A FRAMEWORK TO SIMULATE THE NON-VISUAL EFFECTS OF DAYLIGHT ON THE COGNITIVE HEALTH OF ELDERLY INDIVIDUALS

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A FRAMEWORK TO SIMULATE THE NON-VISUAL EFFECTS OF DAYLIGHT ON THE COGNITIVE HEALTH OF ELDERLY INDIVIDUALS

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LIST OF SYMBOLS AND ABBREVIATIONS

ALFA	Adaptive Lighting for Alertness (Software)
DIVA	Design Iterate Validate Adapt (Software)
Lux (lx)	Unit for Illuminance: the amount of light falling onto a surface
DGP	Daylight Glare Probability
Imp.	Imperceptible Glare
Per.	Perceptible Glare
Dis.	Disturbing Glare
Int.	Intolerable Glare
AD	Alzheimer's Disease
MCI	Mild Cognitive Impairment
RGCs	Retinal Ganglion Cells
EML	Equivalent Melanopic Lux
CS	Circadian Stimulus
nm	Nanometer
CRI	Color Rendering Index
K	Degrees Kelvin
WWR	Window to Wall Ratio
HDR Image	High Dynamic Range Image
TMY	Typical Meteorological Year
VaD	Vascular Dementia
DLB	Dementia with Lewy Bodies
FTD	Frontotemporal Dementia

CNS	Central Nervous System
SCN	Suprachiasmatic Nucleus
ipRGCs	Intrinsically Photoreceptive Retinal Ganglion Cells
VLT	Visible Light Transmitted

SUMMARY

Human health and well-being concerns have been brought to the forefront of building performance assessment through contemporary practices of sustainability design. Within the bounds of sustainability, daylighting plays a critical role in human well-being, specifically non-visual effects such as regulating circadian health, which contributes to alertness and sleep cycles of individuals. Accordingly, interior spatial investigations have been developed through simulation-based workflows, including several modeling tools such as Adaptive Lighting for Alertness (ALFA) (Solemma, 2019). However, research did not yet address challenges in vulnerable communities such as elders and individuals with dementia, focusing specifically on the impact of the non- visual effects of light on their overall health and well-being.

This thesis aims to identify the daylighting requirements and metrics that are needed to design a space for elderly individuals that could entrain their circadian rhythms, promote their health, and well-being while providing an overall enhanced environment. The objectives are: 1) Explain several types of disability challenges facing the elderly population and its relationship to daylighting and circadian rhythms. 2) Define daylighting thresholds and metrics that entrain circadian rhythms and target vulnerable groups such as elderly individuals with certain disabilities. 3) Present a case study of a standard nursing home that showcases simulation techniques that focus on daylighting and health modelling for this vulnerable population, with recommendations for future work validation by deploying an ecologically valid experimental design. 4) Propose a design framework and

recommendation guidelines to assist designers when designing for vulnerable groups to promote their health and well-being.

A standard nursing home model is referenced from the Neuferts Architects Data 3rd edition Architectural Standards and was used as an example model. A simulation experiment is implemented using DIVA for Rhino and Climate Studio to analyze annual point in time illuminance with a threshold divided into three parts: 1500-2000 lux (minimum), 2000-2500 lux (most efficient threshold), 2500-3000 lux (maximum). The hours meeting these thresholds are analyzed into useful daylight hours. Also, Daylight Glare Probability (DGP) is simulated to understand the challenges accompanying high illuminance values that entrain circadian rhythms. The goal of the experiment is to ensure that a standard bedroom includes interior locations that can maintain a threshold of 1 to 2 hours per day with these illuminance values with minimal to non-existent glare.

The results of the simulations are divided into: 1) Baseline with the standard bedroom facing north, south, east, and west orientations and 2) Design alterations of the north and south orientations to meet the threshold and increase the number of hours annually that entrain the circadian rhythm for the elderly and individuals with dementia. The simulations are run using the Atlanta, GA, TMY3 climate file. The baseline case demonstrates that the north orientation hardly receives any adequate daylight throughout the entire year at the head of the bed in the middle of the room. The annual daylight glare probability showcases an average of 17.8% disturbing and intolerable glare annually. On the other hand, the baseline results of the south orientation present an average of 62.8% disturbing and intolerable annual DGP. The south orientation functions slightly better meeting the minimum, required, and maximum lighting thresholds for almost 30% of analyzed daylight hours/ month. The east, and west orientations function better in terms of percentage of daylight hours/ month meeting the threshold, along with less annual DGP. Therefore, the south and north orientations only are expanded and investigated further in the design alterations. Both the north and south orientations in the design case show increased percentage of hours meeting the threshold in the analyzed locations.

This shows the need for design enhancement and improvement to adapt to the needs of the users. Results presented difficulty in circadian entrainment in baseline case orientations due to either higher or lower annual point-in-time illuminance values rather than the required threshold, in addition to increased glare issues at the south, east, and west orientations. Overall, the results indicate that 1) Design alterations are needed for current standard nursing home designs. And 2) Thresholds that entrain the circadian rhythm for elders should be taken into consideration rather than relying on standards that do not focus on such elderly experiences. This thesis provides an overview of a simulation-workflow to create a framework for designers proposing recommendations for enhanced design options that promote the health and well-being of dementia and elderly individuals.

CHAPTER 1: INTRODUCTION

Enhanced sustainable designs that would promote human health and well-being are currently viewed as one of the future requirements of the built environment design (Winer, 2019). According to the World Populations Prospects: the 2019 Revision, by the year 2050, 16% of the world population will be at the age or above 65 years old meaning that one in six people in the world will be at this age (Department of Economic and Social Affairs Population Dynamics, 2019; United Nations, 2019). Elderly individuals might suffer from various types of disabilities that might progress over the years. One of the main concerns of aging is developing dementia which might affect the individual in various forms. The World Health Organization estimates that around 50 million individuals worldwide suffer from dementia with around 10 million new cases yearly. Almost 60 – 70% of dementia cases are diagnosed with Alzheimer’s Disease (World Health Organization, 2020).

Also, based on the Alzheimer’s Association, it is estimated that approximately 15 to 20 % of people at the age of 65 or older have or will develop mild cognitive impairment (MCI) which is often a precursor to dementia that has a high possibility of progressing into AD (Alzheimers Association, 2020b; Matthews et al., 2008). Accordingly, this should drive designers and innovators to come up with advanced solutions tackling various disability challenges that might face the elderly population. Though developing different forms of dementia is not a normal side effect of aging, it will affect many people which is still considered an alarming situation.

On the other hand, it has been shown that elders spend up to 95 % of their time indoors between bedrooms and living rooms (Almeida-Silva et al., 2014). Consequently, this highlights the importance of architecture in providing enhanced indoor experiences that can improve their overall health and well-being.

Under the umbrella of sustainability, daylighting plays an important role in promoting human health, especially through non-visual effects such as regulating circadian health which plays a critical role in stimulating and regulating alertness and sleep cycles in healthy people (Konis, 2017a). However, research did not yet address challenges in vulnerable communities such as elders and individuals with dementia, focusing specifically on the impact of the non- visual effects of light on their overall health and well-being. This becomes a difficult situation for designers when designing for the elderly population.

1.1 Research Purpose

1.1.1 Research Goal

This research aims to provide a better understanding of the current metrics that are available to empower elderly experiences and entrain their circadian system by showcasing the essential criteria of a space design that specifically promotes their health and wellbeing through daylighting. The research aims to establish the link between simulating the non-visual effects of daylighting using DIVA for Rhino, Climate Studio, and ALFA in relationship to elderly individuals and enhancing their cognitive health in indoor environments.

1.1.2 Research Hypothesis

If exposure-based metrics are developed for elderly entrainment of circadian systems, then simulation software will demonstrate architectural performance that supports healthier visual and non- visual environments for such vulnerable groups.

1.2 Research Motive and Structure

1.2.1 Significance

The research assumes that by identifying daylighting metrics that entrain the circadian system in elderly individuals, it will encourage designers and architects to use this as a framework when designing for such vulnerable groups.

1.2.2 Research Objectives

- Explain several types of disability challenges facing the elderly population and its relationship to daylighting and circadian rhythms.
- Define daylighting thresholds and metrics that entrain circadian rhythms and target vulnerable groups such as elderly individuals with certain impairments.
- Present a case study of a standard nursing home that showcases simulation techniques that focus on daylighting and health modelling for this vulnerable population, with recommendations for future work validation by deploying an ecologically valid experimental design.

1.2.3 Research Questions

What are the daylighting requirements and metrics that are needed to design a space for elderly individuals that could entrain their circadian rhythms, promote their health, and well-being while providing an overall enhanced environment?

1.2.4 Target Audience

This thesis provides a detailed understanding of the daylighting metrics that entrain the circadian rhythm in elderly individuals who are either healthy or suffering from certain disabilities along with methods of implementation. The primary target audiences are the architects and building performance researchers, with the aim of using this thesis as a framework to make informed design decisions. This research can be the foundation to build upon further studies in providing enhanced living environments that promote health and well-being.

1.2.5 Thesis Overview

The first chapter is an introduction to the thesis topic and underlines the goals, hypotheses, and objectives. The second chapter provides an understanding of the relation between daylighting, circadian system, and elderly experiences through the literature review. The third chapter is an examination of current standard nursing home design and their adaptability to the daylighting needs of elderly individuals through a simulation-based experimental workflow. The fourth chapter demonstrates the results of a simulation-based experiment. Finally, in chapter five, the evaluation of the findings, and conclusion of this thesis will be presented. Figure 1 demonstrates the general thesis breakdown and workflow.

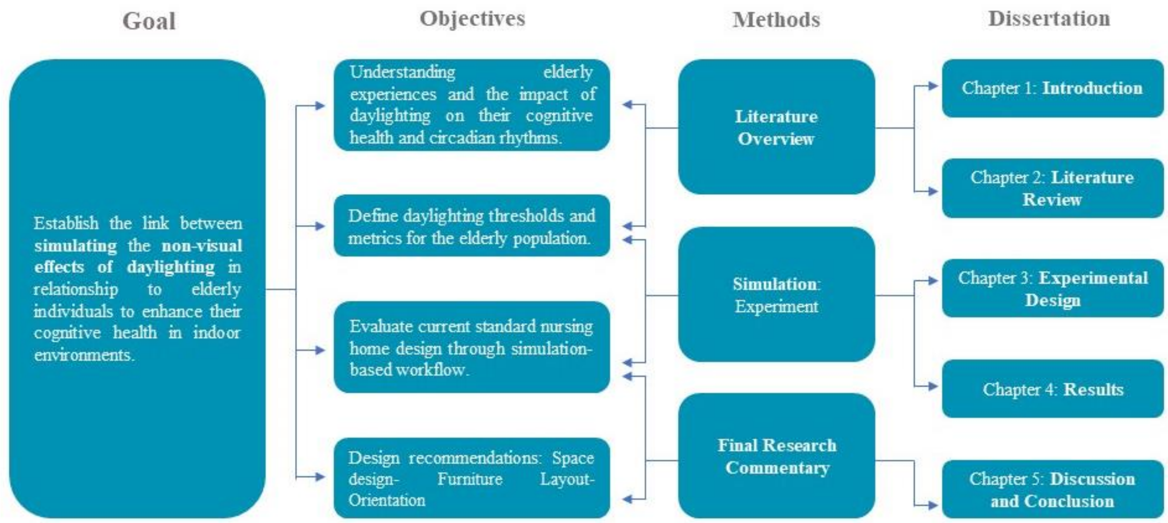


Figure 1- Research process flowchart

1.2.6 Contributions to Knowledge

- Defining lighting thresholds needed for circadian entrainment in the elderly population.
- Creating a simulation-based framework focusing on daylight that could be used by researchers to simulate similar and future projects targeting elders and individuals with dementia.
- Establishing a set of design recommendations for architects and designers to use when designing nursery care for elders to promote their health and well-being.

CHAPTER 2: LITERATURE REVIEW

This chapter aims to develop an understanding of daylighting and its relationship to human health generally and circadian rhythms specifically. The understanding of elderly experiences and disabilities are then explained thoroughly along with daylighting metrics and thresholds needed to entrain their circadian systems.

2.1 Daylighting and Circadian Health

2.1.1 Daylight Effect on Human Health

Throughout history, daylight has been serving as the primary light source to support the practical visual needs for humans indoors as well as playing a rudimental role in decision making of building design, zoning, orientation, interior layout, and many others. (Konis, 2019). Daylighting of interior spaces refers to the amount of daylight admitted within the space contributing to the lighting requirements and possibly providing energy savings through less use of electric lighting (Papamichael et al. 2013). Bringing light into spaces and using it is crucial for the improvement of the human condition, as well as enhancing lifestyles and working conditions of people (Sharp et al., 2014). Interior spaces that are daylit via windows or skylights allow the occupants to maintain a visual connection to the outside world. This also helps in spatial orientation, wayfinding, and allows the users to be aware of their surroundings (Konis, 2018). It is not difficult to believe that the existence of daylight in general, and sunlight is vital to life on earth. Humans, animals, and plants might develop abnormal behaviors and diseases when sunlight is absent because their diurnal cycle is disturbed (Boubekri, 2008). Thus, architectural design plays a significant role to create a healthy living environment (Kim & Kim, 2010). This could be planned by several design qualities that are added to a building allowing daylight to enter sufficiently such as creating atriums, reflecting light shelves, massive windows with appropriate glazing, and several other options (Sapia, 2013). However, the balance between the amount of daylight that enters is crucial to avoid negative impacts such as, thermal and visual discomfort (Wang et al., 2020).

2.1.2 Circadian Rhythm

Numerous studies have illustrated the direct link between daylight and human health. These studies suggest that when daylight exposure is maximized in health care centers and hospitals, patient recovery is accelerated and the length of hospitalization declines. People tend to experience improved moods, cheerfulness, and a sense of positive energy when exposed to daylight. On the contrary, people who are less exposed to daylight experience sadness and in some cases depression (Boubekri, 2004). In addition to that, humans living in special environments such as space flights, submarines, and similar situations with minimal to no daylight access experience circadian disruption (Nie et al., 2020). Kawasaki et al, in 2018 tested sleep and circadian rest-activity changes during long-term daylight deprivation. The study demonstrated that the human circadian rhythm stability decreases, and sleep-wake timing is delayed by the increase of daylight deprivation. Though this study was held on two Antarctic bases (Concordia and Halley VI), it can be deduced that exposure to daylight plays a significant role in human health (Kawasaki et al., 2018). The use of artificial lighting has increased drastically over the years, and is still increasing, however mimicking the daylight performance is very challenging. Though current types of artificial lighting include the use of fluorescent, incandescent and LED’s, their spectral distribution is different than that of daylight, thus, affecting their visual and non-visual performance. In addition to lack of ultraviolet (UV) light which is essential for the creation of vitamin D in the human body (Fasciani et al., 2020). Moreover, the constant use of artificial lighting encourages individuals to use it and access it at any time of the day. This increases the night-time exposure to artificial light which directly affects the human body and might have an impact negatively on health. Besides the effect on the circadian system and sleep disruption, it can also increase the potential of developing heart diseases, cancer, and obesity (Lunn et al., 2017). Generally, daylight is what we as humans evolved to respond to, it can be designed into the building to benefit all users without the dependance on any mechanical or human factor. Thus, focusing on daylight rather than artificial light has been showcased in various benefits.

The term “circadian” evolved in the 1950s from the Latin words circa (“about”) and dies (“day”) (Webster, 2020). The study of circadian rhythms investigates and examines the 24-hour oscillations. The focus is mostly on the biological processes at the molecular, cellular, and behavioral levels (Wulund & Reddy, 2015). The diurnal cycle is mostly affected by the circadian system which accounts for the synchronization of daily changes under the effect of the amount of daylight an individual is exposed to. It is accountable for several behavioral and physiological functions such as alertness level, change of mood, sleep/wake cycles, and body temperature. Therefore, individuals who fail to receive the appropriate amount of daylight exposure are expected to have their 24-h diurnal cycle affected (Andersen, 2015; C.A. Czeisler and J.J. Gooley, 2015)

Consequently, people who are exposed to sufficient daylight are expected to have a satisfactory circadian system allowing them to be further active in their day and experience better sleep cycles and moods throughout their daily lifestyle. However, in some cases such as with elderly individuals, exposure to daylight may not be a typical part of their daily life due to possible physical impairments. Thus, access to daylight loses priority even though it has crucial benefits (Boubekri, 2008).

2.2 Elderly Experiences

This section provides a detailed understanding of several elderly disabilities and challenges. It focuses on elders developing dementia, AD, and specifically MCI which has been highlighted recently due to the scarcity of research focusing on it. These types of challenges are considered as alarming situations affecting the lifestyle of elderly individuals and their caretakers. Thus, highlighting the importance of focusing on them and developing solutions to enhance their overall health and life quality.

2.2.1 Dementia

Dementia is defined as the umbrella term for a range of progressive organic brain diseases characterized by problems with short-term memory and other cognitive deficits. The risk factor to develop dementia is mainly associated with age after 60 years old with prevalence increasing exponentially up to 20% at the age of 85 (Holmes & Amin, 2020). Alzheimer's disease is considered one of the main factors of dementia which affects up to 50- 70% of dementia patients (Lobo et al., 2000). There are other types of dementia that include vascular dementia (VaD), dementia with Lewy bodies (DLB), and frontotemporal dementia (FTD) (Bruun et al., 2018).

Dementia types vary in severity and diagnosis. However, there are criteria for all types of dementia that are considered the most common. Typically, dementia is diagnosed when there are cognitive or behavioral symptoms such as:

- Daily life activities are interfered with and affected. Thus, the ability to focus, function, and work decrease.
- When symptoms are not explained by psychiatric disorders.

- Cognitive impairment is recognized and diagnosed such as loss of memory, or inability to retain new information. The inability to evaluate situations and understand safety risks. Other symptoms include the impairment of visuospatial abilities, impaired language functions, or changes in social behaviours and personality. (Manuscript, 2012).

Accordingly, challenges that face dementia individuals are considered similar in many cases. However, as the disease advances, the impact on daily life increases requiring further home care services to compensate for these issues. Though most adults prefer to stay at home as long as possible, it is estimated that an average of 35- 55% of elders at the age of 65 or above are most expected to transition to a nursing home or facility in their lifetime (Young et al., 2020). This highlights the importance to focus on nursing homes and general home designs for the elderly population to accommodate their needs and promote their overall health.

2.2.2 Alzheimer's Disease (AD)

As mentioned, Alzheimer's disease affects around 60% - 70% of dementia patients (World Health Organization, 2020). AD is classified into different types.

1- Probable AD dementia
2- Possible AD dementia
3- Probable or possible AD dementia with evidence of the AD pathophysiological process (McKhann et al., 2011).

Each type is different in terms of identification and criteria. However, they all share the common symptoms of dementia mentioned in the previous section.

Alzheimer's disease is considered one of the most alarming conditions affecting the elderly population. According to the 2020 Alzheimer's Association report, is estimated that by mid-century around 2050, the number of Americans above the age of 65 or older with AD will grow up to 13.8 million of the total population. This is a steep increase when compared to the 5.8 million Americans with AD today. Further to mention, AD is considered the sixth main cause of death in the United States amongst those at the age of 65 or above (Alzheimer's Association, 2020). Unfortunately, there is no definite cure for dementia or AD at the time of writing this thesis, thus, highlighting the importance of focusing on such vulnerable groups to promote their health and well-being (Demurtas et al., 2020).

2.2.3 Mild Cognitive Impairment (MCI)

Mild Cognitive Impairment (MCI) is one of the common words used in the United States that describes an individual at a transitioning stage between aging and dementia (Luis et al., 2003). In 1999, Petersen et al brought forward the diagnostic criteria for MCI demonstrating that it is the transitional state affiliated with memory impairment that is associated with an increased risk of progression to AD (Ronald C. Petersen, PhD et al., 1999). Alzheimer's disease is a chronic, irreversible brain disorder that affects the cognitive functions of the human body. It is one of the most common types of dementia in elderly populations affecting millions of people worldwide (Lin et al., 2020). A study executed in 2007 mentioned that in the year 2006, there were about 26.6 million cases of

AD in the world. This study predicts that by the year 2050, patients with AD will increase up to 106 million individuals (Brookmeyer et al., 2007). To further highlight this, a study in 2002 indicated that the risk of developing AD is tripled in MCI individuals when compared to healthy individuals (Bennett et al., 2002). Other studies mention that the rates of MCI progressing into AD ranges about 10-30% annually and 20-66% over 3-4 years (Luis et al., 2003; Petersen, 2004). Accordingly, this highlights the importance of addressing such an issue in contributing to the preventive methods of progression to AD. Designers, and architects should be keen on creating enhanced living environments that promote the overall health of MCI individuals and their caretakers.

Accordingly, it is important to understand the different symptoms by MCI. Conventionally people with MCI find difficulty in reporting their symptoms which requires the attention of their caretakers to report on daily difficulties facing their patients or family members. The proper assessment of the capabilities of an MCI individual is crucial to provide suitable solutions and, in some cases, propose preventive progression methods. MCI can be divided into two subtypes which is either an amnestic subtype with memory deficits or a non-amnestic subtype with a cognitive decline other than memory, extending to the impairment of a single domain of function or multiple domains(Van Der Mussele et al., 2013). MCI individuals vary in classification thus creating a variation in their functional abilities. Each classified group finds certain limitations to everyday activities. A study on the deficits in everyday functioning associated with MCI stated that individuals with MCI manifest various scales of impairment in everyday functioning when compared to average cognitive experiences. The study examined 6 everyday functioning domains including Everyday Memory, Everyday Language, Everyday Visuospatial Skills, Everyday

Planning, Everyday Organization, and Everyday Divided Attention. The results of this study stated that functional activities that depended heavily on memory-related abilities were the most vigorously impaired compared with the other functional domains examined. The domains of everyday functioning that seem affected by the MCI predominantly include the types of impairments that are examined and highlighted on formal neuropsychological testing (Farias et al., 2006). Consequently, MCI individuals might face challenges in their everyday life such as organizing daily tasks, grocery shopping, and keeping track of lists, working on their finances, and the like.

Most importantly, MCI individuals might experience neuropsychiatry symptoms such as anxiety, agitation, irritability, and apathy (Rosenberg et al., 2013). In addition, studies show that symptoms of depression are highly recognized in MCI individuals (Ravaglia et al., 2008). It is also considered one of the risk factors for developing MCI where up to 75% of older people with depressive disorders meet the criteria for MCI (Gabryelewicz et al., 2007; Jayaweera et al., 2015; McKinnon et al., 2019). Individuals with MCI might also suffer from insomnia, or lose of interest in daily life and activities, this might lead them to avoid gatherings with friends and family, ending up in isolating themselves away from people (Molano & Vaughn, 2014).

2.2.4 Challenges Facing Elders, MCI, and AD Individuals

MCI and AD dementia individuals face various challenges daily, however, this research will be focusing mainly on the aging eye and mobility challenges. It has been thought historically that AD is restricted to the brain only. However, the understanding of AD has developed to include evidence of ocular changes and involvement (Chiu et al., 2012; Gupta et al., 2020) The retina is an extension of the central nervous system (CNS) which includes the retinal ganglion cells (RGCs). These cells are responsible for translating the visual world through optics nerves that are connected to the brain (Erskine & Herreral, 2015). Unfortunately, because of AD and MCI, deficits occur including loss of cells in the ganglion cell layer, RGC degeneration (Koronyo et al., 2012). Melanopsin- containing RGC is the most affected and lost, thus, affecting the visual ability of the patient along with circadian dysfunction (La Morgia et al., 2016). Accordingly, severe and increased issues of sleep disruption occur with patients (Romanella et al., 2020). A study stated that elders might spend twice as much overnight time in unwanted wakefulness (Bliwise, 1993). In addition, several studies show that melatonin plays an important role in sleep regulation and circadian systems which is mostly controlled by the Suprachiasmatic nucleus (SCN). However, it is also affected and deteriorated as a result of age and diseases such as AD, and MCI (Cooke & Ancoli-Israel, 2011; Romanella et al., 2020).

Another main challenge facing elders, in general, is frailty which estimates a high risk of future disability. It could be defined as a combination of several physical components which might include issues with loss of body mass, issues with walking performance, general weakness, or low physical activities (Liu et al., 2019) (Fried et al., 2001). Accordingly, elders might begin to face challenges to easily move in and out of their houses or nursing homes. A study in 2013 mentioned that elders tend to spend between 80-90% of their time indoors (Bentayeb et al., 2013). This emphasizes the minimal access to daylight that elders are exposed to especially with diseases as MCI and AD.

2.3 Effects of Light on Elderly and Dementia Individuals

As mentioned, dementia, MCI, and common disorders in adults affect those at the age of 65 years or older (McKeel et al. 2007). Accordingly, several functions such as sleep-wake / circadian rhythms affect the overall mood and quality of life (Naismith et al., 2011). Thus, highlighting such an issue requires attention and further research.

Circadian rhythms are affected by the amount of light an individual is exposed to. The existence of daylight affects the synchronization of the circadian system and therefore affecting the excretion of melatonin which is a hormone produced by the pineal organ and is responsible for sleep order in humans (Wurtman 2018). A previous study illustrated a direct relationship between daylight exposure and the correction of circadian rhythms in elderly people. This study relied on daylight exposure without the use of artificial lighting. However, though participants were exposed to some sort of artificial light throughout the day, the focus was on daylight exposure between the hours of 9 – 10 AM and 4-5 PM. The study showcased that daily exposure to daylight caused a noticeable improvement in several complications such as anxiety and insomnia, those which are symptoms of MCI. The study pointed out that sleepiness, fatigue, and alertness at daytime might be improved if elders were exposed to adequate daylight values resulting in improved circadian systems thus, better sleep-wake cycles (Karami et al., 2016).

It is also important to note that a practical study of a long-term, double-blind, placebo-controlled research using bright daylight noted several findings on this topic. The study showed that elderly individuals exposed to bright daylight recorded reduced symptoms of dizziness, headache, and inability to sleep. Additionally, the use of bright daylight as the primary incitement acting on circadian systems improved rhythms of hormones and metabolism as well (Riemersma-van Der Lek et al., 2008). In support of these findings, daylighting can have a critical effect on circadian systems and the benefits of its effects on MCI individuals could be significant.

The human body is exposed daily to a wide variation of illuminance values that are necessary for the entrainment of the circadian system. With a range between 120- 100,000 lux, the difference in such illumination level exposure influences human behavior and physiology (Yan et al., 2019). Much research has been conducted to measure the appropriate lighting values needed for circadian entrainment in young healthy individuals. However, there are currently no minimum requirements regarding exposure to daylight for elderly individuals, or dementia care environments. Thus, the importance of daylight acting as a significant factor in the non-visual effects on the human body has the potential to promote further research rather than relying solely on the factor of safety and visual importance (Konis et al., 2018).

2.4 Daylight Metrics for MCI and Dementia Patients

This section discusses the metrics researched and available that are suggested to entrain the circadian rhythm in elderly individuals especially those with different types of dementia. Each metric could be applied in spaces either by depending on artificial lighting or daylighting. However, the aim of this research is to focus on daylighting solely with its demonstrated positive effects on human health and well-being along with its significant role in sustainability and lowering energy consumption.

