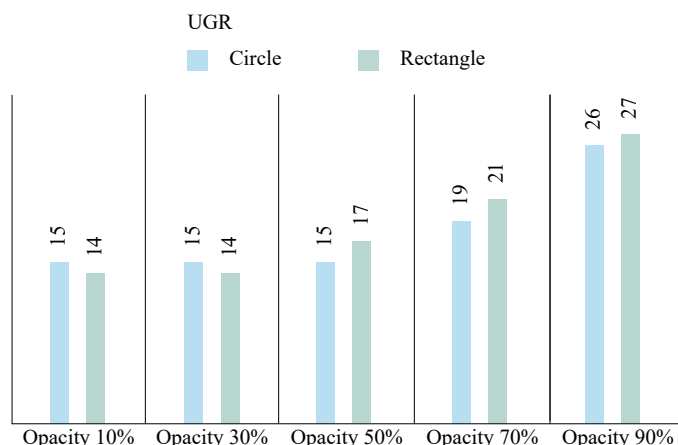


Figure [55]: Differences between circle and rectangle, UGR

7.5 Conclusion

The glare produced by the projector cannot be indicated by a DGP or DGI calculation, since there is no daylight involved. However, the results of the UGR imply that the artificial glare source can produce a visually uncomfortable environment, when the opacity of the circle projected onto the diffuse sheet is minimal 90% or when the rectangle projected has an opacity of minimal 70% or 90%.

8. Experiment I

8. Experiment I

For the setup of the final experiment an analysis is also conducted with participants and not only by equipment and tool measurements, to evaluate the different artificial light settings.

8.1 Goal

The goal of this experiment is to develop the experimental procedure and settings for the second experiment. In experiment II the novel system is tested and compared with a benchmark system and new data is gained regarding predicting glare by analysing one's facial expression. To evaluate the two systems an effective experimental environment has to be made, meaning the experiment room should resemble an office-like space and the artificial glare source should be able to create a visually unpleasant environment for the participant. During experiment I, it is indicated which settings the participants may find comfortable and what not. Furthermore, if the source can create a visually unpleasant environment for the participant (glare) is evaluated, by retrieving responses from participants. During this experiment the participants will also wear the HOBOT to determine the threshold values and they are recorded with the webcam to verify the set threshold values for the AU's. The main objective is, developing the physical characteristics of experiment ii, where the novel control system is evaluated.

8.2 Materials and setup

A room with similarities to an office was built to perform this initial experiment in. A participant will be performing office-like tasks on a laptop screen. The screen will host several short texts and some questions regarding the texts. A notable difference of this office-like setting and a real situation, is that the desk is faced towards the window. Normally, the desk is not faced this way, however for this research it is important to create a visually uncomfortable space, since it is going to be tested if the system can sense that the occupant is indeed experiencing visual discomfort. Therefore, the space is meant to be similar to an office environment and close to earlier experimental research studies done where glare is created.

In figure 56 an isometric 3D illustration presents the setup of this experiment. Indicated with (a), the chair the participant will be seated in. The participant will be seated behind a desk that is in front of a laptop (b) with a camera ((c) Logitech meetup) capturing the facial actions units of the participant. The laptop and computer mouse host the on-screen tasks for the participant. The participant will be wearing a lux sensor ((e)hobo) on the chest. The lux sensor and camera send the output to another laptop (f) processing the output. The facial actions units are processed by OpenFace and the lux readings are carried out by HOBOWare. The driver (g) of the switchable glazing (h) rests on the table behind the artificial façade. The switchable glazing stands on a wooden shelf. The set-up is made from old voting booths, built from aluminium frames. The room has artificial light. Behind the switchable glass is a projector (i) functioning as an artificial glare source. The beamer projects a white circle or square form onto the diffusive screen (j). The circle and square are created in Indesign. Different scenarios are tested, meaning the forms differ in opacity. The room where the experiment is done has windows, all windows are covered with cardboard so no natural light can enter, this way every different scenario and experiment are as similar as possible.

8.3 Participants

A number of 14 participants, of which 11 females and 3 males took part in this study. 13 of the participants aged 18 to 24 and 1 aged 25 to 30. All 14 participants originated from Europe. Due to COVID-19 restrictions only a couple of participants were allowed in the faculty of architecture. Therefore it took 7 days to perform experiments with 14 people. All of the participants were students, most of them from the Faculty of Architecture.

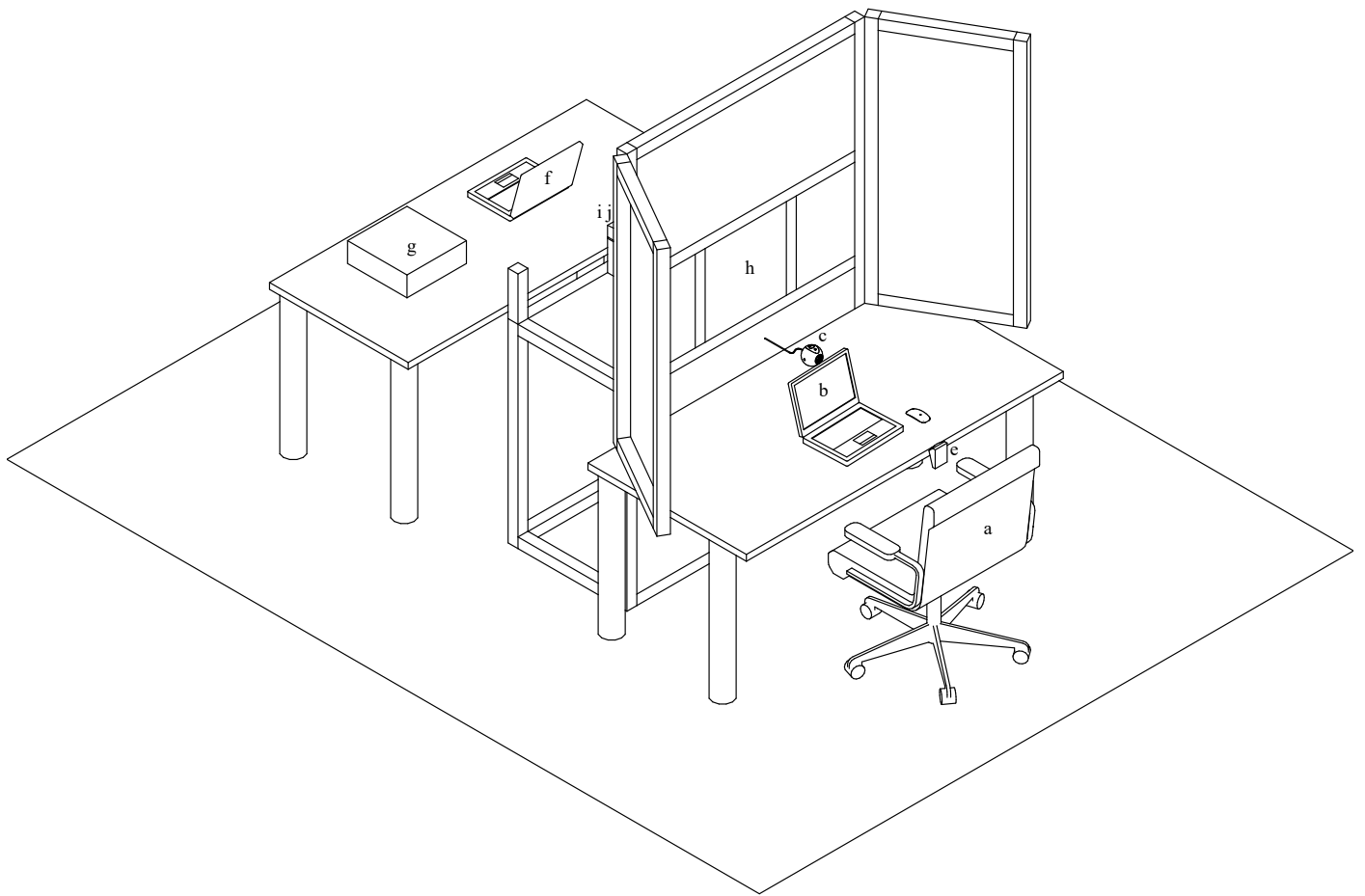


Figure [56]: Isometric 3D illustration of experimental setup

8. Experiment I

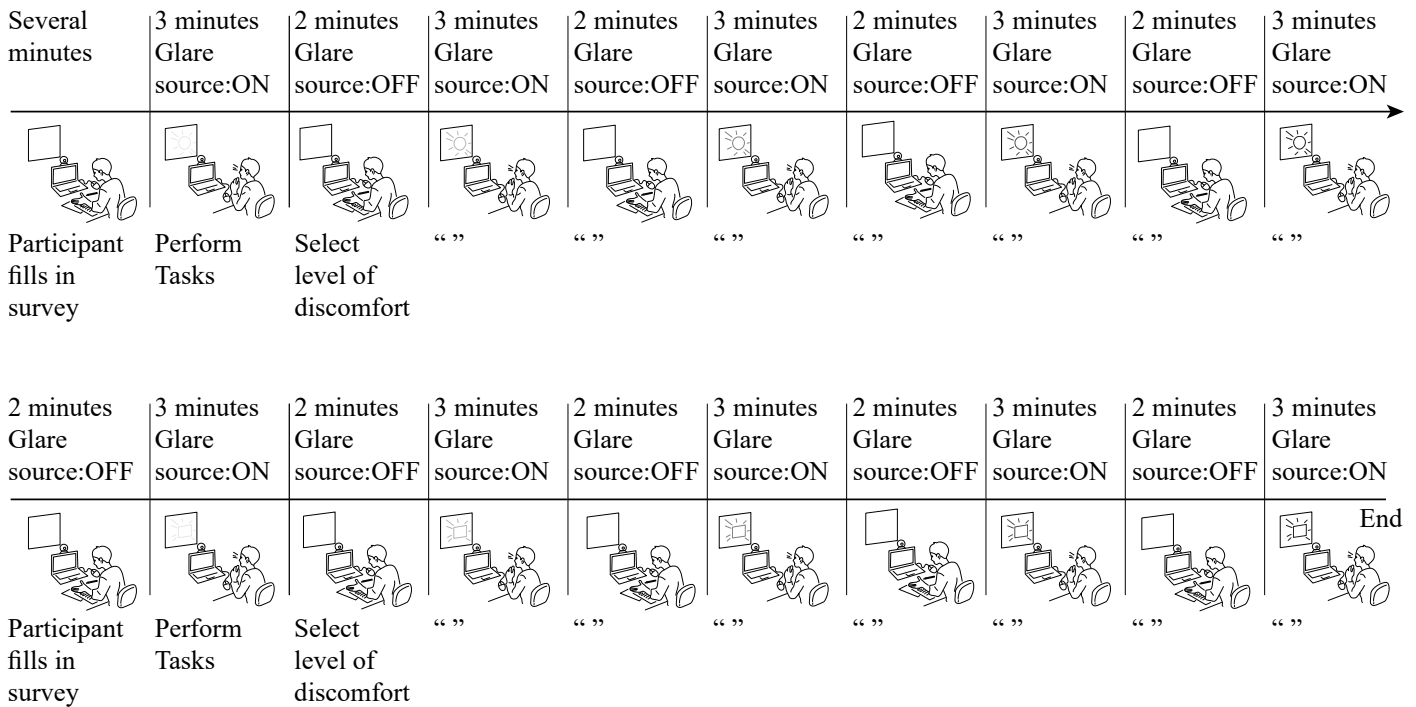


Figure [57]: Experimental I procedure

8.3 Procedure

Before the participant entered the room, the desk, the mouse, the laptop, the HOBOT, a pen and chair were cleaned as a COVID spread prevention. Afterwards the participant was welcome to enter the room and was kindly asked to take a seat behind the desk, in front of the laptop. The height of the eyes of every participant had to be approximately the same during the experiments. This was done by comparing their eye level to a piece of cardboard with the length of 1240 millimeters. The height of the chair could be modified if one was seated too high or too low. The participants were requested to fix the HOBOT with magnets to their chest, near their heart.

The participant was handed an A4 paper with questions regarding the demographics, a brief clarification of the terms; imperceptible, perceptible, disturbing and intolerable and here the participant had to clarify for each different scenario if it was imperceptible, perceptible, disturbing, or intolerable (for reference see appendix 15.1). Lastly the sheet of paper consisted of questions regarding the screen quality of the laptop in front of them and the habituation. The participants could rank the screen quality from 1 to 5 (poor - excellent). Habituation regards the resemblance of the experiment room

to an office-like environment. If the participants found the experiment room similar to an office environment, they could score it with for instance a 5, on a scale from 1 tot 5 (poor - excellent), and if they found it very laboratory-like they could have categorised the experiment room with the number 1.

After the participant had answered the initial questions regarding the demographics and had given permission to be recorded by the webcam, the participant was instructed to read the text on the screen and answer the questions. Told was that the settings in the room were going to be altered.

They all experienced at least ten different scenarios (light settings) that lasted for 3 minutes each (figure 57). In between the light settings a piece cardboard was placed in front of the projector as an obstacle. An obstacle was placed in front of the projector rather than turning it off, because switching the projector constantly on and off is bad for the equipment. The time in between the settings lasted for 2 minutes. During this time they had to choose one of the four ratings (imperceptible, perceptible, disturbing and intolerable) for the setting they were just in. The experiments lasted between 45 and 55 minutes each. After the different settings the last questions on the form are answered by the participant and the form is retrieved.

8. Experiment I

It is important for the participant to begin in a comfortable environment. So every time a participant entered the room, the piece of cardboard was covering the projector. All the components stayed the same during the procedure, except for the settings of the projector. The participants all experienced the same order of scenario, thus the settings were not tested randomly. In the end the participant was thanked and asked if they would like to participate in experiment II as well.

8.5 Results

The procedure was the same for every participant. The preliminary results of the action units captured are described in the results, the lux readings and the survey responses. In the end the threshold values could be augmented and the visual discomfort level of the glare source may be categorised.

8.5.1 Action Units

Only 6 participants were recorded by the webcam, since some malfunctioning occurred during the experiments. The two reasons why the logitech webcam turned off were (i) the USB portal of the laptop to which the camera was connected often lost connection, leading to the webcam restarting and (ii) to record with the webcam, the camera app on the computer (windows 10) was opened, by clicking on the icon off the camera during the experiment, the computer automatically stopped recording, this was at first not known. After a while it was discovered that the camera shut down due to an unaware doing by the experimenter. It was important to keep in mind not to click on the camera icon during an experiment. In the end both problems were fixed, which means it would not happen during experiment II.

The videos that were taken, were processed by OpenFace and the data was briefly analyzed in excel to see whether the threshold values earlier stated could work. However there was not a sufficient amount of clear data from the Action Units. The data was not clear, in a sense that it was difficult to match the OpenFace data with the different scenes. OpenFace provides a Timestamp and not the actual time. This makes it tricky to link the data to the scenario the participant was in. Nevertheless, the data of AU02_r (Outer Brow Raiser) expressed

that participant 14 has a reaction similar to the threshold value generated via a previous research. The particular response of the participant was when the white circle was displayed on the diffuse sheet with an opacity of 90%. The data provided by OpenFace of participant 14 was easier to link with the scenario, since the HOB0 and webcam were turned on very quickly after one another.

8. Experiment I

8.5.2 Lux readings

Of the participants, 11 were wearing the HOB0 and gathered lux data. The data is analyzed and average lux values are calculated. A value of 199 lux is the average of the moments when the cardboard is in front of the projector. When the white circle with an opacity of 90% is projected, the average measure of the lux value is 266,4 lux. One of the participants had a very low lux reading, namely 18 lux, this was because the participant's elbow was leaning on the table, while the participant's head was resting in the palm of their hand. This forms a risk for the control strategy. If the lux levels are too low the glass will not change state, or the glass may even turn from dark to bright again when it is not desired, since the control algorithm would sense a very low light supply. This points out a risk of using a wearable, on the one hand it is personal and relatively close to the eye that could benefit the experience. On the other hand, the participants (unforeseen) behaviour may cause a false reading. The participant's arm, hair or sweater could block the wearable.

8.4.3 Survey

The participants were exposed to 10 different settings of the image projected by the projector. They had to choose a glare rating for each scenario. The tables present the participants' response to the various settings.

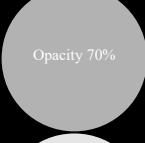
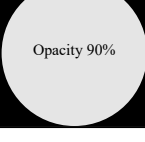
Projection	Participant response
	2 x Imperceptible 12 x Perceptible
	3 x Imperceptible 8 x Perceptible 3 x Disturbing
	1 x Imperceptible 6 x Perceptible 7 x Disturbing
	5 x Perceptible 8 x Disturbing 1 x Intolerable
	3 x Perceptible 8 x Disturbing 3 x Intolerable

Table [5]: Participant responses regarding the level of discomfort (circle)

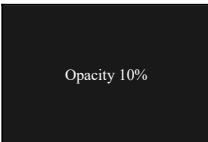
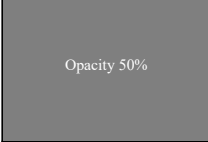
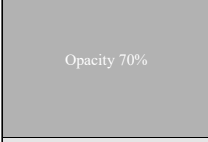
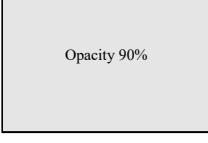
Projection	Participant response
	10 x Imperceptible 4 x Perceptible
	2 x Imperceptible 12 x Perceptible
	12 x Perceptible 2 x Disturbing
	5 x Perceptible 9 x Disturbing
	1 x Perceptible 10 x Disturbing 3 x Intolerable

Table [6]: Participant responses regarding the level of discomfort (rectangle)

8. Experiment I

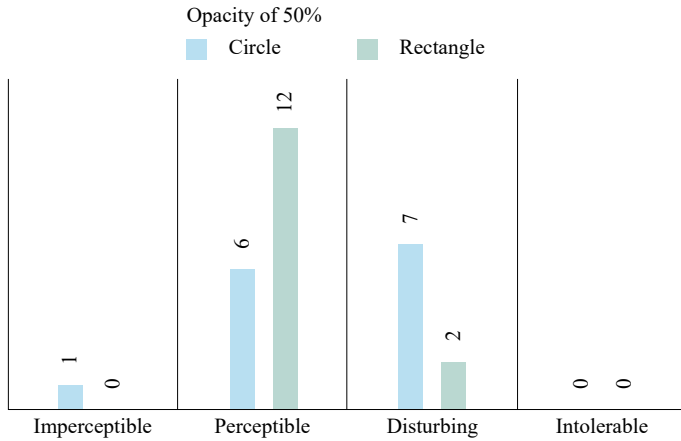


Figure [58]: Difference in glare sensation; opacity of forms 50%

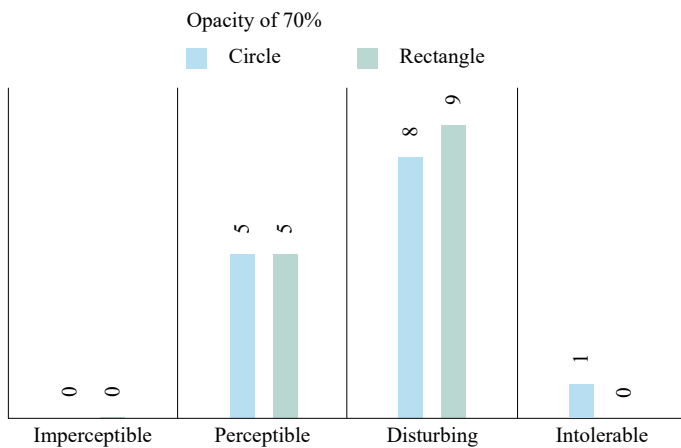


Figure [59]: Difference in glare sensation; opacity of forms 70%

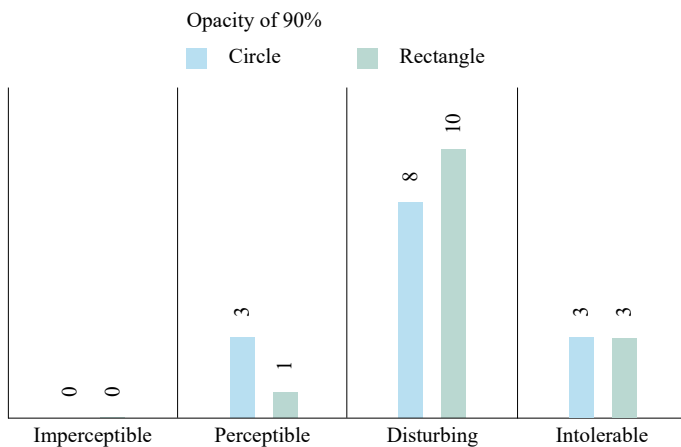


Figure [60]: Difference in glare sensation; opacity of forms 90%

The chart presenting the difference in participant responses, regarding the level of discomfort glare, where the forms are projected with an opacity of 50%, suggests that the circle might be more disturbing for the occupant. The same can be said for the opacity of 70%, although this difference is very little.

However, if a form is projected by the projector with an opacity of 90%, the rectangle seems to be more disturbing. Figure 60 presents that both the circle and rectangle projected with an opacity of 90% are experienced uncomfortable for most of the participants.

The participants were asked about the habituation of the experiment setup. They could rank it from 1 to 5 (Poor to Excellent). A number of 12 participants replied with 4, 1 participant with 3 and 1 participant with 5 (figure 61). Thus, the habituation is ranked with a 4. This indicates that the experimental setup is sufficiently designed to resemble an office-like space.

Furthermore the participants had to judge the screen quality of the laptop hosting the tasks. They could rank it from 1 to 5 (Poor to Excellent). Meaning, for instance, if they found the brightness of the laptop a bit low, they could rate the screen quality with a 2 or 3. An amount of 3 people gave the screen quality a 5, 7 judged it with a 4, 2 people judged it with a 3, 1 participant ranked it with a 2 and 1 more gave it a 1 (figure 61). The average is 3.7. The participants seem to find the screen quality okay.

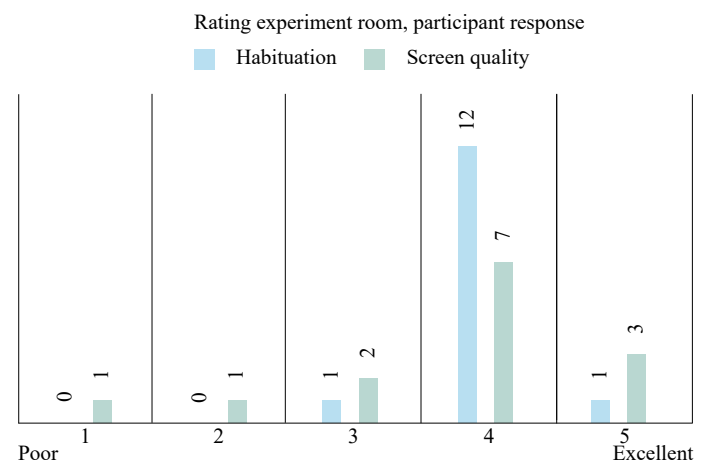


Figure [61]: Participant response rating habituation and screen quality (1 -5, poor - excellent)

Lastly, the participants were asked to give their opinion on the time of the scenarios and the time in between. The responses both give an average of 4.4. This means the participant felt like the timing was well, however, as stated in the literature research (chapter 3) the visual system reacts unconsciously, therefore not much can be said for this information.

8. Experiment I

8.5 Discussion

Some things went wrong during this experiment that should not occur during experiment II. The camera kept on shutting off. This led to a loss of data that could be provided by OpenFace. Furthermore, when the data of the lux and the AU's was studied it was not clear if these were happening at the exact same time. HOBOWare provides the time that the lux value was measured, whereas OpenFace does not. OpenFace presents a timestamp (30 per second), therefore it can be roughly determined, though this is imprecise. This is taken into account for the protocol of experiment II. During the second experiment a piece of paper is taped onto the HOBOWare to cover the lux sensor. The participant is asked to take the obstacle of the HOBOWare directly when the webcam is turned on.

The activity the participant was doing differed from time to time. Some moments the test person was typing and other moments the person was reading a text. After the experiment, participants were told that they had the impression that while they were typing, they were less bothered by the light. This could have been due to the difference in cognitive attention required for these tasks as described in chapter 6. This may have influenced the results of the level of discomfort. As a consequence, for experiment II task sheets are made with mathematical multiple choice questions. This ensures that the test subject mainly looks at the screen of the laptop hosting the questions and uses the mouse to give the correct answer. Thereby, avoiding looking down to the keyboard, which may lead to less glare sensed, which happened since the participants were not as familiar with this keyboard as to their own. Instead of using a laptop, an Ipad or other touch screen device could be used for such an experiment. The participant might move more this way, potentially causing other disadvantages, but the participants would likely all look at the screen the entire duration of the experiment. Moreover, the task the participant is instructed to do influences the potential of capturing the facial action units of that particular participant. If the participant would look down to type, towards the keyboard, problems may arise regarding the output of OpenFace. An illustration expresses the difficulty of capturing the facial action units when the participant would be looking at the

keyboard or at for instance a piece of paper on the desk. The illustration shows that the face of the participant looking towards the screen of the laptop is easier to capture via the webcam (figure 62).



Figure [62]: Differences in tasks influencing difficulty of capturing participants facial expression

Foitos (2020) describes four different commonly used test procedures in the paper “Measuring Discomfort from Glare: Recommendations for Good Practice”, adjustment, matching, discrimination and category rating. Since, there are no external references present, it is a single interval task and the participant cannot adjust or request to adjust the luminance value, this study corresponds to a category rating procedure and its biases. The participants were set in different scenarios one by one. Then they had to choose which sensation applied to that scene, they were requested to categorize the scenario. Given that the participants observed only one visual scene at certain moments and judgements were made against an internal (memory) reference. Biases that may occur with category rating tasks are; (i) stimulus range bias, (ii) order effect, (iii) pre-trial demonstration, (iiii) response scale design, (iiiiii) statistical analysis of rating data (Foitos, 2020).

In this experiment, among other aspects, stimulus range bias and pre-trial demonstration (anchor effects) have probably had an effect on the results. Order effects might also have had a certain impact on the outcome. Stimulus range bias regards the luminance range of the scenarios, the settings of the artificial glare source. This range is selected by the experimenter.