2.4.1 Illuminance Values

The critical question is how much additional illuminance is required to produce melatonin suppression for elders and individuals with MCI and AD? A study conducted in 2001, mentioned that MCI and aging individuals need light values within a space to be as much as five times greater than younger individuals (Brawley, 2010). This includes increased illuminance values and brightness levels. However, findings from various studies mention that elders are exposed to less bright light daily for different reasons including living arrangements, seasonal factors, or health restrictions (Mishima et al., 2001). The amount of illuminance increase needed for an elder individual is drastically higher than a younger individual. As mentioned in the previous section, due to deterioration of the retina, the eye receives less light making it difficult to produce melatonin which directly impacts the circadian rhythm. A research in 2010 demonstrated that an 85-year-old individual needs roughly up to eight times more illuminance values than a 10-year-old for circadian photoreception. Table 1 shows the detailed reference with a guide on how to measure the values needed for each age (Turner et al., 2010).

Table 1: Comparative circadian photoreception at different ages in phakic eyes (Eyes with natural lens). (reproduced from (Turner et al., 2010)).

	10 yrs	15 yrs	25 yrs	35 yrs	45 yrs	55 yrs	65 yrs	75 yrs	85 yrs	95 yrs
10 yrs	1	0.92	0.82	0.64	0.5	0.36	0.26	0.16	0.12	0.1
15 yrs	1.08	1	0.89	0.69	0.54	0.39	0.28	0.18	0.13	0.11
25 yrs	1.22	1.12	1	0.77	0.61	0.44	0.32	0.2	0.15	0.12
35 yrs	1.57	1.45	1.29	1	0.79	0.57	0.41	0.26	0.19	0.16
45 yrs	2	1.85	1.64	1.27	1	0.73	0.52	0.33	0.24	0.2
55 yrs	2.75	2.54	2.26	1.75	1.38	1	0.72	0.45	0.34	0.28
65 yrs	3.84	3.55	3.15	2.44	1.92	1.4	1	0.63	0.47	0.38
75 yrs	6.08	5.61	4.99	3.87	3.04	2.21	1.58	1	0.74	0.61
85 yrs	8.21	7.48	6.74	5.22	4.1	2.98	2.14	1.35	1	0.82
95 yrs	9.99	9.22	8.2	6.35	4.99	3.63	2.6	1.64	1.22	1

Accordingly, Bright Light Therapy is researched to investigate the effects of high illuminance values on elderly individuals with dementia, AD, or MCI. Light therapy is achieved through different measures either artificially using light sources such as a lightbox or using outdoor sunlight exposure during certain times of the day (Forbes et al., 2014). A study consisted of a 1- week adaptation session, a 1-week pretreatment and a 4-week treatment session with bright light therapy resulted in verifying that individuals with early and mild stages of dementia as MCI who are exposed daily to bright light at 3000 lux from 9-11 AM showcase improvement in their circadian systems and cognitive functions (Yamadera et al., 2000). Another study on the effect of bright light and the use of melatonin as a supplement on cognitive and noncognitive functions with elderly residents of a group care facility examined the effects of up to 3.5 years of a daily supplement of light and/or melatonin and its effect on patients with various types of dementia. The study used an interval between 9 AM till 6 PM, keeping lights on with illuminance values higher than 1000 lux measured before the eyes in the gaze direction. The study resulted in proving that the simple increase in illuminance values improved circadian rhythms. Even with the supervised intake of melatonin, it has showed no change in their health without including bright daylight (Riemersma-van Der Lek et al., 2008). A 2019 research recommended that the application of 2000-3000 lux source of light could be considered adequate for stimulating circadian rhythms after exposure of 1-2 hours daily (Balcı Alparslan et al., 2019).

Though the effect of bright light therapy seems to be positive, there could be some downsides to the excessive use of artificial lighting. A study in 2017, questions the safety of high illuminance artificial light. The study which used swiss albino mice to evaluate the effect of such high illuminance light resulted in demonstrating that such high values might induce severe alterations in brain functionality and affect the general health negatively due to the visible electromagnetic radiations (Seke Etet et al., 2017). Though this research does not include human experimentation and investigation, it is still considered an aspect that should be taken into consideration.

2.4.2 Equivalent Melanopic Lux (EML)

The acknowledgment of photoreceptors in the human retina known as Intrinsically Photoreceptive Retinal Ganglion Cells (ipRGCs), has increased the general interest of researchers to study and analyze the non-visual effects of light in human circadian systems (Konis, 2017a). It was shown that these photoreceptors have the highest photosensitivity to light with wavelengths within the range of 447-484nm (Ewing et al., 2017). Researchers have been studying various metrics intending to understand and quantify the biological effects of light. Accordingly, The Equivalent Melanopic Lux (EML) was proposed by Lucas et al. as a measurement of light's effect on the circadian system. They provided a toolbox which analyzes the EML for every five photoreceptors in the eye (Cyanopic, Melanopic, Rhodopic, Chloropic, and Erthyropic) for certain spectrums(Lucas et al., 2013, 2014)

Despite limited research available concerning the minimum requirements for daylight access in buildings to support circadian entrainment, the International WELL Building Institute has developed a building certification system that provides minimum requirements for circadian lighting design (Konis, 2017b). The WELL standard divides the requirements of circadian lighting into four parts; however, the most important part to focus on indicates that EML values of 200 during the daytime and 50 during nighttime should be achieved in all living environments such as bedrooms, bathrooms, or rooms with windows. (International WELL Building Institute, 2020).

Despite the efforts of researchers who have been investigating and working on improving circadian design metrics, the gap remains clear towards the lack of sufficient metrics of lighting for circadian entrainment regarding elderly experiences.

2.4.3 Circadian Stimulus (CS)

The Circadian Stimulus (CS) is a metric proposed by the Lighting Research Center (LRC) at Rensselaer Polytechnic Institute. It is a metric that helps designers understand and apply circadian light in built environments. The LRC provides a free access to the CS calculator to calculate the needed CS within a space. According to research, it is recommended that adults exposed to CS at 0.3 or higher for a one- hour exposure per day, experience improved circadian systems (M.G. Figueiro et al., 2016). The threshold is typically between 0.3 – 0.7 CS. The CS calculator provides various types of luminaires and lighting options that could be chosen to identify the CS required. However, it does not focus on daylight, but rather electrical lighting alternatives (Lighting Research Center, 2020a). Moreover, the LRC provides a free accessible design application platform that could be used by architects and designers when designing different spaces, however, it still raises many concerns when compared to other lighting metrics. The CS design platform provides two options, an office space, or a senior home. When choosing the senior living design, you can choose the type of luminaries and several other design options. The issue is that it does not provide a daylighting option, nor does it give variance above the 0.4 CS. This raises a concern when comparing the CS number to lux values whereas the CS recommended is 0.4 which is at a range of 75 lx to 540 lx throughout the day (Lighting Research Center, 2020b). Though these results might fit younger individuals, this is considered a low illuminance value when compared to the available research on elderly individuals. Thus, further research is required to achieve and ensure proper design requirements for the elderly population.

2.4.4 Short Wavelength

It is important to acknowledge that research has shown that the human circadian system is sensitive to short-wavelength (blue) light and that it has a direct effect on melatonin levels (Thapan et al., 2001). It has been established that short-wavelengths between 440nm-nanometer- and 500nm have the most effect on melatonin suppression by light (Rea et al., 2005). The use of tailored lighting with a low-level “bluish-white” lighting was investigated through a study in 2014 during daytime in 14 nursing home resident rooms. The study focused on individuals with AD and related dementias. It demonstrated that the use of 300-400 lux of bluish-white light has a direct effect on the circadian system

(Mariana G. Figueiro et al., 2014). Though this study does not use daylight as the main metric, the results itself could provide future integration between daylight and artificial light to produce enhanced design metrics and solutions while decreasing the high-intensity values needed for illuminance.

2.5 Daylight Challenges for MCI Eye Complications

When considering daylight and artificial light design for indoor spaces, several complications such as visual and spatial discomfort might occur which require further attention from the designers and architects. This is a result of over illuminating the space or insufficient lighting. For example, individuals with advanced types of dementia or MCI might experience visual hallucinations caused by insufficient lighting within a space (Alzheimer's Society, 2016). One of the reasons could occur during the late day when the sun begins to fade causing the appearance of shadows due to insufficiency of light. This might create confusion, anxiety, and irritation for elders or dementia individuals (Lenham, 2013). Thus, design parameters as visual comfort, glare, brightness, contrast, and adaptation from indoor to outdoor or vice versa should be considered when designing indoor spaces for elderly individuals.

2.5.1 Glare

Further complications include the existence of glare which is one of the most unwanted outcomes of lighting in indoor spaces. Direct and indirect glare from windows causes problems with visual comfort for elderly individuals, especially those with dementia-related problems (Brush et al., 2002). Glare is divided into disability glare and discomfort glare. The definition of disability glare is the lack of a person's ability to see a certain object in a scene due to glare interfering with visual performance and tasks, however, discomfort glare is the premature tiring of the eyes due to glare which might not interfere with visual tasks and is often accompanied by discomfort only (Hensen & Lamberts, 2012). As a result of the high illuminance values needed to improve the overall visual performance of elderly individuals as mentioned before, balancing, and diffusing of daylight might become a priority within the space. A study on lighting solutions for contemporary problems of older adults suggested that to avoid glare caused by the high contrast ratio between daylight and the dim interior light is to bring daylight within the space from several directions. This could be achieved by adding several windows or skylights allowing the light to balance out within the space avoiding the concentration of glare in one direction. However, in some cases, the use of ambient electrical lighting might be needed to improve the overall experience of lighting within the space especially when the addition of windows is not a viable solution (Noell-Waggoner, 2004). The elimination of daylight admission should be avoided when creating solutions to control the amount of glare within the space. Interventions and proper design of façade systems that reduce glare effects along with the addition of blinds and screens that are easily controlled from places near the bed are crucial when using daylight in nursing facilities and homes of elderly individuals (van Hoof et al., 2009).

2.5.2 Light and Color

The increase of lighting to ±2500 lux has been proven to improve circadian rhythms and overall health among elderly and dementia individuals (Calkins, 2011). However, another aspect to take into consideration is how true colors will be. As a result of deteriorating retinas and yellowing of the lens of the eyes of seniors, the use of lighting sources with high Color Rendering Index (CRI) might be needed to improve the overall visual experience (W. Benbow, 2009). This application might include the use of artificial lighting aside from daylighting to enhance visual performance.

A study proposed that a light source with CRI levels within 70-100% provides a natural appearance of objects and colors (B. Benbow, 2014). Also, the temperature of the emitted light measured on the Kelvin scale plays a role in delivering truer colors whereas; values lower than 3000K provide a warmer appearing light that could be used in spaces for relaxation as lounges, while values higher than 3000K are closer to daylight delivering accurate cooler colors (B. Benbow, 2014). Thus, the measurement and knowledge of the Kelvin value especially in electric light if used should be known and identified. This allows a better evaluation of the interior space in terms of true color and appropriate visual perceptions among elderly individuals.

2.5.3 General Design Parameters

Finally, general design parameters could be taken into consideration to improve the use of daylighting within interior spaces. A study modeling the non-visual effects of daylighting in a residential environment suggested that designers should be aware of how occupants might use the space differently from healthy active individuals. It recommended that the distance from the windows is considered as a significant factor in achieving circadian enhancement by daylight, suggesting that designers should place service areas like closets, bathrooms, pantries, and similar areas at the core of the building whilst placing living spaces like bedrooms, living rooms, and kitchens in the areas that are closest to windows (Andersen et al., 2013). Also, parameters as the depth of the space, its size, area, and placement of windows and its locations are all contributing factors to the enhancement of daylighting within a building (Wong, 2017).

Another affecting aspect is contrast sensitivity with elder eyes. Contrast generally allows elders to identify spatial objects while identifying the edge of them with higher clarity. It was proposed that increasing luminous contrast will increase the performance of elderly individuals (Shikder et al., 2012). Thus, interior spaces with dark areas should be resolved to avoid contrast with brighter parts affecting their vision (Torrington, Tregenza, and Noell-Waggoner 2007). Also, the use of higher ceilings could allow natural light to enter efficiently within the space along with proposing skylights as an added design element (Sloane et al., 2005).

Daylighting is considered a vital parameter when designing for elderly and dementia individuals. A well- designed system should typically provide the occupants with sufficient daylight to promote their circadian systems, perform their daily tasks, provide glare control, provide a view to the outside world, and generally save energy and control heat (Day et al., 2019). Accordingly, it was crucial to investigate whether these techniques were taken into consideration when designing for elders or not. This led to the design of an experiment to investigate in the current standards targeting elders. This is demonstrated thoroughly in the next chapter which analyzes current standard designs.

CHAPTER 3: EXPERIMENT DESIGN

This chapter aims to develop an experiment to test current nursing home designs and strategies in terms of daylighting requirements needed for the elderly population. This will allow a better understanding of the available designs and required improvements.

3.1 Experiment Goals and Objectives

This experiment assists architects, and researchers to provide a set of design requirements that promote the health and well-being of the elderly populations specifically focusing on circadian entrainment.

The goals of this experiment are to:

- Verify the current case of typical nursing homes and identify if they fit the needs of the elderly population for circadian entrainment or not.
- Identify acceptable daylight illuminance and glare percentages within a space that entrain the circadian rhythm for the elderly.
- Propose design recommendations as a framework for designers and researchers.

The objectives are:

- To identify and use a typical standard nursing home as a base case.
- Simulate point in time illuminance, point in time glare, and annual daylight glare probability for locations within the nursing home bedroom.

3.2 Experiment Design and Methodology

Figure 2 showcases the experiment workflow. The first step required was to identify the available architectural standards commonly used by architects as reference. The Neufert's Architects Data book for architectural standards was chosen as a commonly used standard (Neufert et al., 2012). The location was assumed to be Atlanta, using Hartsfield International Airport, GA, USA, TMY3 climate file.

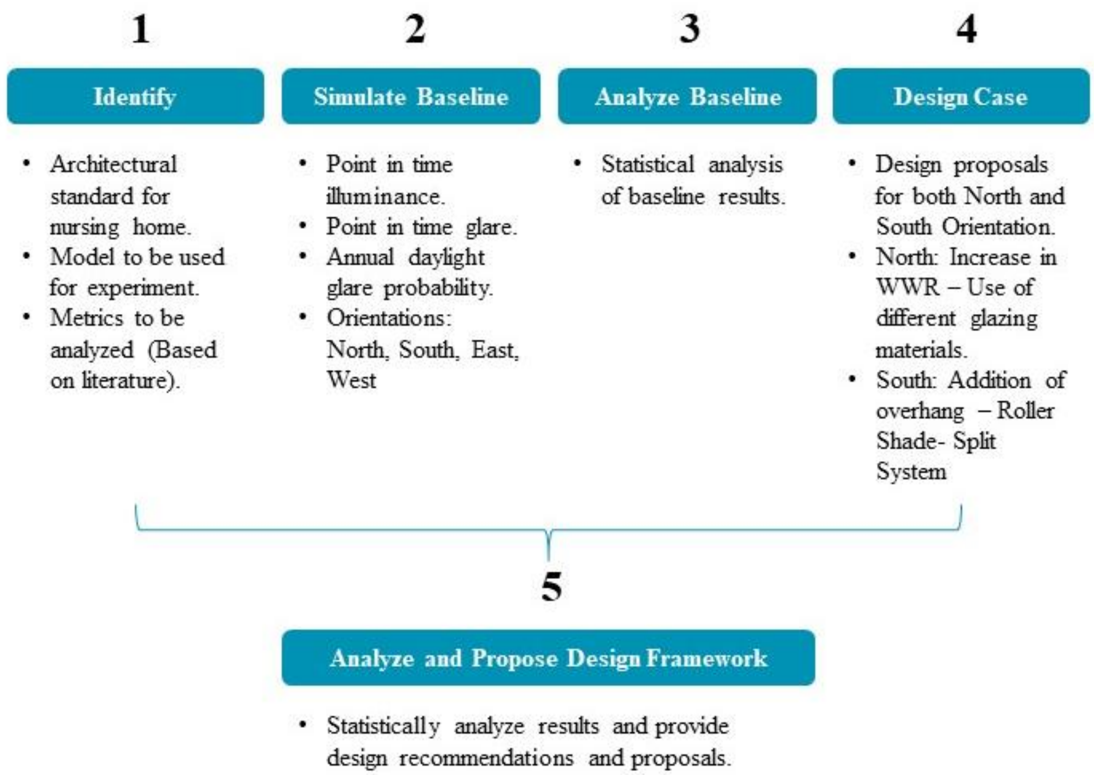


Figure 2: Experiment workflow

The experiment was divided into a baseline case and a design case. The baseline case was to simulate the existing model in different orientations (North, South, East, and West). Accordingly, based on simulating point in time illuminance, annual, and point in time daylight glare probability, the results were analyzed leading to the choice of the North and South orientations for further investigations and experiments which were considered the design case. Each design case differed in the design additions and proposals.

3.3 Simulation Model and Renderings

The choice of model was based on the nursing home design standards within Neufert's third edition book. Through this experiment, only the single-bed bedroom was analyzed.

3.3.1 Simulation Programs and Materials

The programs that were used for simulations and renderings are DIVA in Grasshopper for Rhino, which uses energy plus and radiance along with Climate Studio in Rhino which is built on energy plus and a novel-radiance-based path tracing technology which is developed by the Solemma group. It is important to mention that at the time of starting this research, DIVA was used to simulate point in time illuminance given the advanced parameters it provided which allowed an easier, a more comprehensive, and detailed analysis. The research expanded to simulate equivalent melanopic lux (EML) using the software ALFA which is a tool that uses spectral raytracing to predict the amount of light absorbed by an observer's non-visual photoreceptors, given the location and direction of view. ALFA software is also approved by the WELL Building Standard.

The following tables present the materials assigned in DIVA and Climate Studio to fit the requirements of the experiment. It is also important to highlight that the materials chosen were strictly basic with minimal reflections, as the focus was on the geometry, orientation, and furniture layout of the bedroom. Furthermore, Climate Studio was used later in the research, which resulted in selection of materials with different reflectance percentage as they were updated to match the Illuminating Engineering Society of North America (IESNA) standards.

Table 2: Materials used in DIVA for Grasshopper in Rhino

Layer	Reflectance	Visual Light Transmittance
Ceiling	10%	N/A
Exterior Walls	30%	N/A
Floor	20%	N/A
Furniture	50%	N/A
Glazing_ Single Pane_88	N/A	88%
Glazing_Double Pane_lowE_65	N/A	65%
Ground Exterior	20%	N/A
Interior Walls	70%	N/A
Overhang	90%	N/A
Overhang-Top	72%	N/A
Roller Shade	40%	4%

Table 3: Materials used in Climate Studio for Rhino

Layer	Reflectance	Visual Light Transmittance
Ceiling	70%	N/A
Exterior Walls	50%	N/A
Floor	20%	N/A
Furniture	50%	N/A
Glazing_ Single Pane_88	8%	88%
Glazing_Double Pane_lowE_65	14%	77%
Ground Exterior	10%	N/A
Interior Walls	50%	N/A
Overhang	48%	N/A
Overhang-Top	76%	N/A
Roller Shade	83%	N/A

3.3.2 Model and Window to Wall Ration (WWR)

Figure 3 demonstrates the model design and the locations chosen for analysis. The baseline case did not include any design additions. Point (A) at the head of the bed, while point (B) at the armchair showcase the simulated points. However, the area of analysis was characterized by similar and relevant outputs. Figure 4 is a representative image of the interior space inside the single-bed bedroom.

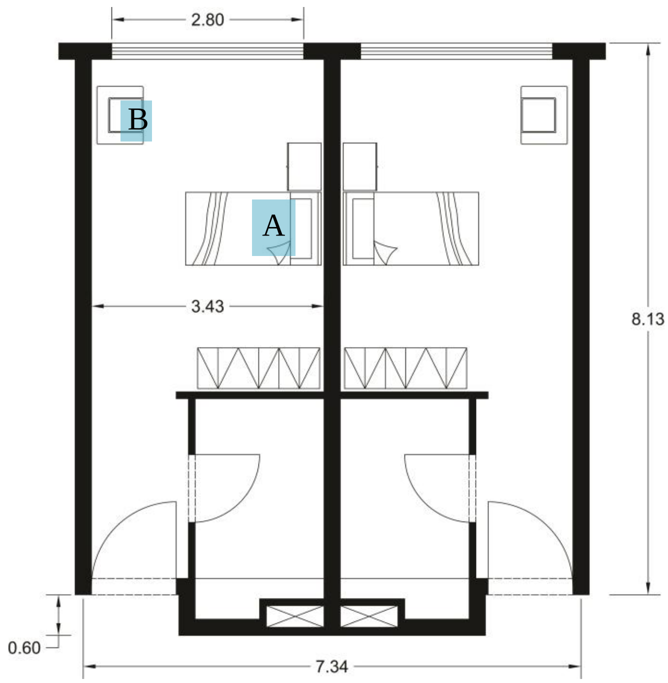


Figure 3: Baseline design model from Neuferts Architects Data

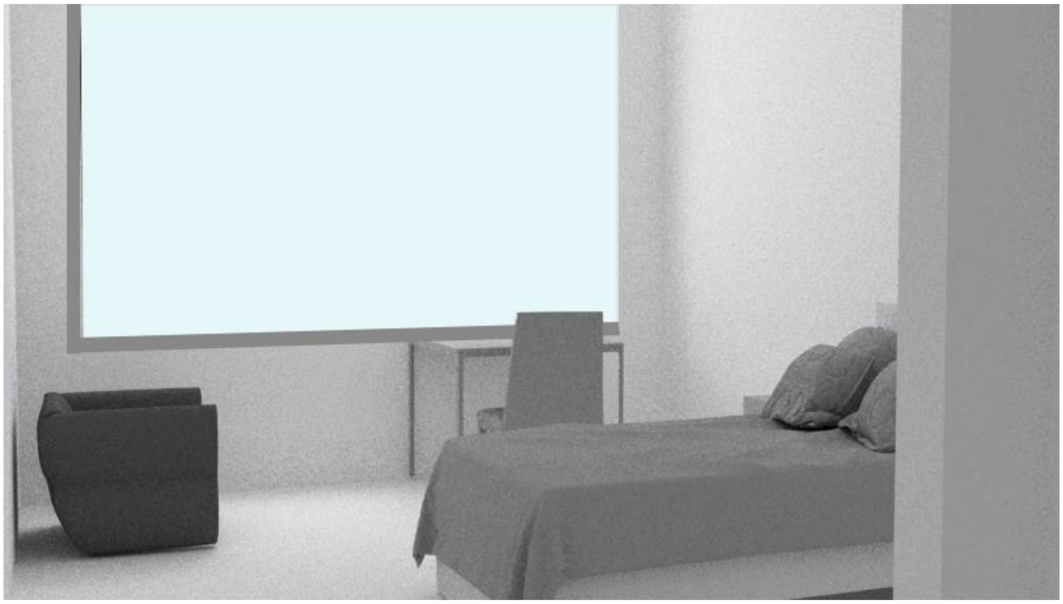


Figure 4: Representative 3D image of the bedroom interior.

It is important to highlight the window to wall ratio (WWR) which plays a critical role in this experiment. According to Neuferts, it is required that the window area should be calculated as a percentage of the room area based on the existing room depth. The general requirements are:

≤ 8m : 16-20% **|** ≤ 8-10 m: 25% **|** ≤ 11-14m: 30% **|** ≤ 14m : 35%

In this experiment, the room depth is 8.8m, thus, greater than 8m. Accordingly, the percentage of the WWR is 25% of the room area based on the depth. Therefore, A window of 2.8 m x 2.7m was assumed to equal 7.5 m3 whereas, the room area is equal to 29 m3. The total area of the wall equals to 14.68 m3. The proposed WWR is approximately 51 % in the baseline case.

Figures 5, and 6, present the design additions where the North orientation was proposed as two different scenarios. Both scenarios included a larger WWR however, one of the scenarios was simulated with a double-glazing window, and the other one was with a single glazing window. This allowed a better understanding of the effect of the type of glazing used along with increasing the percentages of the WWR by 20%. Thus, the new WWR is about 70% in the North orientation. Figure 5 showcases the addition of an overhang and roller shades which were used in different design iterations for the South orientation.

Moving on to the second part of the design investigation, the South orientation was proposed in four different design alternatives to test the elimination of annual glare along with increasing the annual useful daylight hours. Figures 5, and 6 demonstrate the different design alternatives whereas, the first alternative was proposing an overhang with a depth of 1.5m (4.9 ft). The second and third alternatives used a roller shade made of white fabric. The difference is the percentage of the roller shade rolled down, where one of the alternatives uses 100% of the roller shade and the other uses only 50% of the roller shade. The goal is to test if the roller shades are efficient in terms of allowing appropriate daylight to enter the space while blocking most of the glare or not.

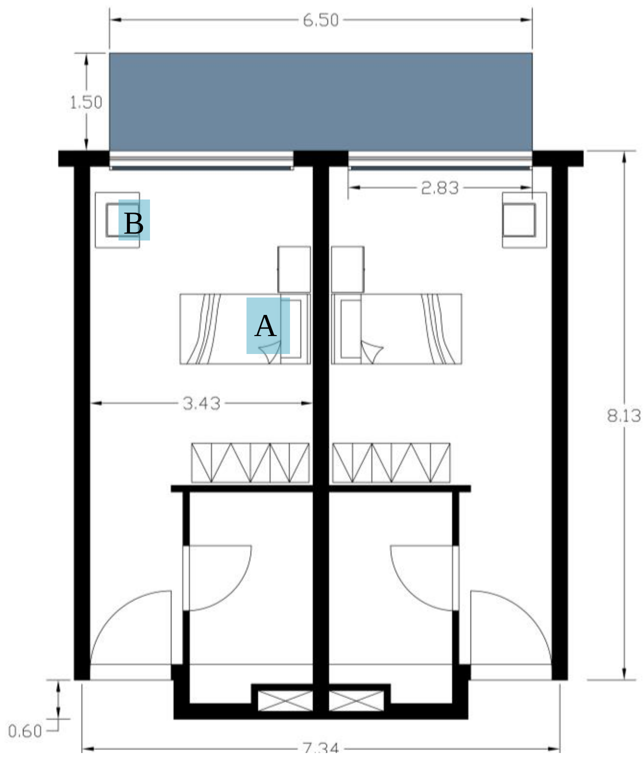


Figure 5: Design case with iteration additions

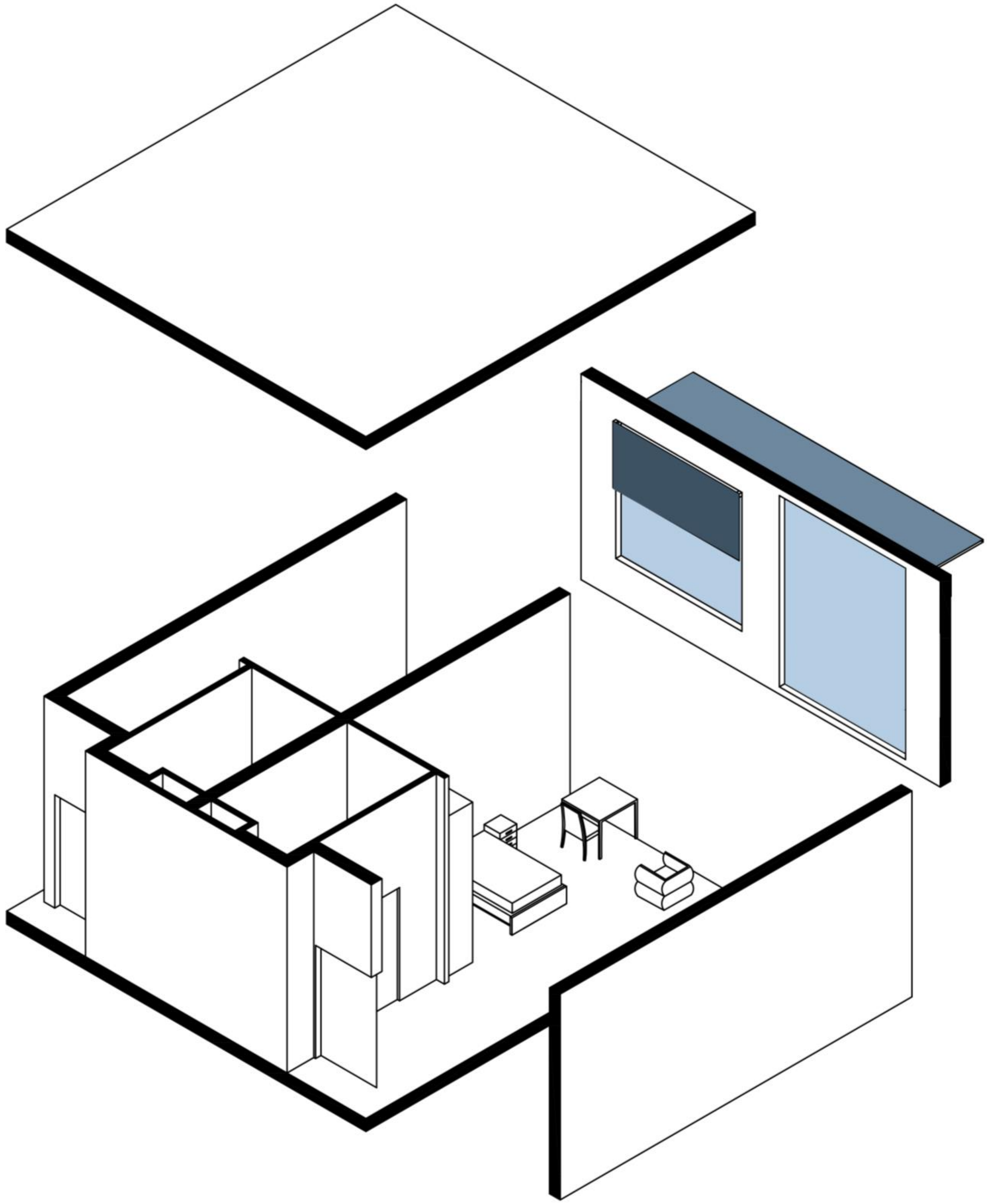


Figure 6: An exploded isometric showcasing design strategy used.

The fourth and final alternative is demonstrated in figures 7, 8, and 9 which showcase a proposal of a set of split-system trials using interior light shelves with different depths, overhangs, and exterior louvers with different angles.

The split system trials were based on different iterations made to adjust the façade. The window was divided into three parts, whereas the first part is above the overhang or light shelf, the second part is the main shading structure, and the third part is below the overhang or light shelf. Eight iterations ran as follows:

1. Opened Louvers, overhang depth 0.5 m, closed louvers at angle 70 degrees.
2. No louvers, overhang depth 0.5m, opened louvers.
3. Closed louvers at angle 70 degrees, overhang depth 0.5m, opened louvers
4. No louvers, interior light shelf depth 0.5m, opened louvers.
5. No louvers, interior light shelf depth 0.7m, opened louvers.
6. No louvers, interior light shelf depth 1m, opened louvers.
7. No louvers, interior light shelf depth 1m, opened louvers at angle 45 degrees
8. Opened louvers, interior light shelf depth 1m, opened louvers.

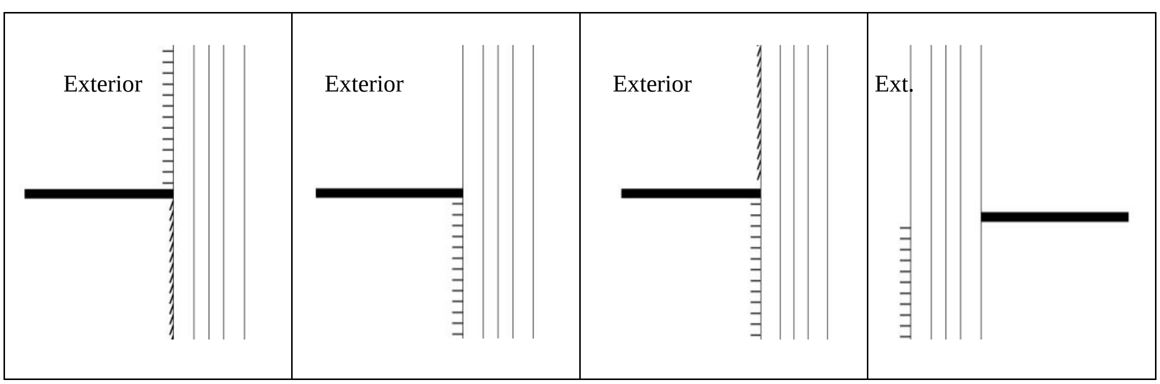


Figure 7: Split system detail section: trials 1 – 4, respectively. O: Outside Orientation.

Trials 1 – 4 showed the least promising values for the point in time illuminance at the head of the bed and the armchair. The overhang along with the louvers were blocking most of the useful daylight values to enter the space making it inadequate for circadian entrainment. In addition to using closed louvers which completely blocked the entrance of light.

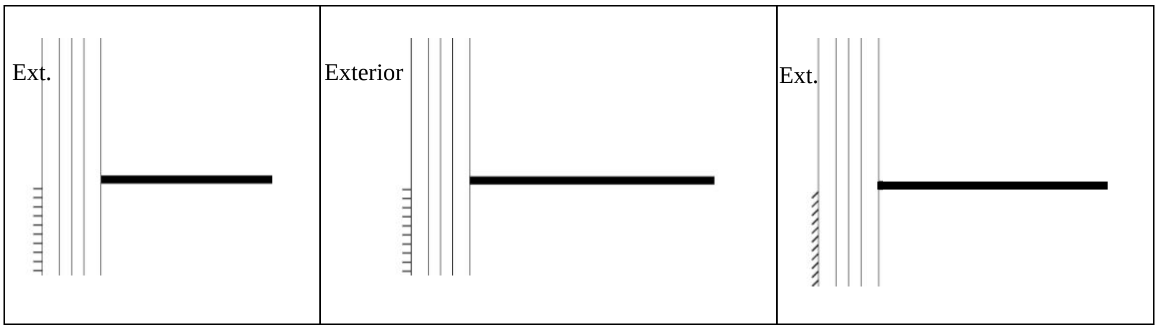


Figure 8: Split system detail sections: trials 5 – 7, respectively. O: Outside Orientation.

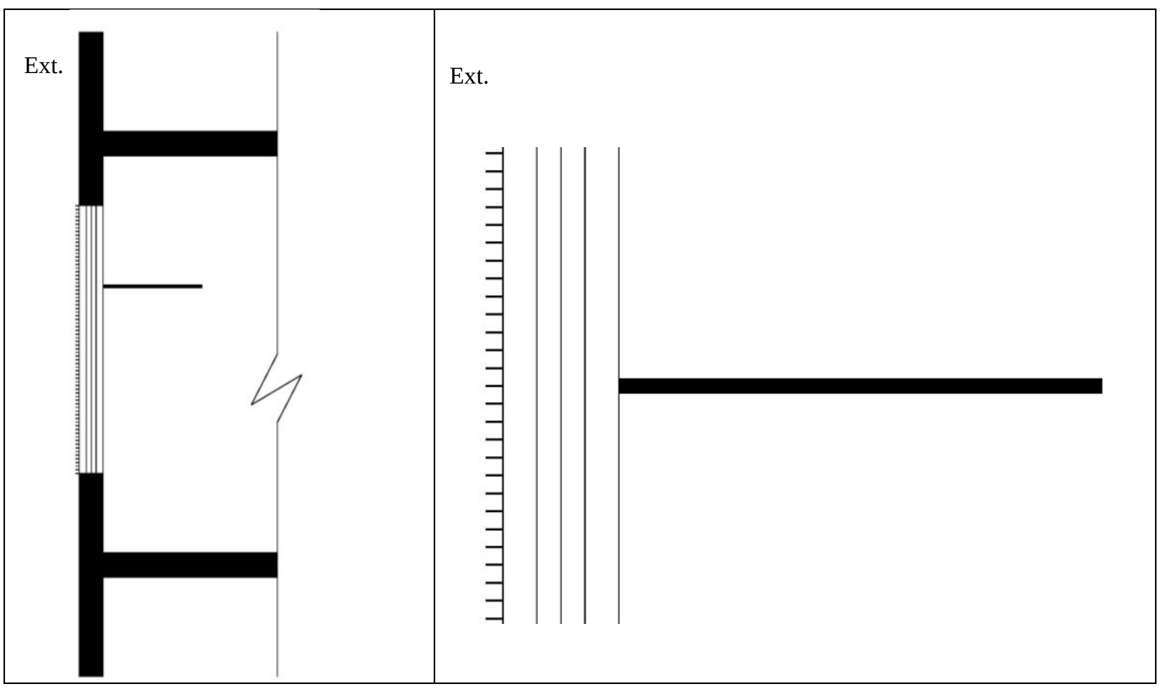


Figure 9: Split system trial 8 – chosen iteration with opened louvers, interior light shelf of depth 1m, and opened louvers.

The next trials included the interior light shelves which provided more promising values especially at the head of the bed allowing more light to enter. However, using louvers was necessary. Both the use of louvers at a 90-degree angle and a 45-degree angle worked well alongside the light shelf. However, by increasing the depth into space, more light was admitted. Figure 9 showcases the chosen iteration.

Finally, the eye level was assumed to be at 0.9m which is equal to 2.95 ft height. This was applied at both the armchair and the head of the bed based on the standards set by the Neufert 4th. Figure 7 demonstrates a re-produced graphic of the referenced images with the dimensions taken into consideration.

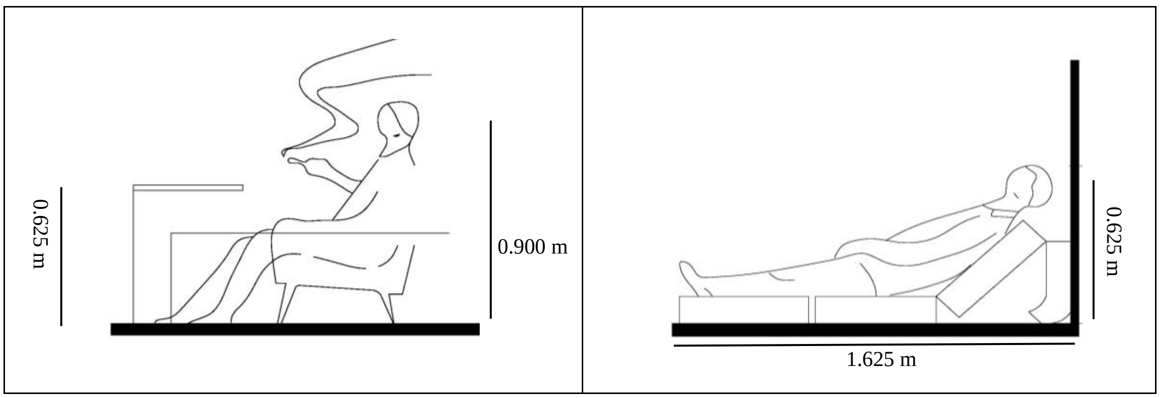


Figure 10: Neufert’s 4th edition, human-scale dimensions (reproduced).

3.3.3 Metrics Analyzed

This experiment focuses on point in time illuminance, annual, and point in time daylight glare probability. The point in time illuminance is the amount of light reaching a point on a surface at a certain time and day in the year.

In this research, we expanded the experiment to include equivalent melanopic lux however, this was not the focus of the experiment given that EML has no reference in the literature for elderly individuals. In addition, accessibility to software programs that simulate EML are not available to all architects and designers. Thus, choosing illuminance and glare could target a larger group of researchers and architects who are familiar with these metrics. Figure 11 showcases the illuminance metric threshold that is analyzed and investigated. The daylight illuminance values are required to fall between the target illuminance value of 2000-2500 lux with an exposure of 1 – 2 hours per day. However, a 500-lux addition target was added above and below the required target given that there might be a difference between individuals and the exact amount of illuminance they might need. We assumed this difference to be about 25% above and below, hence, the 500-lux addition. These values are not as efficient and adequate as the required target however, they might entrain the circadian system with values closer to the strict 2000 – 2500 lux. Accordingly, any other values that did not coincide with these thresholds were considered inadequate for the study. Values below 1500 lux are in-adequate for circadian entrainment based on reference to the literature. However, exceeding 3000 lux were considered to be over- exposed as they might be accompanied with excessive glare issues. It is also not studied and thus, its effect cannot be predicted either positively or negatively.

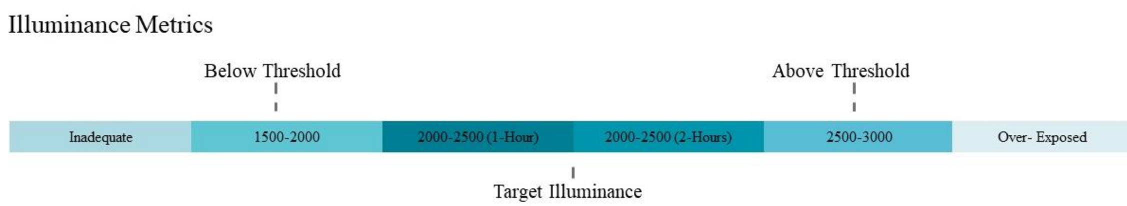


Figure 11: Illuminance metrics

In addition, figure 12 demonstrates the legend for the point in time and annual daylight glare probability targets. Climate studio is used to simulate this metric. The target was to increase the percentage of imperceptible glare. The annual glare percentage is based on the frequency across all views that have an annual DGP higher than 0.4 %.

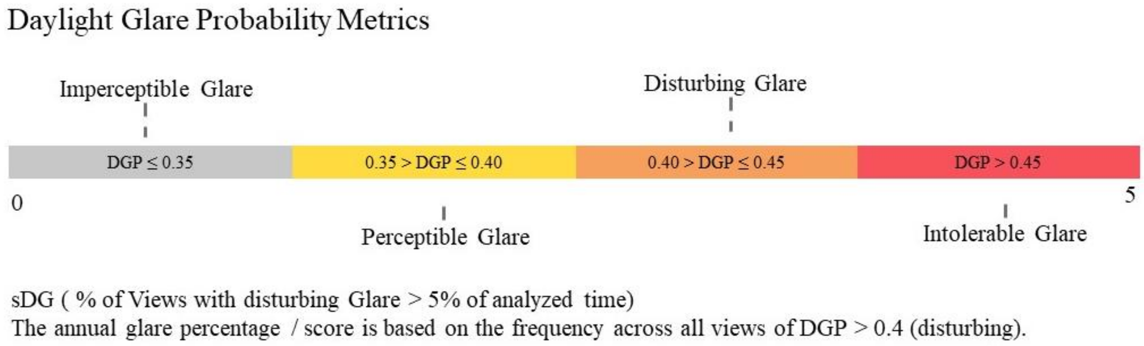


Figure 12: Daylight Glare Probability (DGP) Metrics

CHAPTER 4: RESULTS

This chapter aims to provide the results of the simulation experiments undergone. The simulation-based results are considered key to provide a design recommendation for similar future work.

4.1 Baseline Case Results

This section presents the baseline case results of the single-bed bedroom model. The analyzed space is not modified or improved in any way to test out the performance of the space in its current state. This section demonstrates the North, South, East, and West orientation results of both the point in time illuminance, point in time DGP, and annual DGP which are represented numerically and graphically.

4.1.1 Point in Time Illuminance

Through this experiment, the point in time illuminance was analyzed every day between the hours of 6 AM to 8 PM all year long. This allows a better understanding of the daylight values entering the space at a specific point rather than using annual metrics such as sDA (Spatial Daylight Autonomy) or using Daylight Availability. The following figures showcase the results of the North, South, East, and West orientations at both points, with (A) being at the head of the bed, and (B) at the armchair.

Each month either contains 31 days, 30 days, or 28 days. This is translated into the analyzed daylight hours to be 434 hours when the month has 31 days, 420 hours in months with 30 days, or 392 hours in February. However, the graphs present the percentage of thresholds to allow easier comparison between each month.

As shown in figure 13, the North orientation showcases that point (A), at the head of the bed suffers a huge lack of hours that entrain the circadian system. This location does not receive any sufficient illuminance values throughout the whole year. On the other hand, point (B) reaches between 20 – 30% of daylight values over the year. This showcases that the current design when orienting it towards the North barely entrains the circadian rhythm at the bed location and does not fit the needs of the elderly.

Figure 14 showcases the results of the South orientation. The average percentage of hours that meet the thresholds at the head of the bed are between 20-23% maximum, and at the armchair between 20 – 30 %. Both locations are similar in the percentage of useful hours and are higher in value than the North orientation.

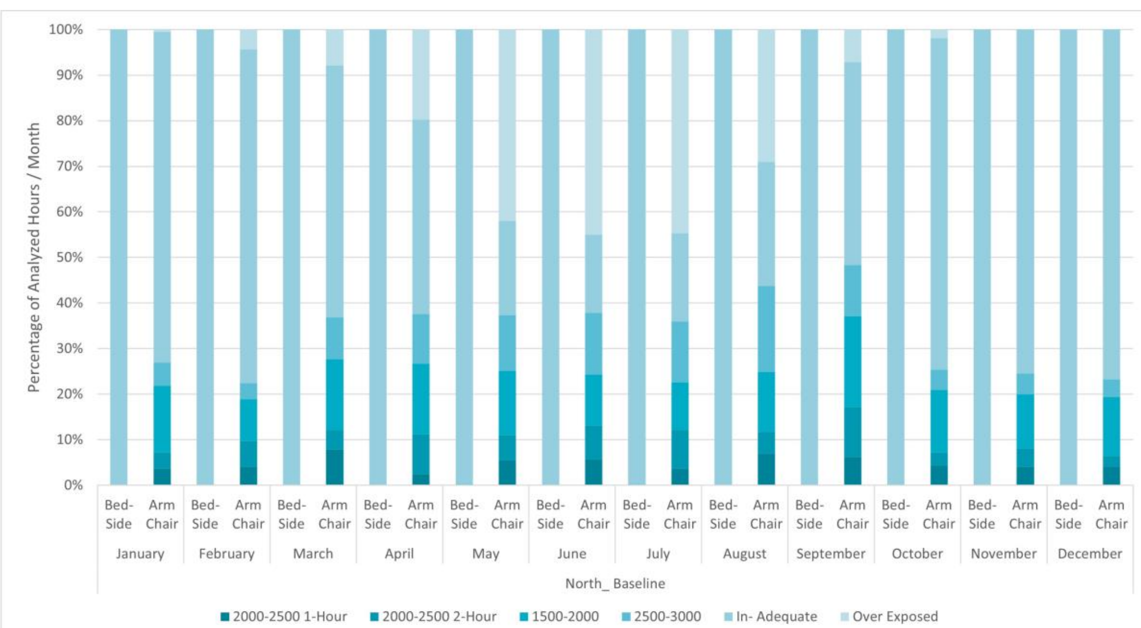


Figure 13: North orientation, annual illuminance values.

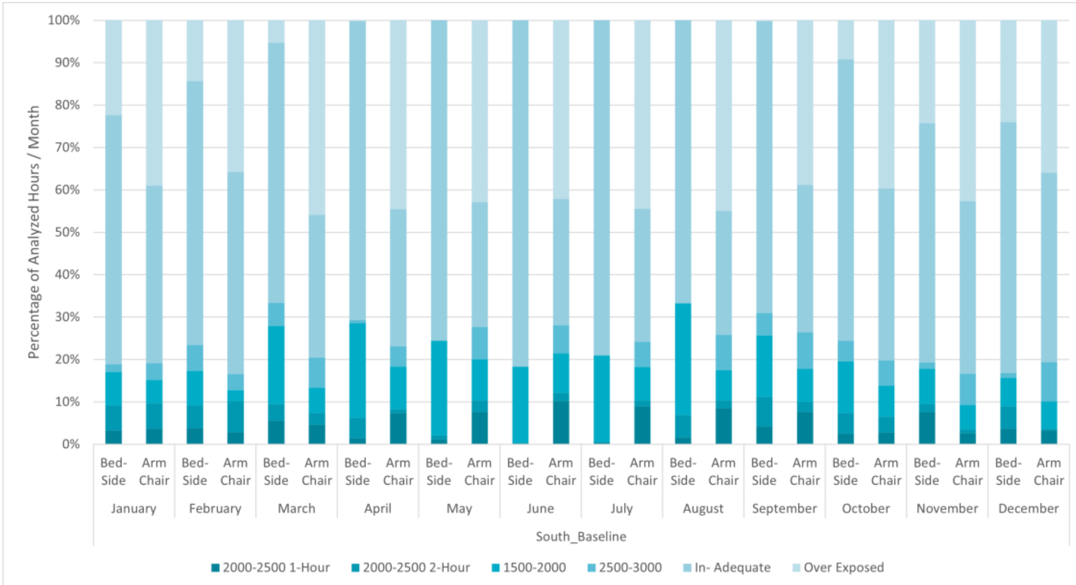


Figure 14: South orientation, annual illuminance values.

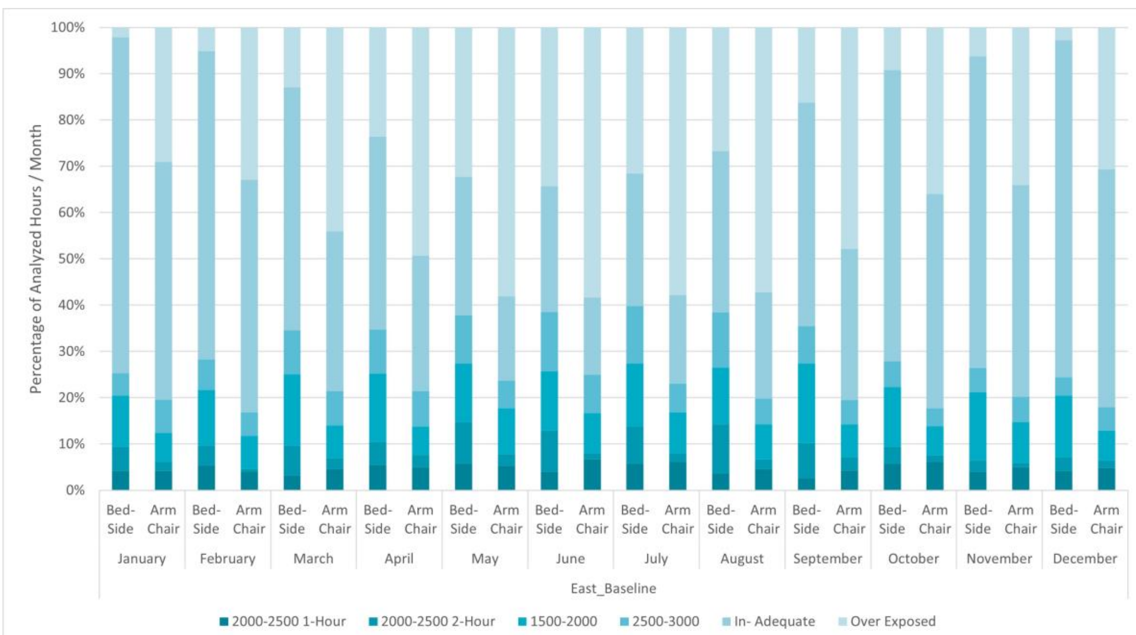


Figure 15: East orientation, annual illuminance values.

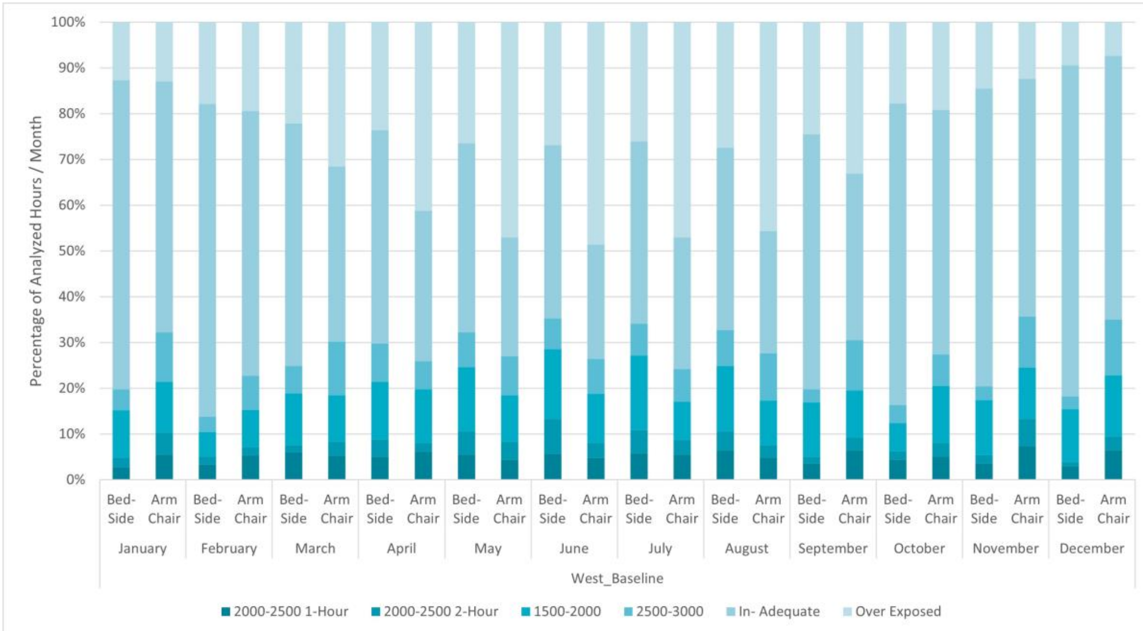


Figure 16: West orientation, annual illuminance values.

Both figures 15, and 16 showcase the results of the East, and West orientations. The average percentage of hours meeting the required thresholds at the head of the bed lies between 30 – 40%, and 20-35% respectively. The armchair values are very similar in percentages to point A. Overall, the values are close to that of the South orientation. However, when represented graphically for each month as figures 17, and 18, showcasing the percentage of useful hours of each orientation, it becomes clear that the South orientation suffer from the least useful hour percentage over the year. Though the comparison at the armchair showcases that the South functions slightly better than the East orientation, figure 17 shows the opposite. In addition, the North performs best at the armchair, however at the head of the bed, it was the only orientation which recorded a zero percentage of useful daylight hours. Therefore, based on these results, the North, and South orientations were chosen to expand the experiment and investigate with design proposals to increase the percentage of useful hours per month.

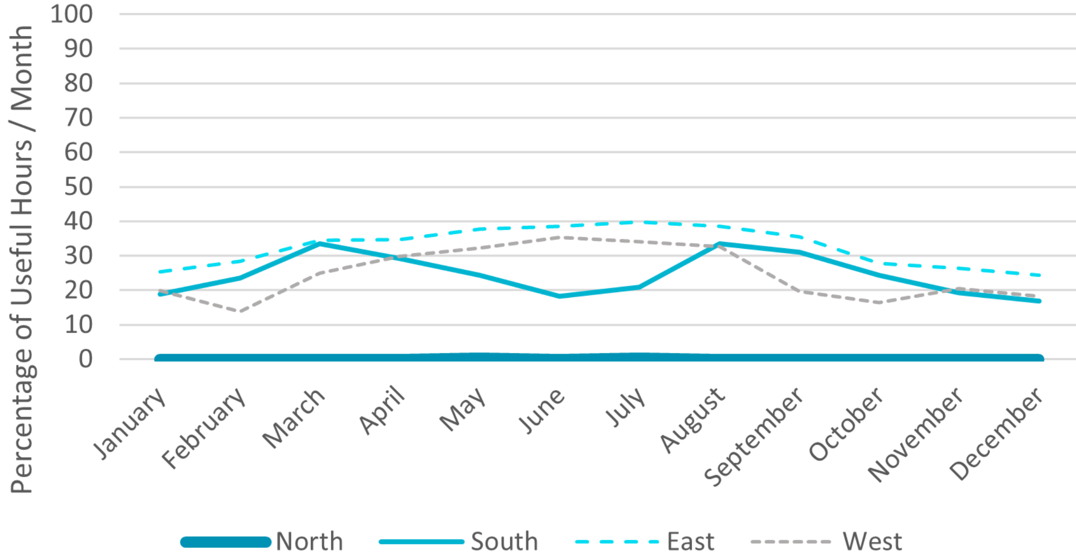


Figure 17: Comparison of baseline case percentage of useful hours/ month at the head of the bed.