8. Experiment I

Regardless of the supposed validity of the selection, these ranges strongly influence the response of the test takers and form an experimental bias. The different light conditions are selected because some of them showed, in the glare assessment, to provide an oversupply of light. Nevertheless, if the brightness of the projector was different or the colour, the results could have been different. Pre-trial demonstration can be compared with anchor effects that have an impact on the results of an adjustment procedure. The anchor point affects the feeling and experience of the occupant, a lower anchor point might result in less people finding the glare condition disturbing, while a higher anchor might lead to more people being disturbed by the conditions (Fotios, 2019). During category rating the anchor point is the visual and memory references held before the first trial. As earlier stated during a category rating procedure, the anchor point is unclear for the experimenter and may vary per participant. Which may lead to more different responses between participants. Regarding the effects of the order, although in between the glare conditions the room was set back to a comfortable setting for two minutes (setting where the cardboard was placed in front of the projector), the order of the glare conditions may have influenced the results. The time between the scenes may have been too short, leading to the scenarios and the order they were in, may have influenced the results.

Regarding the statistical analysis of rating data, it has been suggested that response scales with at least five categories may be analyzed as though they are parametric data and scales with four or less options to choose from, should not (Foitos, 2020). Therefore, the manner of analyzing the results of this data is correct.

8.7 Conclusion

Depending on only the results of the survey projecting a white circle or rectangle with an opacity of 70% or 90%, as an artificial glare source, could be sufficient. It is desired to study the facial expression of the participant as well. The results from OpenFace imply that facial action units are more likely to be captured in a brighter environment, thus by projecting a white form with an opacity of 90%. The circular form resembles, in a sense, slightly more the sun. Glare occurs due to an oversupply of light, mainly caused by the sun. For this reason, during experiment II, a white circle with the opacity of 90% is chosen to form the artificial glare condition. The participants will be instructed to perform tasks hosted by the laptop in front of them and it will be pointed out that they should use only the mouse to give the correct answer to the mathematical questions.

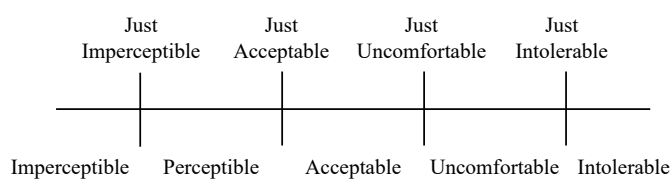


Figure [63]: Different category rating scale (Foitos, 2020)

The response scale design can be different in many ways. Figure 63 presents a scale with more categories to choose from. Foitos (2020) states that this scale is mostly used for rating glare caused by the sun and the Hopkinson response scale, the one used during this experiment, is used more often when evaluating interior lighting. The number of response categories could vary, the category labels and the common understanding of label (terms) could differ per person. Using a different response scale and different descriptions regarding the category labels could lead to different results.

9. Experiment II

9.1 Goal

The goal of this project is developing an interaction between the occupant and the switchable glazing. A method is proposed, in this novel automated shading system, the occupant is added to the loop controlling the switchable glass. The overall goal of the experiment is to identify the reactions of the occupant triggered by glare and how to integrate these in the strategy, hence developing the method. An earlier research project where a similar experiment has been conducted, concluded that AU02, AU04, AU06 and AU10 can be considered in a controlling strategy. During experiment II, it is tested whether the novel strategy works, by means of, among other aspects, comparing it with another more traditional system and analysing if it is more effective than the benchmark. The benchmark, a standard or point of reference against which the controlling system may be compared, is based on an automatic shading control system with a lux sensor placed outdoors fixed to the façade on the height of the occupant's eye, highly influenced by the time of day and orientation.

9.2 Materials and setup

The constructed setup of this experiment is the same as in experiment I. A room with similarities to an office environment was used to perform this experiment in. A participant will be performing office-like tasks on a laptop. The participant will not be using the keyboard, since many keyboards are different, it could lead to participants looking often at the keyboard to search for a character and not the screen. A possible negative effect of working with an unfamiliar keyboard and therefore looking down, towards the keyboard, is that the webcam will have difficulty capturing the participants facial expression. This would make it hard for the software program, OpenFace, to process the data. In a normal situation an office employee would already be familiar with the keyboard and would not have to look down so often.

In figure 64 an isometric 3D illustration presents the setup of this experiment. Indicated with (a), the chair the participant will be seated in. The participant will be seated behind a desk that is in front of a laptop (b) with a camera ((c) Logitech meetup)

capturing the facial actions units of the participant. The laptop hosts the on-screen tasks for the participant and the computer mouse is used to give the answer to each question. Different to experiment I, the participant will be answering multiple choice (A, B or C) mathematical questions. See the appendix for reference (15.5 and 15.6).

The participant will be wearing a lux sensor ((e) HOBO) on the chest, near their heart. The lux sensor and camera send the output to another laptop (f) processing the data. The facial actions units are processed realtime by OpenFace and the lux readings are carried out by HOBOWare. Both provide csv.files with the collected data. The control algorithm on the laptop runs the data and presents the experimenter what state the glass should be in, namely, bright, intermediate or dark. The driver (g) of the switchable glazing (h) rests on the table behind the artificial façade. Via a mobile application and bluetooth connection to the driver the state of the glass is controlled. The brightest state of the glass has a transmission value of 45% and the darkest state a value of 9% ($T_v(\text{bright}) = 0,45$, $T_v(\text{dark}) = 0,09$). The switchable glazing stands on a wooden shelf. The height of the wooden shelf is 930 millimetres from the floor. The room has artificial indoor lighting on the ceiling. These ceiling lights are all on during the experiment. Behind the switchable glass is a projector (i) functioning as an artificial glare source. The projector stands on a platform lifting it 170 millimetres above the wooden shelf. The beamer projects a white circle with an opacity of 90% and a diameter of 130 millimeters onto the diffusive screen (j). The diffusive sheet is bought at kamera express a dutch store for mainly photography related equipment. The room where the experiment is done has windows, all windows are covered with cardboard so no natural light can enter, this way every different scenario and experiment are as similar as possible.

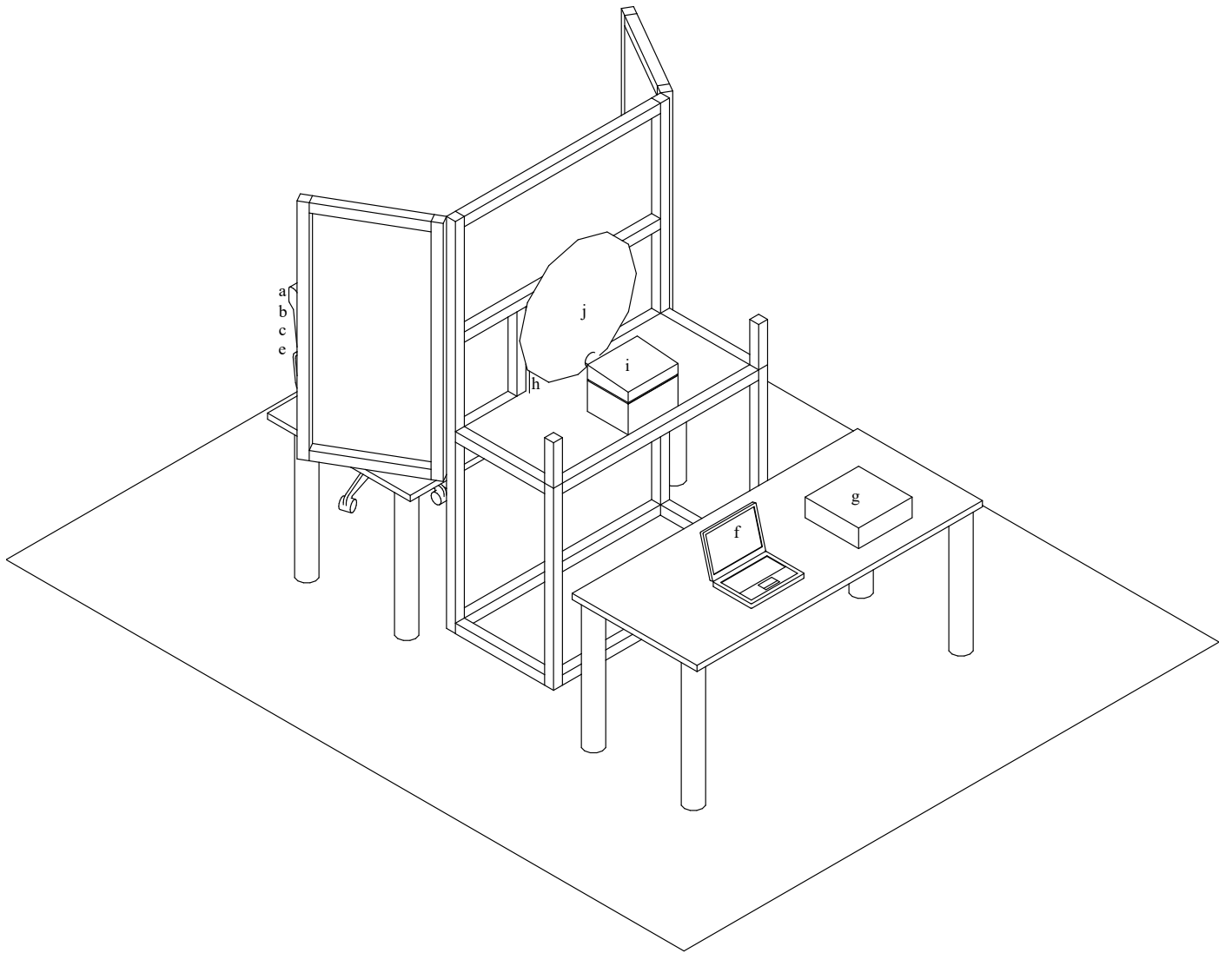


Figure [64]: Isometric 3D illustration of experimental setup

9. Experiment II

9.3 Participants

A number of 16 participants, of which 11 females and 5 males took part in this study (figure 65). 3 of the participants of this experiment, also participated during experiment I. 9 of the participants aged 18 to 24, 6 aged 25 to 30 and 1 aged 31 to 35 (figure 66). 12 participants originated from Europe, 2 from Asia and 2 were American. 10 participants with brown eyes participated, 4 with blue, 1 with green and 1 a mixed eye colour. 9 participants did not normally wear glasses and 7 participants either had glasses or contact lenses (figure 68). Participants could not wear their glasses during this experiment, since OpenFace would have difficulty reading the Action Units if one was wearing glasses. Due to COVID-19 restrictions only a couple of participants were allowed in the Faculty of Architecture per day. Therefore it took at least 8 days to perform experiments with 16 people. All of the participants were students from the Technical University of Delft.

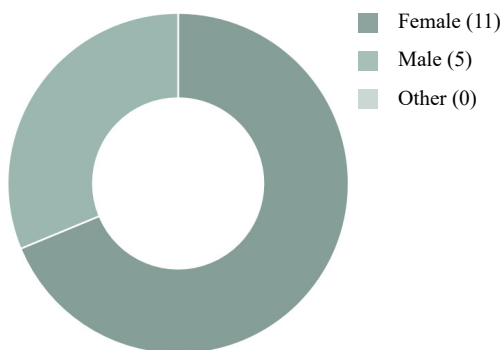


Figure [65]: Gender distribution

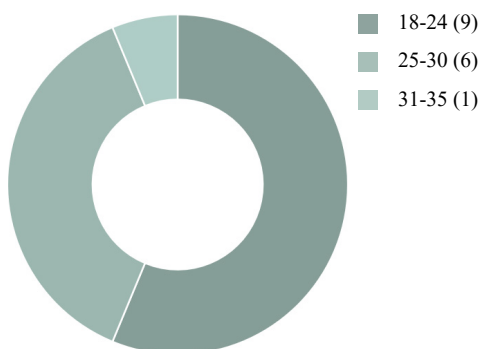


Figure [66]: Age distribution

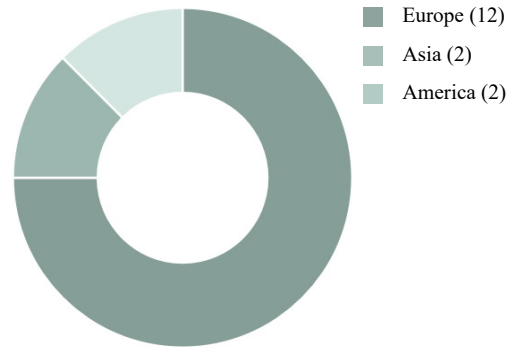


Figure [67]: Origin distribution

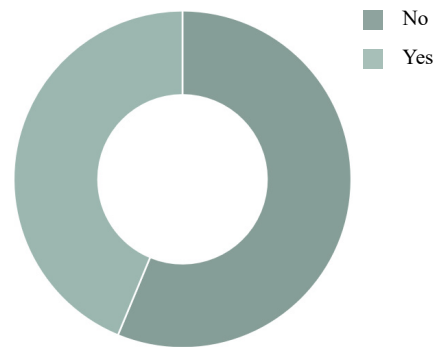


Figure [68]: Need of glasses or contact lenses (yes or no)

9.4 Procedure

Similar to the procedure of experiment I, prior to the participant entering the room, the desk, the mouse, the laptop, the HOB0, a pen and chair were cleaned as a COVID-19 spread prevention. Afterwards the participant was welcome to enter the room and was kindly asked to take a seat behind the desk, in front of the laptop. The height of the eyes of every participant had to be approximately the same during the experiments. This was done by comparing their eye level to a piece of cardboard with the length of 1240 millimeters. The height of the chair could be modified if one was seated too high or too low. The participants were requested to fix the HOB0 with magnets to their chest, near their heart. At this point a piece of paper is taped on the light sensing part of the HOB0, to block it from measuring lux. The obstacle is removed by the participant when the experimenter instructs to do so. The experimenter tells the participant to do this precisely when the webcam is turned on. This timing is important. This way it is easy to link the data of the HOB0 and OpenFace. Later when the data is analysed, it is clear that when the lux readings increase, mostly from approximately 18 lux to more than at least 100 lux, the recording by the camera is turned on and the data is processed by OpenFace.

9. Experiment II

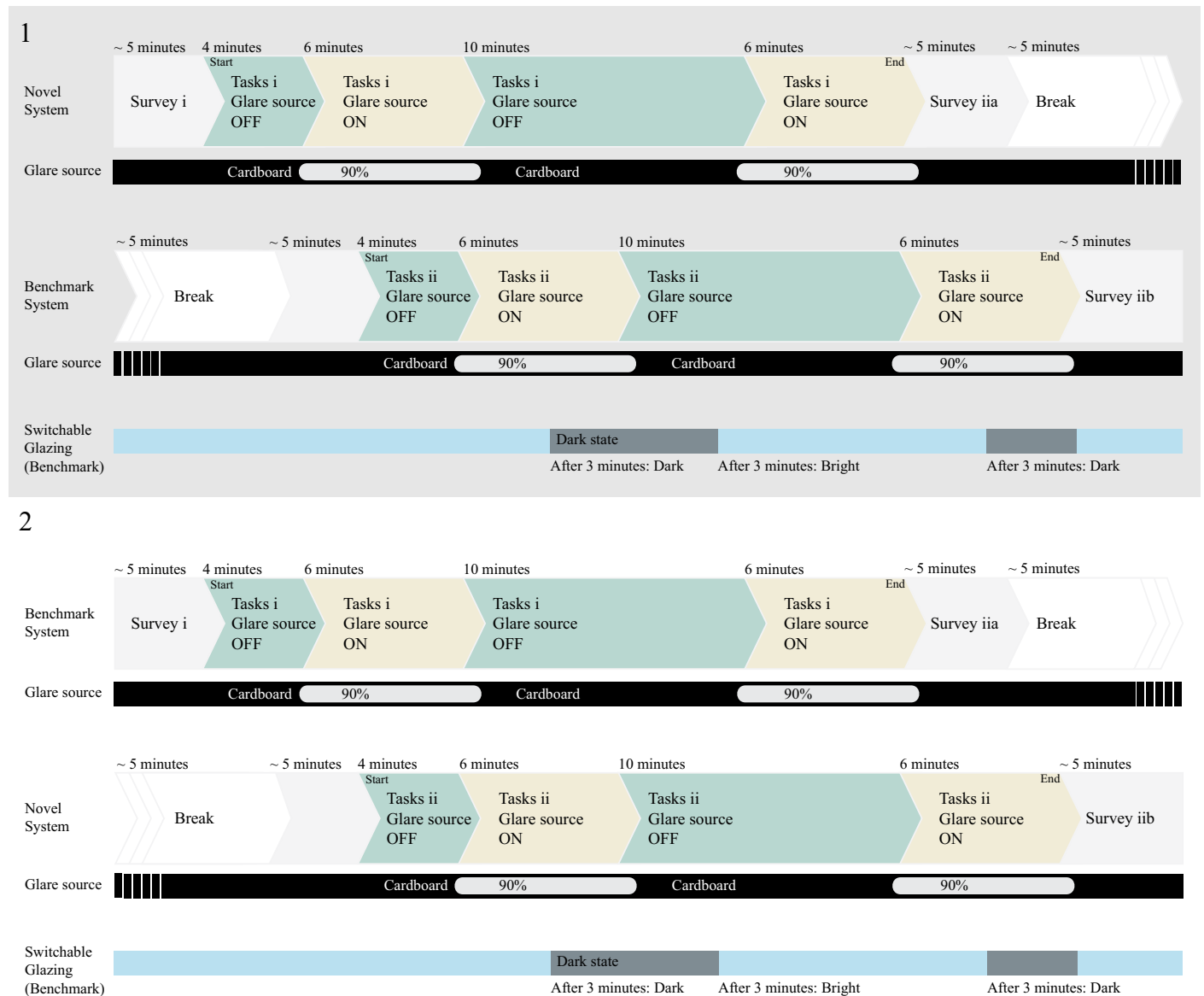


Figure [69]: Timeline of experiment II, two of the four variations (due to randomised task sheets)

The participant was handed an A4 paper with questions regarding the demographics, which are previously described, if they had caffeine, how sensitive to light they are, how many hours they approximately slept and how they were feeling that day. See experiment II survey i in the appendix for reference (15.2). After the participant had answered the initial questions regarding the demographics and had given permission to be recorded by the webcam in front of them, the survey was retrieved by the experimenter. The participant was instructed to make the task sheet, with mathematical multiple choice questions, hosted on the laptop as good as possible. The participant was also told to use the mouse to give the correct answer on the sheet. It was not allowed to use the calculator functions on the laptop. The test person was not permitted to start if it was not told yet by the experimenter.

In total the experiment lasted slightly more than an hour (approximately 70 minutes). See figure 69 for reference.

9. Experiment II

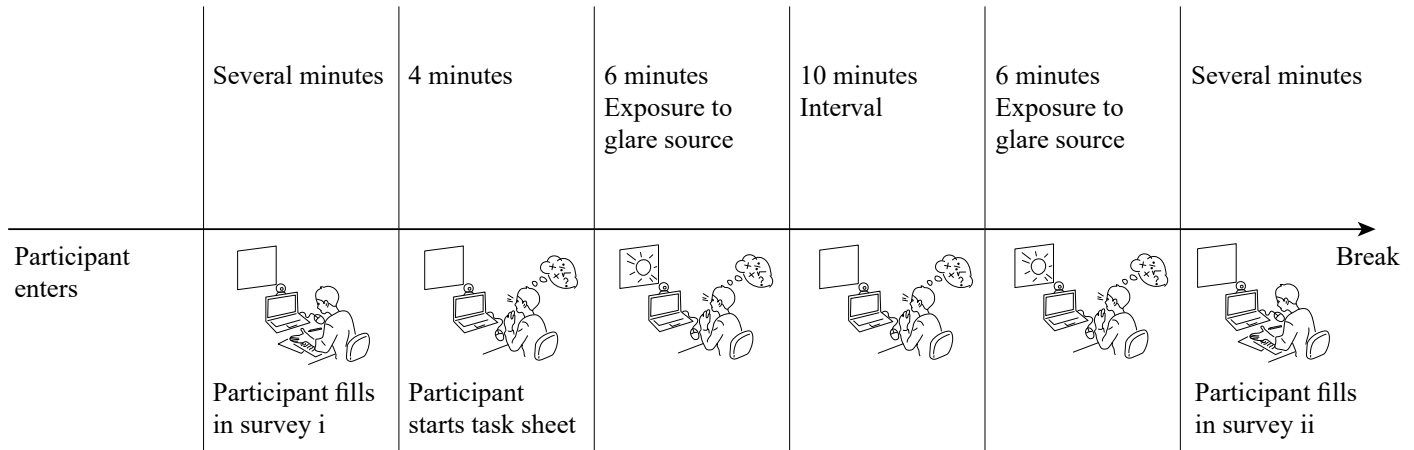


Figure [70]: Experimental procedure, one half (26 minutes)

Firstly, the participants fill in the survey and fix the HOB0 to their clothing. This takes several minutes. Then the participant is instructed to take off the piece of paper blocking the lux sensor and to start the tasks on the screen. This is when the first fixed 26 minutes start. During the first 26 minutes the glass is controlled via either the novel system or via the benchmark system. The participant has to work on either task sheet i or task sheet ii during these first 26 minutes. The task sheets and the answers are in the appendix (15.5 and 15.6). Figure 69 presents the timeline of the entire experiment and the variations, figure 70 presents one half of experiment II. The first 4 minutes the participant is seated in a comfortable environment. The following 6 minutes a bright white circle with an opacity of 90% is projected onto the diffuse sheet. Note that the projector is already turned on beforehand, for the light to reach the glass the cardboard in front of the beamer is removed. After these 6 minutes the cardboard is put back in place, for 10 more minutes. Next the cardboard is removed again and the artificial glare source is projected for the remaining 6 minutes. Afterwards the cardboard is placed back and the first half of the experiment is done. The participant is requested to fill in another survey. See in the appendix experiment II survey iia for reference (15.3). The survey is retrieved by the experimenter.

The participant is allowed to take a break. The break lasts at least 15 minutes. During the break the participant is allowed to exit the experiment room.

After the break the participant is again asked to take a seat in the chair in front of the laptop. The HOB0 is again fixed to the chest with the aid of magnets. The participant is instructed to take off the piece of paper on the lux sensor and the webcam is turned on. The next 26 minutes take place. Every step is the same as the previous 26 minutes, except the glass is controlled differently and the participant will be working on either task sheet i or task sheet ii. Since the participant is wearing the HOB0 during both tests, it is certain that the participant does not know if the novel system is on or the benchmark is applied. The glass always darkens at the same moments for the benchmark system, 3 minutes after the circle is projected onto the diffuse screen. The glass also turns bright, 3 minutes after the cardboard is placed back in front of the projector. See figure 60 as reference. During both 26 minutes a recording is taken with the webcam of the participant to enlarge the data. Eventually the data could provide more accuracy for threshold values. After the second period of 26 minutes, the participant is asked to cover the HOB0 again. The participant is given a final survey (survey iib, appendix 16.4). The survey is almost the same as survey iia. The survey contains mainly questions about the lighting in the experiment room and the last questions are regarding whether the participant felt a difference between the two sessions of 26 minutes and if they had a preference.

After the experiment, the data is reviewed. This applies to the data from the different surveys, the HOB0, OpenFace and also the number of correct answers regarding the task sheet is noted per participant.

9. Experiment II

9.5 Results

Figure 60 presents the four different options of the experiment order. The variants are:

1. First 26 minutes: novel system, task sheet i -
Second 26 minutes: benchmark system. task sheet ii
2. First 26 minutes: benchmark system, sheet i -
Second 26 minutes, novel system task sheet ii
3. First 26 minutes: novel system, task sheet ii -
Second 26 minutes: benchmark system. task sheet i
4. First 26 minutes: benchmark system, sheet ii -
Second 26 minutes, novel system task sheet i

Two of the variations are done by 4 participants, one variation is done by 5 participants and one by 3. The following table expresses the variants, the amount of participants and the specific participant id that carried out the experiment in that variant.

Variant	Participant_count	Participant_id
1	5 participants	1, 6, 7, 8, 12
2	4 participants	1, 2, 4, 5
3	3 participants	10, 13, 14
4	4 participants	9, 11, 15, 16

Table [7]: An overview of the amount of participants and participant id, conducting a specific option of the different four

9.5.1 Survey

In the beginning and at the end the participants had to fill in surveys regarding demographic information, mood, how many hours of sleep they had, questions regarding the characteristics and lighting conditions of the experiment room.

5 of the 16 participants indicated that they (most of the time) usually work in an office environment, 8 of the participants indicated that they sometimes work in an office space and 3 indicated that they never work in an office space (figure 71). All, except for 1 of the participants, had caffeine in the morning during the day of the experiment. 7 of the participants were

in a good mood (7x1), 6 participants graded their mood with a 2, 2 with a 3 and 1 participant graded the sensed mood with a 4 (figure 72). Note that the grade 1 was closest to a good mood and if the participant graded their mood with a 5, they were in a bad mood.

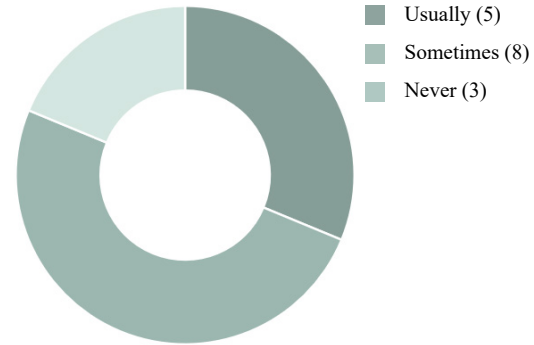


Figure [71]: Responses to “How often do you work in an office environment?”

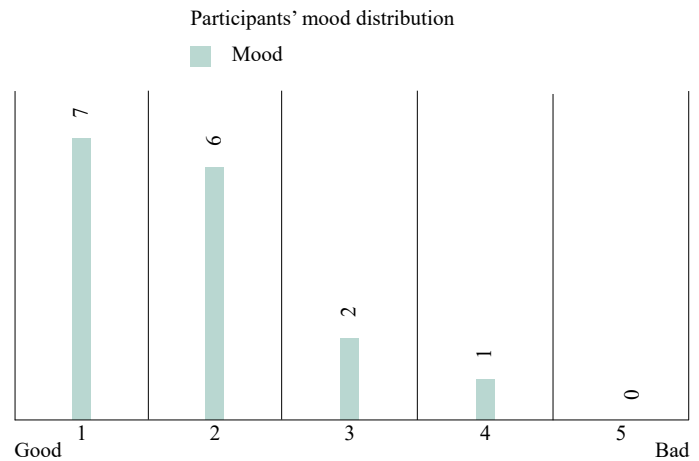


Figure [72]: Participants mood distribution

The average grade regarding the sensitivity to light is a 3.2 (with 1 very sensitive and 5 not at all sensitive) (figure 73).