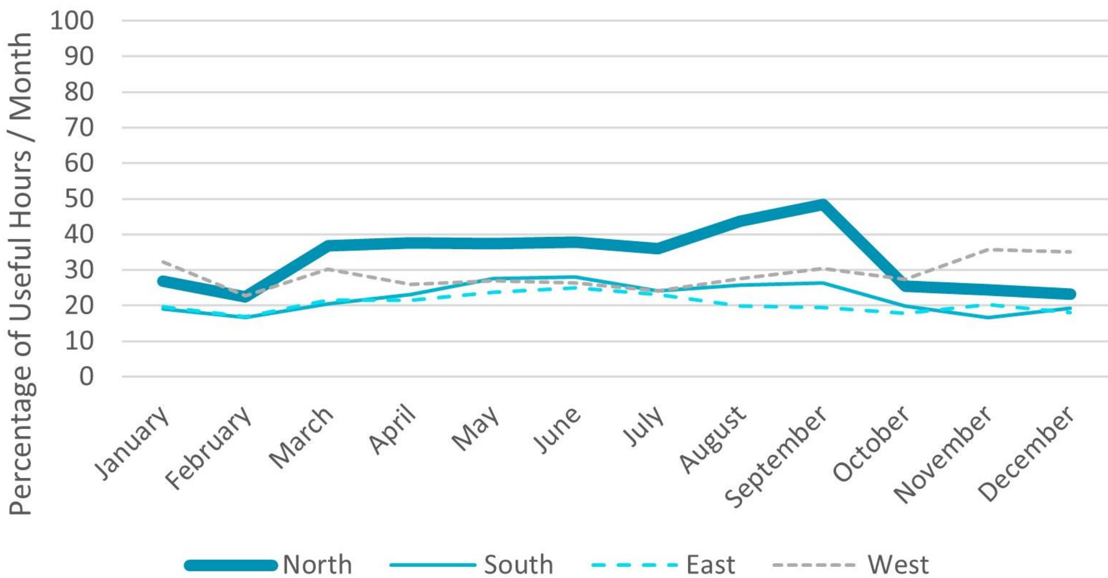
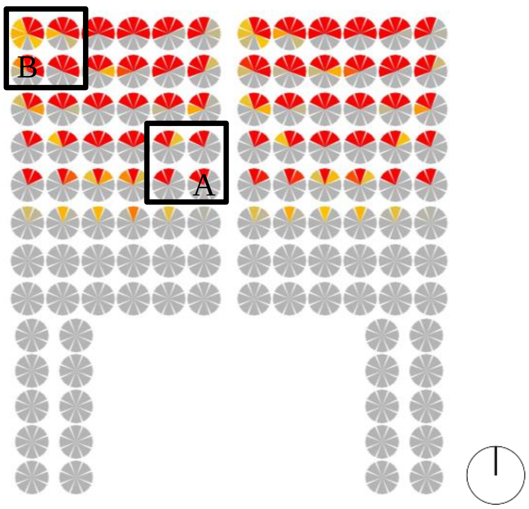


Figure 18: Comparison of baseline case percentage of useful hours/ month at the armchair.

4.1.2 Daylight Glare Probability (DGP)

This section provides the baseline case results of the annual and point in time daylight glare probability for each orientation of the North, South, East, and West. The simulation ran using Climate Studio which analyses the entire room annually.

The figures showcasing the annual DGP plan include black rectangles demonstrating the area analyzed. However, the investigation focused on choosing one sensor index within each area to compare the results of the orientations.



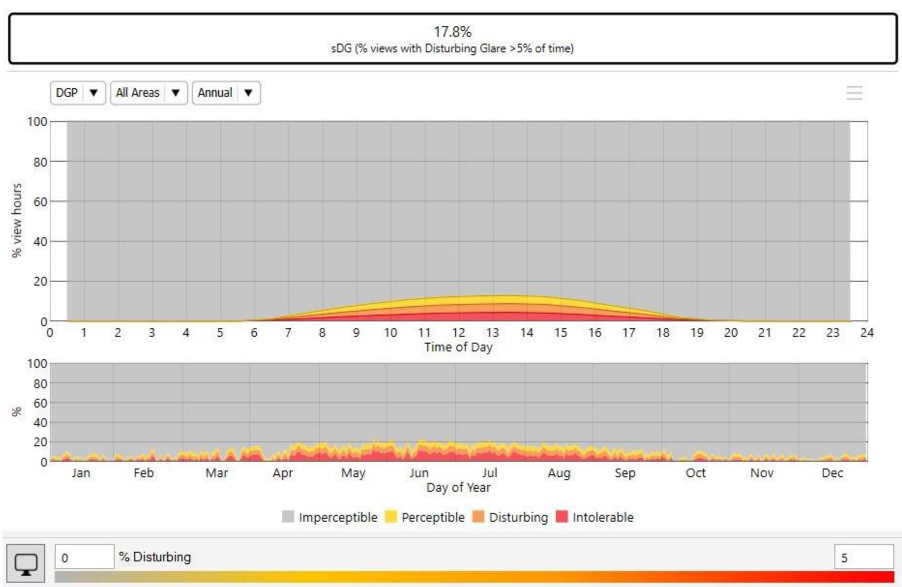
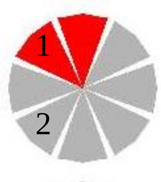


Figure 19: North annual DGP plan and schedule

The annual DGP is analyzed for back to back identical bedrooms. Figure 19 showcases the annual DGP which is at 17.8% throughout the entire room where most of the glare is directed towards the window. However, when looking away from the window you could avoid most glare issues.

The annual DGP in Climate Studio is divided into sensor points. Each sensor point is called a sensor index and is given a number within the plan. Each sensor index is represented by a pie which is divided into 8 numbers called the view index numbers. We expanded the research to analyze point in time glare at both points A and B investigating two view indexes at two different directions at each point where point 1 is usually facing the window, while point 2 is facing away from the window towards the room.

 Figure 20: Sensor Index: Location Point A: Analyzed points 1 & 2- North	 Figure 21: Sensor Index: Location Point B: Analyzed points 1 & 2- North

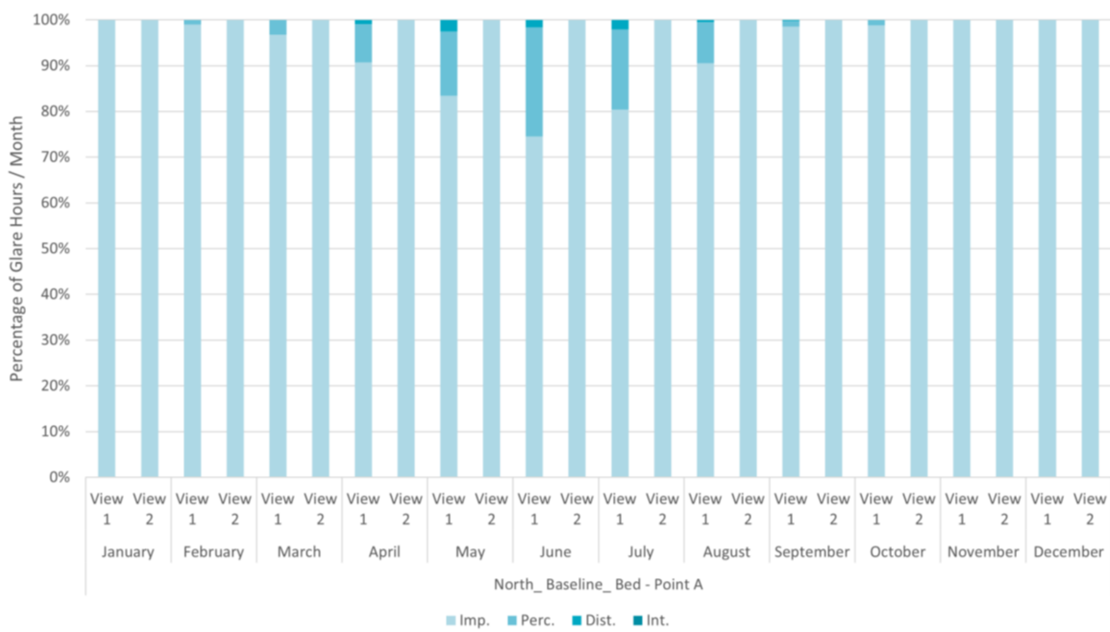


Figure 22: North orientation, point in time glare; Location point A

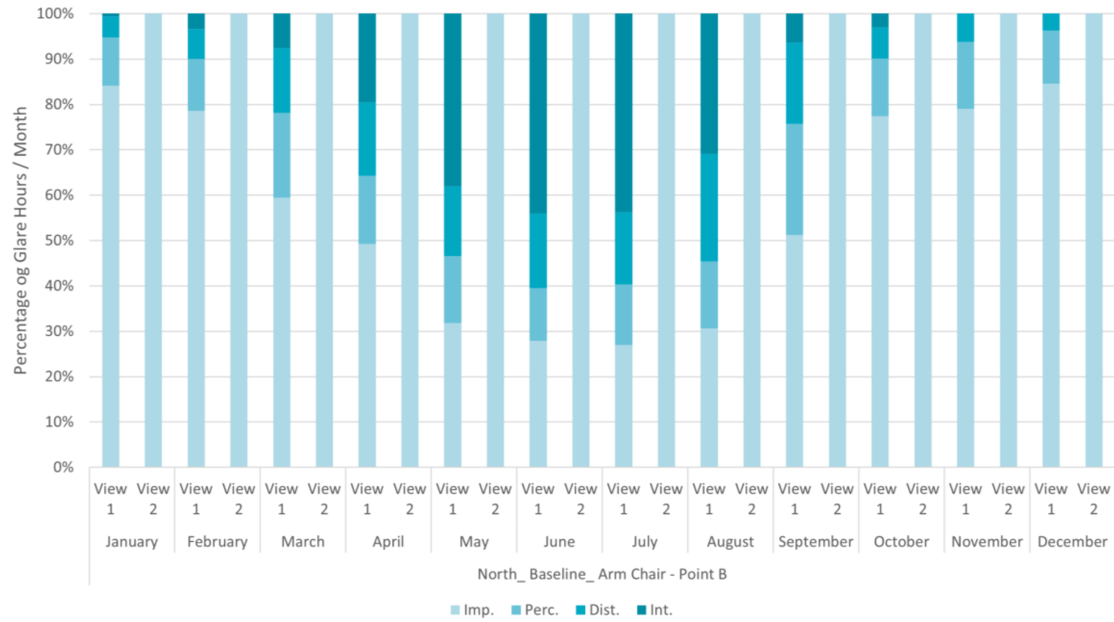


Figure 23: North orientation, point in time glare; Location point B

Figures 22, and 23 demonstrate the point in time glare in the North orientation showcasing imperceptible, perceptible, disturbing, and intolerable glare. Point A at the head of the bed is considered visually comfortable with nearly almost 100% of the analyzed time receiving imperceptible glare. However, point B at the armchair receives a range of perceptible to intolerable glare when looking towards the window – view 1. This issue is resolved when looking slightly away from the window, as view 2 reaches 100% of imperceptible glare over the year.

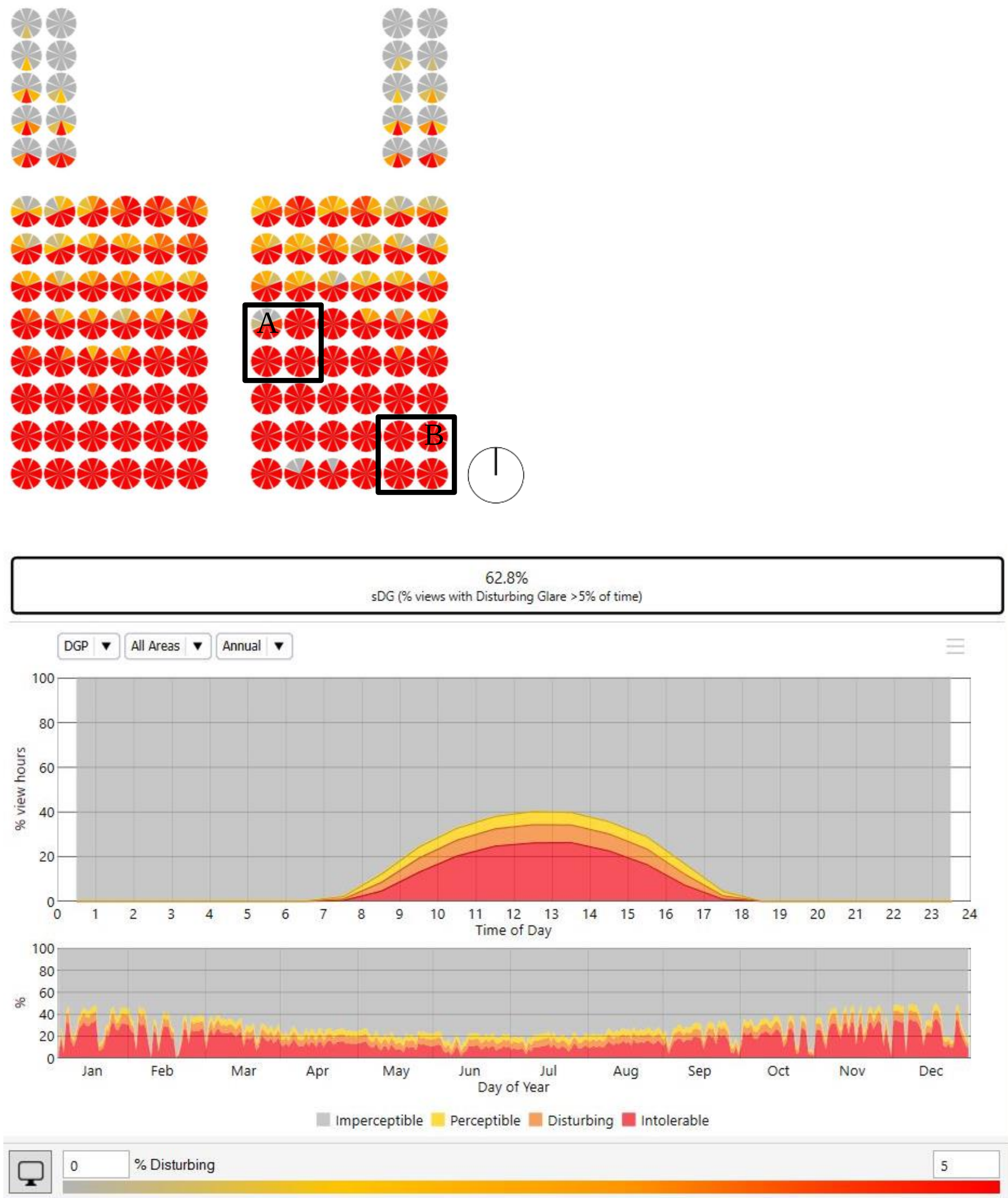


Figure 24: South annual DGP plan and schedule

On the other hand, figure 24 showcases issues with the glare in the South orientation with up to 62.8 % of annual DGP. The entire space suffers from considerably high values of glare making the whole experience uncomfortable. However, when analyzing point in time glare of each sensor index, point A performs very good in terms of glare issues which is showcased in figure 27. Point B, which is shown in figure 28, demonstrates that both views 1 and 2 at the arm chair suffer from high values of glare, where view 1 reaches up to 50% or more of intolerable glare in most months throughout the year.

Figure 25: Sensor Index: Location Point A: Analyzed points 1 & 2- South

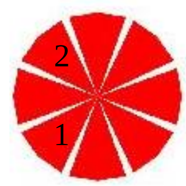


Figure 26: Sensor Index: Location Point B: Analyzed points 1 & 2- South

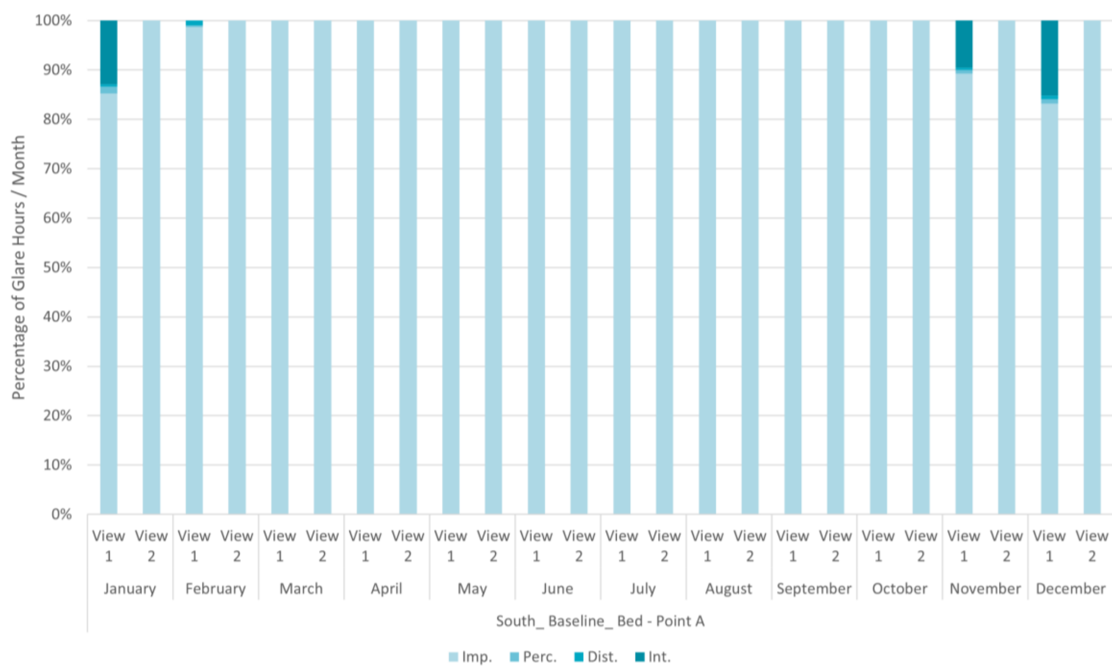


Figure 27: South orientation, point in time glare; Location point A

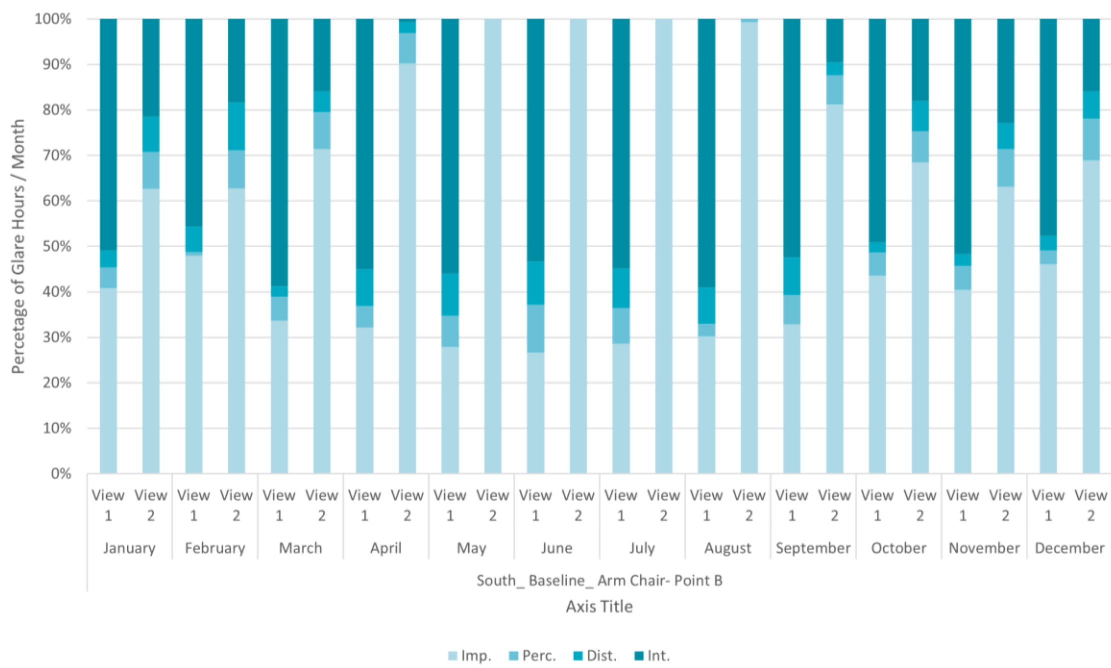


Figure 28: South orientation, point in time glare; Location point B

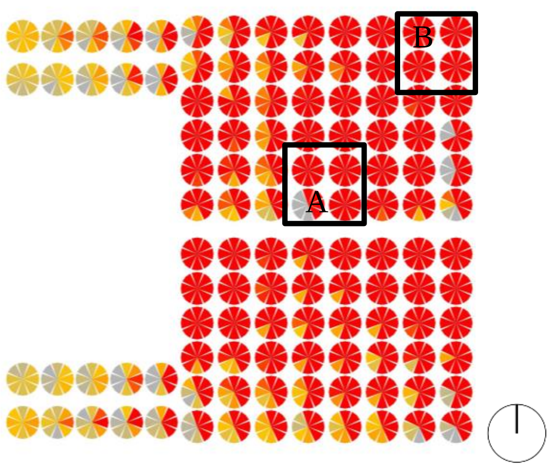
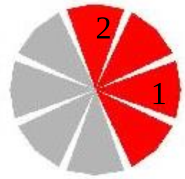
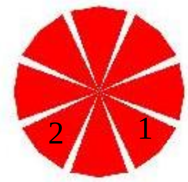


Figure 29: East annual DGP plan

 Figure 30: Sensor Index: Location Point A: Analyzed points 1 & 2- East	 Figure 31: Sensor Index: Location Point B: Analyzed points 1 & 2- East

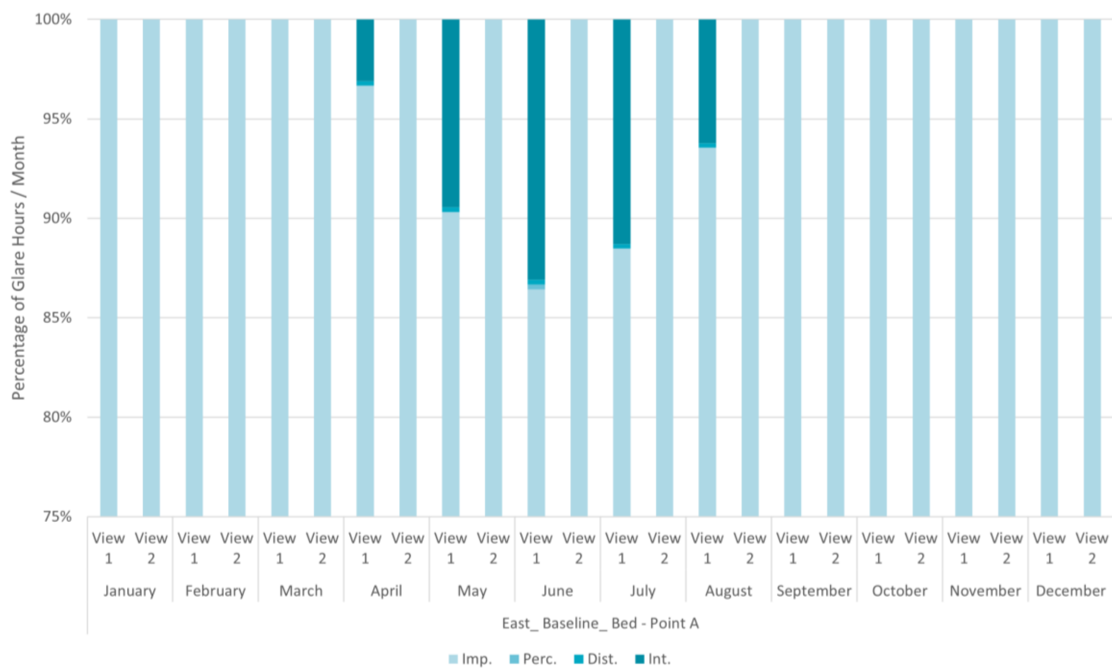


Figure 32: East orientation, point in time glare; Location point A

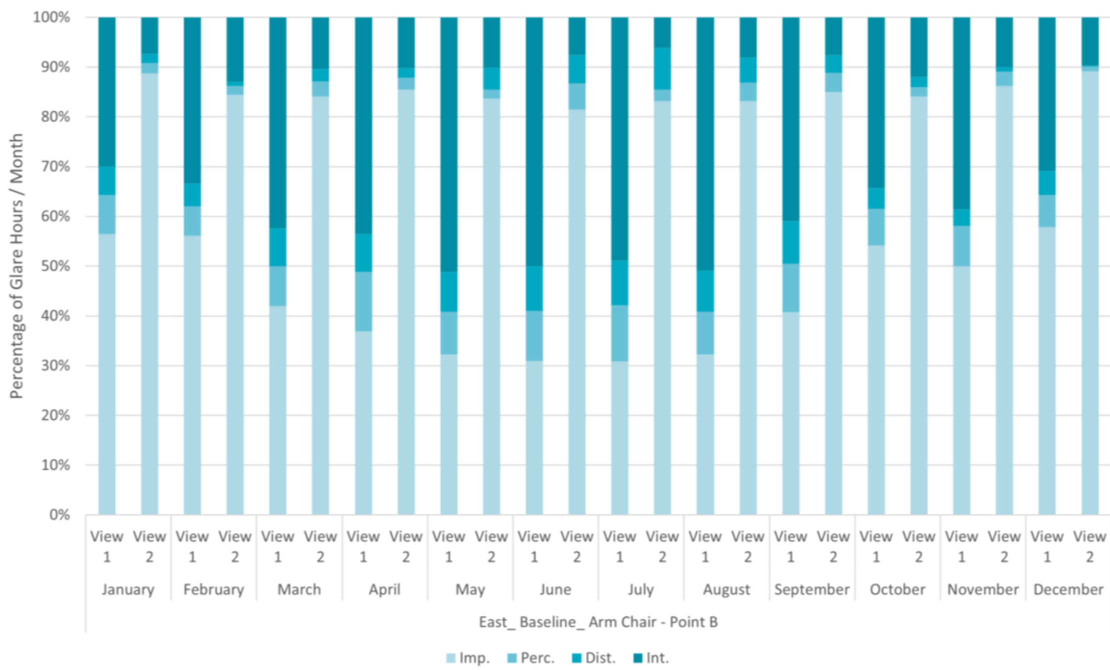


Figure 33: East orientation, point in time glare; Location point A

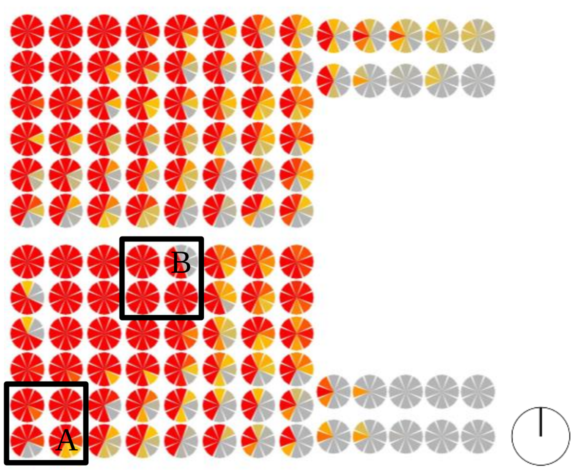
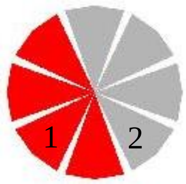