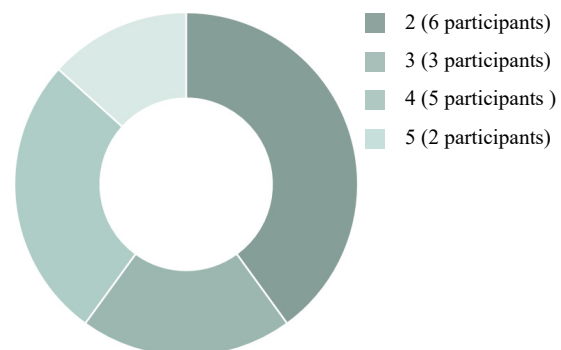


Figure [73]: How sensitive are you to bright light? (very sensitive - 1 2 3 4 5 - not at all)

9. Experiment II

The participants of this experiment were overall not feeling very tired, with an average grade of 4 (figure 74). Notable is that 2 participants answered 2, which is interesting to keep in mind, since the sensitivity to light increases when people feel fatigue.

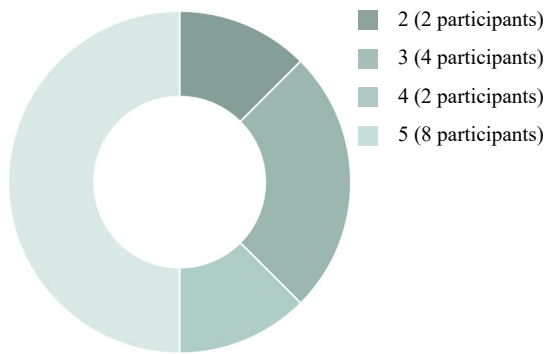


Figure [74]: Are you feeling tired? (yes - 1 2 3 4 5 - no)

After one part of the experiment (26 min.), the participants had to rate the habituation of the room again during this experiment. The habituation was explained to the participant by telling that if the habituation is poor they might feel like a 'lab rat' and if they would consider the habituation good they feel like they are in an office-like environment. With a scale from 1 to 5 (poor to excellent), the habituation of the room scored a 3.3. The participants also had to evaluate what they found of the lighting conditions of the room (with the glare source turned off). They gave the lighting conditions a 3.6 out of a scale from 1 to 5 (dark to bright).

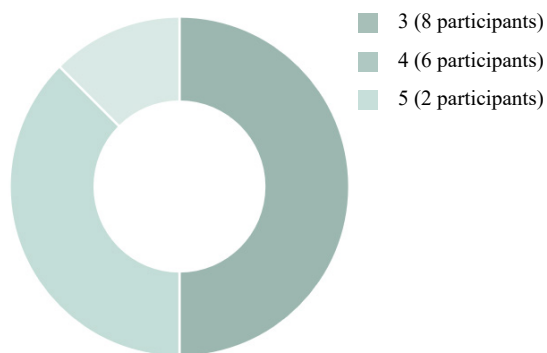


Figure [75]: Rating of the lighting conditions (Dark - 1 2 3 4 5 - Bright)

Furthermore, the participants had to evaluate what they found of the screen quality of the laptop they had to make the tasks on. The screen quality was given a 3.1 (scale 1 to 5, poor-excellent). Interestingly here, two participants graded the habituation of the room with a 2 and even a 1 (lowest score) (figure 76), these participants also gave the screen quality a low score. It may have been that they are used to working on a monitor in an office environment with a better screen quality.

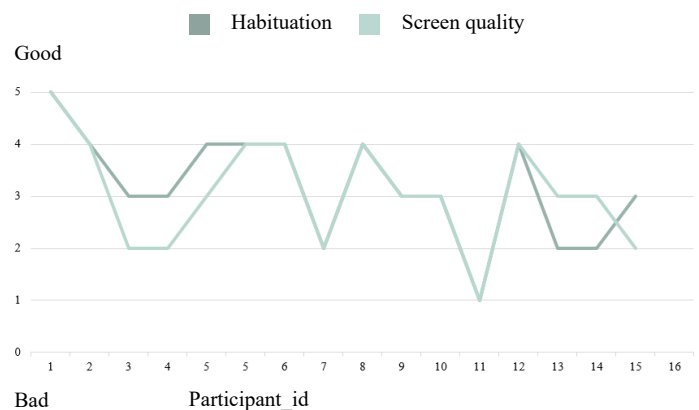


Figure [76]: Habituation and screen quality judgements per participant

9. Experiment II

After a period of 26 minutes the participants had to answer two questions about the sensation of glare and if they were bothered by the light. The questions were: “how would you describe the degree of glare experienced when performing the tasks?” and “when reading the texts during the tasks, how much were you bothered by the light?” The participants had to answer these questions for both of the times each the artificial light source was revealed during the 26 minutes. The bar charts present the differences in amount of people between the evaluation of glare during the novel and the benchmark system (figures 77 & 78).

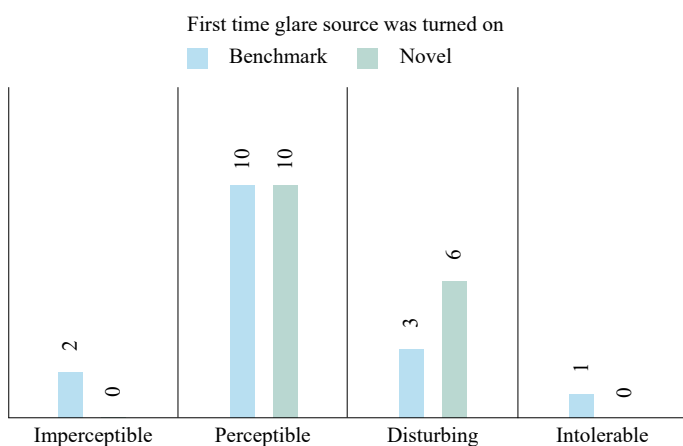


Figure [77]: Difference in glare sensation, first exposure

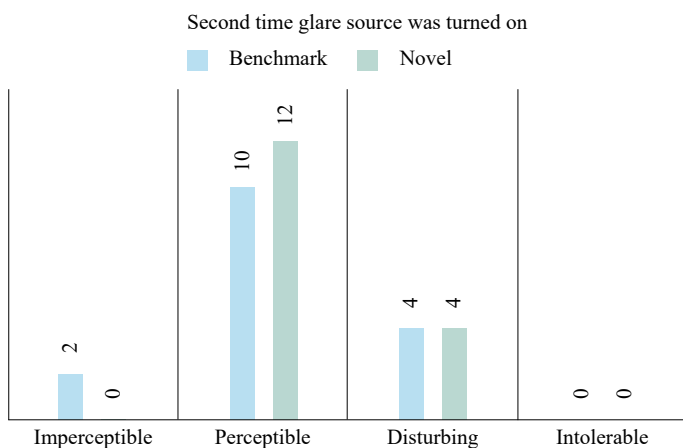


Figure [78]: Difference in glare sensation, second exposure

The participants evaluated the sensation of glare slightly better during the second time they were exposed to light (for reference see bar charts)

The pie charts present the amount of people that were bothered or not bothered by the light while reading the text from the tasks (figures 79, 80, 81 and 82). When looking at the pie charts from the benchmark system, the second time the glare source was exposed to the participants, they were overall less bothered by the light while reading the text. In contrast to this, during the novel system the participants were overall a bit more bothered by the light the second time the glare source was turned on. Interesting might be to investigate whether this was due to the facial reaction being less obvious for OpenFace to recognize, because the participant may have, unconsciously, got used to the glare source. This will further be investigated during the analysis of the action units and the taken into account in the discussion.

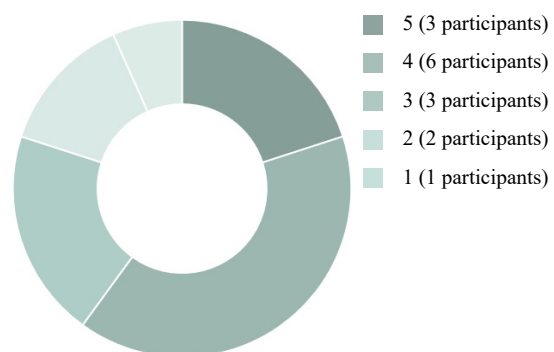


Figure [79]: Benchmark system, first time exposure to glare source, bothered by the light during reading from the screen score (very much - 1 2 3 4 5 - not at all)

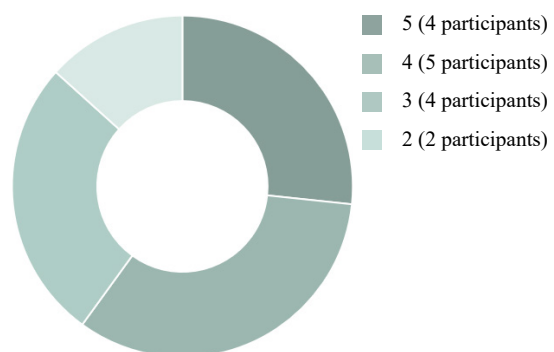


Figure [80]: Benchmark system, second time exposure to glare source, bothered by the light during reading from the screen score (very much - 1 2 3 4 5 - not at all)

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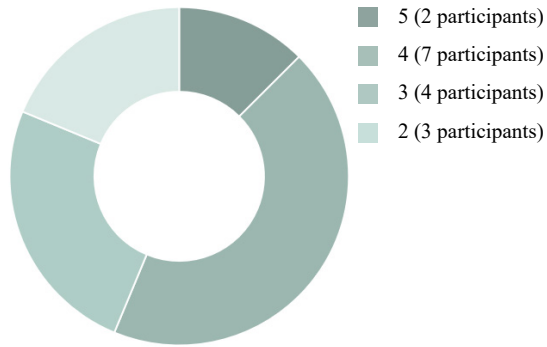


Figure [81]: Novel system, first time exposure to glare source, bothered by the light during reading from the screen score (very much - 1 2 3 4 5 - not at all)

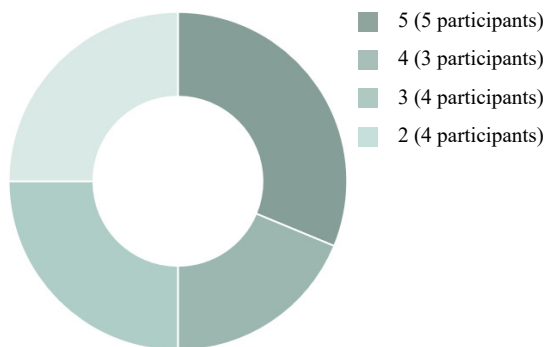


Figure [82]: Novel system, second time exposure to glare source, bothered by the light during reading from the screen score (very much - 1 2 3 4 5 - not at all)

After both trials of 26 minutes they were also asked if they had a preference regarding the light conditions between the two blocks of 26 minutes. Half of the participants did not have a preference, a quarter preferred the novel system and a quarter preferred the benchmark system. This was asked in a manner that the participant did not know if he or she gave a preference for the novel or benchmark. They had to indicate their preference by responding if the first 26 or second 26 minutes was more comfortable.

9.5.2 Productivity

The difficulty of the task sheets should be the same. Both consisted of 124 mathematical multiple choice questions each. The questions are seventh grade math assignments. Each correctly answered question counts for one point. In total, 124 points can be scored. The task sheets of all participants are checked, The questions made (seen by the participant) are noted (i), the questions correctly answered (ii) and the amount of mistakes are taken into consideration (iii). The scores on all three aspects are written down, linked to the control system that was applied. The first three participants had shorter task sheets. These task sheets were a bit too short. The participants managed to finish the sheets in less than 26 minutes. Therefore, the score of these participants are not relevant. The other 13 participants' scores are presented in the following tables.

Participant_id	Benchmark_system_made	Novel_system_made
4	104	110
5	96	87
6	93	95
7	104	100
8	105	107
9	101	110
10	112	86
11	112	116
12	83	78
13	120	113
14	70	74
15	112	109
16	116	111

Table [8]: Mathematical questions made during the two systems

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Participant_id	Benchmark_system_ correct	Novel_system_correct
4	100	107
5	96	87
6	91	94
7	97	99
8	101	105
9	96	106
10	97	73
11	101	110
12	76	74
13	112	109
14	70	74
15	107	107
16	113	107

Table [9]: Mathematical questions correctly made during the two systems

Participant_id	Benchmark_system_ mistakes	Novel_system_ mistakes
4	4	3
5	0	0
6	2	1
7	7	1
8	4	2
9	5	4
10	15	13
11	11	6
12	7	4
13	8	4
14	0	0
15	5	2
16	3	4

Table [10]: Mistakes in mathematical questions made during the two systems

Multiple paired T-tests are executed in SPSS. This is a statistical procedure evaluating whether the mean of the differences in scores for each individual participant differ significantly from zero. In the first pair, the amount of questions made (seen by the participant) is analysed between the benchmark and novel condition. The mean of the differences for this pair is 2.46 ($t(12)=0.993$, $p=.340$). This implies that no support is found for a significant difference (slightly higher amount of questions seen for benchmark) between the two conditions. In the second pair, the amount of questions correctly made are compared. The mean difference found is very small in slight favor of the benchmark condition, and not found to be significant (0.38 , $t(12)=0.152$, $p=.881$). In the final pair, the mean difference of the mistakes made for each participant between the conditions is examined. The results show that in the novel condition less mistakes are made with a difference of 2.08 ($t(12)=3.32$, $p=.003$). The latter is found to be significant ($p<.05$). It should be noted that the improvements in accuracy in the novel condition could be explained by the fact that overall less questions were answered in the novel condition giving the participants more time per question. Furthermore, the presented results should be interpreted with caution given the small sample size of the experiment, as well as the fact that not all assumptions for the analysis are met. Specifically, the variables seem to not be normally distributed and various outliers are present (see boxplots in appendix 15.7). Outliers are not removed given the already small sample size.

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9.5.3 Action Units

As discussed in the literature review a facial response due to glare occurs most likely around the eyes of the occupant. For this reason various Action Units (AU), mainly around the eyes are studied. Four action units are initially implemented in the control system after reviewing the previous study conducted by Allen et al. (2019). Hence, while analysing the data generated during the operation of the novel control system, the four added AU's are mainly studied. Over the course of the benchmark operation, the settings of the experiment room are the same for every single participant. Therefore, while studying this data, more AU's were studied. The following actions units are analyzed: AU01 (Inner brow raiser), AU02 (Outer brow raiser), AU04 (brow lowerer), AU05 (Upper lid raiser), AU06 (Cheek raiser), AU07 (Lid tightener), AU09 (Nose wrinkler), AU10 (Upper lip raiser) and AU45 (blink).

Since four of AU's are in the novel control system, it was expected that these Action Units would provide data that would imply that the participant was experiencing glare. During the first trials of the experiment often the control system signalled the glass to change state even if the glare source was not even on yet, due to a too high a lux value and the majority of the Action Units giving different output than expected. Therefore, the decision was made to exclude AU04_r, AU10_r and AU06_r from the controlling system. Only Action Unit 2 could still trigger the glass to change. On the following pages graphs show the output from AU02_r and the lux for every participant. The novel control system does not only influence the glass with the output of an Action Unit, it also reacts to a relatively high lux value. After the first three participants, it was noticed during the experiment that the lux data in combination with the AU was very important. Almost in every experiment, with each participant, the glass was changed during the novel system caused by a combination of a high lux value and an action unit, namely: participant 1 (both times the participant was exposed to glare created by the artificial glare source), participant 2 (the second time the glare source was turned on), participant 4 (both times the glare source was turned on), participant 5 (triggered at unwanted moment, when there was no exposure due to the glare source), participant 6 (both times

the participant was exposed to light, first time more clear), participant 8 (both times the participant was exposed to glare), participant 9 (both times the participant was exposed to glare), participant 10 (only during the first time the participant was exposed to glare), participant 12 (only the second time the participant was exposed to glare), participant 13 (moments already before the participant was exposed to glare), participant 14 (both times the participant was exposed to glare), participant 15 (the second time exposed to to glare). For reference see the graphs on the following pages (figure 83 & 84).

Participant_id	Reaction_AU02_ first_exposure	Reaction_ AU02_second_ exposure	Reaction_ AU02_interval
1	x	x	
2		x	x
3			x
4	x	x	
5			x
6	x	x	
7			x
8	x	x	
9	x	x	
10	x		x
11			x
12		x	x
13			x
14	x	x	x
15		x	
16			x

Table [11]: Key moments regarding lux value and AU02_r reaction per participant

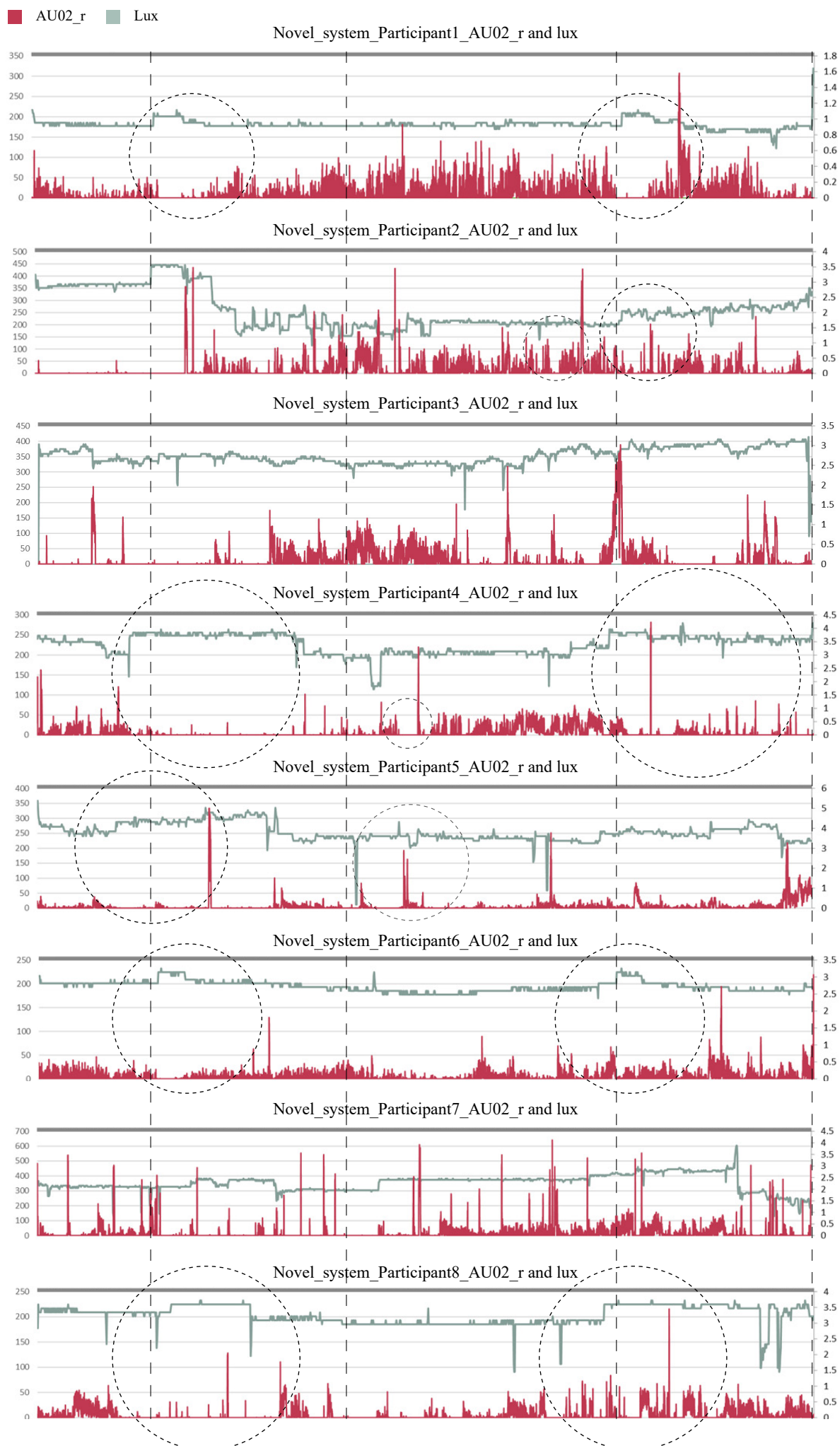


Figure [83]: AU02_r data compared with the lux value of the wearable in real-time measurements (half of the participants)

■ AU02_r ■ Lux

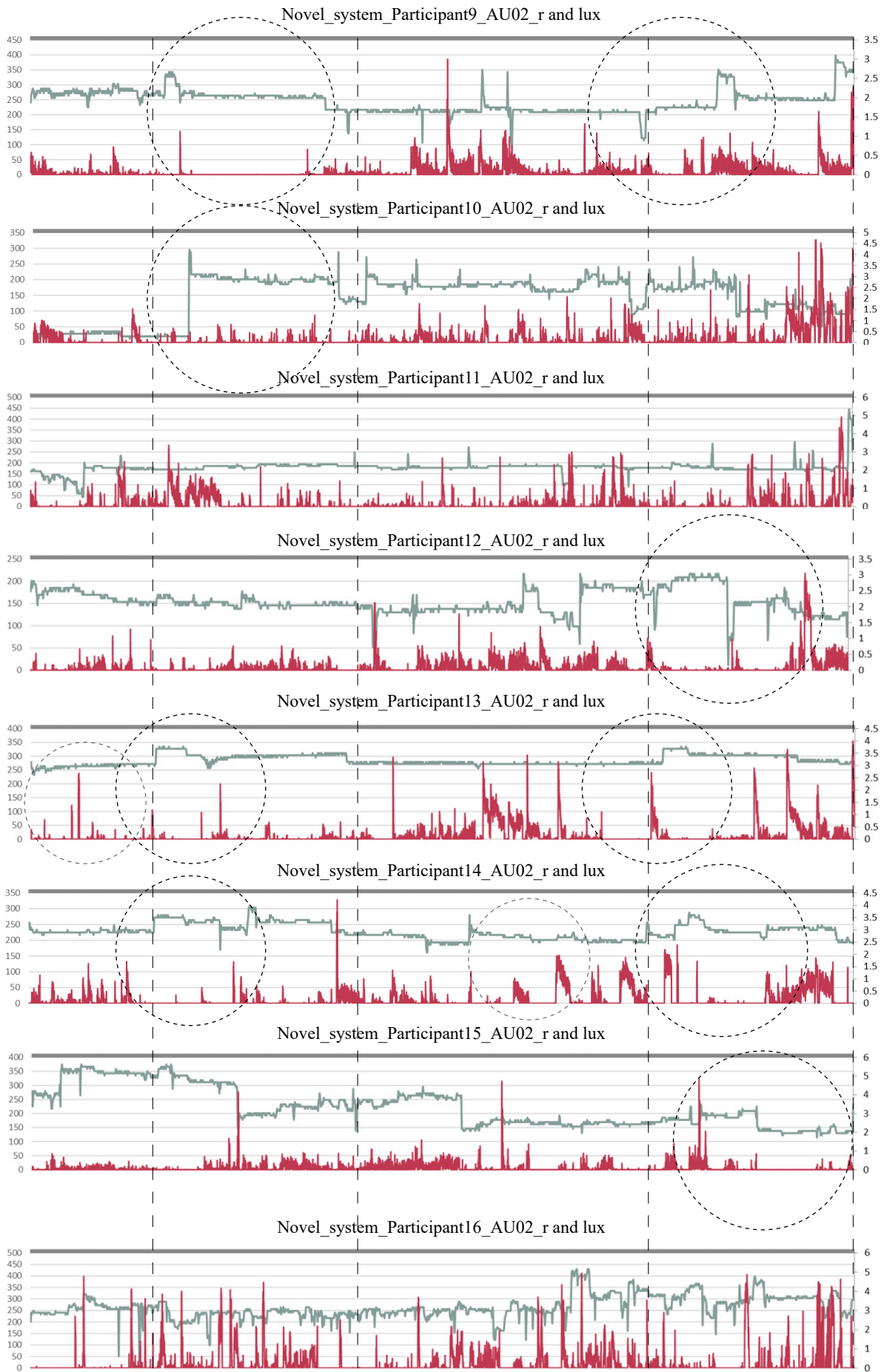


Figure [84]: AU02_r data compared with the lux value of the wearable in real-time measurements (half of the participants)

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The data shown in the graphs imply that there is a certain correlation between the AU and the lux value. The data from participants 1, 6 and 8, in particular, present a strong correlation between the Action Unit and the over supply of light. Sometimes the novel system implied that the glass should change, while there was no exposure to the artificial glare source. This leads to questioning the threshold values and method used. Yet, the results indicate that eyebrow movements could be used. More research is needed to improve this. How to conduct this is further elaborated on in the discussion. The threshold values of the novel system were:

Lux	AU02_r	AU04_r	AU10_r	AU06_r	Result
>200	<0.2				0.5
>250	<0.2				1
>200		<0.2			0.5
>250		<0.2			1
>200			<0.4		0.5
>250			<0.4		1
>200				<0.2	0.5
>250				<0.2	
>270					0.5
>300					1

Table [12]: Threshold values

The threshold values are based on data gathered from measurements taken during a previous study the glare assessment and experiment I. The lux values chosen are the average of the lux measured by the wearable in the first experiment. For only the lux to indicate whether the participant is experiencing glare, the threshold value is much higher. This value is selected by taking the levels of discomfort into account and when the participant found the level of discomfort, mainly intolerable, the lux values indicated a lux of approximately 270 or higher. When the result was 0.5 a signal was sent that the glass should change to intermediate state and when the result was 1 a signal was sent that the glass should change to dark state.

As described, more AU's are evaluated with the results from the benchmark. The following actions units are analyzed: AU01 (Inner brow raiser), AU02

(Outer brow raiser), AU04 (brow lowerer), AU05 (Upper lid raiser), AU06 (Cheek raiser), AU07 (Lid tightener), AU09 (Nose wrinkler), AU10 (Upper lip raiser) and AU45 (blink). Results from some participants indicated a correlation between some of the Action Units and the luminance level the participant was in. The results are presented via graphs containing the particular AU and lux value over time. The parts of the graph that show some possible reaction due to light are indicated via grey boxes. The reactions shown in the graphs are compared with the participants responses, regarding the level of discomfort due to glare, retrieved via survey ii.