Figure 34: West annual DGP plan

 Figure 35: Sensor Index: Location Point A: Analyzed points 1 & 2- West	 Figure 36: Sensor Index: Location Point B: Analyzed points 1 & 2- West

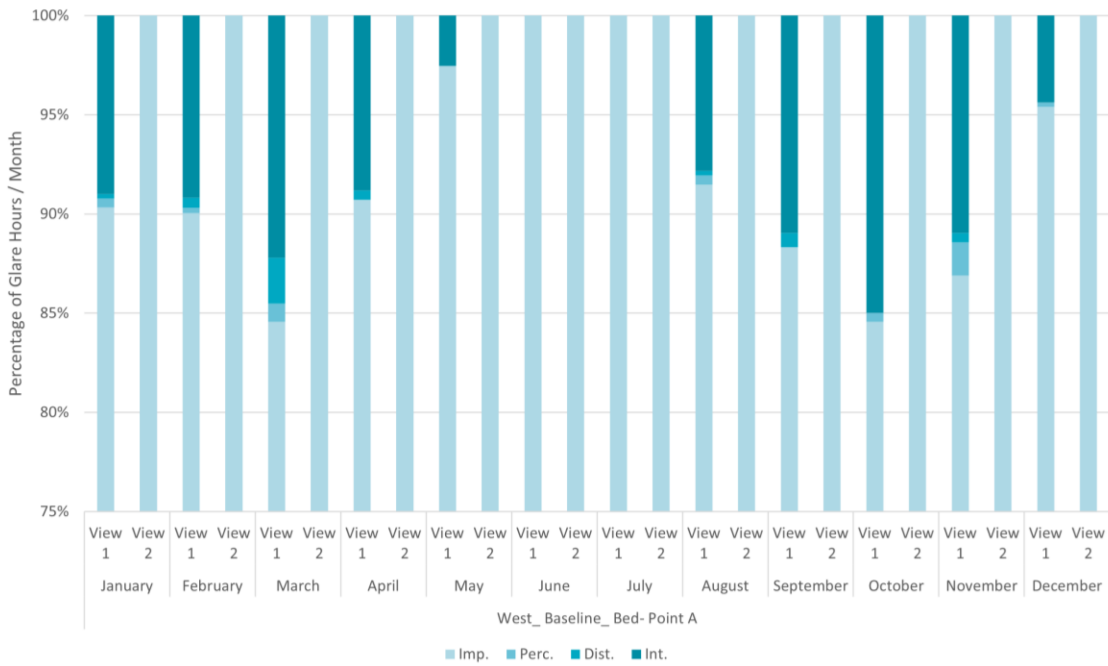


Figure 37: West orientation, point in time glare; Location point A

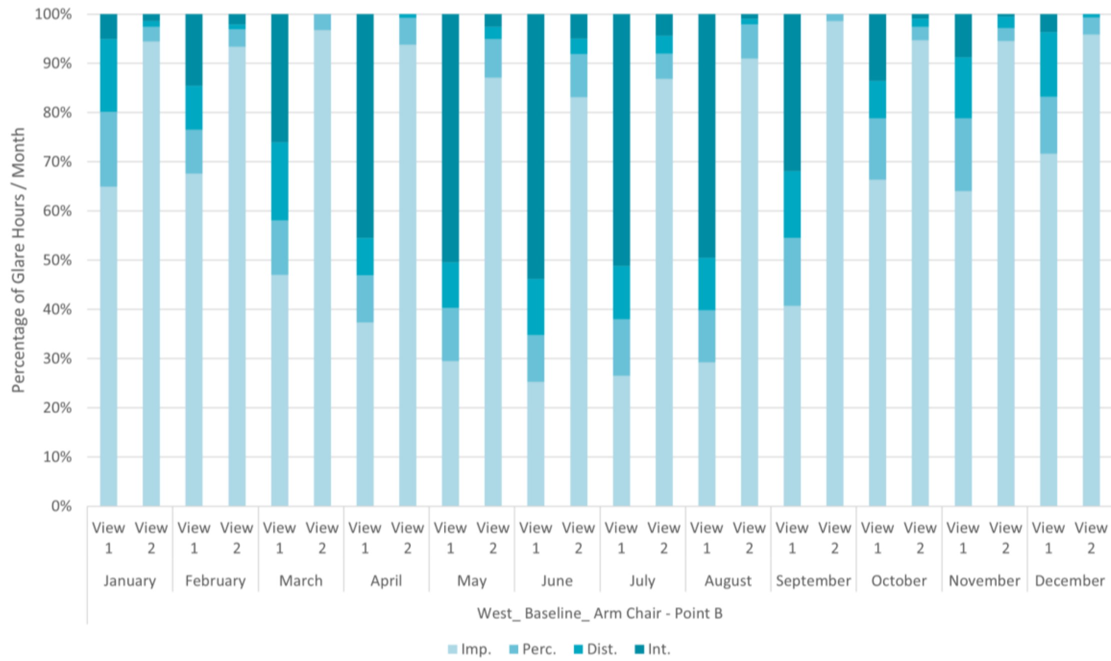
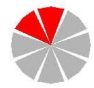
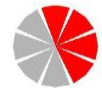
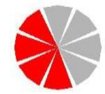


Figure 38: West orientation, point in time glare; Location point B

Figures 29, and 34 showcase the annual DGP plan at both the East and West orientations with an average of 68.1 % and 52.6% of annual glare, respectively. The East orientation experiences slightly higher glare values than the South Orientation over the entire plan.

Based on these results, we compared between the baseline results at each orientation to indicate which orientation suffers most from glare issues. Table 4, demonstrates a one on one comparison between the annual DGP at each sensor index at both points A, and B.

Table 4: Comparison of annual DGP percentage between at both points A, and B

		At Head of the Bed - Point 1			
		North	South	East	West
Sensor Index					
Percentage of Annual Glare		17.80%	62.80%	68.10%	52.60%
Avg. % of Glare	Imperceptible	95%	98%	97%	96%
	Perceptible	4%	0%	0%	0%
	Disturbing	1%	0%	0%	0%
	Intolerable	0%	2%	3%	4%
		Arm Chair - Point 2			
Sensor Index					
Avg. % of Glare	Imperceptible	79%	51%	54%	72%
	Perceptible	6%	6%	6%	7%
	Disturbing	8%	9%	9%	9%
	Intolerable	7%	34%	32%	12%

Figures 39, and 40 demonstrate the percentage of imperceptible hours received at each orientation in the baseline case at both views 1 and 2 at the armchair. The comparison of the baseline case at the head of the bed was unnecessary given that most of the glare issues lie at the armchair. As shown in figure 39, the south orientation has the least percentage of imperceptible hours throughout the year when compared to other orientations. Though view 2 which is analyzed when looking away from the window showcases months are comfortable with up to 100% of imperceptible glare. Still, the issue remains constant with high glare values affecting mostly the south.

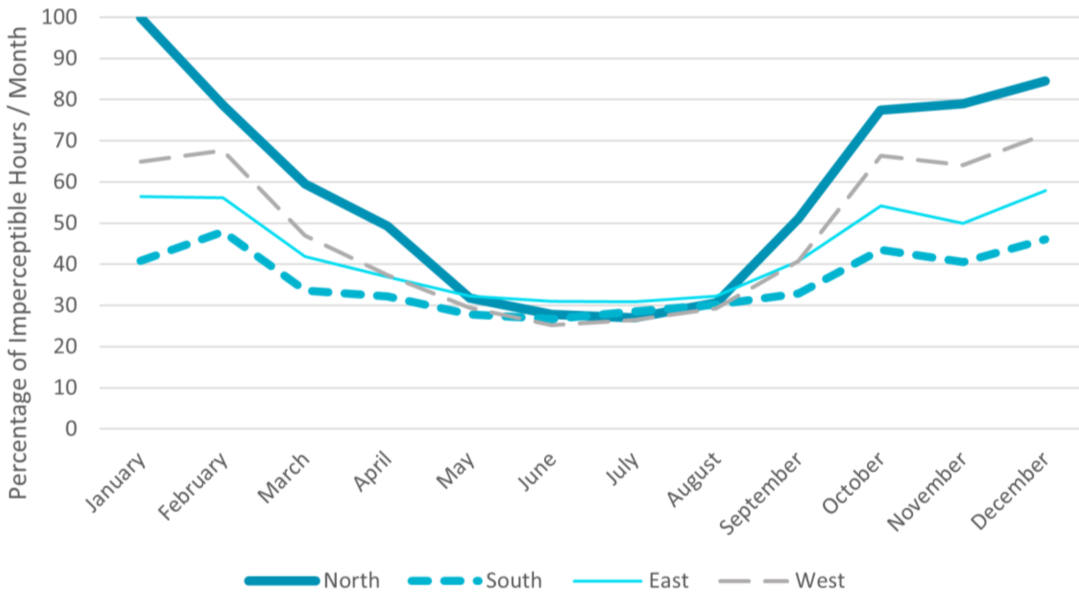


Figure 39: Imperceptible Glare Hours- Baseline comparison- Armchair View 1

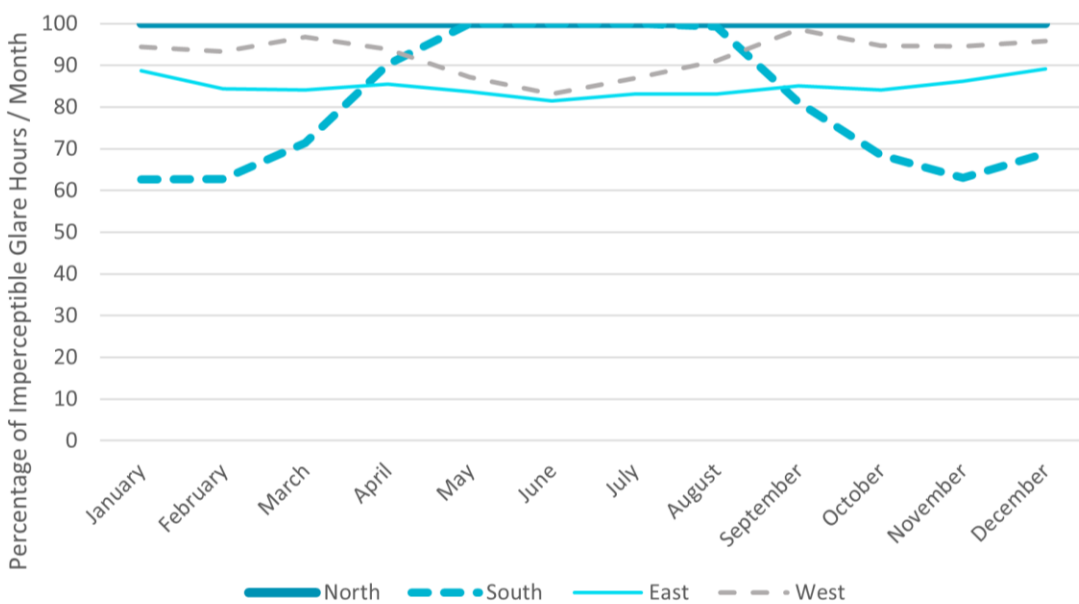


Figure 40: Imperceptible Glare Hours- Baseline comparison- Armchair View 2

4.2 Design Case Results

As a result of the baseline analysis, the research was extended to include design proposals for both the North and South orientations. The North and South orientations were chosen based on the analysis of the point in time illuminance which showed that they both include the least useful hours that entrain the circadian system per year. In addition to the high annual glare values that cover most of the south orientation plan. The goal was to propose design alternatives that would improve the overall quality of daylight within the space by increasing the number of useful hours and minimizing the annual DGP.

4.2.1 Point in Time Illuminance

Both figures 40, and 41 show a significant improvement in the number of useful daylight hours when compared to the baseline case result. However, iteration 2 which uses the double glazing provided better results over the year, given that the use of single glazing has higher visual light transmittance which overexposed the space with higher illuminance values. In addition, the percentage of hours meeting the required thresholds ranges between 10-70 % over the year at both points A and B. This is a huge increase in the number of daylight hours that entrain the circadian rhythm could promote the health and well-being of the users.

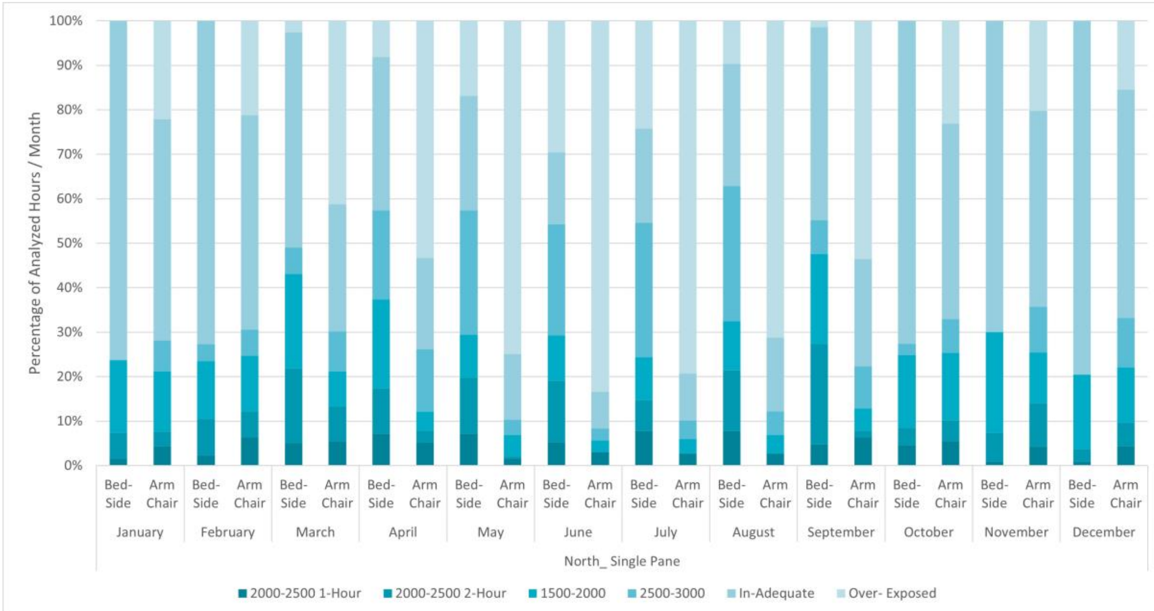


Figure 41: North orientation with single glazing and increased WWR, annual illuminance values.

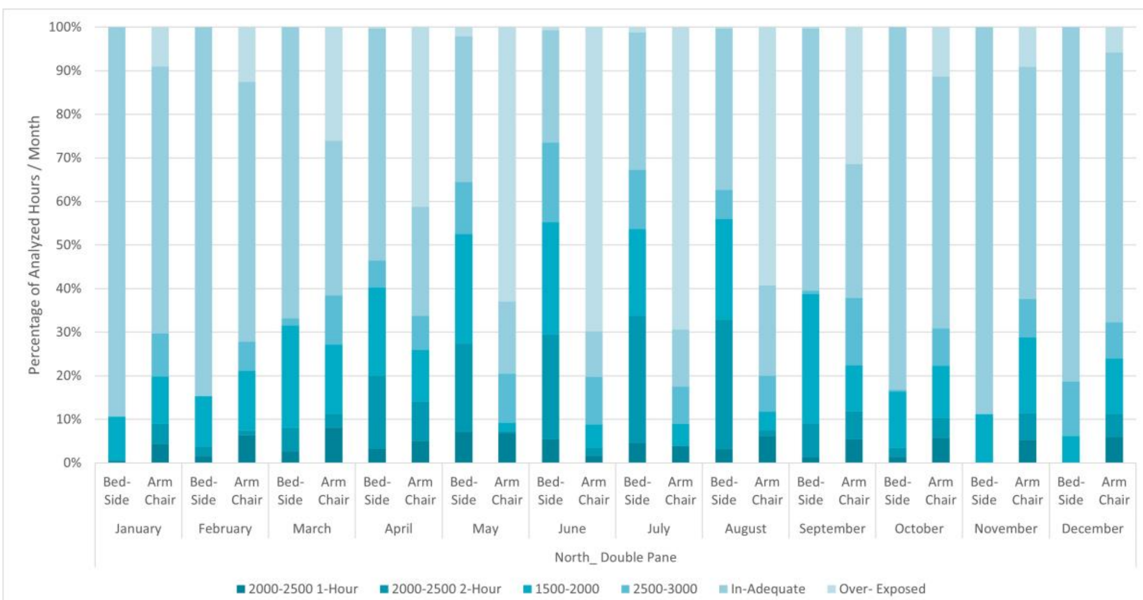


Figure 42: North orientation with double glazing and increased WWR annual illuminance values.

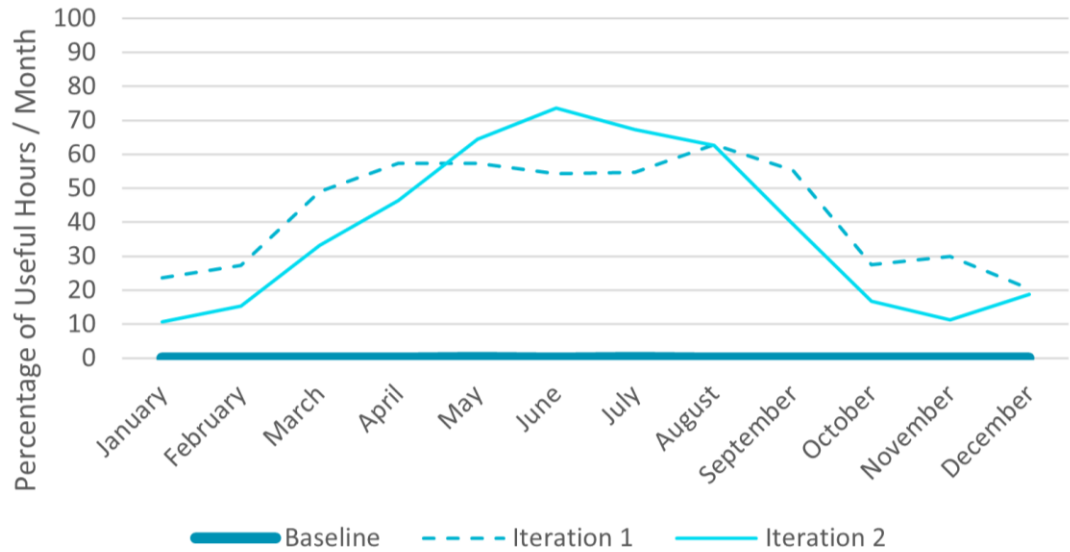


Figure 43: Comparison of north design case percentage of useful hours/ month at the head of the bed.

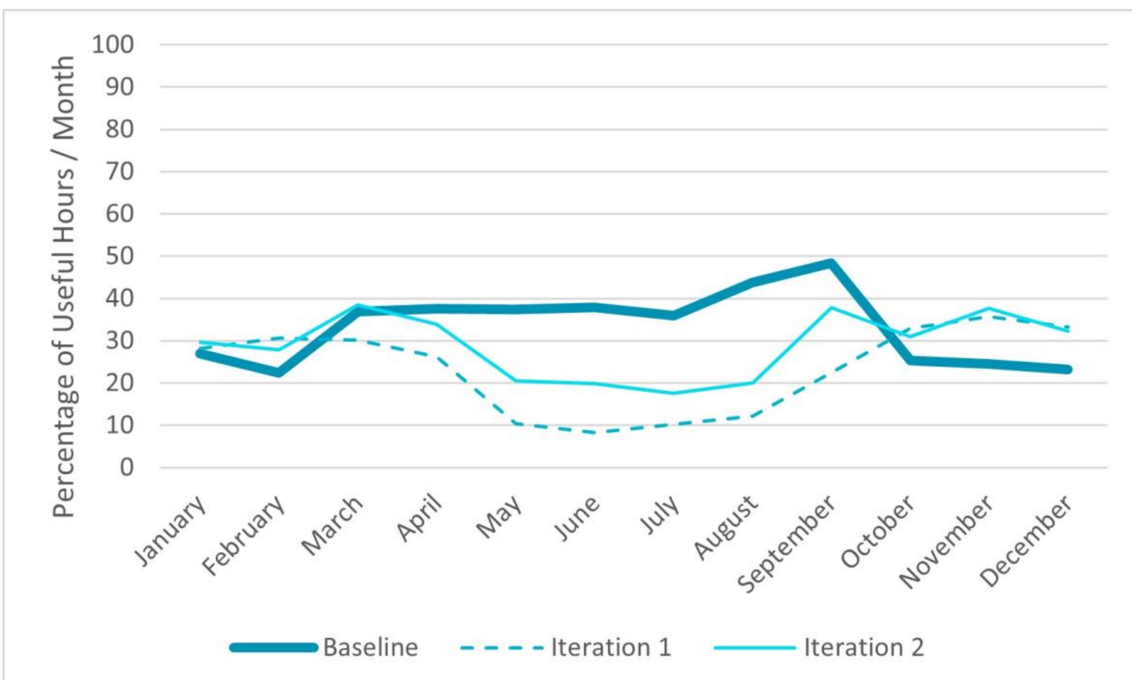


Figure 44: Comparison of north design case percentage of useful hours/ month at the armchair.

Figures 43 and 44 allow a better understanding and easier comparison for both cases when compared to the baseline case results. The performance and existence of useful daylight hours was increased significantly at point A, however, point B at the armchair was over exposed. The double-pane glazing in the second iteration is performing slightly better especially at the armchair.

Moving on to the second part of the design investigation, the South orientation as mentioned was proposed in four different design alternatives. However, when choosing the split system specifically, each split system iteration was simulated through DIVA to investigate the quality of useful daylight hours entered within the space at both points A and B in June, September, December, and March 21st. Figure 9 showcases the chosen iteration for full analysis which includes the highest daylight values achieving the main thresholds between 2000 – 2500 lx at an exposure of 1 -2 hours. Though the analysis included 4 days only over the year, it represented the equinox and solstice of the year which allow a better understanding of the daylight performance throughout the year. Based on these iterations, an annual point in time illuminance was simulated and is represented in the following figures for each iteration in the south orientation.

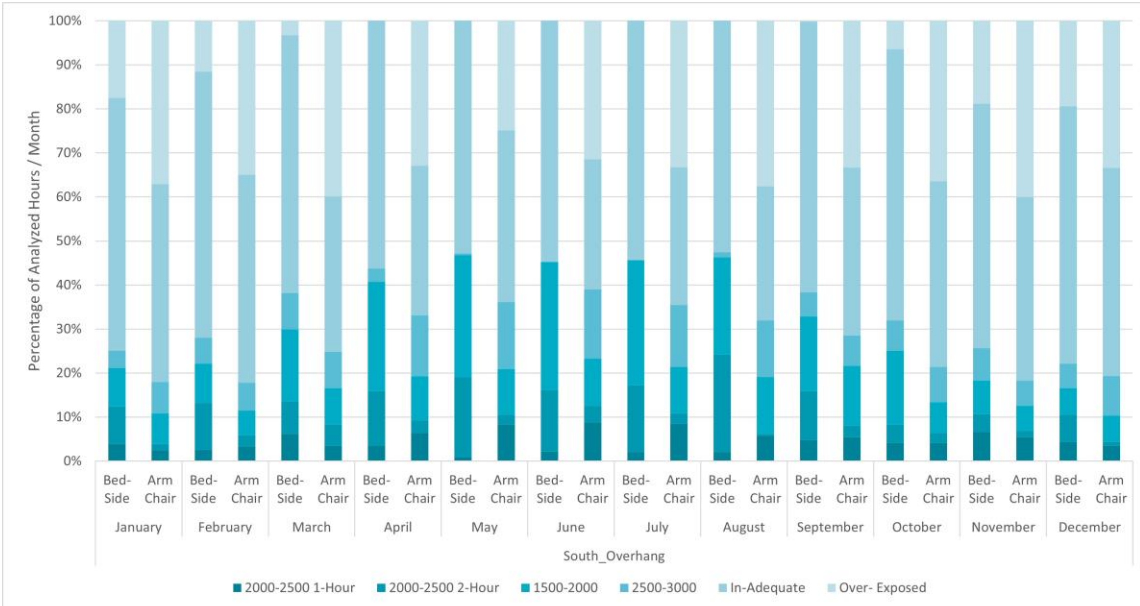


Figure 45: South orientation with overhang, annual illuminance values.

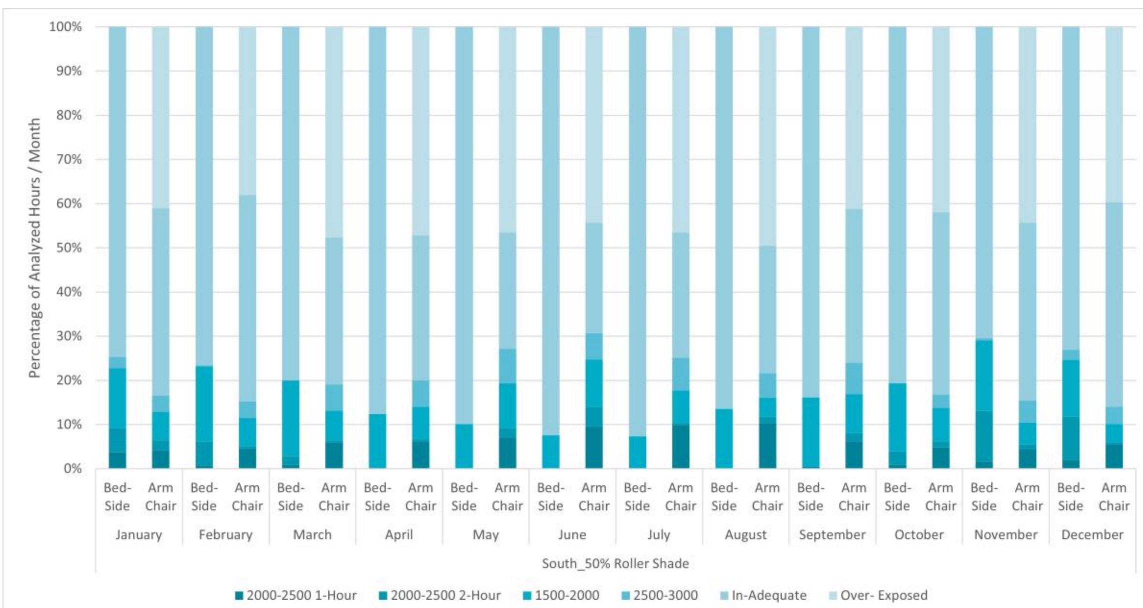


Figure 46: South orientation with 50% roller shade, annual illuminance values.