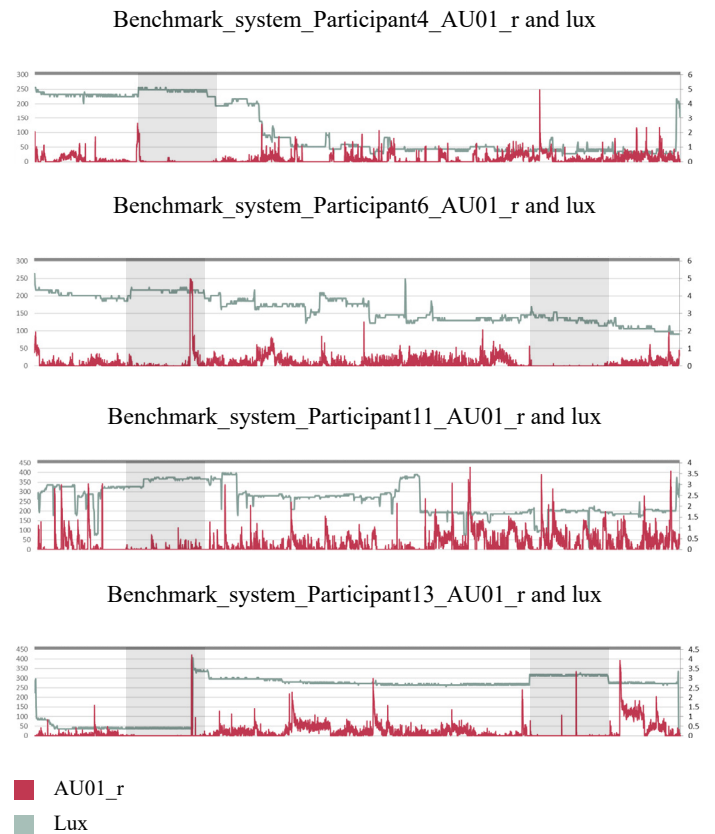


Figure [85]: Results of participants who showed a in reaction in the inner brow raiser Action Unit intensity

Some reaction which may have been due to the artificial glare source is noticeable when analyzing the data from the inner brow raiser intensity (AU01_r). Participant 4, participant 6, participant 11 and participant 13 show a reaction in the particular AU, that may be due to light (figure 85). Participant 4 showed some form of response via the inner brow raiser intensity during the first exposure to glare. However, the participant responded in the second survey that the level of discomfort was perceptible

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during this point of time. Furthermore, the participants barely face difficulty reading the task on the screen (ranked is with a 4). Furthermore, the participants barely face difficulty reading the task on the screen (ranked is with a 4). This could have been due to several things, three of those could be; (i) either the participant unconsciously experienced a level of discomfort, (ii) the reaction in AU01_r did not indicate a level of discomfort, it only indicated that there was change of luminance in the scene, (iii) the participant experienced a level of discomfort, but responded to the question on the survey that the glare was perceptible, since the glass changed state after 3 minutes, the average level of discomfort may have moved towards perceptible by the participant because the participant considered the entire time of exposure to glare for this question. This points out that gathering participant responses via surveys at the end of the experiment, and not real-time as well, could cause difficulties connecting components of the gained data. De output of AU01_r regarding participant 6 expresses a level of correlation between the AU and the light. Yet, this participant as well, did not indicate to be disturbed by the light during both times the participant was exposed to the light of the artificial glare source. In addition, the moments participant 11 and 13 show some reaction in the AU that could be related to the light produced by the projector, they indicated the level of discomfort due to glare perceptible. Participant 13 even mentioned not to be disturbed by the light at all, while reading the tasks on the screen (the participant ranked it with a 5).

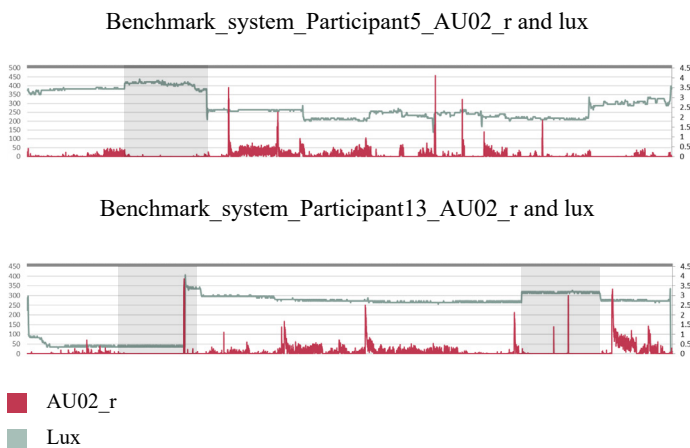


Figure [86]: Results of participants who showed a reaction in the outer brow raiser Action Unit intensity

The intensity of AU02, the outer brow raiser Action Unit, shows a reaction in the data of two participants during the benchmark system. Participant 5 shows a more clear reaction in the data of the AU while being exposed to the glare source for the first time. The participant responded to be disturbed by the glare source at this moment. The participant indicated to find the level of discomfort only perceptible during the second time artificial glare source was on. The results of the AU during this moment are less clear to point out a reaction. Participant 13 also showed some response here, that could be related to light. Although as earlier described, the survey results of the participant mention that the participant was not, consciously, disturbed by the glare source.

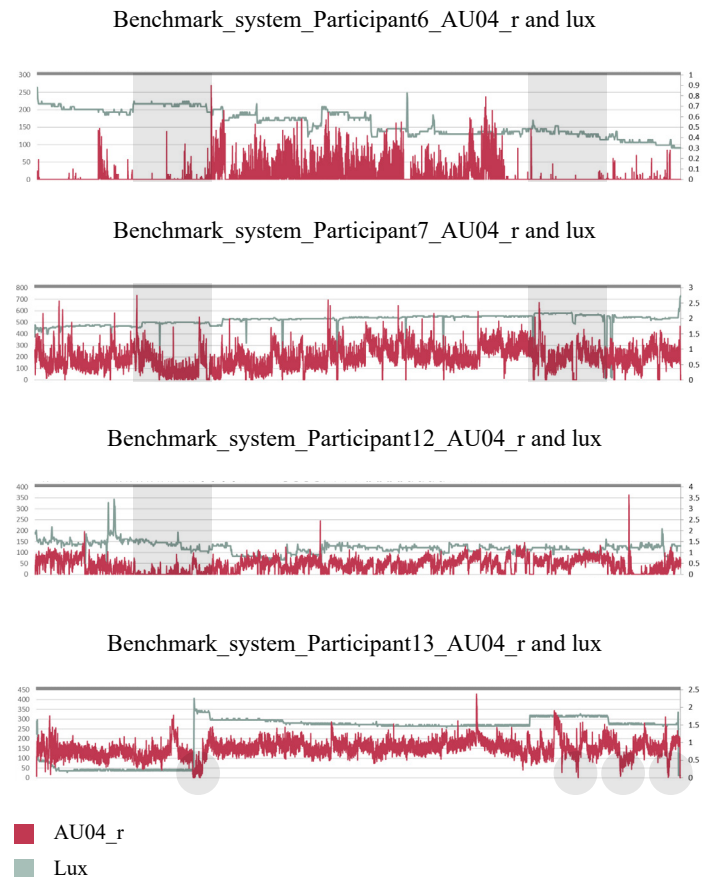


Figure [87]: Results of participants who showed a reaction in the eye brow lowerer Action Unit intensity

Results of the eye brow lowerer show some relation between the AU and the supply of light. During the benchmark less reaction was noticed regarding the data of this Action Unit. For participants 6, 7, and 12 there is a slight decrease noticeable in the output of the intensity. Participant 6 found the level of glare perceptible both times.

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Participant 7 found the light disturbing the second time exposed to the source for 6 minutes. Participant 12, where the reaction is the most clear the first time the artificial glare source was projected onto the diffusive sheet, categorized the light as intolerable. The difference of the sensation of glare experienced by participant 12, while the settings are exactly the same, could be a result of multiple factors, for instance (i) the last questions in the task sheets were more difficult than the first ones, thus it is expected that these questions required more cognitive attention, (ii) or the participant got used to the light. Kent (2019) found that participants tolerated glare more when the task required a higher degree of cognitive attention. The results of participant 13 show that the output of the Action Unit reaches the lowest scores during the projection of the glare source, the data reaches 0 in this case. The participant found the degree of glare perceptible both times.

The results shown in AU04_r are not very obvious to our eyes, meaning it is not clear through studying the graphs. However, via a machine learning method of statistical analysis, done over all the 17 participants who participated in a research in Cambridge, Action Unit 4 showed to correlate the most with the lux value (Allen et al, 2019). The results from the previous study showed a more clear relation via the graphs though. Therefore, the same machine learning statistical method was applied during this experiment for one of the participants, participant 1, to compare it with the results that could be seen through graphs. A correlation heat map is created, the map points out that AU04_r and AU07_r correlate the most with the lux value (figure 88). When looking at the graph showing the reaction in AU04_r, it is not noticeable that there is a reaction here due to light (figure 89). However, the correlation indicated between the AU's and lux value is very little. This would be more interesting if the data of all the participants during the benchmark system would be integrated, however the reliability of this analysis can be questioned since the lux value from the HOBO fluctuated and some factors lead to problems regarding wearing the lux sensor near the heart. This is further elaborated on in the discussion.

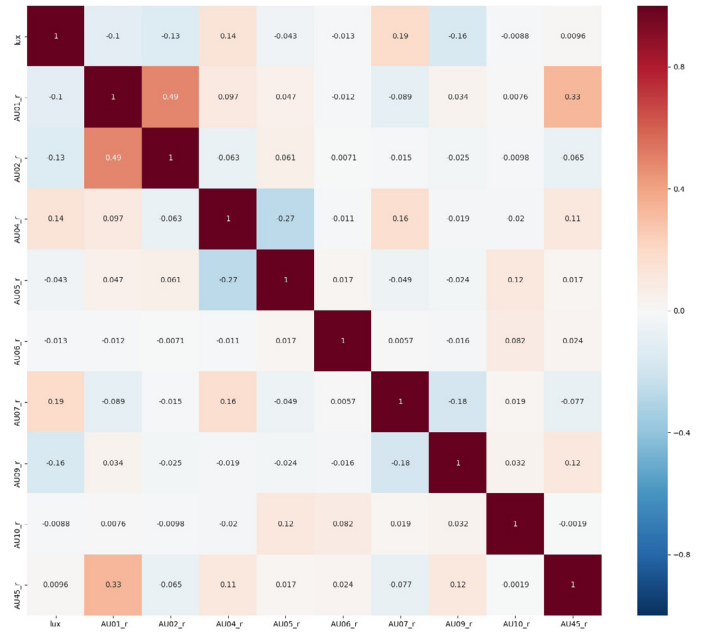


Figure [88]: Correlation heat map between AU's and lux value of participant 1

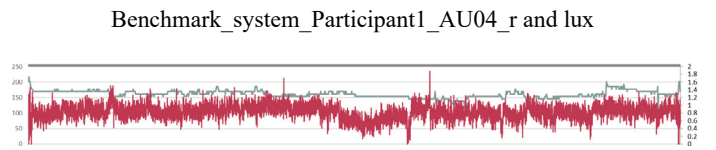


Figure [89]: Results of participant 1; the reaction of the eye brow lowerer Action Unit intensity

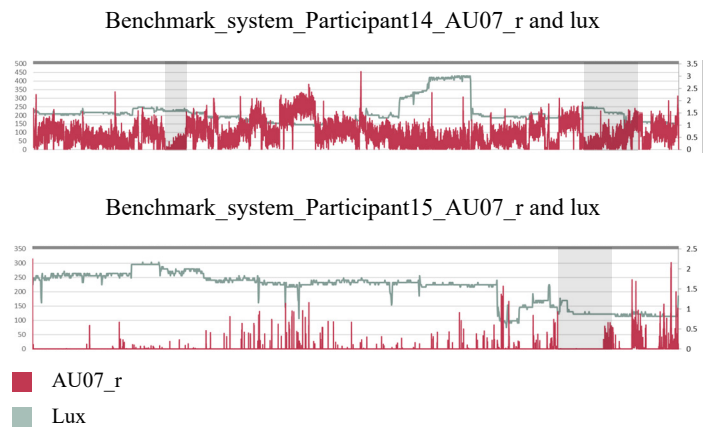


Figure [90]: Results of participants who showed a reaction in the lid tightener Action Unit intensity

An amount of two participants showed a reaction in the data of Action Unit 7, the lid tightener. The correlation heat map also indicated a relatively larger correlation between this particular AU and light, compared to other action units. Participant 14 shows a slight decrease in the intensity of the AU.

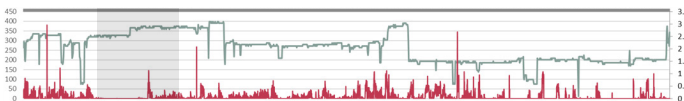
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The graph of participant 15 expresses a low intensity in the AU especially during the time period the artificial glare source was turned on. Nevertheless the participant responded to be more disturbed by the glare during the first time the light was projected onto the diffusive sheet. This stresses again, the importance of gathering the consciously experienced level of discomfort from the occupant real-time. The reactions visible in the graphs are however not very obvious to the eye.

Benchmark_system_Participant2_AU09_r and lux



Benchmark_system_Participant11_AU09_r and lux



Benchmark_system_Participant15_AU09_r and lux



Figure [91]: Results of participants who showed a in reaction in the nose wrinkler Action Unit intensity

Three participants showed a reaction in the nose wrinkler that could be caused by the light. Participant 2 shows that the intensity of the AU during exposure to the artificial glare source is lower. However, the participant found the glare imperceptible both times. Participants 11 and 15 show a possible reaction due the lighting conditions during the first time the projector light was exposed. Notable is that participant 11 indicated not to be disturbed by the light both times and participant 15 indicated to be disturbed by the light the first period of 6 minutes.

AU05 (Upper lid raiser), AU06 (Cheek raiser), AU10 (Upper lip raiser) and AU45 (blink) did not present participant's reactions that could be related to the lighting conditions. During the benchmark, the participants 1, 8, 9 and 16 did not show clear reactions via graphs.

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9.5.4 Lux data

Immediately noticeable in the previous chapter regarding the results of the Actions Units, the lux values sometimes did sometimes not correlate with the light settings of the scenario during a specific time, meaning the values fluctuate a lot and were not really reliable therefore it was difficult to match the AU values to the lux value generated by the HOB0. When the lux value was back under 190 (threshold value 190 lux), the glass was supposed to return to a bright state. This was tricky sometimes. The graph presents the lux data produced by the wearable HOB0 of three participants during the benchmark control system (figure 92). Clearly the data varies a lot. The scenarios were always the same during the benchmark control group. That the HOB0 would fluctuate this much was not expected. The three graphs displayed in figure 93 present very odd readings by the HOB0, pointing out that there is much difficulty sensing the possibility of glare via lux values of a wearable.

Multiple factors caused problems, namely, (i) fluctuation of the HOB0, (ii) obstacle covering the lux sensor, (iii) slight different locations of sensor due to the fact that it was a wearable, (iiii) the lux sensor was interior, thus when the glass changed to dark state, the lux value measured, it indicated that there was no glare, so signalled to turn back to bright state, if the lux sensor were to be placed exterior this would not occur. This is further elaborated on in the discussion.

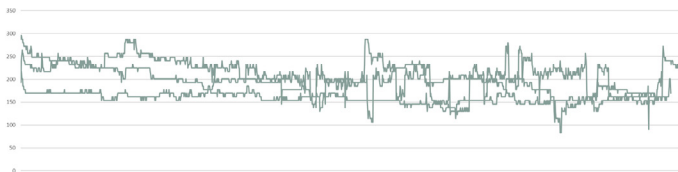


Figure [92]: Lux data of participant 1, 2 and 3 (benchmark system applied)



Too high



Too low



Too low

Figure [93]: Worrisome lux data

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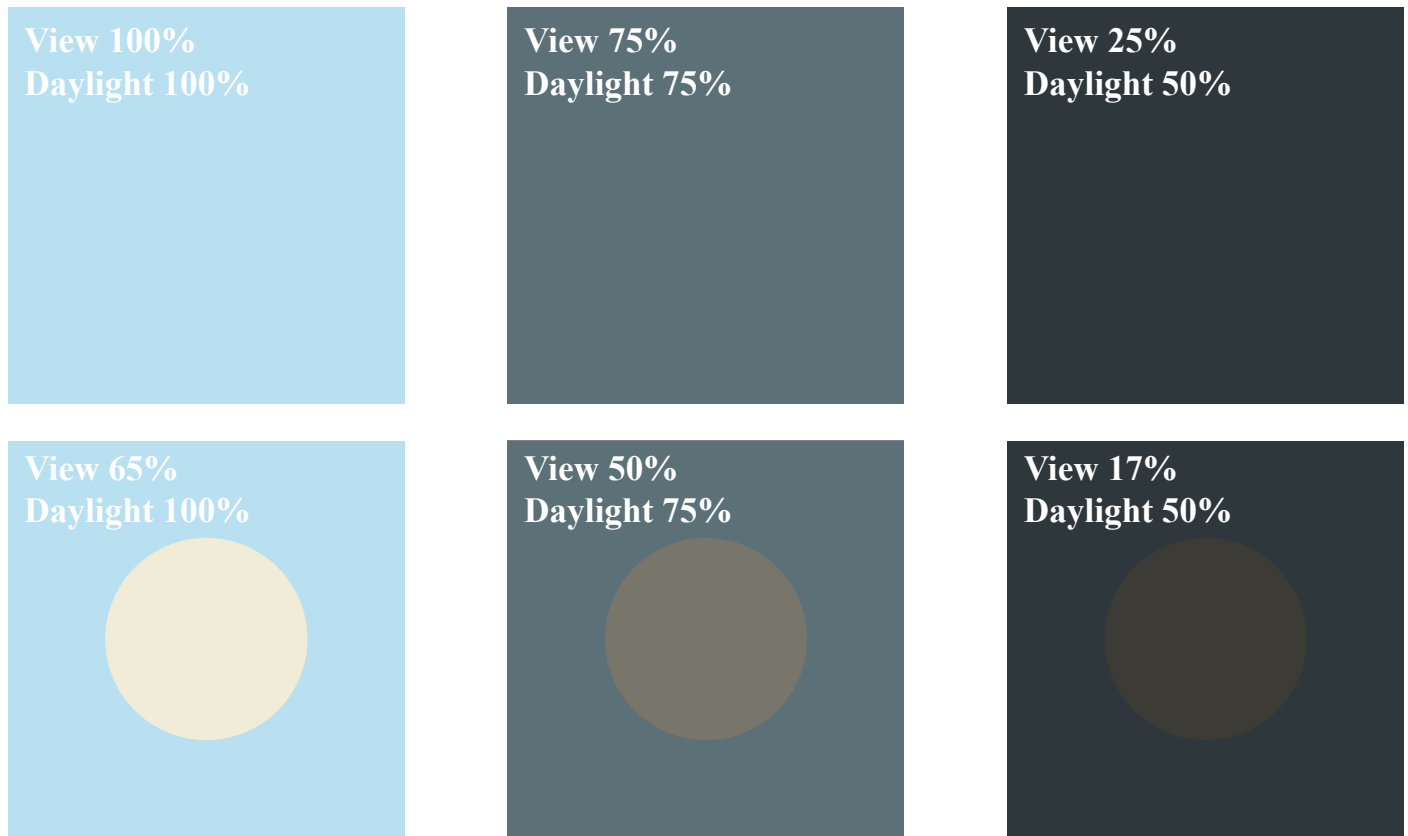


Figure [94]: Scoring system

9.5.5 Availability of view and daylight

A scoring system for the availability of view and daylight is made to investigate which system offered more view and daylight. The Konica minolta T-10 Illuminance meter is used to measure the illuminance at eye level. The glare source was turned on and the lux was measured with three different glass states, namely (i) bright state had an average lux value of 597 lux, (ii) intermediate state had an average value of 562 lux (half) and (iii) dark state had an average value of 498 lux. The average lux value of the darkest state is 84% of the lux value of the brightest state. The average lux value of the intermediate state is 94% of the lux value of the brightest state. Known is that the brightest state of the glass has a transmission value of 45% and the darkest state a value of 9% ($T_v(\text{bright}) = 0,45$, $T_v(\text{dark}) = 0,09$)(this information is provided by Merck). The brightest state would score 100% on daylight, since this state can let through the biggest amount of daylight. 9 is 20% of 45, in the middle of 100% and 20% is 60%. Therefore the intermediate state scores 94% plus 60%, divided by 2, which leads to 77%. The darkest state of the glass scores 84% plus 20%, divided by 2, which leads to 52%. Then these two averages were rounded to 75% and 50%.

The scoring for the availability of daylight is as follows:

Daylight_score_bright_state : 100%

Daylight_score_half_state : 75%

Daylight_score_dark_state : 50%

A view score has also been made. By taking pictures of the glass in the different states and with the artificial glare source on and off, the presence of view was assessed (see appendix 15.8). The photo of the glass in the brightest state was duplicated and a black box was placed on the glass. The opacity of the black box was reduced until it resembled the view of the original photos during the intermediate and darkest state the most. For the blackbox to create about the same amount of view as the photo taken of the glass in an intermediate state the opacity must be roughly 35%. The view is thus reduced by approximately 65%. For the box to create a similar scenario as in the photo taken of the glass in dark state the opacity must be approximately 85%. According to this method, the presence of view is reduced to about 15%. The photos taken show more reflection than that is actually experienced by the occupant. Therefore the view does not decrease by 85% and 35%, instead by 75% and 25%.

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The circle projected as the artificial glare source has a diameter of 13 centimetres. This is 32% of the surface area of the glass, leading to a decrease of view by at least 32% due to the obstacle (for reference see appendix 15.8).

The availability of view is evaluated via the following scoring system:

View_score_bright_state_glaresourceOFF: 100%

View_score_half_state_glaresourceOFF: 75%

View_score_dark_state_glaresourceOFF: 25%

View_score_bright_state_glaresourceON: 65%

View_score_half_state_glaresourceON: 50%

View_score_dark_state_glaresourceON: 17%

Using the scoring system, the amount of daylight is evaluated and compared between the benchmark and novel condition (for mean scores see table). This is done by using a one sample t-test which tests whether the mean of all participants' novel condition differs significantly from the set benchmark value (83). Results show that mean scores are lower in the novel condition compared to the benchmark condition. This difference, however, is not significant (mean = 78, $t(15)=-1.021$, $p=.328$). For view the same test is conducted (for mean scores see table) in order to investigate whether the participants' novel condition view differs significantly from the set benchmark value (64). The analysis was done first with all data. This provided a slightly lower, but not significant, score in the novel condition compared to the benchmark (mean= 62.56, $t(15)=-0.284$, $p=.780$). This result is unexpected given the purpose of the experiment. Therefore, exploring the data showed three results that could be considered outliers in the sample. These are outliers since the glass turned to a dark state due to the strangely high lux values. These lux readings were most likely not due to the artificial glare source, but due to the indoor ceiling lights in the experiment room. These are cases 3, 5 and 15. Removing these cases yields a higher mean score in the novel view condition compared to the benchmark condition. This difference is found to be significant (mean = 71, $t(12)=2.688$, $p=.020$), implying that the view was better in the novel condition. However, it should be noted that the scores in each condition did not seem to follow an approximately normal distribution. Given that this is an assumption for the test used, the results need to be interpreted with caution.

	Benchmark Daylight	Novel Daylight	Benchmark View	Novel View	Novel View (-5, 7, 15)
Mean	83%	79%	64%	62%	71%

Table [13]: Mean values (benchmark vs novel)

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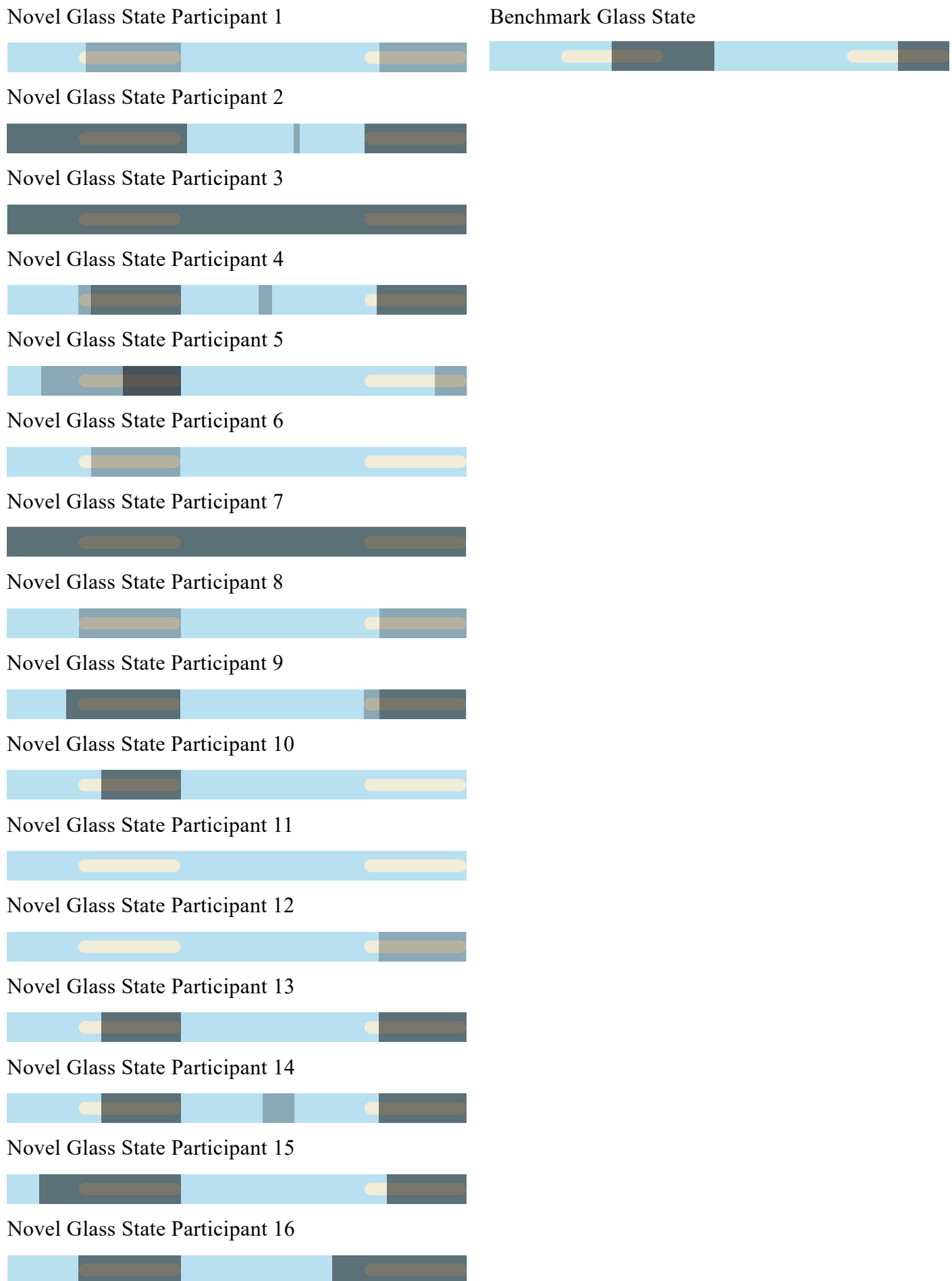


Figure [95]: Glass states, all participants

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9.5 Discussion

In the discussion the results are discussed and indicated is where uncertainties are. Moreover are different detailed proposals of improved setups that could address some of the uncertainties presented.

9.5.1 Survey

It can be seen from the results of the initial questionnaire that the participants are all relatively young (about the same age) and not of much varied ethnicity. The fact that they are all young may have played a role in the results. As someone gets older, their eyes deteriorate. This may affect how someone experiences glare and thus the level of discomfort, but also the facial expression. Culture and origin might influence certain data. How an individual personally reacts to light depends on many factors, such as age, eye sight, origin and culture. It is difficult to say whether or not it is better to include people of different ethnicities. It can make the test group larger and more diverse, but it also brings an extra variable that can influence the data all together. Imagine every participant is from the same part of a country and all approximately the same age, one outcome may occur more often and the result would be easier to see. However, the result could then be questioned to be significant, since it would not be known to work for people of different groups. It can be seen that there were also significantly more female participants. This may have influenced the final results. Participants with and without glasses are quite equally divided, as is the sensitivity the participants have indicated towards light.

The second survey had questions regarding the experimental setup. The results of the second questionnaire show that the space sufficiently resembles an office space, however, it would have been interesting to ask why, for example, the space did not resemble an office space. The habituation scored overall fine, but it may have been scored with a lower average due to the quality of the screen in front of them. In the same set up, with a different screen, the results may have been different. Since, the laptop they worked on was smaller than a normally used monitor in an office environment, a monitor may increase the level of habituation. The factor decreasing the level of habituation is

important since it can support or point out concerns for the feasibility of applying the system in real-world office buildings. It makes a lot of difference whether it is because of the lux sensor or webcam (attached to, and even faced towards the occupant, constantly capturing data), or because it is a small laptop in the experiment room the test subjects are working on, instead of a large monitor. One says something about the new system and the other says nothing about the new system, that only says something about the set up of the experiment. Some participants found the lighting conditions very bright, it may have been interesting to know.

At the end of each 26 minutes the participants were asked, via survey ii, how they experienced the glare and whether they could read the text on the screen properly. In the end, it was not entirely clear whether their chosen answer was about the 6 minutes that the light source was on, or whether they were just talking about the moment that the light source was on and the glass was transparent. To prevent this, it is useful to have the participant indicate this during the test. Similar to research done by Kent (2019), he asked participants to indicate what they thought of it 10 seconds after the light source was turned on. Moreover the effectiveness of only four options and the explanation of these options (imperceptible, perceptible, disturbing, intolerable) could be discussed. Every survey had an explanation of the terms on it, yet some participants asked what they should pick while they were filling in the form. An example was somebody who asked if he should have picked perceptible or disturbing, he said: "I did not really mind the light being on, although when it turned off, it felt pleasant". Some more explanations could have been added to the terms. Defining emotions or thoughts could have been added to the descriptions of the terms. Or another option could be to add more options to pick from, for instance: (i) just imperceptible, (ii) just acceptable, (iii) acceptable, (iiii) just disturbing, (iiiii) just intolerable. These extra terms would also have to be explained.

During the benchmark system both times the glare source was turned on for 6 minutes, the glass turned to dark state after 3 minutes, there was no difference in scenario, the exposure to glare was exactly the same both 6 minutes. Yet, some participants described the level of discomfort disturbing during one of the 6

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times and only perceptible the other 6 minutes. The participants may have gotten used to the light and have found it therefore less disturbing, this could be a reason. It could also have been that the longer the participant was seated, the more the participant leaned forwards to read the tasks from the screen and a lesser amount of light from the source could have reached their eyes. However these reasons would explain why someone was less disturbed the second time exposed to glare. For participants 7, 10 and 16 this was not the case. These participants indicated that the second time they were exposed to glare was disturbing, but the first time they found the light from the artificial glare source perceptible.

In the discussion of the first experiment a couple of biases that could occur due to adjustment and category rating are explained namely: (i) stimulus range bias, (ii) anchor effects, (iii) order effects, (iiii) direct versus indirect control and (iiiii) the visual task (Foitos, 2020). Since there were more variations of the experiment and participants are about equally divided over the variations (and the tasks are randomised) order effects do not cause biased results here. In this experiment stimulus range bias, anchor effects and the visual tasks may have influenced the results. The stimulus range bias, regards the range of the artificial glare source which is chosen by the experimenter, however, this is chosen via a prior experiment (experiment I) where other test subjects participated, therefore, the level of biased results due to this factor is little. The visual task may cause biased results, since the questions got harder at the end of the task sheets. These could have led to a higher degree of cognitive attention needed by the participant and therefore their level of discomfort experienced during the second exposure.

9.6.2 Productivity

Measuring productivity is complex. This experiment aimed to analyse productivity by looking at the results from the mathematical sheets made during the experiment. The amount of questions read/made, correctly answered and mistakes were counted and compared between the two systems. There was not a sufficient amount of people to suffice the assumptions of normality in the paired T-test and outliers were present. There was no significant difference in the amount of questions read by the

participants found, however in the novel condition less mistakes were made. This could be due the fact that they had longer per question given that they answered less questions. To be able to say more about the productivity more participants would be needed and it would be better to perform the experiment over a longer period of time. Another quite simple aspect that could have been added to measure the productivity was to record the screen of the laptop that hosted the tasks. Essential for this is that if it were to be recorded a clock should be visible on the screen to link the recording to the moments that there is exposure to glare. Via this recording the time it takes the participant to answer the questions when there is glare could be compared to the situation that the glare source is not on.

9.6.3 Action Units

During this experiment the timestamp of the action units could be linked to the data from the lux meter, because the participant was instructed to take off the obstacle on the HOBOT that covered the part that measured lux exactly at the time the camera was turned on. That Action Unit 4 did not show as clear data as an earlier conducted research done by Allen et al. (2019) was unfortunate for the control system. This could have been due to several things. The set up of that experiment was quite different, the most obvious differences were the angle of the participant to the window (45 degree angle) and the type of artificial glare source. During their experiment a diffusive screen was used, instead of a projector (point source) that was used for this research project. To be able to conclude that these factors influenced the results, more experiments should be done where all the variables are the same, except for instance the angle of the desk towards the window. Future research is going to be performed in the Light Van, here it would be relatively easy to change the position of the desk.

The Action Units are difficult to evaluate via looking at graphs, therefore to find a correlation between the lux values and the data provided by OpenFace can be done more effectively by performing a statistical analysis via machine learning. This is done for 1 participant and it already shows data that was otherwise not visible to the eye. It would be interesting to combine the

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data of every participant and perform this analysis, however there is a concern about the effectiveness of this with the data gained during this performed experiment. The lux data is less reliable and could be high at moments where the participants did not experience glare. It could be an option to use only the participants for this analysis where the lux data seems reasonable. However, the sample size would decrease to such a degree that the results could lose significance. A matter of avoiding this, can be by capturing lux and light via different manners.

9.6.4 Lux readings

The lux sensor data fluctuated. This was problematic since it was difficult to set a threshold value regarding these largely varying outputs. The HOBO was not placed on the ideal location of the participant. A wearable lux sensor configured in glasses would be the most convenient, since it is closest to the eyes. However this is nonexistent. Placing the HOBO on the head of the participant would be very intrusive. Instead of this the HOBO is located in the chest near the occupant's heart. This caused problems though (figure 96). Since the mousse was on the right side of the laptop, the left hand of the occupant was free for the participant to rest their head on. Someone's hair could have been covering it, or a cardigan could have accidentally covered the wearable lux sensor.



Figure [96]: Various obstacles covering lux sensor

A manner to fix this problem would be to fix the HOBO elsewhere, for instance at eye level on the exterior side of the facade, or next to the participant, interior, on a standard at eye height (or fixed to the

wall behind the participant). Placing the lux sensor next to the participant also raises some concerns. Maybe the occupant would cover the lux sensor some way. This has to be carefully looked at.

After looking at the data gathered during this experiment and the method of statistical analysis via machine learning it would be recommended to perform a similar experiment (like the benchmark, where the conditions are the same) where data is gathered via the webcam, a wearable lux sensor, a sensor indoor on eye level and a sensor exterior at eye level. If this data were to be analysed via a similar form of machine learning done for this research and a correlation map would be generated, it could point out whether the results of the lux sensors correlate or not. Imagine the correlation of lux values derived from the wearable being very little with the data from the other lux sensors, it would point out the potential and relation of the wearable lux sensor. Improvements regarding the performance of the lux in the novel system would be to place the lux sensors outside as well, since the lux levels decrease via the darkening of the glass, the lux levels indoor decrease with it, so setting a threshold value for the lux (measured indoor) that signals the glass to brighten is pretty difficult.

For incorporating the novel system into real office buildings, instead of, or perhaps in addition to using the extra lux sensor placed outdoors, it may be interesting to incorporate a certain time limit to the glass. Glare does not occur the entire day, it happens during specific times of the day. It may be an option to set a limit of for instance 15 minutes where the glass should return back to a brighter state.

9.6.5 Availability of view and daylight

The methods of the scoring system that was applied to the analysis of view and daylight, is up for debate. There may be more objective manners of doing this. The method of scoring the view might have given the different scenarios a lower or higher ranking than that it should have been. The scoring system is partially subjectively developed by the experimenter, but another person may rate the degree of view differently per scenario. The manner of scoring the two, view and daylight, was inspired by the paper "Building envelope impact on

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human performance and well-being: experimental study on view clarity”, where an overview of research methods on human visual perception and performance measurements in relation to daylight and view was provided (Ko, 2017). A method using photos to evaluate the glare was created for this graduation project, which relates to their method. However there should be noted that further research to improve and support the scoring system is needed from human subject testing and may be even optimized throughout advanced computational image analysis algorithms. This is out the scope of this graduation project. A proposal to effectively and quite quickly improve the scoring system is by performing tests with participants where they would have to categorize the availability of view. These tests could be done with actual sunlight and an artificial glare source.

Furthermore, the control for the benchmark relates to newly developed methods of shading technology influenced by time of the day, orientation and a lux sensor placed on the façade. These tend to react too late in the real world, this is implemented to this experiment by delaying the system by 3 minutes. However, in the real world conditions this is different. The delay can last for maybe 15 minutes, instead of 3. This would be too long to implement in this short experiment. Mirroring what happens in actual office buildings and applying it to experimental setups, to correlate the two, is important and should be done with caution to gain valuable data.

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9.6 Conclusion

The objective of the experiment was to (i) identify Action Units triggered by the light produced by the artificial glare source, which could be added to a dictionary of FAU responses due to light, and (ii) test whether the proposed novel system works, by means of increasing productivity, increasing view and the potential use of daylight.

This experiment points the inner brow raiser intensity (AU01_r), outer brow raiser intensity (AU02_r), the brow lowerer (AU04_r), the lid tightener intensity (AU07_r) and the nose wrinkler intensity (AU09_r) as the commonest responsive Facial Action Units due the exposure to light produced by the artificial glare source. There is a potential of analyzing the data via statistical analysis through machine learning for finding correlations between the data of the lux sensor and the AU's, however the effectiveness of this analysis with the data captured during this experiment is debatable due to the sometimes strangely measured lux values. Nevertheless, The novel proposed system was able to sense the presence of the light produced by the artificial glare source during the majority of experimental procedures conducted.

Whether the novel system provides potential benefits regarding productivity of the occupant cannot be said due to the small sample size. Even though the number of mistakes made in the task sheets was significantly less during the novel condition. The difference between the availability of daylight in the novel and benchmark system was not found to be significant. Yet, the difference between the view, while excluding three outliers, implied that the view was better in the novel condition. However, it should be noted that the scores in each condition did not seem to follow an approximately normal distribution. Given that this is an assumption for the test used, the results need to be interpreted with caution. The comparison in this experiment showed that the novel system is no worse than the benchmark, which is a step towards improving the development of dynamic shading systems that leads to a bright future with affective windows.

To improve the system further experimental research studies have to be conducted where; (i) the occupant's response regarding the level of discomfort is immediately (in real-time) gathered, (ii) the matter how to improve the potential for each individual to have their own system is investigated, (iii) the light is measured by more sensors in different places (for instance fixed to the wall) real-time to determine which one is most beneficial and relation ought to be considered with the architectural design of the building (iiii) the experimental set up mirrors an actual office building to enhance the correlation of the data gathered during such experimental studies, also to study the data with real sunlight, the most common source of glare.



Figure [97]: Impression of the system in an office building and objective

10. Translating the system into real-world offices



Figure [98]: 3D impression of the new system and its visible, to the occupant, components

Architectural design options and applications regarding the tools, equipment, materials and characteristics are elaborated on. The main tools to add to an office environment for the novel system are: webcams capturing Facial Actions Units, lux sensors sensing the supply of light to evaluate whether the occupant's face is reacting to light and the switchable glazing. Naturally, there are also parts needed to connect these sensors with the glazing such as wiring, or bluetooth devices and a very smart computer is needed to process all the data. However, regarding the design, focus is laid on what can be seen by the occupants (office employees). This is because not only do the users see the components, but the components also see the user, in a sense. This chapter discusses the webcams that are required and possible privacy concerns it may cause, the options for wearable light sensors, and the switchable glazing provided by Merck.

10.1 Capturing the occupants Facial Action Units

To create an interaction between individual occupant and the switchable glazing a webcam is needed at every work spot in the office, otherwise the switchable glazing cannot react due to personal preferences.

This is important since the two most important advantages of sensing discomfort due to glare with this system are: (i) it is not as obtrusive and disruptive as other methods and (ii) it offers to collect data regarding individual preferences, meaning where one may experience visual discomfort due to glare, another may find it comfortable difference could appear in the data gained, by processing it through an algorithm it could be evaluated and the switchable glazing near the person experiencing discomfort may change, while the window near the other participant may stay the same (figure 97). Webcams can be bought or the webcams from the monitors could be used, however since the quality of a webcam in a monitor is usually quite poor, the captured data may be less useful and harder to process by OpenFace.

For the experiments conducted during this research project there was made sure that every participant approved of being recorded. Imagine the importance of the approval by office employees in existing buildings, when the system would be applied there. It immediately raises privacy concerns. Ways to avoid these concerns or to deal with them are: (i) the camera cannot be connected to the internet so it cannot be hacked,

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(ii) the images from the camera are deleted after a certain time, for example after 5 minutes, (iii) the camera does not record anything if there is no person in the picture. Deleting the images after a period of time could avoid privacy concerns, however, if the data is kept for a longer period of time, statistical analysis by machine learning could be performed on data of an occupant and processing the data of a specific individual could be optimized. The last one seems relatively easy to apply since OpenFace measures “confidence”, if the confidence is low OpenFace has difficulty detecting a face. When the confidence would reach a low value (threshold) the recording by the webcam could be automatically stopped.

10.2 Wearable light sensors

There is a growing interest regarding the amount of daylight people encounter, since daylight can benefit health, well-being and even more (for reference see figure 104 on page 109). Resulting in developments in wearables that measure the amount of daylight a person meets per day. Therefore there are newly developed wearable sensors measuring light, such as (i) the spectrace and (ii) lys (figure x and x). The spectrace is developed at Geneva’s Haute Ecole d’Art et de Design de Genève, the EPFL-based Laboratory of Integrated Performance In Design. It is a light sensor designed to analyse how much and what kind of light the occupant’s eyes register during a day. The spectrace can be worn on the person’s shoulders like headphones or can be fixed to the occupants clothing with the aid of magnets. The wearable is intended to accompany all of a person’s activities, whether professional, social or sporting. Imagine a future where the office employee would wear such a device during office hours and during other activities, gaining data about the spectrum and processing the data in a manner that could sense what the occupant needs. The lys is a small, coin-sized, light sensor that can be worn as a broche developed in Denmark. The lys tracks not only lux, but also colour levels through sensors aiming to replicate the eye’s photoreceptors. The lys tracks real-time data and the occupant receives analysed data throughout the lys mobile app. Here an indication is given whether one has encountered a sufficient amount of natural light.

By providing this information, the developers of Lys claim that the wearable will help the users boost their sleep-wake cycle, concentration and energy. Picture the data from such a wearable added to the novel control system. However both these light sensors were not available for this research, but when the novel system would be more developed, it would be attractive to add such wearables to the implementation of the system into an office building.



Figure [99]: Spectrace (*)

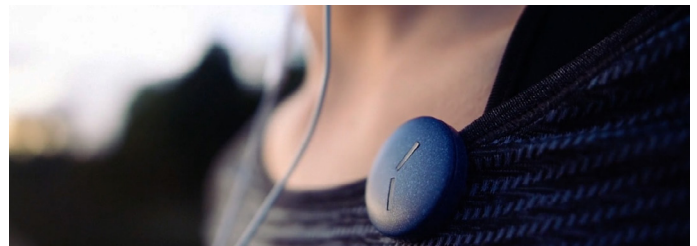


Figure [100]: Lys (*)

During this project the HOB0 is used as a wearable, although it is not meant to be worn. The HOB0 is relatively small so therefore it was not very obtrusive for the participants in the experiments to wear near their heart. During the experiments some problems regarding using the HOB0 as a wearable and not fixing it to a wall, interior or exterior, come to surface. This motivates a design decision to possibly exclude the wearable from the controlling system, for now, and adding light sensors to the façade. Note that by excluding is meant here to not use the data for the controlling system, but using it is certainly recommended to gather more data and to hopefully, in the future, spot the correlation between the data regarding the lights and the Facial Action Units. The sensors placed on the exterior of the façade should be placed on all the sides of the building, so facing north, south, east, and west. Different from a wearable, where every office employee would need one, there is no need to apply a light sensor for each and every occupant in the building.

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Regarding the energy needed for the sensors this could provide a small benefit to the energy the control system would require. The sensors that would be placed on the exterior of the wall, should be at eye level and the locations of the sensors could depend on where the desks are placed. Placing less light sensors may reduce the costs as well of applying the novel system. However a partial component of the benefit that the control system has, investigates whether an individual occupant is experiencing glare, is lost in a sense. The wearable would suffice for a more personal related data (focussing on an individual). The argument that the novel system could benefit the productivity of the office employees, and therefore benefit the company economically, may be affected when the lux sensors are only applied on the exterior. Thus, applying a cheaper system at first, since there would be less light sensors needed on the exterior, could lead to more costs after a longer time period.

10.3 Switchable glazing

The third main component seen by the office employee in a real-world office and affecting their environment is the switchable glazing. During this project the glazing developed by the involved industrial partner, Merck, is used. Therefore design options regarding their switchable glass are elaborated on. The company is able to create dynamic glass in many different appearances. It can vary from shape, form, size, transparency, colour and more.

The Niemeyer Sphere, is a very recently realized architectural design, where the switchable glazing developed by Merck is integrated into the façade, in Leipzig, Germany (figure 101). The white concrete and glass sphere now inhabits the corner of a 19th-century factory. The sphere provides an unusual and beautiful dining space, with views overlooking the city. Via the use of the switchable glazing by Merck and their liquid crystal technology, the final visual effect and the utilization of the space was created. The pattern of the glass and the technology of the glazing offer impressive sun protection, with respect to the design aspects. Each of the 144 individually manufactured triangular glass modules of various sizes can change transparency instantaneously. The architectural design faces southwest.

This led to concerns regarding the possible troubling heat gain via the glass. However with the switchable glazing applied the glass can darken if needed preventing too much solar radiation transmitted through the window. Moreover by darkening some of the glass modules, glare could be avoided, providing the occupants to enjoy their dinner, while maintaining the view over the city. The sphere forms a blend between art and technology. The design sets high standards for the architecture of the future. At Merck they explain that the design of the Sphere is all about well-being, sustainability, and controlling the building's energy footprint. Their glass technology makes this possible by providing invisible shading and preventing overheating while remaining true to the designer's vision.

At Merck they can produce windows up to 3,5 meters. The windows can change state and some windows even can change state partially, in a manner that the top part would be dark and the bottom bright. Figure 101 prestens illustrations showing the many different possibilities. At Merck they also offer glass with different colours. For instance orange-like or green/blue. The interest for integrating a slight orange window into the facade could be for a building located in a more cold, rainy, cloudy environment. Think of when it is snowy, skiers and snowboarders wear orange goggles providing more view on the mountain, while when it is sunny, goggles coloured slightly blue or green provide better view. Merck's glass can provide the same benefit. The transparency of their glass can depend on the mixture between the glazed sheets. One negative aspect of the glass may be, it needs energy to be in a bright state, which means if the building would have a power out, the glass could darken unwanted. Merck's Product offers many advantages and opportunities to the designer as it can form all kinds of sizes, multiple mixtures and colours, and it is adaptable.



Figure [101]: The Niemeyer sphere, Merck's switchable glazing applied in the field (photo derived from Merck)

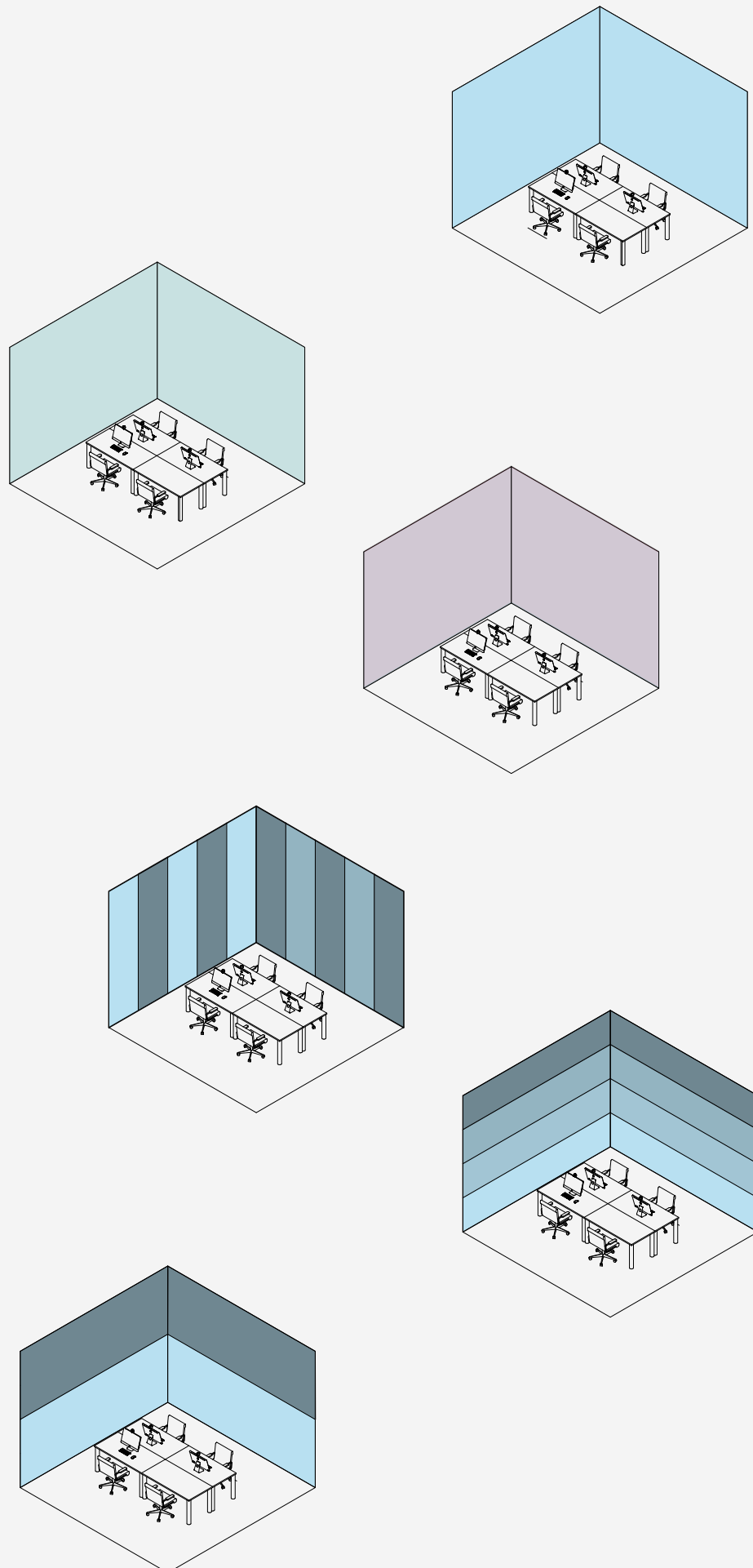


Figure [102]: Many design options regarding the glazing provided by Merck

11. Conclusion

To combat climate change, it is key to decrease the energy emissions accountable to the built environment. This calls for high-end architecture and engineering designs, quality constructed components and affective operating systems. Therefore, smart buildings face several challenges. They must be sustainable in the use of resources alongside integrating advantageous evolving building technologies and should react to the occupants' needs including their health and well-being (Clements-Croome, 2018). Affective operation evolves around the study and development of systems that can recognize, interpret, process, and simulate human affects/emotions. An affective window understands the occupant's feelings, mood, and glare response. In this study an affective window, a seamless interaction between the glazing an occupant, is explored. The main research posed is "How can an automated system, consisting of switchable glazing and a system that can sense the needs of the occupant, be used to control glare in an effective manner?".