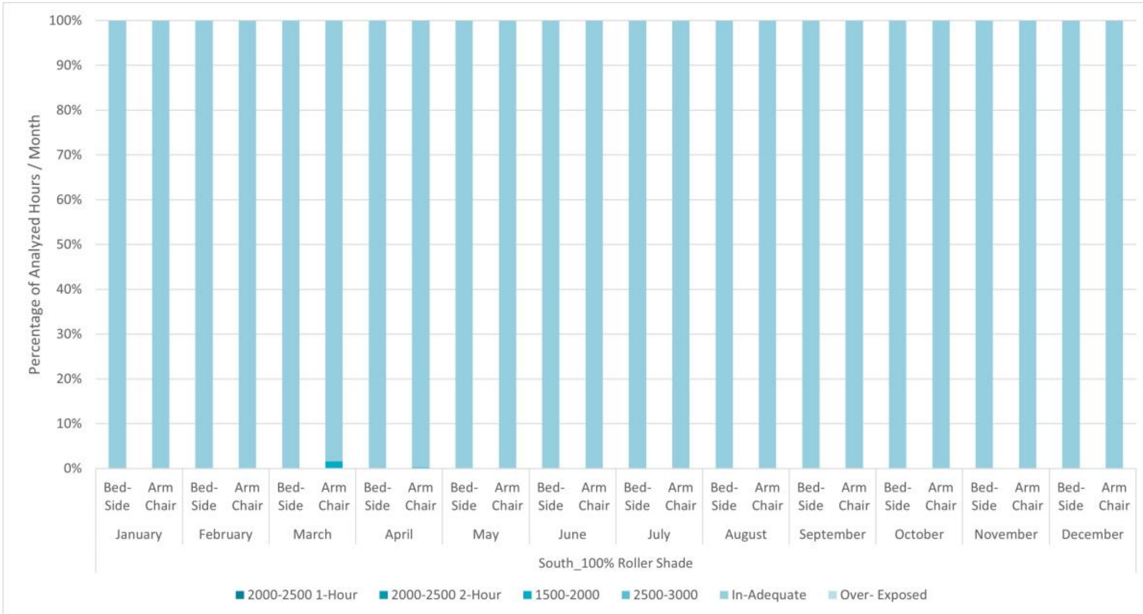


Figure 47: South orientation with 100% roller shade, annual illuminance values.

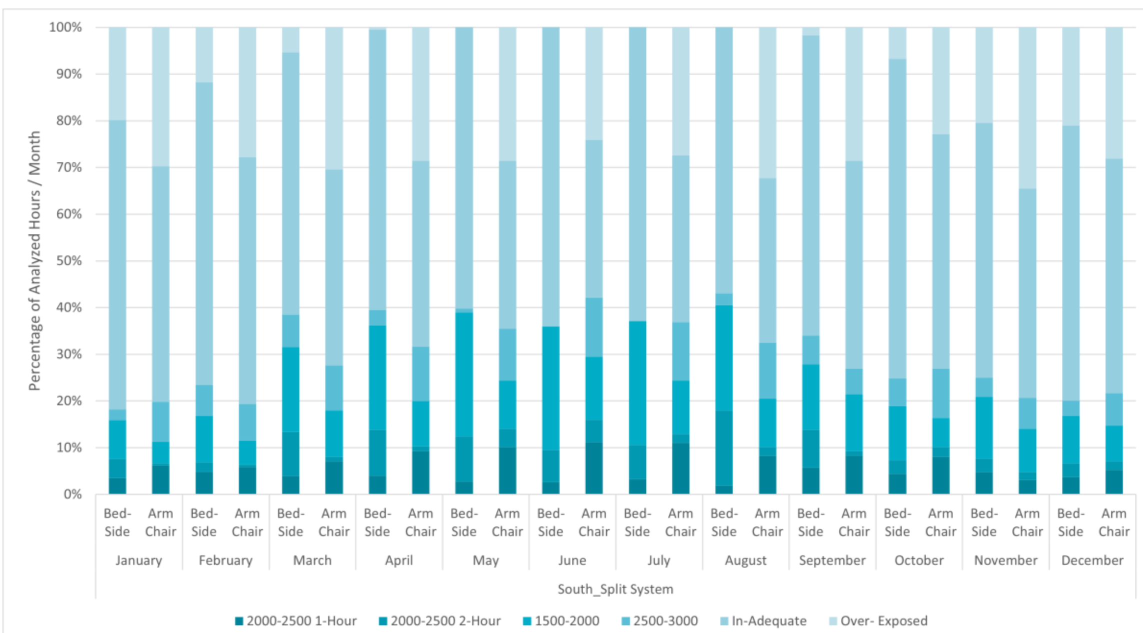


Figure 48: South orientation with split system, annual illuminance values.

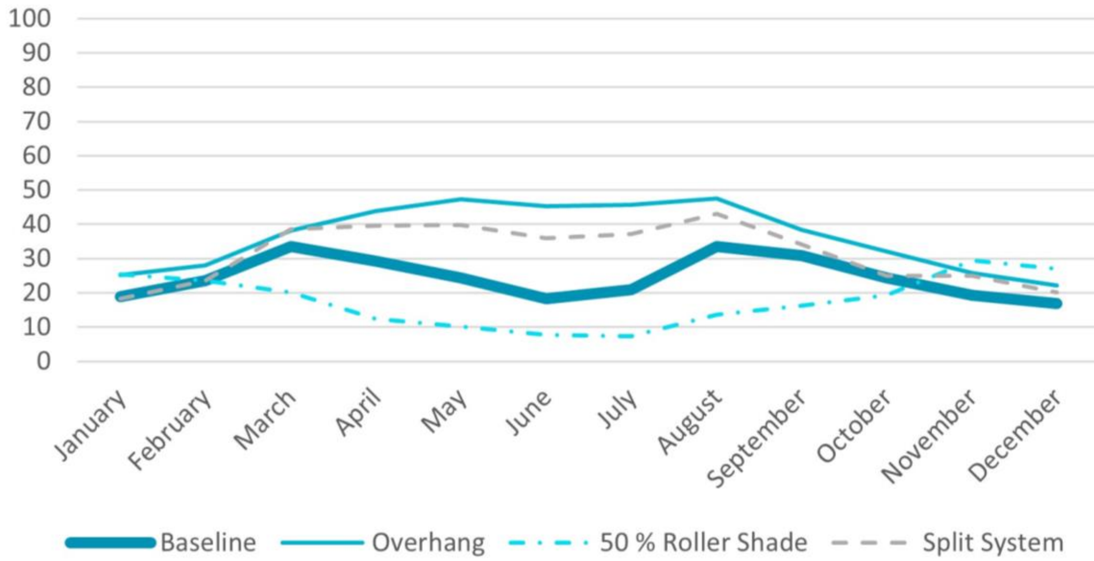


Figure 49: Comparison of south design case percentage of useful hours/ month at the head of the bed.

According to the results demonstrated in figures 45, 46, 47, and 48, the best performing scenarios were the use of the overhang and the split system. However, the use of roller shades in both cases did not show promising percentages of useful daylight as it did not allow enough useful light to enter the space.

Figures 49, and 50 demonstrate the performance of each iteration in terms of useful daylight hours. As mentioned, the overhang, and the split system iteration both perform better however, the split system scenario showcases the best outcome given the percentage of increased useful daylight hours when compared to the baseline case. The graphs demonstrate that at both the bed and the armchair, useful daylight hour percentages increase with an average of 10-20% especially in months of April, May, June, and July. The 100% roller shade iteration was not added to these graphs given that it does not allow any daylight to enter, thus it cannot be compared as it performs worse than the baseline case.

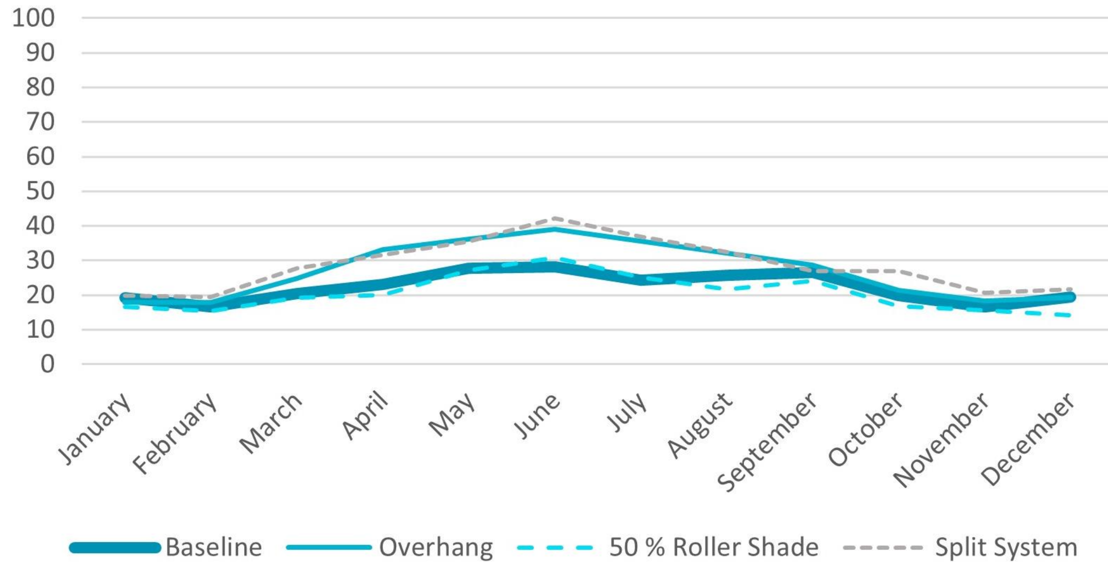


Figure 50: Comparison of south design case percentage of useful hours/ month at the armchair.

4.2.2 Daylight Glare Probability

This section presents the analyzed annual and point in time daylight glare probability in the proposed design iterations. Figures 51, and 52 showcase the results of the North Orientation iteration with the increased WWR and the Single glazing window material. Though the annual glare throughout the entire room does not exceed much than that of the baseline case. The analysis of the point in time glare was simulated for the same views of the baseline case. The results demonstrated a significant increase in glare especially at the armchair. However, this issue is again resolved when turning slightly away from the window as view 2 showcases a 100% of imperceptible hours reaching the armchair in that direction.

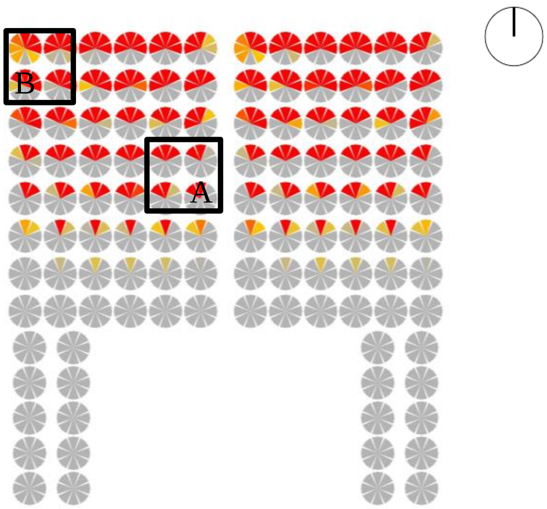


Figure 51: North Iteration 1 Single Glazing, annual DGP plan.

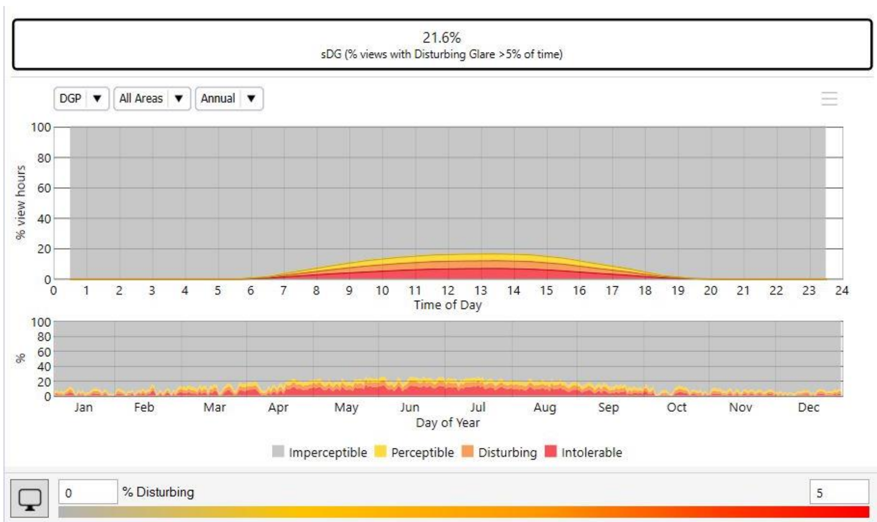


Figure 52: North Iteration 1 Single Glazing, annual DGP schedule.

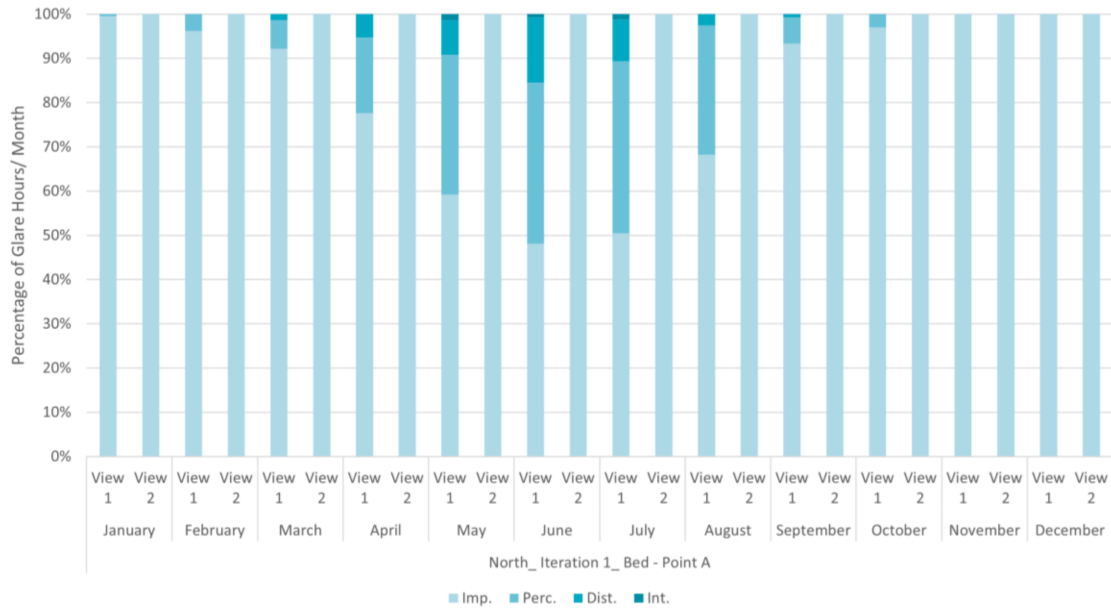


Figure 53: North orientation iteration 1, Increased WWR, Single Glazing; point in time glare; Location point A

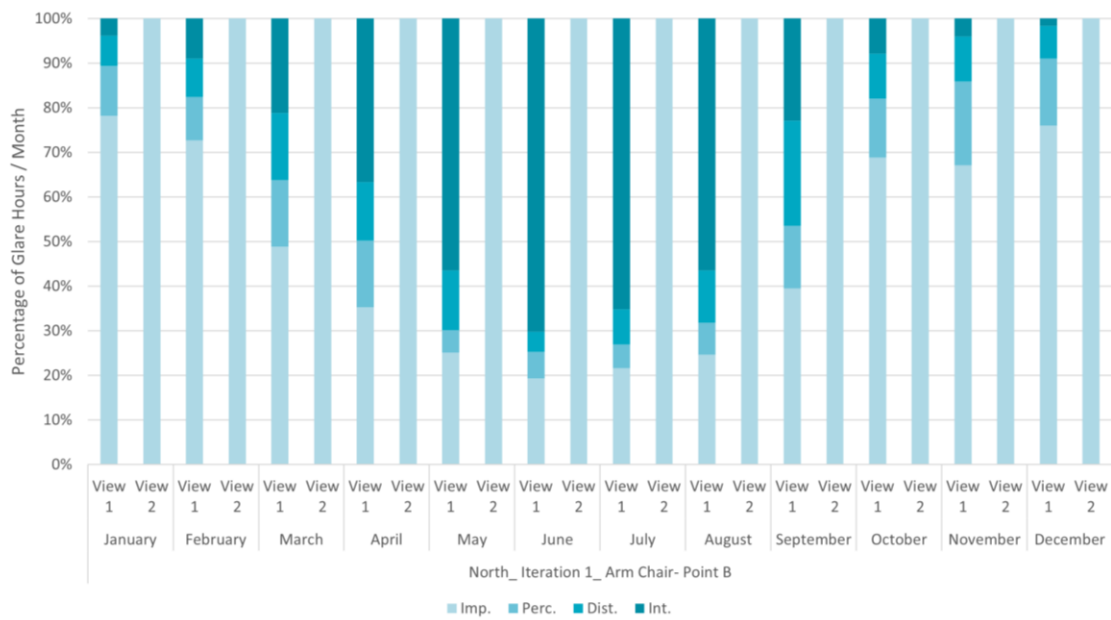


Figure 54: North orientation iteration 1, Increased WWR, Single Glazing; point in time glare; Location point B

Figures 53 and 54 demonstrate a detailed breakdown of the analyzed daylight hours with imperceptible, perceptible, disturbing, and intolerable glare. The annual DGP is slightly improved when using the double-glazing window material in iteration 2 as shown in figures 55, and 56. It can be inferred that both iterations results are very close. Figures 57, and 58 showcase the point in time glare results at both points A, and B.

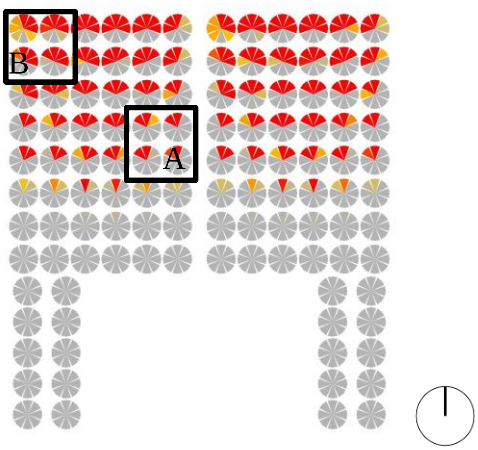


Figure 55: North Iteration Double Glazing, annual DGP plan.

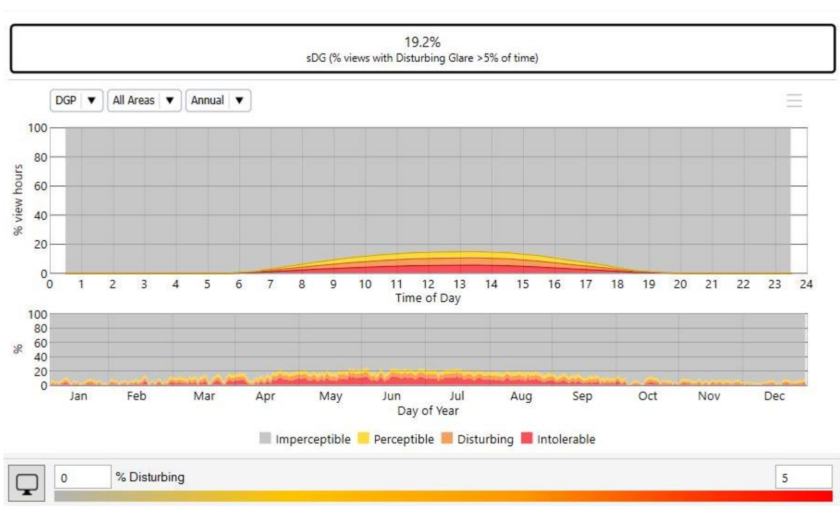


Figure 56: North Iteration Double Glazing, annual DGP schedule.

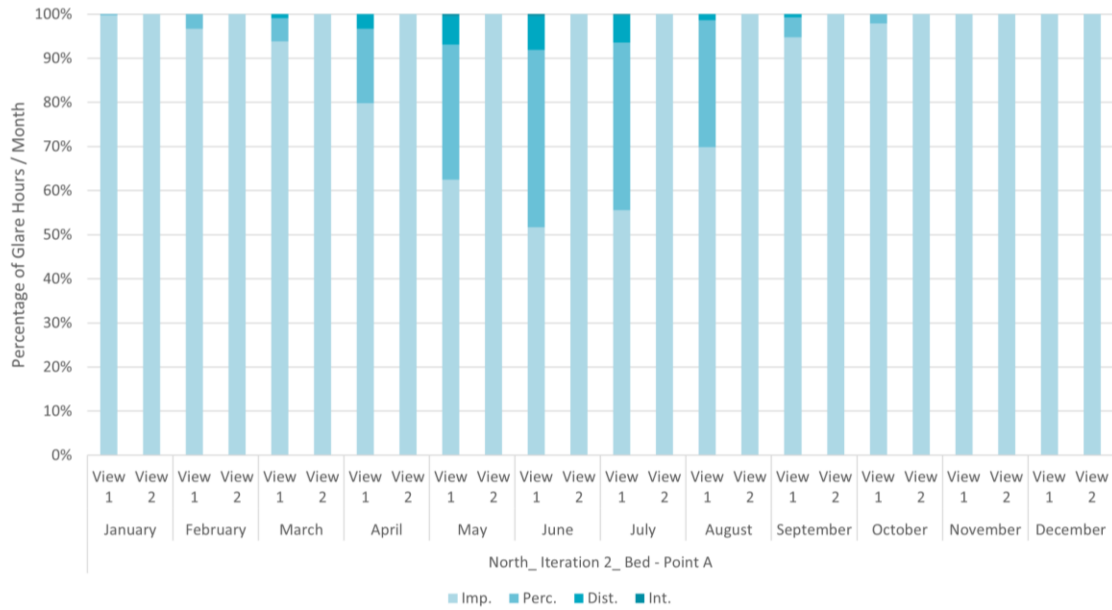


Figure 57: North orientation iteration 2, Increased WWR, Double Glazing; point in time glare; Location point A

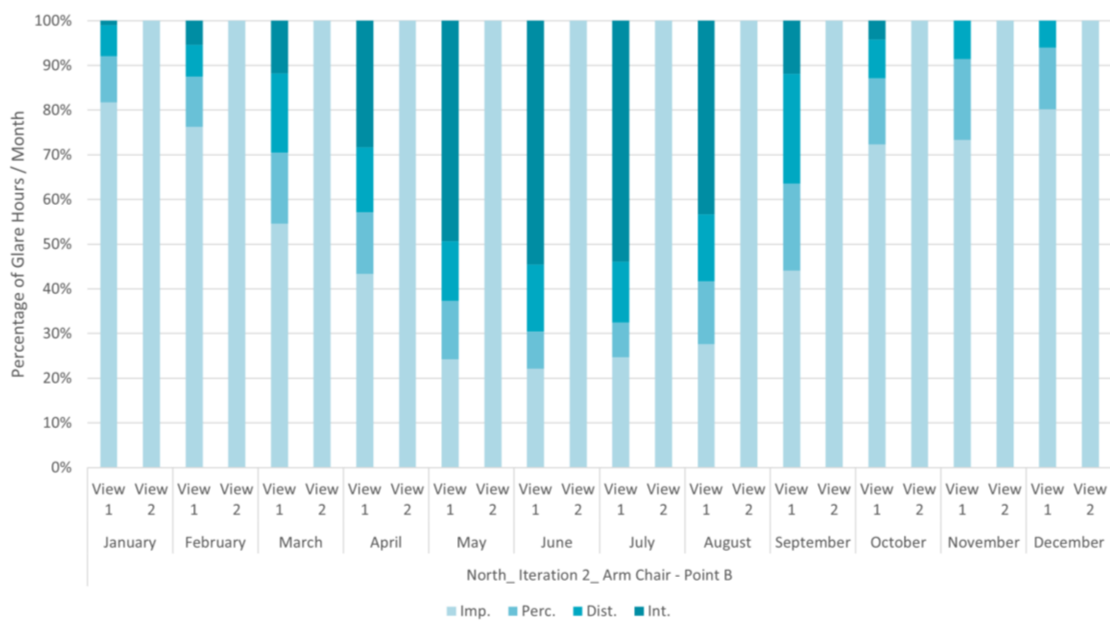


Figure 58: North orientation iteration 2, Increased WWR, Single Glazing; point in time glare; Location point B

Table 5: Comparison of North Orientation iterations, annual DGP percentage at both points 1, and 2.

		Bedside	
		Single	Double
Sensor Index			
Percentage of Annual Glare		21.60%	19.20%
Avg. % of Views	Imperceptible	93%	94%
	Perceptible	5%	5%
	Disturbing	2%	1%
	Intolerable	0%	0%
		Arm Chair	
Sensor Index			
Avg. % of Views	Imperceptible	73%	77%
	Perceptible	7%	7%
	Disturbing	9%	8%
	Intolerable	11%	8%

However, when looking at figure 59, there is a slight difference and increase in the number of hours that include imperceptible glare. Though the difference is not significant, it still could be recommended that the double-glazing functions better than the single glazing. Figure 60 demonstrates view 2, when looking away from the window. This showcases that the issue with glare at the armchair in the north orientation could be easily avoided at select times of the day by looking slightly away from the window.

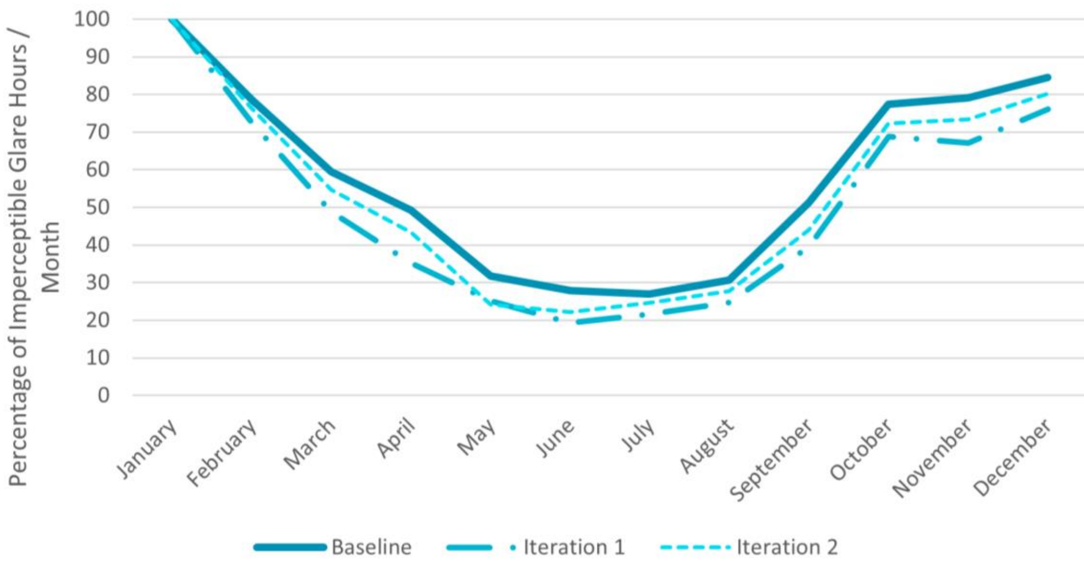


Figure 59: Imperceptible Glare Hours- North orientation comparison- Armchair View 1

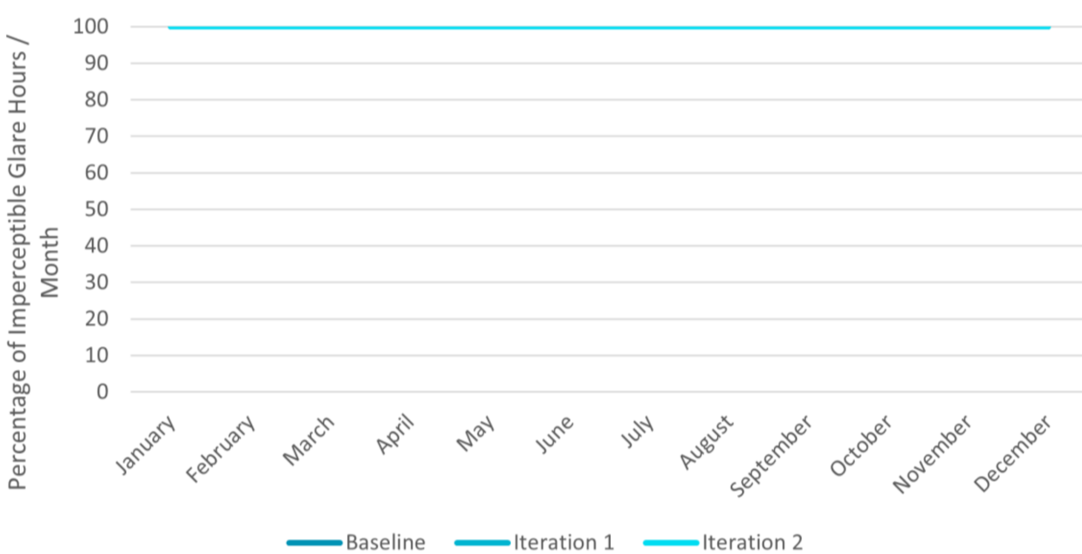


Figure 60: Imperceptible Glare Hours-North orientation comparison- Armchair View 2

The second part of the design investigations was the South orientation iterations. Figures 61, to 76 demonstrate the point in time and annual DGP for each iteration.