A novel system is proposed that aims to sense the need of the occupant, hence effectively controlling the switchable glazing provided by the Industrial partner, Merck. The system can detect glare via a webcam capturing FAU (Facial Action Units) and a wearable lux sensor measuring the light in the space. Two experimental studies with participants are done to (i) develop the physical characteristics of the experiment room, (ii) set the threshold values, (iii) gain more data that could be added to a future dictionary for detecting glare via FAU, and (iiii) evaluate the novel system via comparing it with a benchmark system. Activities in the form of a possible response to light mostly appeared in the results from the inner brow raiser intensity (AU01_r), outer brow raiser intensity (AU02_r), the brow lowerer (AU04_r), the lid tightener intensity (AU07_r) and the nose wrinkler intensity (AU09_r). The outer brow raiser intensity is shown to reveal the most clear activity due to light in the conducted experiments. Applying machine learning techniques to the data could help to further explore the relationship between FAU and lux measurements, looking for statistical significance that is not visible to the human eye. It may help to identify the key FAU for detecting glare. The overall comparison of productivity, daylight and view led to no significant result.

However, the small experiment study suggests that in its prototype form, it is no worse than the benchmark, for some participants it was better.

To further development of the system, improvements for experimental studies are posed; (i) capturing the occupant's response regarding the level of discomfort is immediately (in real-time) gathered, (ii) the matter of how to improve the potential for each individual to have their own system is investigated, (iii) the light should be measured by more sensors in different places (for instance fixed to the wall). It should be measured in real-time to determine which one is most beneficial. Furthermore, relation ought to be considered with the architectural design of the building. (iiii) The experimental set up mirrors an actual office building to enhance the correlation of the data gathered during such experimental studies, also to study the data with real sunlight, the most common source of glare.

The findings mean, for the field of architecture, that the real-time data shows that it is possible to measure, iterate upon and optimise indoor visual comfort for the occupant. Switchable glass can effectively be controlled by sensing the occupants' visual discomfort and reacting to the occupants' needs. For applying, the system to existing office buildings, needed to say, is that certain components should be implemented in the control system regarding privacy concerns of the occupant.

As more data is gathered, there are more opportunities to explore the relationship between facial responses due to light.

12. Sustainability



Figure [103]: Sustainable Development Goals

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12.1 Theoretical framework

In 2015, all United Nations member states adopted the 2030 Agenda for Sustainable Development, which provides a guide to peace and prosperity for people and the planet, now and in the future. At its centre are the 17 Sustainable Development Goals (SDGs), 17 targets to make the world a better place, which are an urgent call to action by all countries - developed and developing - in a global partnership (figure 103). They recognise that eradicating poverty and other deprivations must go hand in hand with strategies to improve health and education, reduce inequality and boost economic growth - all while tackling climate change and working to preserve earth's oceans and forests. The theoretical framework points out how this research, the new control system and Merck the company behind the switchable glazing, with the objective that it should minimise visual discomfort and enhance the use of daylight, relates to various Sustainable Development Goals.

12.2 Good health and well-being

SDG number 3 is the first goal that the project refers to, "Ensure healthy lives and promote well-being for all at all ages". Literature shows that not working in an office environment with daylight may affect health and well-being. Light is needed for visual processes, without light people cannot see. Moreover, light influences non-visual processes, these processes can be divided into immediate and long-term effects (Hanifin, 2007). Picture a bright environment, one instantly feels much more alert than in the dark. After a longer period, the biological clock reacts to light and accordingly influences mood and performance during the day. Furthermore, the biological clock also regulates the day-to-day pattern of alertness (Górnicka, 2008). The human sensation of comfort and delight as well as the pupil response, melatonin suppression and alertness are immediate effects. Long term effects can result in change of physiological circadian rhythms, alertness pattern and health (Górnicka, 2008). Boubekri (2014), compared participants working in artificial light to people working in daylight. The results show that the form of light has effects even beyond the workplace, for instance, the participants with only artificial light sleep an average of 46 minutes less per night.

Research shows that lack of sleep and poor sleep quality have a number of consequences for health and safety. For example, insufficient sleep and reduced sleep quality have been linked to higher cortisol levels in the evening, disrupted glucose metabolism, a heightened appetite due to lower leptin and higher ghrelin values plus a higher body mass index, as well as increased tiredness and decreased performance, alertness and mental concentration, which can lead to an increased error rate and subsequently to an increased risk of injury (Boubekri, 2014). A prior similar study showed that the ranges of vitality, social functioning and mental health scores for those who worked in dark offices were lower than those for those who worked in offices with more lighting (Mills, 2007). Accordingly, working in an office environment with sufficient exposure to daylight is important for the health and well-being of staff. The goal of the control system is to create a visually pleasant indoor office environment, it could enhance the possible use of daylight and therefore it may improve the health and well-being of the occupant. Not only could it improve the visual environment by the use of natural light, it may also benefit the availability of view. A prior human related advantage is the aspect that the occupant can enjoy a view (Christoffersen and Johnsen, 2000). Christoffersen et al. studied 20 Danish buildings to figure out what the most positive aspects of the window was (Christofferson et al., 1999). The results show that office employees prefer to sit near windows. They found that the occupants like to be able to check the weather outside and to have the option to open the window (Christofferson et al., 1999). Farley and Veitch (2001) point out that a view, preferably a view on nature, could lead to positive effects on work and well-being. Windows with a view of nature were shown to improve work and well-being in a multitude of ways, including enhancing job satisfaction, job value, perceptions of self-efficacy, perceptions of physical working conditions, life satisfaction, and reducing the intention to quit and the recovery time of surgical patients. Hellinga (2013) states that the most frequently mentioned benefit of windows was the view to the outside that it provides, followed by access to daylight (Hellinga, 2013). Hellinga confirms the findings of Christoffersen et al. (2000) and Farley and Veitch (2001), namely, that providing a view to the exterior is most appreciated by the building users (Hellinga, 2013).

12. Sustainability

Conclusively, literature shows that enhancing the use of daylight and increasing the availability of view, affects the well-being of the occupants. Therefore it helps to reach the third SDG.

12.3 Affordable and clean energy

The energy consumption of the built environment accounts for 40% of the European Union's (EU) total energy consumption and 36% of the EU's total CO₂ emissions, making it essential to reduce the energy utilization to meet the sustainable development goals (European Commission, 2013). In the paper "Life cycle energy analysis of buildings: An overview" 73 buildings were evaluated, both residential and office, across 13 countries (Ramesh, 2010). The results point out that 80-90% of the buildings' energy utilization is in the operational phase and 10-20% in the embodied phase (Ramesh, 2010). Thus, reducing the operating energy, through passive and active technologies, can improve the energy performance of a building's life cycle, even if the embodied energy increases a little (Ramesh, 2010). Operating energy use varies per sector, for an office building it is mainly distributed to HVAC, lighting, electric equipment (for instance computers), lifts, domestic hot water and some other uses (Sisson, 2009). The concept of the new control system could aid in reaching the seventh SDG, "Ensure access to affordable, reliable, sustainable and modern energy for all". A sub target of this goal is, by 2030, the global rate of improvement in energy efficiency should be doubled. An indicator for this is the energy intensity measured in terms of primary energy and Gross Domestic Product (GDP). The ratio of primary energy supply to GDP, defines the global energy intensity. The first set goal was to decrease the global energy intensity annually with 2.6%. Unfortunately since the improvement of the energy use in 2017 and 2018 were lower than the target, namely a decrease of 1.7% and 1.2%, the global energy intensity should improve with 2.9% per year to reach 7.3. Accomplishing this objective will require an improvement in energy efficiency, where not only implementations of policies are needed (such as codes and standards, for instance BREEAM and LEED), but also technological change and advances in energy management in the industrial and buildings sectors deliver efficiency improvements. Briefly explained in the introduction is that the control strategy could benefit the energy

performance of office buildings in the future, since the system powers the transparency of the switchable glazing that affects the properties of the layer (liquid crystals) in between the glazing. Glazing systems generally have a large impact on the total energy consumption of office buildings (Graiz, Azhari, 2019). Glazing properties can affect the transmitted solar radiation, heat losses and gains, which has an impact on the energy usage for lighting and HVAC. A great deal of the energy used by office buildings is needed for heating, ventilation, air conditioning (HVAC) and lighting (Department of the Environment and Energy, 2012). Figure 105(a) indicates the approximate distribution of the energy supply for an office building: 39% is used for HVAC, 25% for lighting, 22% for electric equipment (for instance computers), 4% for lifts, 1% for domestic hot water and 9% for other uses. Figure 105(b) shows that HVAC alone is more energy demanding than equipment, lifts, domestic hot water and other uses all together. This points out that reducing the energy need of the HVAC and lighting via smart use of glass and daylight has a potentially large impact on the energy use. Modifying and thereby reducing the energy needs of these two domains could strongly benefit the energy efficiency of an office building.

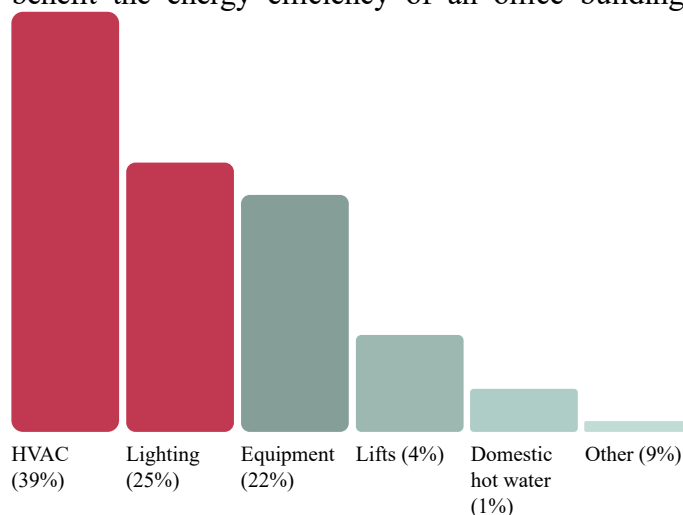


Figure [105(a)]: Typical energy distribution

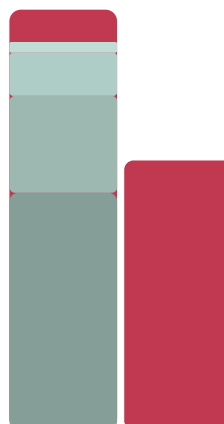


Figure [105(b)]: Typical energy distribution

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Building automation is another development that is essential due to the fact that manual operation building technologies (unaware insufficient doing) can increase the energy utilization (Sisson, 2009). Unsustainable energy utilization will continue to grow in all areas due to the growth of the world population (expected to be nearly 50% higher in 2050 than in 2000) and from increasing energy use per person. User behaviour (positive and negative) can make a substantial difference. Wasteful behaviour could raise the energy use with 33%, while clever energy (the minimum) use could decrease it by 32%. This means that energy use of buildings may be cut by 60%. An example of wasteful behaviour is, when the indoor environment is too bright and the occupant is experiencing visual discomfort, the occupant closes the blinds and turns to artificial energy demanding sources, such as indoor lighting. When highly reflective blinds are completely closed by the occupant, the heat gain may be reduced by approximately 45%. Thus, the occupant could be tempted to turn on the available heating devices, such as the radiator. Eventually, the occupant tends to leave the blinds closed, although, as the position of sun in relation to the façade changes during the day, it would not be needed anymore (Edwards, 2002). A number of studies have already shown that the user does not often adjust the blinds position, almost only when the light from the sun is too bright, the occupant closes the blinds (Escuyer, 2001). When the occupant retracts the blinds or shutters, one does so mostly to increase the amount of daylight, to save energy or to create a view (Galasiu & Veitch, 2006). Unfortunately, the occupant usually does not open the blinds quickly (Meerkbeek, 2014). Because of the unaware insufficient use of the blinds, due to the visual discomfort of the occupant, the energy performance of the building decreases (Paik, 2006). Building automation is a promising solution to reduce the carbon footprint of the built environment (Favoino, 2015).

12.4 Decent work and economic growth

The eight SDG in the agenda for 2030 8 states “Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all”. The main objective of this project and the novel control system is to decrease the visual discomfort experienced by occupants. Meaning that the glare, the negative sensation of light, should be minimized and the availability of view should be increased.

Visual comfort contributes to the indoor environment quality. The indoor environment quality has an impact on the buildings’ occupants’ comfort, well-being, health and productivity (Ong, 2013). Well-being is strongly connected to health and productivity (Adams, 2019). Happy and healthy office employees are more productive than office employees with poorer well-being (Hamar, 2015). Increasing productivity of office employees could lead to economic growth. Consequently, good indoor environment quality might benefit businesses worldwide economically, as 90% of typical business operating costs can be spent on staff (WGBC, 2014).

This research could not have been done without the aid of the industrial partner Merck. The industrial partner Merck has provided the switchable glazing and the controller for this project and will provide more for future research. All nations are called upon to uphold and protect human rights and basic freedoms to reach SDG 8. As a global company, Merck is also urged to respect and protect human rights in their own company and in their supply chain. They are dedicated to upholding the appropriate and fair labor and social standards. At Merck, they are constantly working to integrate human rights due diligence into their processes in an effort to minimize the risk of human rights violations and to protect these rights within their sphere of influence. They expect their suppliers and service providers to comply with their ethical, social and legal standards. Daylight is a fundamental part of human biology. As earlier explained, natural light has a whole host of health benefits (Figure 104). Exposure to natural light supports the regulation of vitamin D, serotonin and melatonin in the human body and promotes healthy eye development. However, the majority of days are spent indoors, moving between homes and offices (or at least before the pandemic). The importance of natural light is known in modern-day architecture. This led to exciting new forms and possibilities with glass. More and more glazed façades appeared and often floor-to-ceiling windows were implemented in new office buildings. The benefits of natural daylight are clear, as it has been shown that office workers who sit near windows sleep on average for 46 minutes longer than those who don’t and workplaces with good levels of natural light benefit from productivity gains between 3% and 40%.

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During the experiment conducted in this research the availability of view and the productivity of the participant was studied. Whether the participant was more productive during the novel system or benchmark system could not be said. However, the availability of daylight seemed to be promising during the use of the novel control system. Eventually the novel system should have a positive effect on the productivity of the office employee. This is yet to be proven, more research has to be done, with more participants in a real office environment and over a longer time period, to ensure this benefit.

12.5 Industry, innovation and infrastructure

The world is becoming more digital, some people might even call these times the digital revolution. However not every country can keep up the pace of the technological advancements. The result is that 20% of the population in low- and middle class income are not online. Therefore the United Nations set up SDG 9, “Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation”. A resilient infrastructure should be achieved globally by 2030. This is done by, among other things, providing people better access to technology. Target 9.5 reads “Enhance scientific research, upgrade the technological capabilities of industrial sectors in all countries, in particular developing countries, including, by 2030, encouraging innovation and substantially increasing the number of research and development workers per 1 million people and public and private research and development spending”. An important indicator for reaching many SDGs, including targets 8.2 (achieve higher levels of productivity of economies through diversification, technological upgrading and innovation, including through a focus on high value added and labor-intensive sectors) and 9.5, is the total number of personnel (researchers, technicians and other support staff) working in research and development (R&D), expressed in full-time equivalent, per million inhabitants. The fields of science, technology and innovation are key drivers of economic growth and development. Progress in these fields requires trained staff engaged in R&D. For the research done during this project other research studies have been used and further elaborated on.

An investment in R&D is done here for realising more sustainable innovative solutions for office buildings. Throughout experiments with the novel method of sensing glare, new data is gained which can be the new ‘soil’ for future R&D.

As an innovative company Merck also cares about this target. The liquid crystals in between the double glazing that influence the transparency of the glazing fulfill more purposes. Scientists faced a rather odd appearance in 1888, when working with a chemical substance. It transitioned through a state that was neither solid, liquid, nor gas, when it was heated. The phenomenon was studied and physicists named it liquid crystals. At Merck they have been exploring the possibilities of liquid crystal for over 110 years. Merck launched their lyristal materials in 1969. It is the basis for modern-day flat-screen technology and is used in today’s televisions and smartphones. The company has not stopped innovating with liquid crystal materials and technologies. Hence, they have developed various uses from vibrant displays, smart windows and digital optics to create faster and more reliable communication through smart antenna technology. The possibilities of liquid crystals are still explored and Merck aims to develop more uses with it. For instance, they are developing liquid crystals for smart antennas that can use satellite communication to provide Internet access to even the most remote areas of the world.

12.6 Sustainable cities and communities

SDG 11 states “Make cities and human settlements inclusive, safe, resilient and sustainable”. With the growing population of the world and the number of people expected to live in cities in 2050, attention is drawn towards realising more high-rise buildings in cities in order to accommodate the increasing number of working and living people. In 2018, 55% of the world’s population lived in urban environments (United nation, 2018). In 2030 60% of the population is expected to live in urban areas and in 2050 this may rise to 68% (United Nations, 2018). Cities all over the world already have high-rise buildings with glazed façades and the idea of even more in the future stresses the importance of improving the building energy performance. Imagine the impact of sustainable, energy efficient, high-rise buildings on the world’s emissions.

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Therefore, an optimal design of glazing and control over the amount of daylight transmitted through glass is important to reduce CO₂ emissions. This led to demanding better solutions and improvements on shading technology. Nowadays shading systems are more technically developed and offer dynamic and automated products. The high-rise buildings should be built from more sustainable materials and the energy performance should increase to create more sustainable cities and communities. This research project itself cannot significantly prove that it reduces the energy demand of an high-rise office building, but it can help other studies for automatic shading strategies.

12.7 Responsible consumption and production

“Ensure sustainable consumption and production patterns”, that is what the twelfth SDG stands for. The novel control system explained and designed during this research potentially ensures a more sustainable consumption of the operating energy of a building. To prevent greenwashing, it is important to keep in mind that new technology could solve some problems, but will also bring new ones. Think of how transportation was improved by horses and carriages. The horses left their faeces on the roads and were polluting the streets. In 1886 the world’s first car was introduced. People assumed this was an improvement for the streets and the environment. With cars they no longer had to use horses for transportation and therefore they would not pollute the streets anymore. As a result cars became more and more popular. After all, the streets were clean. These fossil fuel slurping machines were supposed to be an improvement for the surroundings. Now there are more than 1 billion vehicles spread around the world. This is just one example where the consequences became maybe even worse than the solution. Cars were not the first, think of the fridge (1800). This was an innovative and sustainable idea to keep your food cold so it would last longer. An old fridge consumes lots and lots of energy. Tgus, the food lasts longer, however it costs a lot of energy. Every invention has its advantages and disadvantages. SDG 12 stresses that more attention should be paid to both sides of the solution. With that being said, the materials and equipment needed to incorporate the control system should be investigated.

The equipment needed for this system to operate should not increase the amount of, among other things, electric waste and chemical waste. Several targets of SDG 12 emphasize the importance of this, namely 12.1 states “Implement the 10-year framework of programmes on sustainable consumption and production, all countries taking action, with developed countries taking the lead, taking into account the development and capabilities of developing countries” which is indicated by “Number of countries with sustainable consumption and production (SCP) national action plans or SCP mainstreamed as a priority or a target into national policies”, and 12.4 reads “By 2020, achieve the environmentally sound management of chemicals and all wastes throughout their life cycle, in accordance with agreed international frameworks, and significantly reduce their release to air, water and soil in order to minimize their adverse impacts on human health and the environment” which is indicated by “number of parties to international multilateral environmental agreements on hazardous waste, and other chemicals that meet their commitments and obligations in transmitting information as required by each relevant agreement”. Since 1970, worldwide consumption of material goods has tripled. The world continues to use natural resources unsustainably (figure 106).



Figure [106]: Global material footprint

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The UN’s objective is clear, the amount of waste produced should be reduced significantly by furthering prevention, reduction, recycling and reuse. To investigate where the possible concerning new waste will come from, the needed tools to implement the system in the real world are summed up; (i) electronic devices to sense the visual discomfort, such as a smart computer (hosting the algorithm), webcam (capturing facial action units) and lux meter (light intensity indicator), (ii) the electronic controller of the switchable glazing and (iii) the switchable glazing itself. Implementing this system into the real world requires quite some electronic devices. This may be a bit concerning due to the fact electronic waste grew with 38% from 2010 until 2019, while the amount of electronic devices recycled is less than 20% (figure x). Interesting is to research what could be recycled and how to minimise the need of new webcams for instance and light sensors. Webcams may already be incorporated in some of the monitors in offices. A manner to use these could decrease the need for new webcams. Due to the pandemic (COVID-19), more webcams could have been purchased and needed by companies and individuals, maybe even these could be used when they are no longer needed by the owner. Light sensors are already steadily increasing. To implement the control system in a space where light sensors are already used, the current sensors could be used and maybe no new ones would have to be added.

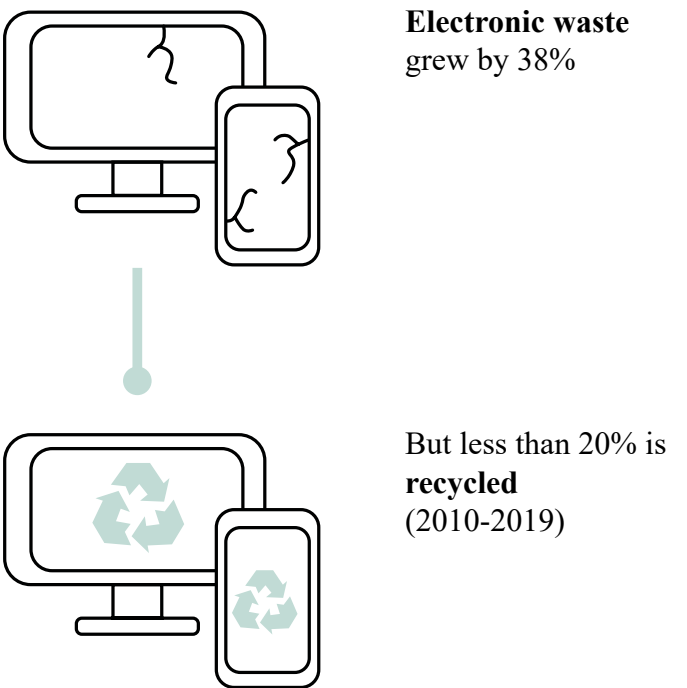


Figure [107]: Electronic waste and recycle

The manufacturing, transportation and powering of the switchable glazing raises more concerns, regarding the increasing amount of waste. Preventing the generation of waste, for instance by developing new production processes or optimizing existing ones is certainly on Merck’s agenda. Waste often contains many valuable raw materials that can be reused in the production stream. The company’s target is to reduce the environmental impact of their waste disposal by 5% by 2025 (figure 107). Although waste contains valuable raw materials that can be reused in the production stream, it can also pose a risk to the environment. They consider it essential to prevent or recycle as much of their waste as possible. Merck desires to reduce their environmental footprint. The company’s approach is to limit the loss of raw materials and reduce the impact of their waste disposal practices on the environment.

Unfortunately sometimes it is not always feasible to optimise the current production of their materials, they do their best to reuse the accrued waste to produce materials or generate energy. They support the circular economy approach through their Merck Waste Scoring System, for reference see figure 108, and the related goal of recycling. Waste separation makes it possible to recover and recycle raw materials, while non recyclable waste is discarded in an environmentally sustainable manner in line with the strictest waste disposal standards. They are constantly striving to improve their production and analyzing their current production of waste via their own scoring system. Hopefully, they can achieve their goal by 2025 and contribute to SDG 12.

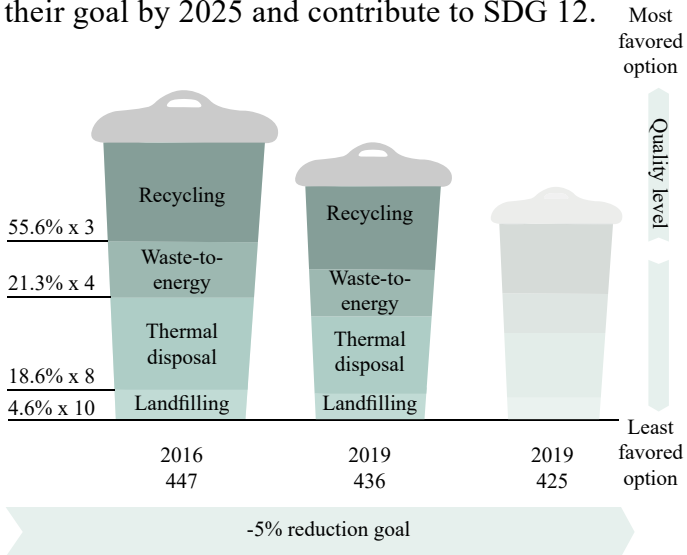


Figure [108]: Electronic waste and recycle

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12.1.7 Climate action

Climate change is firmly on the agenda. The thirteenth target therefore reads “Take urgent action to combat climate change and its impacts”. To reach this goal it is important to integrate climate change measures into national policies, strategies and planning. This calls for flexible solutions that can be effective even if the climate changes. The control system can easily be modified to new or different climate reactions. Since the system can react to realtime information it would work even if the climate changes. The transparency and therefor solar heat gain through the switchable glazing could be adapted in such a way that when less heat is needed indoor this could be taken care of and when more heat is needed indoor do to a colder environment, more natural light can enter the building via an increasing transparency of the glass if necessary.

12.1.8 Partnership for the goals

Finally, this research project aids in achieving SDG 17, “Strengthen the means of implementation and revitalize the global partnership for sustainable development”. The novel proposed system and the research joins various partnerships between different groups, two universities, University of Cambridge and Delft University of Technology, and an industrial company, Merck. The project also incorporates knowledge from various domains, for instance, the aid of computational intelligence, the switchable glazing and the psychological aspects involving the facial expressions, health and well-being. The project therefore combines knowledge from different places in Europe to create more sustainable offices that are suited for environments all over the world. The tricky aspect here is that people’s wishes and demands regarding light are different globally due to, among other things, culture and ethnicity. Furthermore, occupants’ facial expressions may be different over the world due to ethnicity, stressing the importance of gaining more data.

13. Reflection

During the Sustainable Design Graduation studio a method to effectively control switchable glazing is studied. The subject was a bit tricky and new to get into right away, however it is so incredibly interesting, thus the perfect challenge. Right at the start, everything went at a fast pace. Introduction meetings with the two external advisors were set immediately and they gave uptempo lectures explaining methods and practical components. Since there have been a few previous studies where the same topic had been investigated, it was important to bear in mind that it was not needed to reinvent the wheel.

13.1 The approach

The approach to this research proceeded as described. First, a research plan was drawn up. In it, the problems were listed, the gap was clarified and the main objective was set. A main research question was written in order to achieve the goal and in an attempt to answer the main question, a number of sub questions was formulated. The first few weeks consisted mainly of literature research. This was done using literature study to understand and implement knowledge that already existed. To give an example of this, research was done into what is glare. How to calculate glare and more. This was important to avoid getting lost in the search for manners to evaluate glare and this was not the scope of the research. The scope was to define how the switchable glass could be controlled in an effective manner. For the next step it was important to get a grip on what was in the system made during this research, so which components were needed? This was done by constantly drawing schematic schemes and sections with every component in it. Visuals of the system were made and analysed. By means of experimental research, the system, its operation and its inheritance were tested. Hence, after the literature study, the design phase started. It started with the development of the system and then with the design of an experimental setup. Knowledge of the literature study was applied in designing the experimental space. Also many measuring equipment tools were used to access the glare rate of the experimental setup. The experiments tested the potential of the system. The setup consisted of many different components which required computational and practical skills. The computational part was obtained through online courses (edX).

The practical component was gained through previous courses such as Bucky Lab and through the help of tutors including Marcel Bilow, Alessandra Luna Navarro and Mark Allen. In summary, the research included a literature review, a design component, a computational domain, a practical building component (building an artificial office room) a few experimental studies and finally an extensive analysis of data.

13.2 How and why

The literature study was done to obtain and apply existing knowledge. So first, a series of research questions were formulated to obtain knowledge about glare, existing facades, existing control systems etc. These were answered through mainly literature review. The design was done by visualising the new system. With the help of visualisations, components and their work could be understood. Briefly, the new proposed system is a solar radiation control system in which light is measured by a lux sensor and a camera that analyses the user's face is used. Computational knowledge was gained through online classes taken at edX. The experiments were important to carry out to find out if the system works and could be applied in reality. This is relevant since it is a new idea and it is significant to indicate whether it is realistic. It was also possible by experimenting to gain insight into components (certain facial expressions, action units) that would be useful to add to the system. Before the experiments were carried out, extensive literature research was carried out into performing experiments with light. Through trial and error, the experiment was rehearsed again and again until it went well, especially with the researcher (myself) as the test subject. This was done many times.

13.3 Feedback

During this research, a handful of people were involved. The mentors helped, the external advisors, an assistant professor who knows a lot about working with light and evalglare and the building master of Building Technology at the faculty (i.e. the one who is very familiar with working hands-on work, building models and structures). In the beginning, there was relatively more guidance than in the end. The many coaching sessions in the beginning were pleasant to get the research project in order.

13. Reflection

A lot of emphasis was put on methodology in the beginning which was very good because it was a research project with many different components. Especially the first and second mentor helped a lot with this part. Super cool was that, just after P2, there was a consultation with the company involved, Merck. In July, there was even an appointment in the office, which fortunately was still possible during these difficult times (the pandemic). It was super interesting to go through their office and factory and see how their product was produced. Also, practical skills were guided in the beginning. For example, working with measuring instruments, computer programmes and building an experiment room that could also be disassembled. The guidance of the external advisors (Phd candidates) and mainly the help of the master builder played a major role in this part. It was important that the construction could be dismantled, because the pandemic might make it impossible to do the experiments at the faculty. The advisors from outside have always been well involved with the project. Through Zoom, we had contact every other week and sometimes even weekly. They helped a lot with the experiments and the analysis of the data. All this was very new for me and very efficient to do with guidance. The communication went smoothly and it was pleasant to not only talk about this research project, but also their interesting research projects. Sometimes we forget how much we learn from an informal conversation where others talk about their project and process. The appointments with the mentors weakened at a certain point, which could perhaps have led at the end to more emphasis on the experiments than on the design process and the implementation of the new system on an office building. It would have been nice to be able to go to the office of one of the mentors now and then, for instance to ask a quick question. However due to the circumstances, the meetings were mainly on Zoom and everyone had to work from home. I also noticed that when something was not quite clear on Zoom, it was more difficult to keep asking until I fully understood a subject than during a meeting that normally could have taken place at the faculty. I really enjoyed the way my supervisors helped me. The manner that they gave feedback was by advising me to have a look at certain literature, pointing out interesting webinars and by asking questions about why and how I made certain decisions was a very

pleasant way of guiding me. That my mentors and external advisors showed me many different researches and pointed out interesting webinars to attend was delightful. It was pleasant to know what literature is useful. The webinars were lovely to attend because it can be an enjoyable, valuable break.

13.4 Learning goals

In the beginning, a number of learning goals were set in the graduation plan handed in a week before the P2 presentation. In the graduation plan was explained that the research topic is related to Building Technology in many ways, for instance: (i) gaining knowledge in existing shading systems such as switchable glazing, (ii) gaining knowledge about the relation between architecture and light, (iii) exploring the possibilities of reducing the energy demand of the built environment by controlling the solar radiation through glazing, (iiii) developing a novel controlling system, (iiiii) exploring and understanding the possibilities of Python. It was important for me to master some practical skills. Some of these were familiar, such as setting up a demountable construction, others were more unfamiliar, such as computational work and carrying out an experiment. Besides acquiring practical skills, it was also important to apply the knowledge gained during previous courses (of the master track Building Technology). The knowledge gained during the course Research Methodology, knowledge about energy during the course Zero Energy Design and presentation techniques gained during the course SWAT were important to apply. The practical skills were mainly gained in the beginning of the project. The knowledge that was already known was applied the entire time of the project. Furthermore, I also learned more about my own interests and competence. I already knew that I find working with others enjoyable and encouraging. During the project I noticed that I had to take some more initiative and had to dare to make choices. This was the first time I carried out experimental research at the university and it was hard work, but great fun. At first, I underestimated the work involved, things often went wrong, but when it did work, it was such a pleasure. Every time an element of the setup of the system came together or worked, it gave me so much energy. Doing experiments together with others was an incredibly cool experience and I would love

13. Reflection

to do it again in the future. Sometimes I found it difficult to put as much attention and time into all the components. This resulted in more energy spent on research than on design. Design did play a role in the research, however the design still lagged behind a bit. For the future, I would like to learn to work out the methodology and the planning more thoroughly. I would pay attention to how much time is spent on each part and I feel that the iterative aspect may have fallen behind as well. Later, I would like to continue working with others, gain more knowledge in AI in the built environment, perform exciting experiments and especially keep on challenging myself.

13.5 Relevance

Building efficiency should be reviewed as enhancing the performance of a complex system created to deliver occupants a comfortable, secure, and appealing living and work environment (Quadrennial Technology Review, 2015). This calls for high-end architecture and engineering designs, quality constructed components, and affective operating systems. The graduation project is about creating a new controlling system for existing building technologies. Now there is little interaction between the comfort of the occupant and the existing new building technologies. The project aimed to improve automatic control technology for society. This research is about a completely new controlling strategy. The experimental study conducted is important to see and analyse if this manner of controlling makes sense and does actually form a benefit to automatic controlling systems. The experimenting in the field could point out positive and negative effects of existing and a new controlling system. Which means that this project could lead to many more new human-centered controlling systems. Others could also take on the scientific project and improve the system, since more research in the field and data is needed.

13.6 Ethics

To investigate whether the new system could work in practice, research was carried out with the help of test subjects. No ethical statement had to be made for this research. However, they did have to sign a paper in advance stating that they approved of being filmed. In practice (meaning by implementing this in real-world office buildings), this could also cause some problems regarding privacy. Ways to avoid this are as follows: (i) the camera is not connected to the internet so it cannot be hacked, (ii) the images from the camera are deleted after a certain time, for example after 5 minutes, (iii) the camera does not record anything if there is no person in the picture.

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15. Appendix

15.1 Experiment I - Survey

Circle the correct one:

Is it all right if this is recorded: yes, no

Age: 18-24, 25-30, 31-34

Gender: Male, female, other, prefer not to say

Origin: Africa, America, Antarctica, Asia, Oceania, Europe

Height: 150-155, 156-160, 161-165, 166-170, 171-175, 176-180, 181-185, 186-190, 191-195, 196-200, 201-205, 206-210

Definitions:

Imperceptible: I do not notice the light/ glare source

Perceptible: I notice the light/ glare source, but I am not bothered by it

Disturbing: I notice the light/ glare source. I am able to read the screen, probably perform tasks. However, it is bothering me, and I would like to do something about it.

Intolerable: I notice the light/ glare source I cannot stand it. It must change immediately.

Circle the definition that you think fits your experience.

1 Imperceptible, Perceptible, Disturbing, Intolerable

2 Imperceptible, Perceptible, Disturbing, Intolerable

3 Imperceptible, Perceptible, Disturbing, Intolerable

4 Imperceptible, Perceptible, Disturbing, Intolerable

5 Imperceptible, Perceptible, Disturbing, Intolerable

Circle the definition that you think fits your experience.

1 Imperceptible, Perceptible, Disturbing, Intolerable

2 Imperceptible, Perceptible, Disturbing, Intolerable

3 Imperceptible, Perceptible, Disturbing, Intolerable

4 Imperceptible, Perceptible, Disturbing, Intolerable

5 Imperceptible, Perceptible, Disturbing, Intolerable

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On a scale of 1 to 5, do you think the time in between scenarios is enough to acclimatize?
Poor 1, 2, 3, 4, 5 Excellent

On a scale of 1 to 5, do you think the time during scenarios is enough to acclimatize?
Poor 1, 2, 3, 4, 5 Excellent

Do you wear glasses or contact lenses? Yes, No, prefer not to say

How would you judge the quality of the screen?
Poor 1, 2, 3, 4, 5 Excellent

What do you think of the habituation?
Poor 1, 2, 3, 4, 5 Excellent

15. Appendix

15.2 Experiment II - Survey i

Time and date:

Circle the correct one:

Is it alright if this is recorded: yes, no

Age: 18-24, 25-30, 31-24

Gender: Male, female, other, prefer not to say

Origin: Africa, America, Antarctica, Asia, Oceania, Europe

Height: 150-155, 156-160, 161-165, 166-170, 171-175, 176-180, 181-185, 186-190, 191-195, 196-200, 201-205, 206-210

Eye colour: Green, blue, brown, grey, other

Do you wear glasses or contact lenses? Yes, No, prefer not to say

How often do you work in an office environment? Always, most of the time, sometimes, rarely, never

Did you have caffeine in the morning? Yes, No

How would you describe your mood?

Good 1 2 3 4 5 Bad

How sensitive are you to bright light?

Very sensitive 1 2 3 4 5 Not at all

How many hours did you sleep last night?

0-2 hours, 2-4 hours, 4-6 hours, 6-8 hours, 8-10 hours, 10-12 hours, 12-14 hours, Other

On average, how many hours of sleep do you have each night?

0-2 hours, 2-4 hours, 4-6 hours, 6-8 hours, 8-10 hours, 10-12 hours, 12-14 hours, Other

Are you feeling tired?

Yes 1 2 3 4 5 No

15. Appendix

15.3 Experiment II - Survey iia

Time and date:

Circle the correct one:

How would you rate the lighting conditions in the room?

Too dark 1 2 3 4 5 too bright

How would you judge the quality of the screen?

Poor 1 2 3 4 5 excellent

What do you think of the habituation?

Poor 1 2 3 4 5 excellent

The artificial glare source was turned on twice. The following questions are for the first time the light was on:

Definitions:

Imperceptible: I do not notice the light/ glare source

Perceptible: I notice the light/ glare source, but I am not bothered by it

Disturbing: I notice the light/ glare source. I am able to read the screen, probably perform tasks. However, it is bothering me, and I would like to do something about it.

Intolerable: I notice the light/ glare source I cannot stand it. It must change immediately.

How would you describe the degree of glare experienced when performing the tasks?

Imperceptible, Perceptible, Disturbing, Intolerable

When reading the texts during the task, how much bothered were you by the light?

Very much 1 2 3 4 5 Not at all

The following questions are for the second time the light was on:

How would you describe the degree of glare experienced when performing the tasks?

Imperceptible, Perceptible, Disturbing, Intolerable

When reading the texts during the task, how much bothered were you by the light?

Very much 1 2 3 4 5 Not at all

15. Appendix

15.4 Experiment II - Survey iib

Time and date:

Circle the correct one:

How would you rate the lighting conditions in the room?

Too dark 1 2 3 4 5 too bright

How would you judge the quality of the screen?

Poor 1 2 3 4 5 excellent

What do you think of the habituation?

Poor 1 2 3 4 5 excellent

The artificial glare source was turned on twice. The following questions are for the first time the light was on:

Definitions:

Imperceptible: I do not notice the light/ glare source

Perceptible: I notice the light/ glare source, but I am not bothered by it

Disturbing: I notice the light/ glare source. I am able to read the screen, probably perform tasks. However, it is bothering me, and I would like to do something about it.

Intolerable: I notice the light/ glare source I cannot stand it. It must change immediately.

How would you describe the degree of glare experienced when performing the tasks?

Imperceptible, Perceptible, Disturbing, Intolerable

When reading the texts during the task, how much bothered were you by the light?

Very much 1 2 3 4 5 Not at all

The following questions are for the second time the light was on:

How would you describe the degree of glare experienced when performing the tasks?

Imperceptible, Perceptible, Disturbing, Intolerable

When reading the texts during the task, how much bothered were you by the light?

Very much 1 2 3 4 5 Not at all

You have been seated in this room twice for 26 minutes,

Did you prefer the settings of the first 26 minutes or the second?

First, second, no difference

If so, why did you prefer the first or second 26 minutes of the experiment?

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15.5 Task sheet i

Multiply and divide:

1. $4 \times 10 =$ _____

- a. 40
- b. 44
- c. 50

2. $(-1) \times (-12) =$ _____

- a. 13
- b. 12
- c. -12

3. $56 \div 8 =$ _____

- a. 7
- b. 6
- c. 8

4. $40 \div 10 =$ _____

- a. 4
- b. 10
- 8

5. $(-6) \times (-2) =$ _____

- a. 12
- b. -12
- c. 18

6. $7 \times 10 =$ _____

- a. -70
- b. 70
- c. 10

7. $2 \times 4 =$ _____

- a. 8
- b. 10
- c. 12

8. $10 \div (-1) =$ _____

- a. -10
- b. 10
- c. 1

9. $11 \div 1 =$ _____

- a. 10
- b. 1
- c. 11

10. $10 \times 1 =$ _____

- a. 11
- b. -11
- c. 10

Addition:

11. $(-1) + (-4) +$ _____ $= -6$

- a. (-1)
- b. (-2)
- c. (1)

12. $9 +$ _____ $+ (-4) = 0$

- a. (-5)
- b. (-4)
- c. (5)

13. $6 + (-5) +$ _____ $= -8$

- a. (-8)
- b. (-9)
- c. (-7)

14. _____ $+ (-3) + (-10) = -21$

- a. (-8)
- b. (-7)
- c. (-6)

15. $4 + (-4) +$ _____ $= 3$

- a. 2
- b. 4
- c. 3

16. _____ $+ (-1) + (-3) = -10$

- a. (-5)
- b. (-6)
- c. (-4)

17. $1 +$ _____ $+ (-10) = -6$

- a. 3
- b. 2
- c. 4

18. $(-5) + (-2) +$ _____ $= -10$

- a. (-4)
- b. (-3)
- c. (-5)

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19. _____ + 9 + (-2) = 1

- a. (-6)
- b. (-7)
- c. (-8)

20. _____ + (-10) + 9 = -5

- a. (-5)
- b. (-3)
- c. (-4)

Subtract:

21. $10 \frac{1}{2} - 6 \frac{1}{2} =$

- a. 5
- b. 4
- c. 6

22. $2 \frac{11}{12} - 1 \frac{8}{12} =$

- a. $1 \frac{3}{12}$
- b. 2
- c. 1

23. $14 \frac{1}{2} - 3 \frac{1}{2} =$

- a. 12
- b. 11
- c. 10

24. $9 \frac{4}{6} - 3 \frac{4}{6} =$

- a. 5
- b. 4
- c. 6

25. $8 \frac{1}{10} - 7 \frac{7}{10} =$

- a. $\frac{4}{10}$
- b. $\frac{3}{10}$
- c. 1

26. $9 \frac{3}{10} - 9 \frac{1}{10} =$

- a. $\frac{4}{10}$
- b. $\frac{5}{10}$
- c. $\frac{2}{10}$

27. $8 \frac{1}{6} - 5 \frac{2}{6} =$

- a. $2 \frac{5}{6}$
- b. 3
- c. $2 \frac{4}{6}$

28. $7 \frac{1}{2} - 5 \frac{1}{2} =$

- a. 1
- b. 2
- c. 3

29. $-\frac{1}{11} - (-\frac{27}{11}) - (-\frac{6}{11}) =$

- a. $2 \frac{10}{11}$
- b. $3 \frac{1}{11}$
- c. $-3 \frac{1}{11}$

Decimals:

30. $0,656 + 0,01 =$

- a. 0,666
- b. 0,657
- c. 0,667

31. $0,2 + 0,21 =$

- a. 0,221
- b. 0,41
- c. 0,42

32. $0,22 + 0,091 =$

- a. 0,311
- b. 0,303
- c. 0,321

Decimals:

33. $\dots + 3,91 = 4,41$

- a. 0,4
- b. 0,3
- c. 0,5

34. $\dots + 1,97 = 6,67$

- a. 5,7
- b. 4,6
- c. 4,7

35. $\dots + 2,36 = 3,31$

- a. 0,75
- b. 0,95
- c. 1,04

Two decimals:

36. $-3.9 + 1.5 =$ _____

- a. -2.4
- b. -2.5
- c. -2.6

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37. $6.61 + (-0.7) =$ _____

- a. 5.91
- b. 5.81
- c. 5.71

38. $-0.1 + (-7.31) =$ _____

- a. -7.41
- b. -7.30
- c. -7.51

39. $-2.1 + 0.3 =$ _____

- a. -1.6
- b. -1.7
- c. -1.8

40. $-0.62 + (-0.8) =$ _____

- a. -1.42
- b. -1.44
- c. -1.52

41. $0.4 + (-4.17) =$ _____

- a. -3.68
- b. -3.77
- c. -3.78

42. $0.9 + (-1.49) =$ _____

- a. -0.59
- b. -0.60
- c. -0.61

43. $1.86 + 1.8 =$ _____

- a. 3.55
- b. 3.56
- c. 3.66

44. $0.1 + 7.1 =$ _____

- a. 7.2
- b. 7.3
- c. 7.4

45. $-4.19 + 0.8 =$ _____

- a. -3.39
- b. -3.40
- c. -3.38

46. $-6.78 + 0.5 =$ _____

- a. -6.28
- b. -6.29
- c. -6.30

47. $-7.9 + (-0.3) =$ _____

- a. -8.2
- b. -8.1
- c. -8

Three decimals (addition):

48. $-1.2 + 4.7 + (-2.6) =$ _____

- a. 0.7
- b. 0.8
- c. 0.9

49. $3.1 + (-3.5) + (-1.6) =$ _____

- a. -1
- b. 1.5
- c. -2

50. $0.7 + 3.9 + (-0.6) =$ _____

- a. 3.7
- b. 4
- c. 4.3

51. $0.4 + (-4) + (-1.1) =$ _____

- a. -4.6
- b. -4.7
- c. -4.8

52. $2.6 + (-3.1) + (-1) =$ _____

- a. -1.5
- b. -1.6
- c. -1.7

53. $-1.9 + 6.4 + (-3) =$ _____

- a. 1.4
- b. 1.5
- c. 1.6

54. $-0.1 + (-2.9) + 3.5 =$ _____

- a. 0.5
- b. 0.6
- c. 0.7

55. $-2.3 + (-5.6) + 1.2 =$ _____

- a. -6.6
- b. -6.7
- c. -6.8

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56. $2.8 + 6.4 + (-1) = \underline{\hspace{2cm}}$

- a. 8.2
- b. 8.3
- c. 8.4

Three decimals (subtract):

57. $-2 - 2.6 - (-5) = \underline{\hspace{2cm}}$

- a. 0.3
- b. 0.4
- c. 0.5

58. $1.2 - 4 - 3 = \underline{\hspace{2cm}}$

- a. -5.6
- b. -5.7
- c. -5.8

59. $2.4 - 4.6 - (-2) = \underline{\hspace{2cm}}$

- a. -0.2
- b. -0.3
- c. -0.4

60. $-4.9 - (-0.5) - (-5.3) = \underline{\hspace{2cm}}$

- a. 0.8
- b. 0.9
- c. 1

61. $0.8 - (-0.8) - 1.3 = \underline{\hspace{2cm}}$

- a. 0.3
- b. 0.2
- c. 0.1

62. $-4.9 - 4.9 - (-5.2) = \underline{\hspace{2cm}}$

- a. -4.6
- b. -4.7
- c. -4.8

63. $1.7 - (-0.9) - 2.9 = \underline{\hspace{2cm}}$

- a. -0.1
- b. -0.2
- c. -0.3

64. $-1.6 - 4.8 - 3.6 = \underline{\hspace{2cm}}$

- a. -9.8
- b. -9.9
- c. -10

65. $-5.1 - (-2.5) - (-4.6) = \underline{\hspace{2cm}}$

- a. 2
- b. 2.1
- c. 2.2

66. $2.0 - (-2) - (-6) = \underline{\hspace{2cm}}$

- a. 10
- b. 10.1
- c. 10.2

67. $-3.1 - (-5) - (-6) = \underline{\hspace{2cm}}$

- a. 7.7
- b. 7.9
- c. 8.1

68. $5 - (-1.2) - (-3) = \underline{\hspace{2cm}}$

- a. 9
- b. 9.1
- c. 9.2

Four decimals:

69. $-3.0 + 2 + (-2.3) + (-6.8) = \underline{\hspace{2cm}}$

- a. -10.1
- b. -10.2
- c. -10.3

70. $-5.2 + (-4.9) + 1 + (-6.8) = \underline{\hspace{2cm}}$

- a. -15.8
- b. -15.9
- c. -16

71. $-1.0 + (-3.2) + (-1.4) + (-7.8) = \underline{\hspace{2cm}}$

- a. -13.2
- b. -12.4
- c. -13.4

72. $1.1 + 0.64 + 0.5 + 1.4 = \underline{\hspace{2cm}}$

- a. 3.64
- b. 3.65
- c. 3.67

73. $-7.80 + (-1.01) + (-1.78) + (-1.34) = \underline{\hspace{2cm}}$

- a. -11.94
- b. -11.93
- c. -11.92

15. Appendix

56. $2.8 + 6.4 + (-1) =$ _____

- a. 8.2
- b. 8.3
- c. 8.4

Three decimals (subtract):

57. $-2 - 2.6 - (-5) =$ _____

- a. 0.3
- b. 0.4
- c. 0.5

58. $1.2 - 4 - 3 =$ _____

- a. -5.6
- b. -5.7
- c. -5.8

59. $2.4 - 4.6 - (-2) =$ _____

- a. -0.2
- b. -0.3
- c. -0.4

60. $-4.9 - (-0.5) - (-5.3) =$ _____

- a. 0.8
- b. 0.9
- c. 1

61. $0.8 - (-0.8) - 1.3 =$ _____

- a. 0.3
- b. 0.2
- c. 0.1

62. $-4.9 - 4.9 - (-5.2) =$ _____

- a. -4.6
- b. -4.7
- c. -4.8

63. $1.7 - (-0.9) - 2.9 =$ _____

- a. -0.1
- b. -0.2
- c. -0.3

64. $-1.6 - 4.8 - 3.6 =$ _____

- a. -9.8
- b. -9.9
- c. -10

65. $-5.1 - (-2.5) - (-4.6) =$ _____

- a. 2
- b. 2.1
- c. 2.2

66. $2.0 - (-2) - (-6) =$ _____

- a. 10
- b. 10.1
- c. 10.2

67. $-3.1 - (-5) - (-6) =$ _____

- a. 7.7
- b. 7.9
- c. 8.1

68. $5 - (-1.2) - (-3) =$ _____

- a. 9
- b. 9.1
- c. 9.2

Four decimals:

69. $-3.0 + 2 + (-2.3) + (-6.8) =$ _____

- a. -10.1
- b. -10.2
- c. -10.3

70. $-5.2 + (-4.9) + 1 + (-6.8) =$ _____

- a. -15.8
- b. -15.9
- c. -16

71. $-1.0 + (-3.2) + (-1.4) + (-7.8) =$ _____

- a. -13.2
- b. -12.4
- c. -13.4

72. $1.1 + 0.64 + 0.5 + 1.4 =$ _____

- a. 3.64
- b. 3.65
- c. 3.67

73. $-7.80 + (-1.01) + (-1.78) + (-1.34) =$ _____

- a. -11.94
- b. -11.93
- c. -11.92

15. Appendix

Multiply two decimals:

74. $0.3 \times 0.05 =$ _____

- a. 0.015
- b. 0.15
- c. 0.0015

75. $-0.09 \times (-0.08) =$ _____

- a. 0.72
- b. 0.072
- c. 0.0072

76. $0.004 \times 0.05 =$ _____

- a. 0.0002
- b. 0.002
- c. 0.02

77. $0.06 \times 0.005 =$ _____

- a. 0.0003
- b. 0.003
- c. 0.03

78. $0.05 \times 0.08 =$ _____

- a. 0.004
- b. 0.04
- c. 0.4

79. $-0.08 \times (-0.7) =$ _____

- a. 0.56
- b. 0.056
- c. 0.0056

80. $0.3 \times 0.05 =$ _____

- a. 0.015
- b. 0.15
- c. 0.0015

81. $-0.7 \times (-0.08) =$ _____

- a. 0.052
- b. -0.056
- c. 0.056

82. $-0.09 \times (-0.08) =$ _____

- a. 0.00076
- b. 0.0072
- c. 0.0076

Multiply three decimals:

83. $-0.3 \cdot (-0.3) \cdot 0.7 =$ _____

- a. 0.064
- b. -0.063
- c. 0.063

84. $-0.5 \cdot 0.06 \cdot 1.8 =$ _____

- a. -0.054
- b. -0.056
- c. -0.058

85. $0.03 \cdot (-0.8) \cdot 1.5 =$ _____

- a. -0.038
- b. -0.036
- c. -0.034

86. $1.5 \cdot 0.05 \cdot 0.7 =$ _____

- a. 0.0525
- b. 0.0325
- c. 0.0435

87. $0.8 \cdot 1.6 \cdot 0.2 =$ _____

- a. 0.156
- b. 0.264
- c. 0.256

88. $0.5 \cdot (-0.5) \cdot 1.5 =$ _____

- a. -0.375
- b. -0.385
- c. -0.395

89. $1.7 \cdot 0.2 \cdot (-0.6) =$ _____

- a. -0.204
- b. -0.322
- c. -0.200

90. $0.09 \cdot 1.7 \cdot 0.1 =$ _____

- a. 0.0153
- b. 0.0156
- c. 0.0

91. $0.05 \cdot (-0.6) \cdot (-0.2) =$ _____

- a. 0.006
- b. 0.008
- c. 0.012

15. Appendix

92. $-0.4 \cdot 1.5 \cdot 1.4 =$ _____

- a. -0.56
- b. -0.64
- c. -0.84

Multiply using the distributive property:

93. $7(5 + 6n) =$

- a. $35 + 42n$
- b. $77n$
- c. $30 + 30n$

94. $4(10 + 9c) =$

- a. $80c$
- b. $40 + 34$
- c. $40 + 36c$

95. $7(11 + 7w) =$

- a. $77 + 49w$
- b. $77 + 48w$
- c. $77 + 54w$

96. $4(4 + 9a) =$

- a. $12 + 36a$
- b. $16 + 36a$
- c. $12 + 34a$

97. $4(9 + 5t) =$

- a. $36 + 20t$
- b. $34 + 25t$
- c. $34 + 20t$

98. $4(10 + 3w) =$

- a. $40 + 16w$
- b. $40 + 12w$
- c. $30w$

99. $6(6m + 7) =$

- a. $36m + 42$
- b. $64m + 56$
- c. $36m + 54$

What is the correct one:

100. $14/14 =$

- a. 1
- b. 0
- c. $7/8$

101. $45/5 =$

- a. 9
- b. 8
- c. 7

102. $11/4 =$

- a. $2 \frac{3}{6}$
- b. $2 \frac{1}{2}$
- c. $2 \frac{3}{4}$

103. $15/6 =$

- a. 2
- b. $2 \frac{2}{6}$
- c. $2 \frac{1}{2}$

104. $45/6 =$

- a. $7 \frac{1}{2}$
- b. $7 \frac{1}{6}$
- c. $7 \frac{1}{3}$

105. $37/15 =$

- a. $2 \frac{7}{30}$
- b. $2 \frac{7}{15}$
- c. $2 \frac{23}{30}$

106. $23/17 =$

- a. $1 \frac{6}{17}$
- b. $1 \frac{5}{17}$
- c. $1 \frac{4}{17}$

107. $14/7 =$

- a. 2
- b. 3
- c. $1/2$

108. $35/8 =$

- a. $4 \frac{3}{5}$
- b. $4 \frac{3}{4}$
- c. $4 \frac{3}{8}$

109. $43/8 =$

- a. $5 \frac{8}{16}$
- b. $5 \frac{3}{8}$
- c. $5 \frac{1}{4}$

15. Appendix

Ratio:

110. Grace has 187 coins. Of the coins, $\frac{2}{11}$ are nickels, $\frac{5}{11}$ are dimes, and the rest are quarters. What is the ratio of Grace's nickels to dimes to quarters?