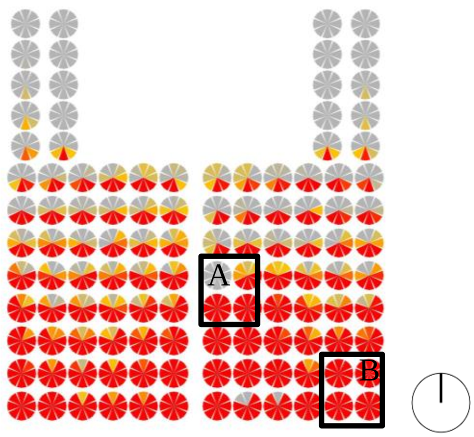


Figure 61: South Iteration Overhang, annual DGP plan.

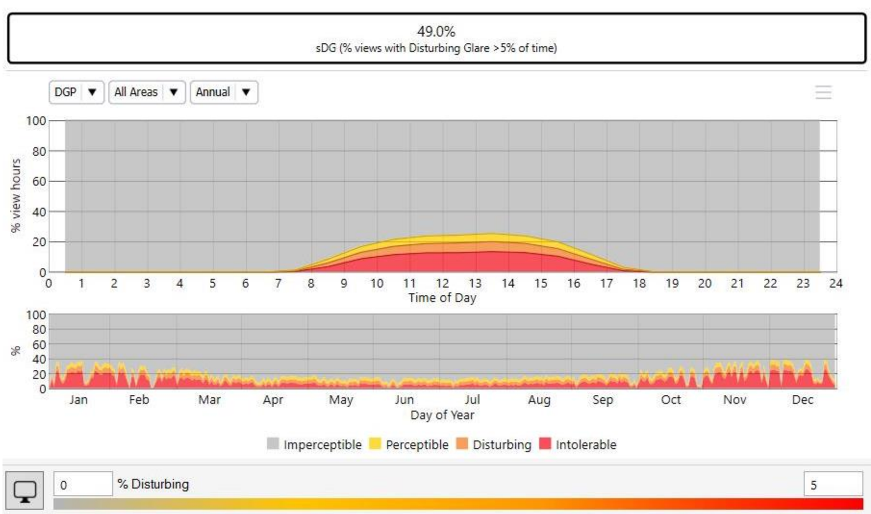


Figure 62: South Iteration Overhang, annual DGP schedule.

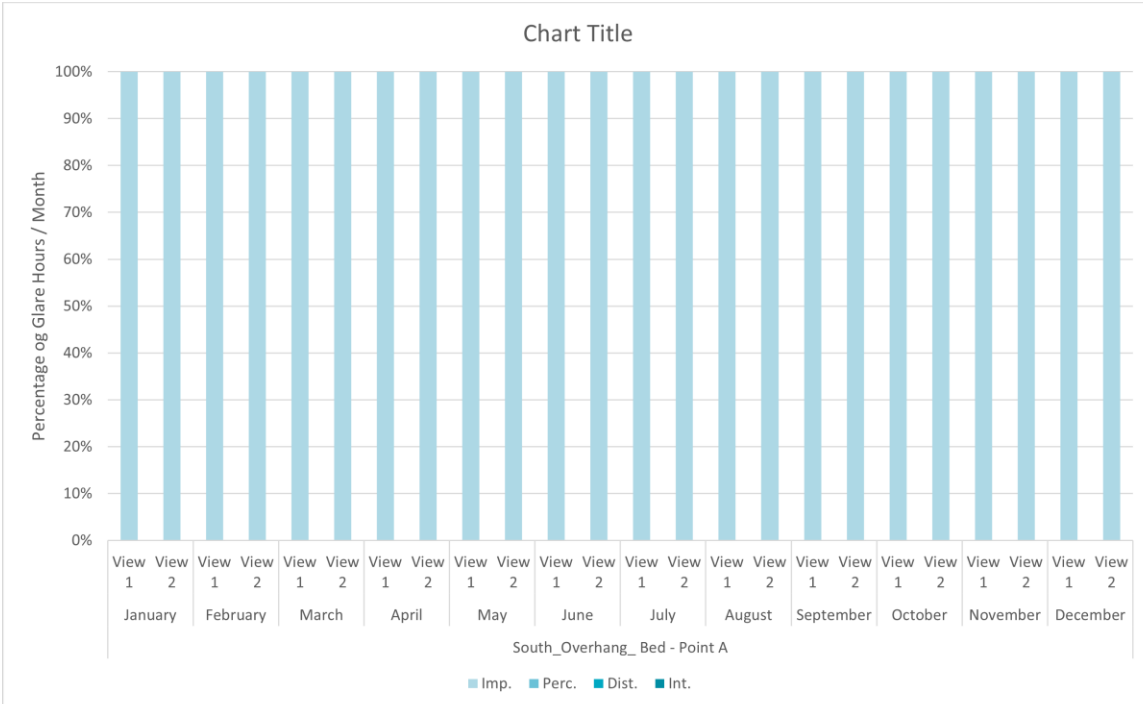


Figure 63: South orientation iteration 1, Overhang; point in time glare; Location point A

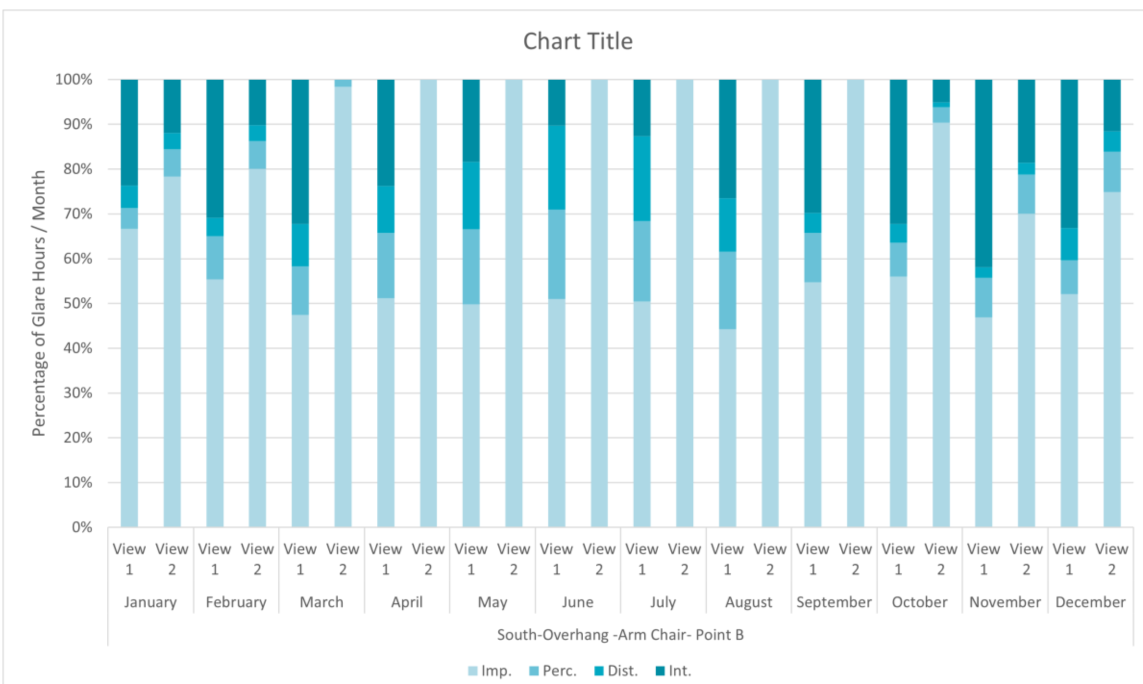


Figure 64: South orientation iteration 1, Overhang; point in time glare; Location point B

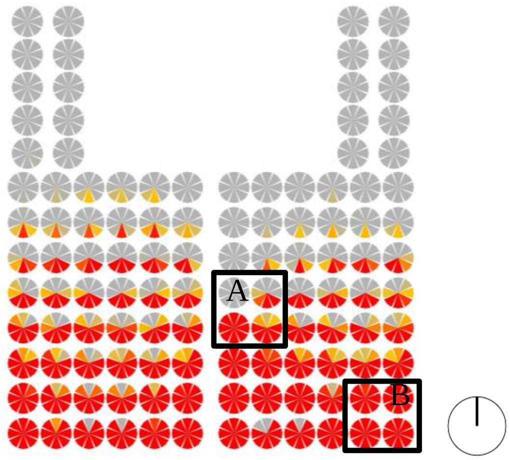


Figure 65: South Iteration 50% Roller Shade, annual DGP plan.

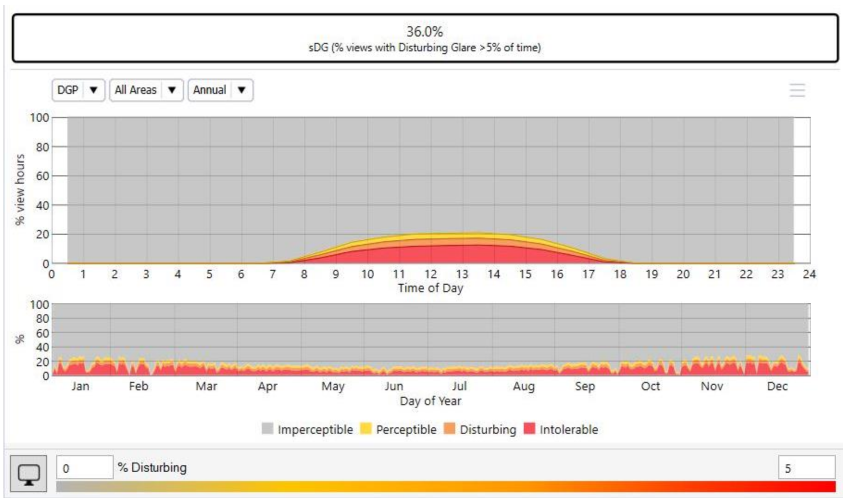


Figure 66: South Iteration 50% Roller Shade, annual DGP schedule.

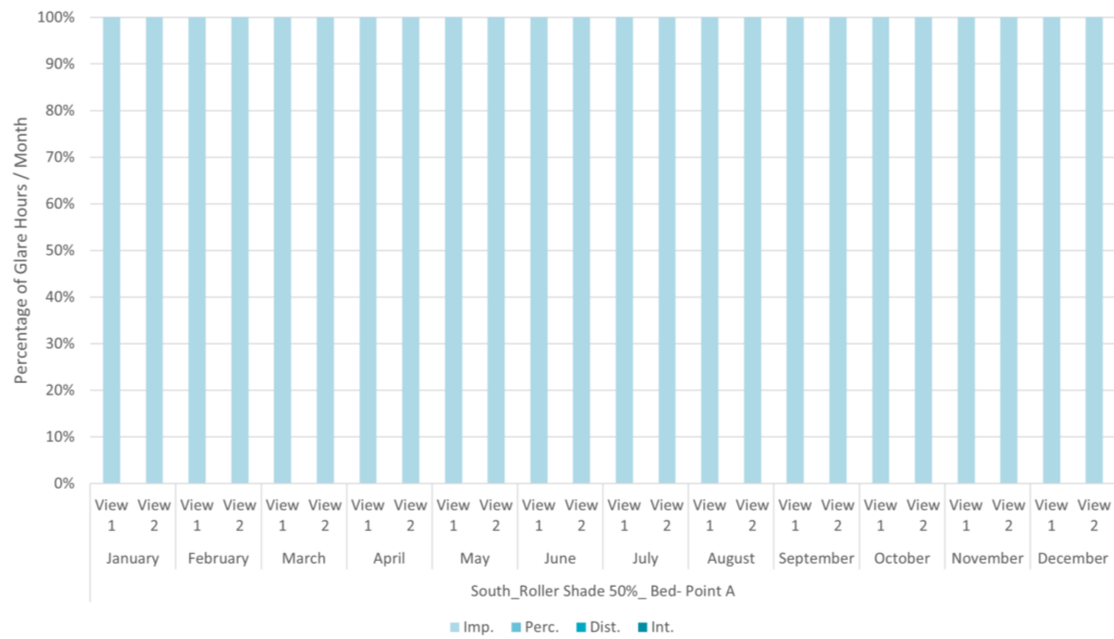


Figure 67: South orientation iteration 2, Roller Shade 50%; point in time glare; Location point A

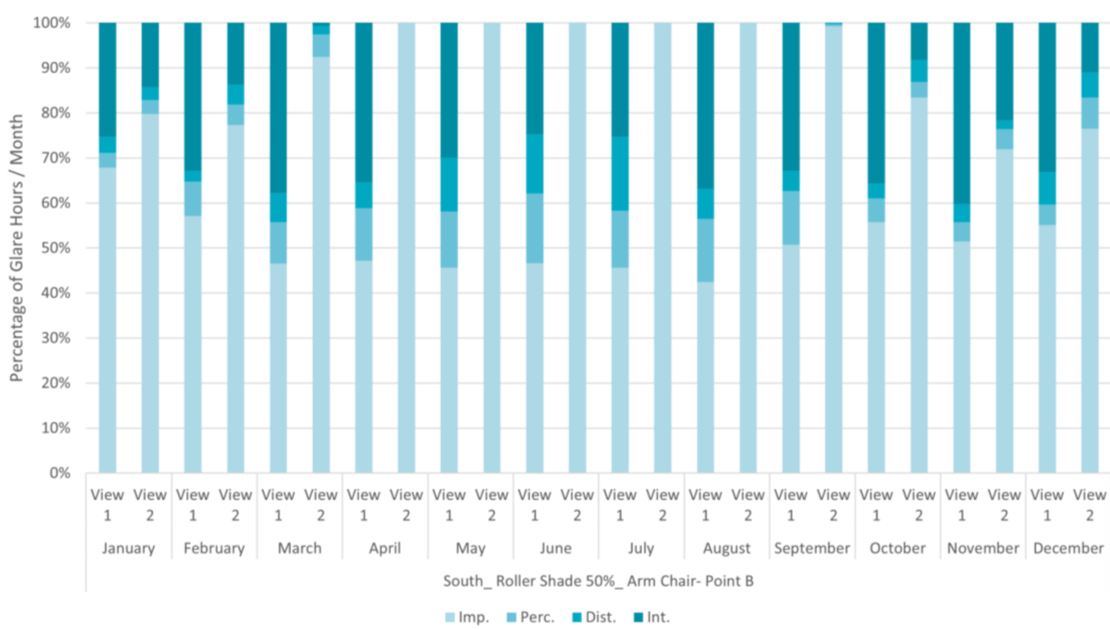


Figure 68: South orientation iteration 2, Roller Shade 50%; point in time glare; Location point B

The difference between the annual glare percentages in the overhang iteration, and the 50% roller shade iteration is slightly noticeable in the plans at both the analyzed points. However, the overall space is improved slightly in terms of glare issues.

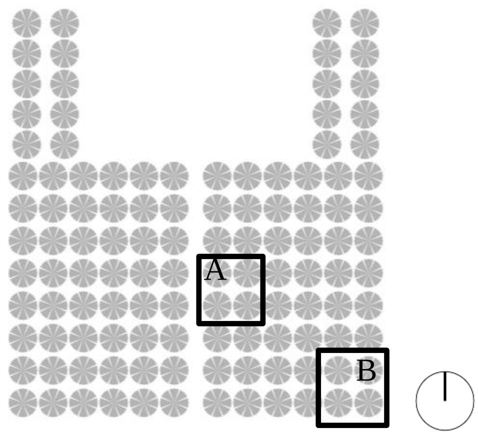


Figure 69: South Iteration 100% Roller Shade, annual DGP plan.

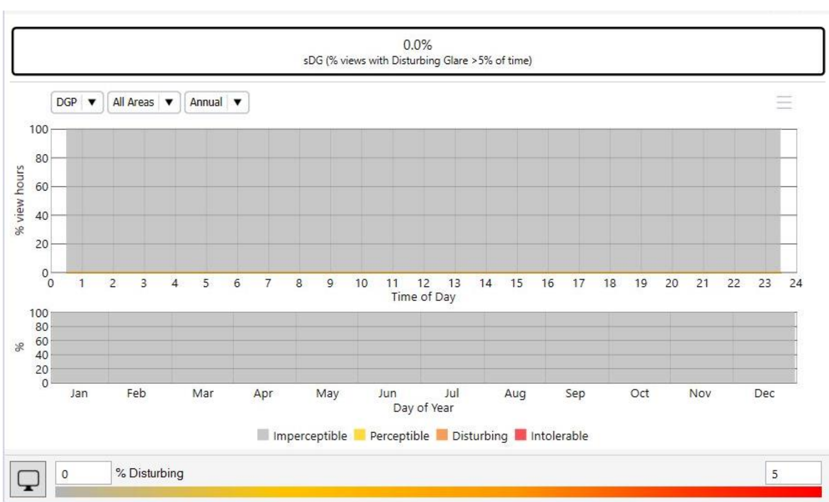


Figure 70: South Iteration 100% Roller Shade, annual DGP schedule.

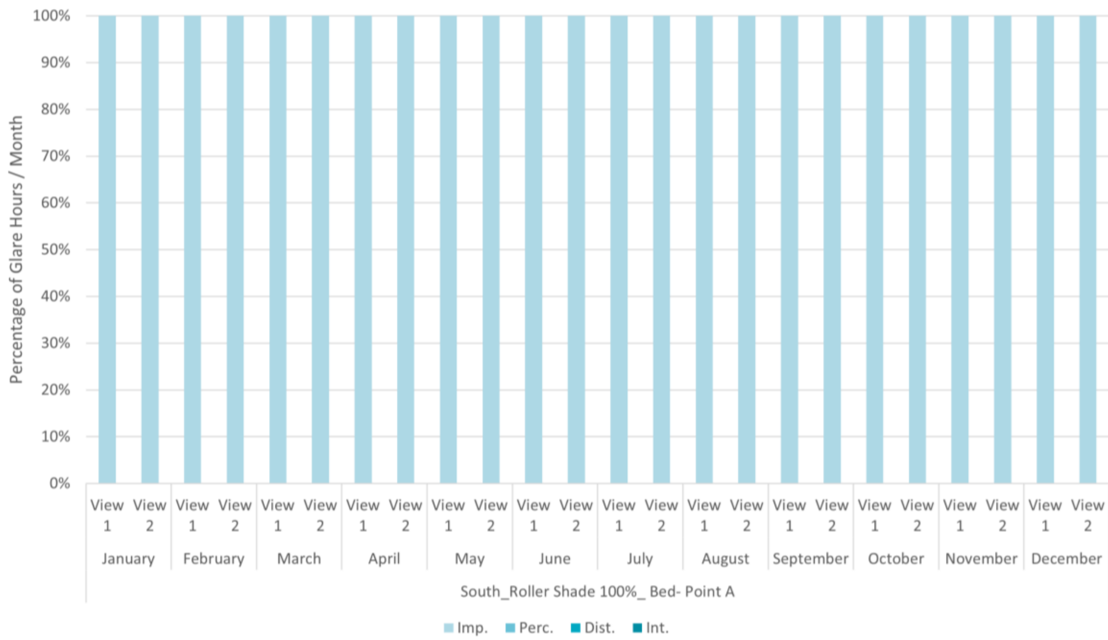


Figure 71: South orientation iteration 3, Roller Shade 100%; point in time glare; Location point A

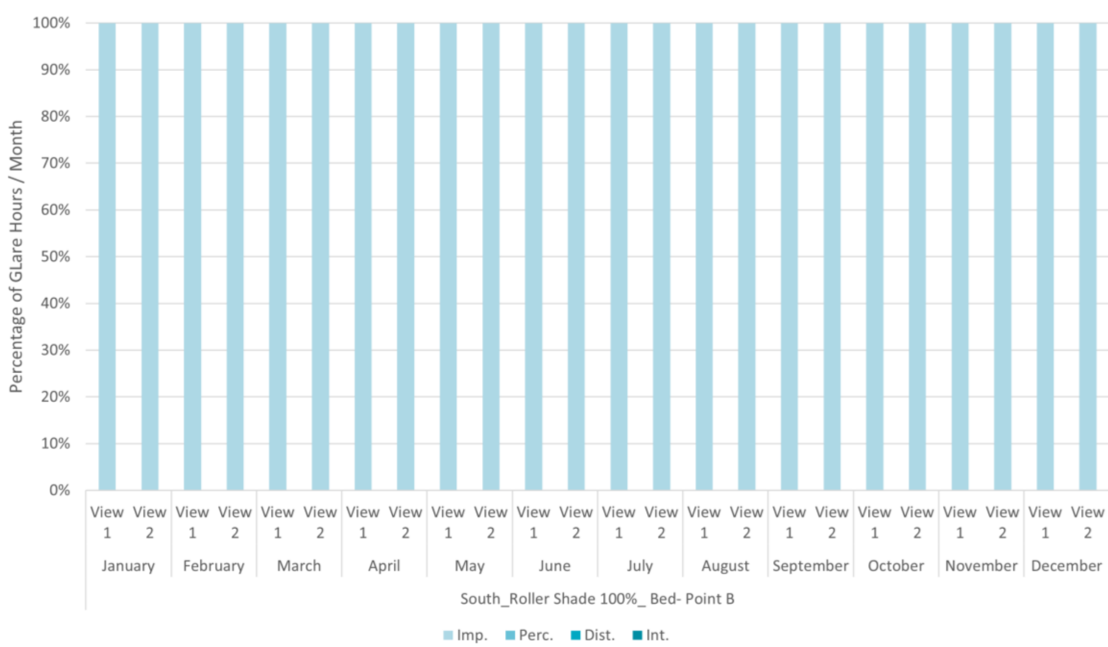


Figure 72: South orientation iteration 3, Roller Shade 100%; point in time glare; Location point B

Though figures 69 - 72 represent the idealistic, most required glare situation which is at zero percent. This iteration based on the point in time illuminance analysis demonstrates that it prevents all daylight to enter the space, hence the 0 % annual and point in time DGP.

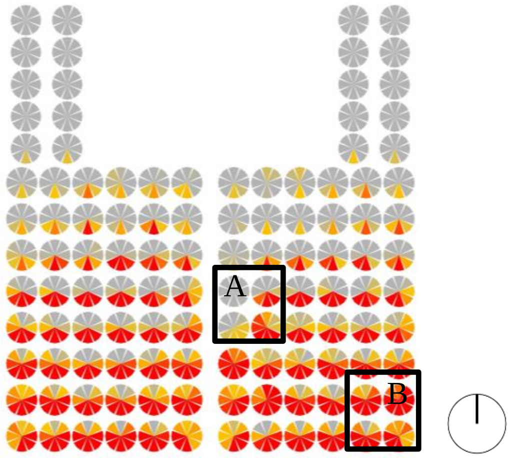


Figure 73: South Iteration Split System, annual DGP plan.

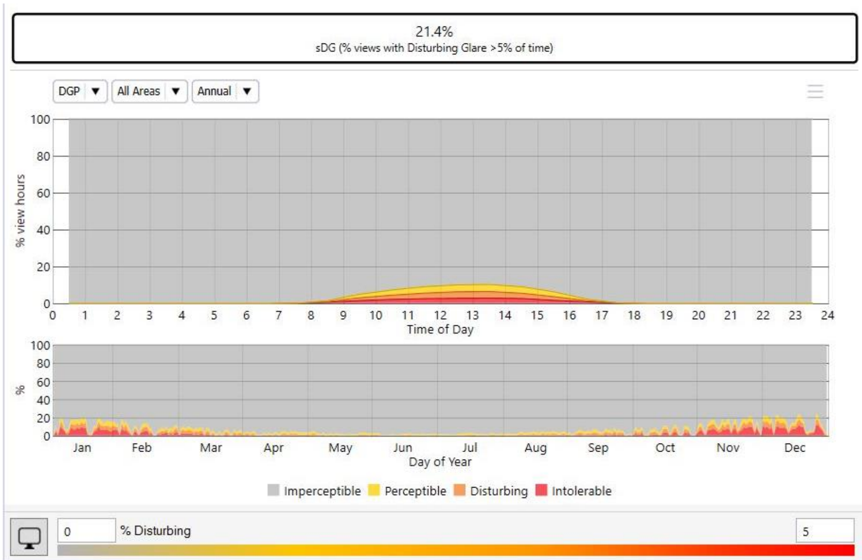


Figure 74: South Iteration Split System, annual DGP schedule.