- a. 2:6:3
- b. 2:5:4
- c. 2:5:6

111. Jayden and Ethan share a reward of \$50 in a ratio of 3 : 2. What fraction of the total reward does Ethan get?

- a. 20
- b. 40
- c. 30

112. A truck is carrying apple juice, grape juice, and pear juice bottles in a ratio of 4 : 3 : 3. If there are 76 apple juice bottles, then how many grape juice bottles are there?

- a. 57
- b. 64
- c. 23

113. A jar contains 490 beans. Of all the beans, $\frac{5}{7}$ are mung beans and the rest are lima beans. What is the ratio of mung beans to lima beans?

- a. 4:3
- b. 5:2
- c. 5:3

114. A kennel has 100 dogs in total, some are puppies and some are adult dogs. The ratio of puppies to adult dogs in a kennel is 3 : 2. How many adult dogs are there?

- a. 70
- b. 65
- c. 60

115. The ratio of girls to boys in a gardening club was 3 : 6. There were 54 boys. How many total members were there in the club?

- a. $24 + 54$
- b. $29 + 54$
- c. $27 + 54$

116. Jacob and Caden share a reward of \$40 in a ratio of 2 : 3. What fraction of the total reward does Jacob get?

- a. 18
- b. 16
- c. 17

Word problems and proportions:

117. A boat can travel 362.6 kilometers on 181.3 liters of gasoline. How far can it travel on 144.3 liters?

- a. 277.15
- b. 288.15
- c. 281.20

118. A boat can travel 35 miles on 7 gallons of gasoline. How much gasoline will it need to go 180 miles?

- a. 37
- b. 36
- c. 46

Speed:

120. Cindy rides her bike with a constant speed of 8 km/h. How long will she take to travel a distance of 12 kilometers?

- a. 2 hours
- b. $1 \frac{1}{2}$ hours
- c. $1 \frac{1}{3}$ hours

121. An airplane flies with a constant speed of 580 miles per hour. How long will it take to travel a distance of 2030 miles?

- a. $3 \frac{1}{2}$ hours
- b. $3 \frac{1}{3}$ hours
- c. $3 \frac{1}{4}$ hours

122. A train travels with a constant speed of 28 miles per hour. How long will it take to travel a distance of 63 miles?

- a. $2 \frac{1}{3}$ hours
- b. 2 hours
- c. $2 \frac{1}{2}$ hours

15. Appendix

123. An airplane flies 2666 km with a constant speed of 1032 km/h and another 2294 km with a constant speed of 888 km/h. How much time in total does it take to travel these distances?

- a. $5 \frac{1}{6}$ hours
- b. $5 \frac{1}{2}$ hours
- c. $5 \frac{1}{3}$ hours

124. John roller skates 40 km in 2 hours. What is his average speed in kilometers per hour?

- a. 20 km/h
- b. 22 km/h
- c. 10 km/h

Derived from:

https://www.homeschoolmath.net/worksheets/grade_7.php#intro

15. Appendix

15.6 Task sheet ii

Multiply and divide:

1. $4 \div 2 =$ _____

- a. 2
- b. 1
- c. 0

2. $5 \times 8 =$ _____

- a. 40
- b. 20
- c. 60

3. $2 \times 5 =$ _____

- a. 15
- b. 10
- c. 5

4. $30 \div (-6) =$ _____

- a. -4
- b. -5
- c. -6

5. $(-5) \times (-2) =$ _____

- a. 12
- b. 10
- c. -10

6. $10 \div 2 =$ _____

- a. 2
- b. 4
- c. 5

7. $44 \div 11 =$ _____

- a. 4
- b. 5
- c. 6

8. $2 \times 7 =$ _____

- a. 12
- b. 14
- c. 16

9. $80 \div 8 =$ _____

- a. 8
- b. 9
- c. 10

10. $11 \times 3 =$ _____

- a. 33
- b. 44
- c. 55

Addition:

11. $(-2) +$ _____ $+ (-2) = -7$

- a. (-3)
- b. (-2)
- c. (-4)

12. _____ $+ (-8) + 10 = 2$

- a. 1
- b. 0
- c. 2

13. _____ $+ (-1) + 5 = -3$

- a. -7
- b. -9
- c. -8

14. $(-9) +$ _____ $+ 3 = -7$

- a. (-2)
- b. (-1)
- c. 1

15. $(-1) +$ _____ $+ 3 = -8$

- a. (-9)
- b. (-10)
- c. (-11)

16. $4 +$ _____ $+ (-8) = -7$

- a. (-3)
- b. (-5)
- c. (-4)

17. $(-7) + (-5) +$ _____ $= -5$

- a. 6
- b. 7
- c. 8

18. $6 + (-10) +$ _____ $= -4$

- a. (-2)
- b. (-1)
- c. 0

15. Appendix

19. $5 + (-8) + \underline{\hspace{2cm}} = 0$

- a. 1
- b. 2
- c. 3

20. $10 + \underline{\hspace{2cm}} + (-5) = 3$

- a. (-2)
- b. (-1)
- c. 0

Subtract:

21. $10 \frac{3}{4} - 4 \frac{3}{4} =$

- a. 5
- b. 6
- c. 4

22. $13 \frac{2}{8} - 11 \frac{1}{8} =$

- a. $2 \frac{1}{8}$
- b. $2 \frac{2}{8}$
- c. $2 \frac{3}{8}$

23. $13 \frac{4}{6} - 4 \frac{2}{6} =$

- a. 9
- b. $9 \frac{1}{3}$
- c. $9 \frac{3}{6}$

24. $7 \frac{1}{2} - 7 \frac{1}{2} =$

- a. 0
- b. 1
- c. $\frac{1}{2}$

25. $12 \frac{2}{4} - 11 \frac{2}{4} =$

- a. 0
- b. 1
- c. $1 \frac{1}{2}$

26. $11 \frac{4}{8} - 11 \frac{3}{8} =$

- a. $\frac{1}{8}$
- b. $\frac{1}{4}$
- c. 3.8

27. $8 \frac{1}{2} - 3 \frac{1}{2} =$

- a. 5
- b. $5 \frac{1}{2}$
- c. 4

28. $11 \frac{4}{5} - 3 \frac{3}{5} =$

- a. 8
- b. $8 \frac{1}{5}$
- c. $8 \frac{2}{5}$

29. $\frac{5}{8} + \frac{29}{8} - \frac{5}{8} =$

- a. $3 \frac{7}{8}$
- b. $3 \frac{5}{8}$
- c. $3 \frac{1}{2}$

What is the correct one?

30. $\frac{22}{16} =$

- a. $1 \frac{3}{8}$
- b. $1 \frac{4}{8}$
- c. $1 \frac{2}{8}$

31. $\frac{42}{17} =$

- a. $2 \frac{4}{17}$
- b. $2 \frac{8}{17}$
- c. $\frac{27}{17}$

32. $\frac{15}{3} =$

- a. 4
- b. 5
- c. $5 \frac{1}{3}$

33. $\frac{37}{12} =$

- a. $3 \frac{1}{12}$
- b. $3 \frac{2}{6}$
- c. $3 \frac{1}{6}$

34. $\frac{11}{5} =$

- a. 3
- b. $2 \frac{2}{5}$
- c. $2 \frac{1}{5}$

35. $\frac{38}{20} =$

- a. $1 \frac{4}{5}$
- b. $1 \frac{9}{10}$
- c. $1 \frac{19}{20}$

36. $\frac{57}{19} =$

- a. 3
- b. $3 \frac{1}{19}$
- c. $3 \frac{3}{19}$

15. Appendix

37. $35/6 =$

a. $5\frac{5}{6}$

b. $5\frac{2}{3}$

$5\frac{2}{6}$

38. $56/5 =$

a. $11\frac{1}{4}$

b. 11

c. $11\frac{1}{5}$

39. $46/19 =$

a. $2\frac{4}{19}$

b. $2\frac{8}{19}$

c. $2\frac{9}{19}$

Decimals:

40. $0,930 + 0,31 =$

a. 1,231

b. 1,241

c. 1,24

41. $\dots + 1,42 = 4,12$

a. 2,7

b. 3,6

c. 2,6

42. $2,73 + \dots = 8,23$

a. 5,6

b. 6,5

c. 5,5

Decimals:

43. $0,922 + 0,85 =$

a. 1,877

b. 1,872

c. 1,772

44. $0,75 + 0,788 =$

a. 1,538

b. 1,558

c. 1,438

45. $\dots + 3,30 = 5,80$

a. 2,40

b. 2,50

c. 5,7

Two decimals:

46. $3.74 + (-0.7) =$ _____

a. 3

b. 3.04

c. 3.06

47. $0.6 + (-3.5) =$ _____

a. -2.1

b. -2.7

c. -2.9

48. $1.3 + (-2.0) =$ _____

a. -0.6

b. -0.7

c. -0.8

49. $6.0 + (-0.6) =$ _____

a. 5.2

b. 5.3

c. 5.4

50. $0.0 + 1.7 =$ _____

a. 1.6

b. 1.7

c. 1.8

51. $-6.3 + 1.2 =$ _____

a. -5

b. -5.1

c. -5.2

52. $0.0 + 1.6 =$ _____

a. 1.6

b. 1.7

c. 1.8

53. $-6.6 + 0.1 =$ _____

a. -6.3

b. -6.4

c. -6.5

54. $-0.7 + 1.8 =$ _____

a. 1.1

b. 1.2

c. 1.3

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55. $8.5 + 1.6 =$ _____

- a. 10.1
- b. 10.2
- c. 10.3

56. $5.46 + 0.1 =$ _____

- a. 5.57
- b. 5.56
- c. 5.55

57. $-4.20 + (-0.7) =$ _____

- a. -4.9
- b. -4.8
- c. -4.7

Three decimals (addition):

58. $0.1 + 6 + 3.9 =$ _____

- a. 9
- b. 9.5
- c. 10

59. $0.8 + (-4) + 3.7 =$ _____

- a. 0.4
- b. 0.5
- c. 0.6

60. $3.4 + 2 + 2.7 =$ _____

- a. 8.1
- b. 8.2
- c. 8.3

61. $1.7 + (-5) + 2.5 =$ _____

- a. -0.6
- b. -0.7
- c. -0.8

62. $2.8 + 6 + 0.8 =$ _____

- a. 9.6
- b. 9.7
- c. 9.8

63. $-1.0 + (-2.0) + (-0.5) =$ _____

- a. -3.6
- b. -3.5
- c. -3.4

64. $-2.1 + (-5.3) + (-2.8) =$ _____

- a. -10.2
- b. -10
- c. -9.8

65. $2.6 + 5 + (-0.1) =$ _____

- a. 7.3
- b. 7.4
- c. 7.5

66. $0.3 + (-1.8) + 0.3 =$ _____

- a. -1
- b. -1.2
- c. -2.2

Three decimals (subtract):

66. $-4.7 - (-0.7) - 0.5 =$ _____

- a. -4.3
- b. -4.4
- c. -4.5

67. $5 - 1.0 - (-4) =$ _____

- a. 8
- b. 7
- c. 6

68. $0.0 - 2.1 - 4.6 =$ _____

- a. -6.7
- b. -6.6
- c. -6.5

69. $-1.5 - 1.2 - 3.2 =$ _____

- a. -5.9
- b. -6.0
- c. -6.1

70. $2.5 - (-1.2) - (-2.3) =$ _____

- a. 5.9
- b. 6
- c. 6.1

71. $-1.5 - 0 - (-4) =$ _____

- a. 2.5
- b. 2.4
- c. 2.3

15. Appendix

72. $-4.6 - (-1.9) - 1.8 =$ _____

- a. -4.5
- b. -4.6
- c. -5.7

73. $-4 - (-3.9) - 5 =$ _____

- a. -5.1
- b. -5
- c. -4.9

74. $6 - 2.1 - 3 =$ _____

- a. 0.9
- b. 0.8
- c. 0.7

75. $1.4 - (-4.0) - 3.1 =$ _____

- a. 2.2
- b. 2.3
- c. 2.4

76. $-3.2 - (-4.6) - 1 =$ _____

- a. 0.2
- b. 0.3
- c. 0.4

77. $5 - 1.8 - 1 =$ _____

- a. 2.2
- b. 2.1
- c. 2

Four decimals:

78. $0.6 + 6.23 + (-0.5) + 0.6 =$ _____

- a. 6.93
- b. 6.94
- c. 6.95

79. $0.52 + (-5.2) + (-3.1) + (-6.5) =$ _____

- a. -14.28
- b. -14.29
- c. -15.39

80. $0.74 + (-2.70) + (-7.22) + (-7.34) =$ _____

- a. -17.52
- b. -16.52
- c. -15.52

81. $1.0 + (-2) + (-0.2) + (-4.9) =$ _____

- a. -5.2
- b. -6.1
- c. -6.2

82. $2.04 + (-2) + (-6.02) + (-2.89) =$ _____

- a. -8.87
- b. -9.88
- c. -8.88

Multiply two decimals:

83. $-0.7 \times (-0.08) =$ _____

- a. 0.056
- b. 0.0056
- c. 0.56

84. $-0.4 \times 0.9 =$ _____

- a. -0.36
- b. -0.036
- c. 0.36

85. $-0.04 \times 0.3 =$ _____

- a. -0.012
- b. -0.12
- c. 0.12

86. $0.6 \times 0.004 =$ _____

- a. 0.024
- b. 0.24
- c. 0.0024

87. $-0.06 \times 0.006 =$ _____

- a. -0.0036
- b. -0.000036
- c. -0.00036

88. $-0.01 \times 0.11 =$ _____

- a. -0.0011
- b. -0.011
- c. -0.00011

90. $-0.4 \times 0.9 =$ _____

- a. 0.28
- b. -0.42
- c. -0.36

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91. $0.004 \times 0.05 =$

- a. 0.000125
- b. 0.00002
- c. 0.0002

92. $-0.04 \times 0.3 =$

- a. -0.012
- b. -0.120
- c. -0.0012

Multiply three decimals:

93. $0.3 \cdot (-0.4) \cdot 1.1 =$ _____

- a. -0.132
- b. -0.122
- c. -0.1

94. $0.07 \cdot 0.8 \cdot 1.3 =$ _____

- a. 0.0728
- b. 0.0724
- c. 0.0721

95. $-0.5 \cdot (-1.0) \cdot 0 =$ _____

- a. 0
- b. 0.5
- c. -0.5

96. $0.06 \cdot 0.3 \cdot 0.5 =$ _____

- a. 0.01
- b. 0.009
- c. 0.008

97. $0.2 \cdot 0.6 \cdot 1 =$ _____

- a. 0.12
- b. 0.16
- c. 0.2

98. $-0.3 \cdot 1.7 \cdot (-0.9) =$ _____

- a. 0.567
- b. 0.546
- c. 0.459

99. $-0.1 \cdot 0.07 \cdot 1.1 =$ _____

- a. -0.0076
- b. -0.0077
- c. -0.0097

100. $-0.4 \cdot (-0.7) \cdot 1.2 =$ _____

- a. 0.336
- b. 0.366
- c. 0.333

101. $-0.4 \cdot 0.0 \cdot 1.4 =$ _____

- a. 0
- b. 4
- c. -0,4

102. $-0.5 \cdot 0.5 \cdot (-0.2) =$ _____

- a. 0.1
- b. 0.15
- c. 0.05

Multiply:

103. $5(3b + 1) =$

- a. $10b + 5$
- b. $20b$
- c. $15b + 5$

104. $7(4y + p) =$

- a. $24 + 7p$
- b. $28y + 7p$
- c. $21y + 7p$

105. $2(5m + 2) =$

- a. $10m + 2$
- b. $20m$
- c. $10m + 4$

106. $3(7q + y) =$

- a. $21q + 3y$
- b. $24q + 3y$
- c. $27q + 3y$

107. $8(7y + t) =$

- a. $64y + 8t$
- b. $56y + 8t$
- c. $54y + 8t$

108. $7(3q + r) =$

- a. $24q + r$
- b. $21q + 7r$
- c. $24q + 7r$

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109. $5(2p + 9) =$

- a. $10p + 45$
- b. $5p + 45$
- c. $10p + 40$

Ratio:

110. Grace has nickels, dimes, and quarters in the ratio of 5 : 2 : 5. If 25 of Grace's coins are quarters, how many nickels and dimes does Grace have?

- a. 25 nickels & 10 dimes
- b. 10 nickels & 10 dimes
- c. 10 nickels & 25 quarters

111. A kennel has 65 dogs in total, some are puppies and some are adult dogs. The ratio of puppies to adult dogs in a kennel is 2 : 3. How many puppies are there?

- a. 26
- b. 27
- c. 30

112. A bag contains 80 marbles, some red and some white. The ratio of red marbles to white ones is 2 : 3. How many red marbles are there?

- a. 34
- b. 32
- c. 36

113. Sophia and Caden share a reward of \$45 in a ratio of 3 : 2. How much does Caden get?

- a. 16
- b. 26
- c. 18

114. Ethan and Aiden share a reward of \$84 in a ratio of 3 : 3. How much does Ethan get?

- a. 42
- b. 84
- c. 12

115. A truck is carrying peach juice, grapefruit juice, and apple juice bottles in a ratio of 3 : 4 : 5. If there are 100 apple juice bottles, then how many juice bottles in total are there?

- a. 240
- b. 200
- c. 120

116. The ratio of girls to boys in a chess club was 1 : 4. There were 5 girls. How many boys were there in the club?

- a. 36
- b. 20
- c. 25

Word problems:

117. 43 kg of tomatoes cost \$305.30. How many kilograms of tomatoes can you get with \$312.40 ?

- a. 43
- b. 44
- c. 45

118. 21 kg of bananas cost \$136.50. How much would 29 kg cost?

- a. 190
- b. 188.5
- c. 170.5

Speed:

119. A police car drives 540 km in 4 hours 30 minutes. What is its average speed in kilometers per hour?

- a. 140 km/h
- b. 120 km/h
- c. 130 km/h

120. A train travels for 3.9 hours with a constant speed of 41 km/h and then for another 26 minutes with a constant speed of 81 km/h. What distance did it go?

- a. 185,9
- b. 190,3
- c. 180,7

121. David rides his motorcycle 15 km in 15 minutes. What is his average speed in kilometers per hour?

- a. 60 km/h
- b. 70 km/h
- c. 100 km/h

15. Appendix

122. David rides his horse with a constant speed of 18 km/h. How long will he take to travel a distance of 64.5 kilometers?

- a. $4 \frac{1}{3}$ hours
- b. $4 \frac{1}{4}$ hours
- c. 4 hours

123. An airplane flies with a constant speed of 840 km/h. How far can it travel in $1 \frac{3}{4}$ hours?

- a. 1560 km
- b. 1470 km
- c. 1280 km

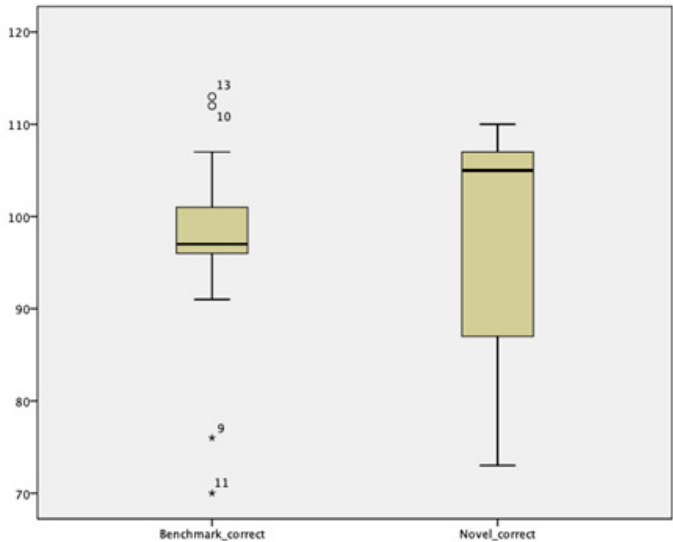
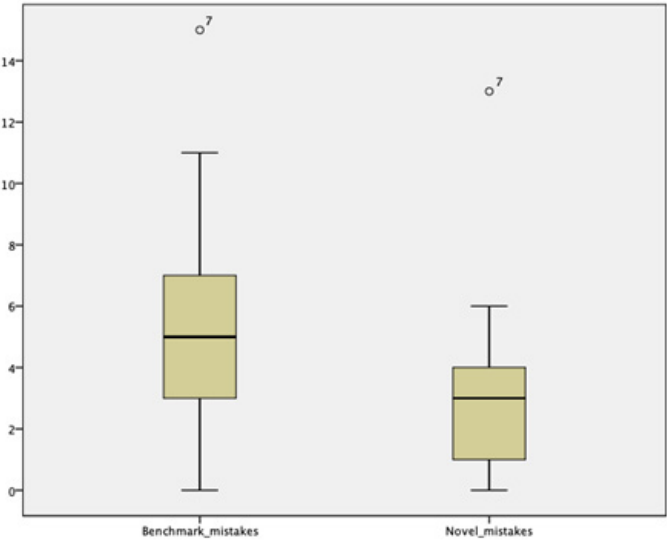
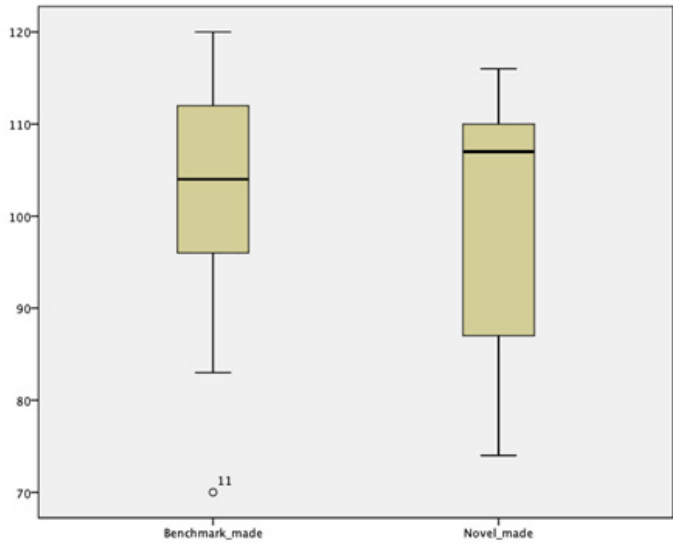
Nancy rides her horse with a constant speed of 24 km/h. How far can she travel in 3 hours 50 minutes?

- 80 km
- 87 km
- 92 km

15. Appendix

15.7 Paired samples test: productivity

Paired Samples Test									
		Paired Differences					t	df	Sig. (2-tailed)
				Std. Error Mean	95% Confidence Interval of the Difference				
					Lower	Upper			
Pair 1	Benchmark made - Novel made	2.46154	8.94069	2.47970	-2.94127	7.86434	.993	12	.340
Pair 2	Benchmark correct - Novel_correct	.38462	9.03270	2.50522	-5.07379	5.84302	.154	12	.881
Pair 3	Benchmark_mistakes - Novel mistakes	2.07692	2.06000	.57134	.83208	3.32177	3.635	12	.003



15. Appendix



Real photos



One photo with black square on it

15.8 Evaluating the availability of view

Black square opacity intermediate state is 40%

Black square opacity dark state is 85%

15. Appendix



Real photos



One photo with black square on it

Black square opacity intermediate state is 35%

Black square opacity dark state is 85%

15. Appendix



Real photos



One photo with black square on it

Black square opacitiy intermediate state is 35%
Black square opacitiy dark state is 80%