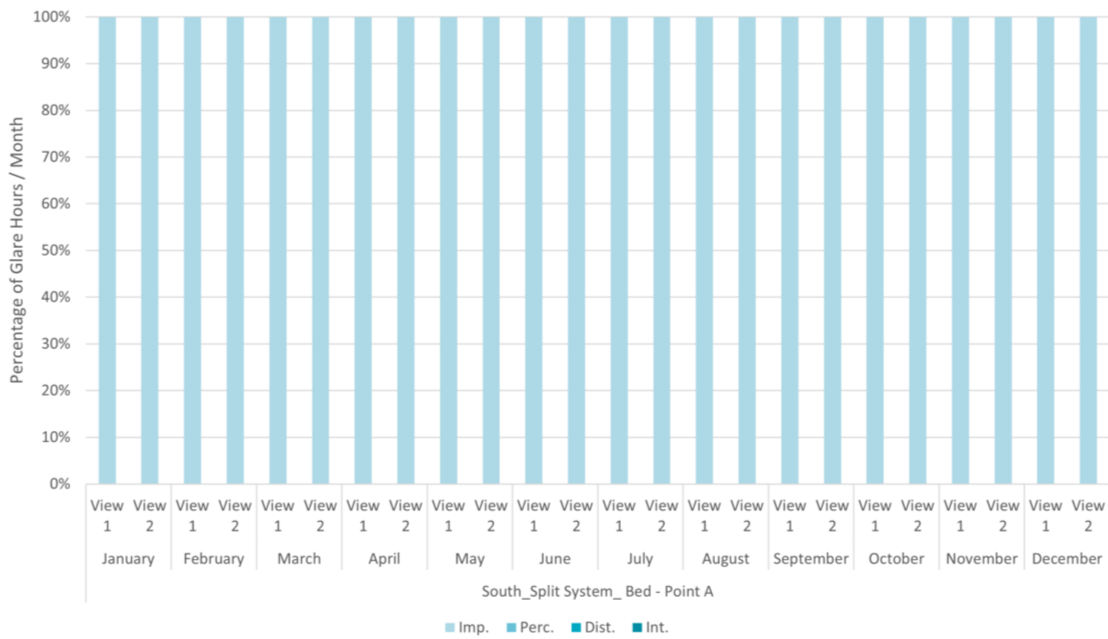


Figure 75: South orientation iteration 4, Split System; point in time glare; Location point A

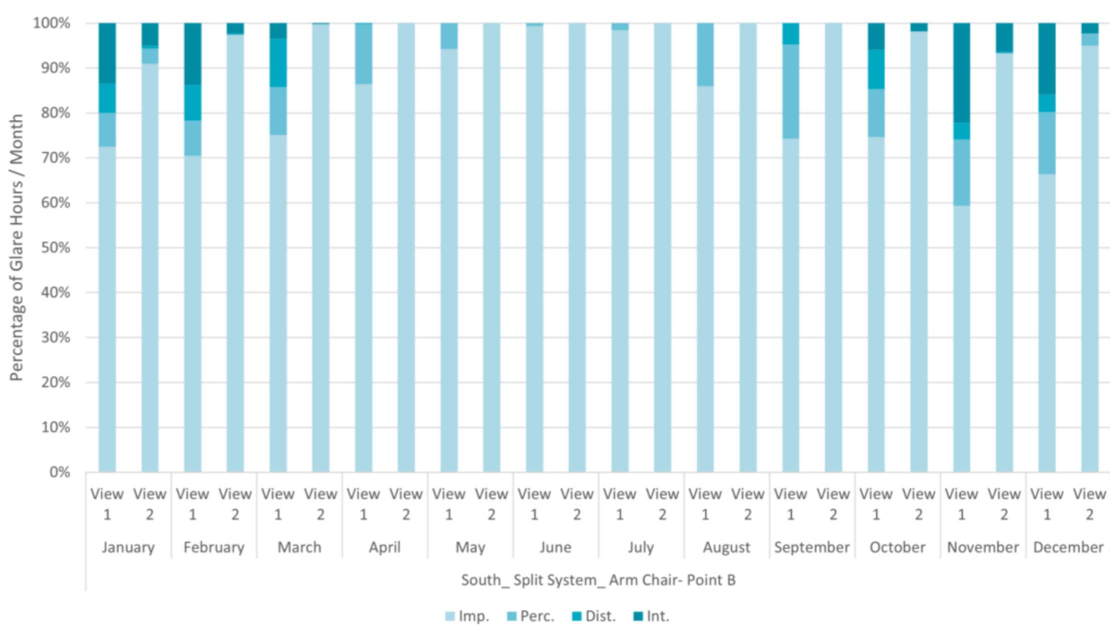
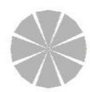
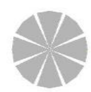
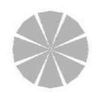
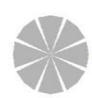


Figure 76: South orientation iteration 4, Split System; point in time glare; Location point B

According to the annual and point in time DGP results of the split system, it is the best performing iteration in terms of solving glare issues especially at point B. It is also clear in table 6 whereas the percentage of imperceptible glare is increased at the armchair when compared to the overhang and roller shade iterations.

Table 6: Comparision of south orientation iterations, annual DGP percentage between both points 1, and 2

		Bedside			
		Overhang	50% RS	100% RS	Split
Sensor Index					
Percentage of Annual Glare		49.00%	36.00%	0.00%	21.40%
Avg. % of Views	Imperceptible	100%	100%	100%	100%
	Perceptible	0%	0%	0%	0%
	Disturbing	0%	0%	0%	0%
	Intolerable	0%	0%	0%	0%
		Arm Chair			
Sensor Index					
Avg. % of Views	Imperceptible	65%	60%	100%	87%
	Perceptible	7%	6%	0%	4%
	Disturbing	9%	9%	0%	4%
	Intolerable	20%	25%	0%	5%

Figures 77, and 78 demonstrate a drastic increase in percentage of hours with imperceptible glare hours. The split system is functioning best when compared to other iterations.

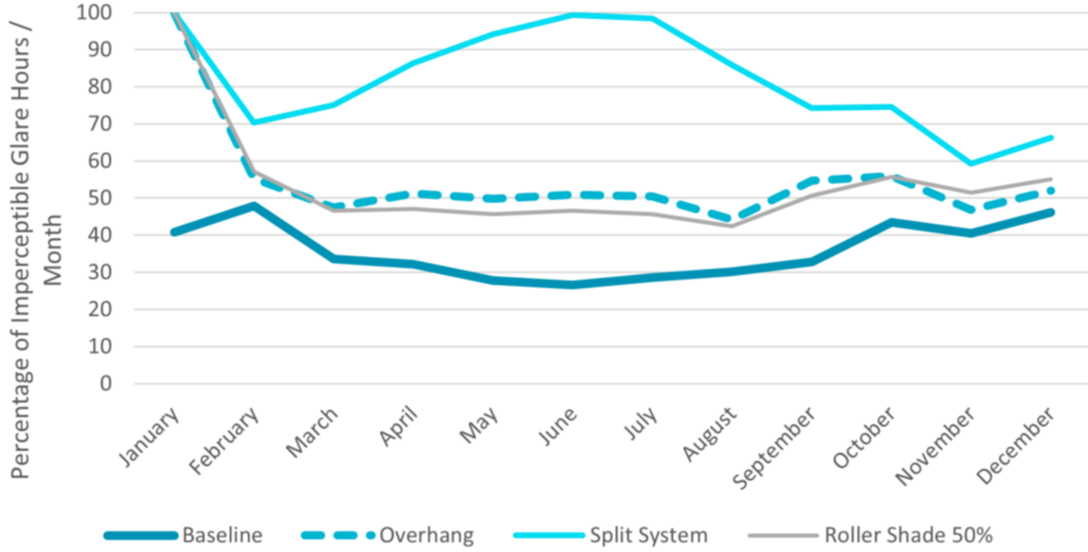


Figure 77: Imperceptible Glare Hours-South orientation comparison- Armchair View 1

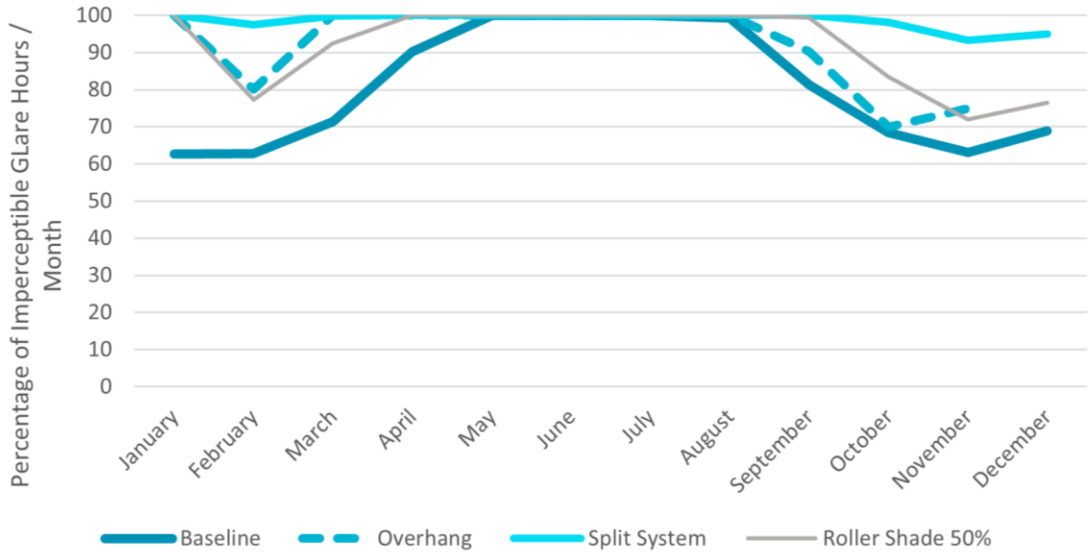


Figure 78: Imperceptible Glare Hours-South orientation comparison- Armchair View 2

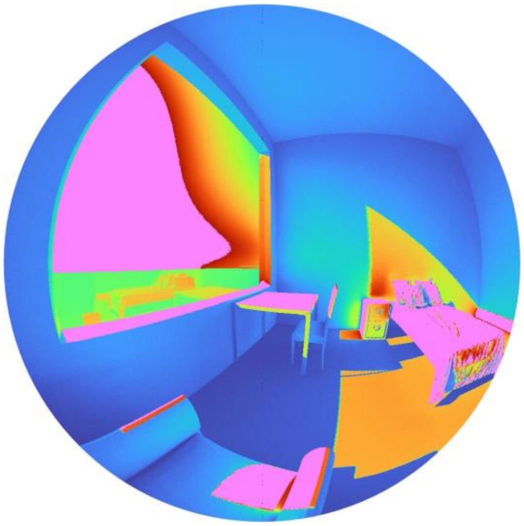


Figure 79: HDR Image: Dec. 21st- 12 PM – Baseline Case- Intolerable Glare

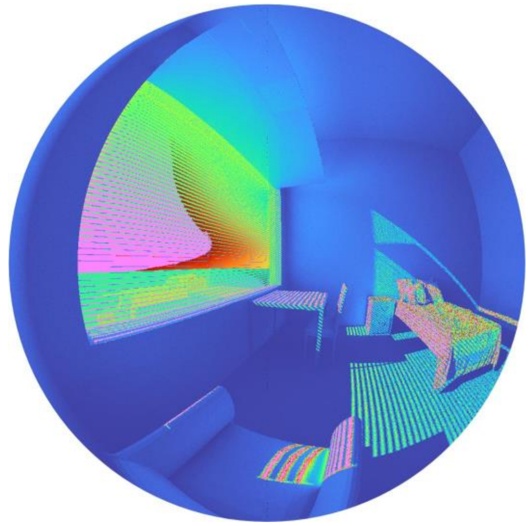


Figure 80: HDR Image: Dec. 21st- 12PM- Split System- Imperceptible-Perceptible Glare

Figures 79 and 80 demonstrate a comparison between HDR images of the south baseline case result and the split system improvement. HDR is a technology that improves the range of color and contrast in a digital image which allows more detail to appear in both the bright and dark areas of the scene.

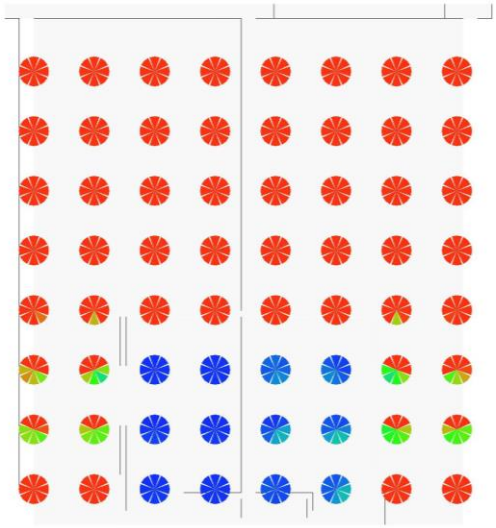
4.2.3 Equivalent Melanopic Lux- ALFA

Based on the literature review indicating that illuminance values between 2000-2500 lux are considered as an adequate value that entrains circadian rhythms, a follow-up experiment is discussed as a trial of the north orientation to test the relevance of EML as a metric. The software ALFA was used to test out the availability of 450-500 EML in the standard room when illuminance values are at 2000-2500 lux. This threshold is assumed based on the literature review section discussing the illuminance metric. The analyzed time frame is during June, September, and December 21st starting from 7 AM till 6 PM.

Table 7: Equivalent Melanopic Lux (EML) – glazing facing north direction- indicator of existing range of EML within 450-500 EML at points A and B

	At head of Bed			At Armchair		
	June	Sept.	Dec.	June	Sept.	Dec.
7:00	√	x	x	√	√	x
8:00	√	√	x	√	√	√
9:00	√	√	√	√	√	√
10:00	√	√	√	√	√	√
11:00	√	√	√	√	√	√
12:00	√	√	√	√	√	√
13:00	√	√	√	√	√	√
14:00	√	√	√	√	√	√
15:00	√	√	√	√	√	√
16:00	√	√	√	√	√	√
17:00	√	√	x	√	√	x
18:00	√	x	x	√	x	x

Table 7 shows that both points A and B indicate EML levels above 450 EML at most times of the day in select simulated seasons. Figures 87 and 88 showcase an example grid system that was produced by ALFA. This grid divides the required plan/ space into points with 360-degree directions. Each point uses the legend to show the values ranging between 0 to 450 EML. Both figures are an example of the simulation output for each time of day during two different months.



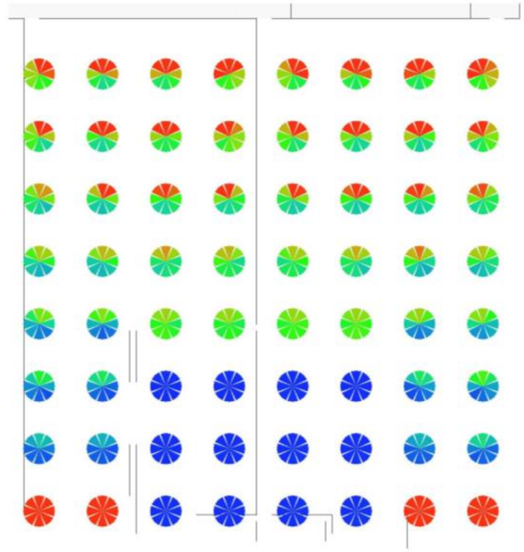


Figure 81: Percentages of views between 0-450 EML on June 21st at 8 AM.

Figure 82: Percentages of views between 0-450 EML on December 21st at 8 AM.

Based on this analysis, figure 89 presents the percentage of views above 450 EML within the space. It is considered adequate at most times of the day on the 21st of June, September, and December. Percentage values range from 0 – 75% of views above 450 EML across the whole bedroom and not only at points A and B. This is considered as a positive indication of alertness within this standard bedroom which proposes that the dependence on illuminance values between 2000-2500 lux could be adequate to test the existence of proper EML values within a space. Thus, further testing of the south orientation was un-necessary.

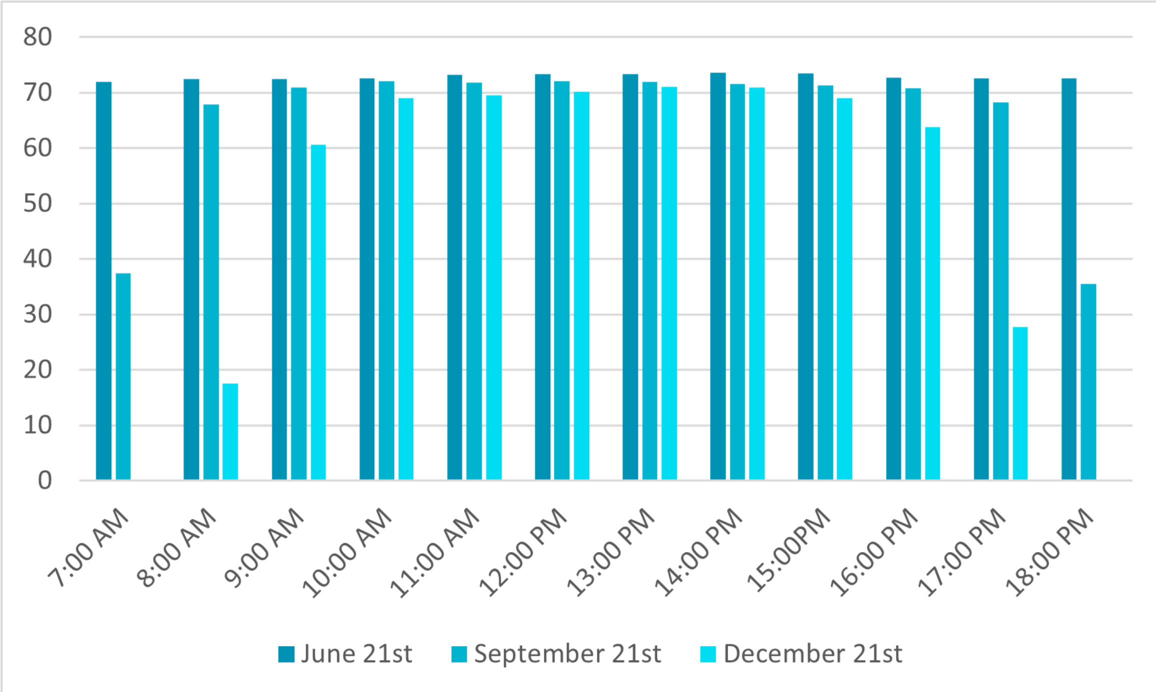


Figure 83: Percentages of views above 450 EML

4.3 Design Measures and Recommendations

This section provides a set of general design recommendations and considerations based on the results of the experiment that could be implemented for future projects or retrofitting existing projects. Design considerations for conceptual and initial design phase include the orientation of the building, the addition of shading elements, and the consideration of window to wall ratio. However, in some cases, the project is already built and in use making it harder to adjust the daylight requirements for the elderly. This requires a different set of recommendations which could include the consideration of the furniture layout or the addition of shading elements that are easily applicable to existing buildings.

4.3.1 The Orientation of the Building

Based on the results of both the baseline and design case experiments, the orientation of the building plays a major role in the amount of light admitted within a space. This consideration is crucial to ensure proper access to daylight along with understanding the functionality of the space.

When designing for the elderly, the focus on daylight becomes very important. Thus, it is recommended to run daylighting simulations and understand sun path diagrams to accurately orient the building towards the most beneficial direction. However, as shown in the experiment, the south orientation for example might cause severe glare issues which could be solved by rotating the window openings to a different orientation allowing proper access to light.

It is important to note that different locations, different sky conditions, and surrounding buildings will create different results. However, the importance of the orientation remains constant in all.

4.3.2 Shading Elements

The use of shading elements is required in spaces that experience high glare challenges or increased illuminance values. However, shading elements could be divided into two types. The first type shown in figure 82 is considered in the conceptual or initial design phase which could include the use of built overhangs, louvers, or side-fins that are embedded within the building façade. This type of shading depends mostly on daylighting simulations to be able to accurately place these shading elements. Through the design case, the overhang was used as an element to eliminate the amount of glare entering the space. Though the experiment only focused on a horizontal overhang in the south orientation, it still proved to be very efficient and useful. However, placing the overhang or louvers horizontally or vertically depends solely on the orientation of the window and which direction it is looking at whereas in many cases, vertical louvers function best in East or West orientation, unlike horizontal louvers or overhangs.

Figure 83 showcases the second type of shading elements that could be added to the exterior or interior façade of a building. The addition of small width louvers or Venetian blinds which could be either implemented in the early stages of design or added after construction. This type of shading could be preferred by the users as it allows them to directly adjust the angles to their preference. However, the depth of the louvers should not be too large to allow daylight to enter properly. This option also proved to work best in terms of glare elimination.

In addition, the use of roller shades as shown in figure 84 could be another method used to eliminate glare issues especially with pre- existing buildings. Based on the design case in the South orientation, the use of roller shades was tested out. Though the results of the 100 % lowered roller shade prevented the admittance of light, the use of up to 50% of the shade acted efficiently in terms of the amount of light admitted and solved some of the glare issue. Therefore, it is recommended to implement roller shades when there is a need for a quick and easy solution to eliminate glare along with allowing proper daylight values to enter the space.

On the other hand, the use of Venetian blinds is not examined thoroughly, however, based on the results of the split blind system strategy, it is shown that the use of venetian blinds whether placed on the exterior or interior of the window, it still provides an efficient solution to mitigate glare while admitting proper daylight that promote the health and well-being of the users. In addition, the use of venetian blinds could allow a better view of the outside rather than roller shades if lowered completely.

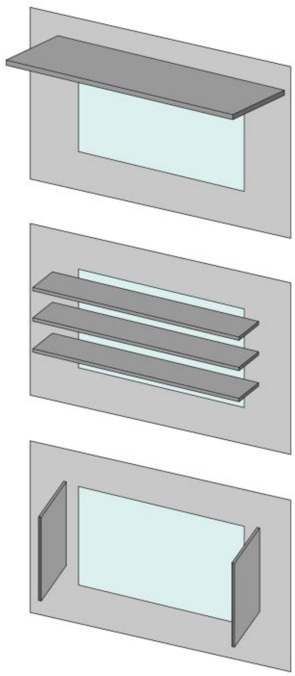


Figure 84: Overhang design iterations

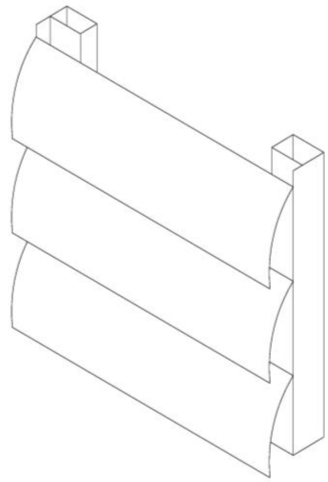


Figure 85: Example of louver design (Thermia Barcelona, n.d.)

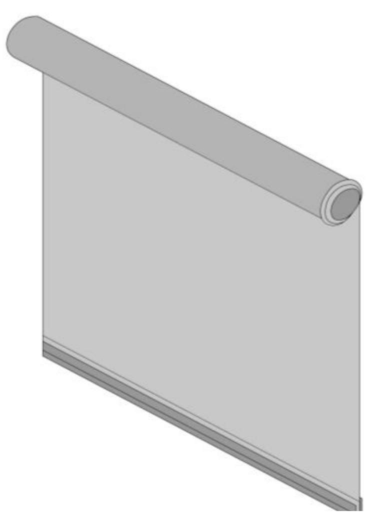


Figure 86: Roller Shade Design

4.3.3 Light Shelves

The use of an interior light shelf could be recommended for spaces for deep floor plans without the option of adding more windows. This design addition allows light to be reflected into space while maintaining acceptable and useful daylight hours within the space. Though the design iterations experimented with was for the south orientation only, it is believed that the use of light shelves along with a shading element could provide promising results.

It is recommended to use highly reflective materials to allow the daylight to be reflected in space. Thus, the use of materials like mirrors as part of the light shelf could have a great impact on how space receives daylight.

4.3.4 Window to Wall Ratio (WWR)

Another design aspect to consider during the initial design phase is the WWR. Figure 85 represents a simple graphical demonstration of the percentage of the WWR. Based on the design case experiment, the change of the WWR in the North orientation played a major role in the amount of light entering the space. Though calculating the WWR is usually a standard based on the building type, architectural standards as used referenced in the experiment, or certifications, it is advisable to consider increasing or decreasing the WWR based on accurate daylight simulations. This accurately examines the space and the amount of light it receives to ensure that the daylight values entering are suitable for the users, especially the elderly population.

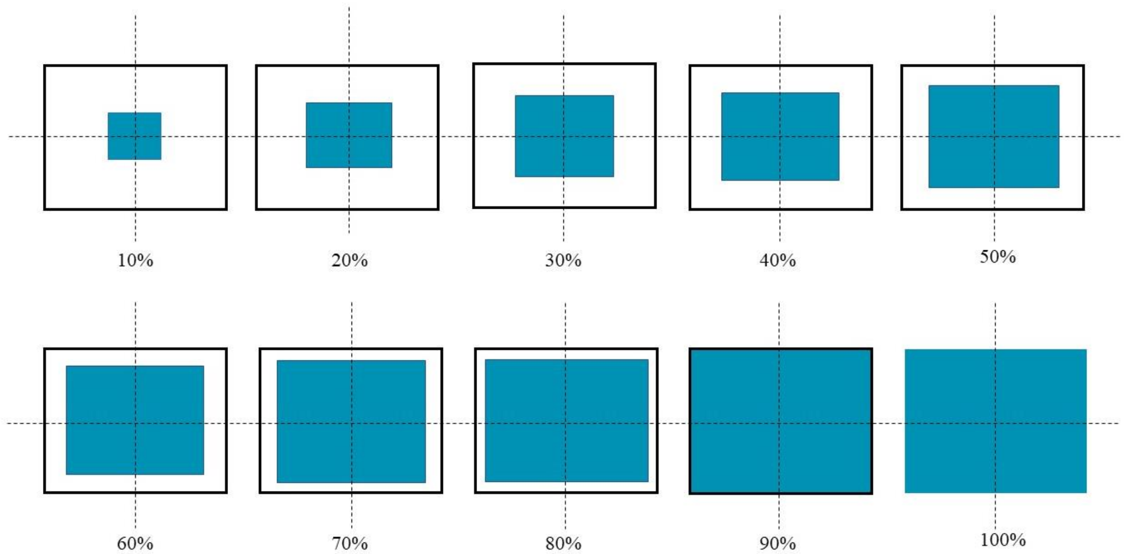


Figure 87: WWR with reference to (Wen et al., 2017).

4.3.5 Furniture Layout

Finally, the last design recommendation to consider is the furniture layout within the space or building. Based on the simulated experiment, it was assumed that the users were either sitting in an armchair right next to the window or sitting on the bed in the middle of the room. Accordingly, it is recommended that space should be divided into 4 equal sections. This allows the designer to understand the space with reference to the window location. The furniture should be oriented towards the window and should be placed by maximum within half of the room depth. The closer the furniture is to the window, the more it is considered beneficial. However, as mentioned before, glare should be taken into consideration. Both the baseline and design cases showcased promising daylight values in the North orientation when placed close to the window – in the first quarter of the room-. However, the south orientation suffered from high glare issues which could be illuminated by placing the furniture in the 2nd quarter which ensures proper access to daylight along with avoiding glare issues.

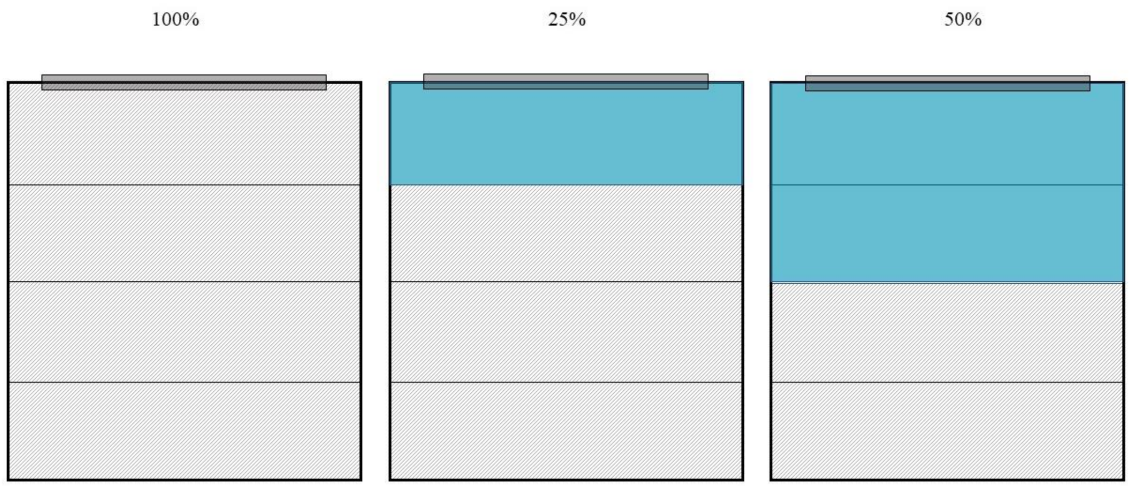


Figure 88: Space breakdown for furniture layout.

4.3.6 Daylight Design Recommendations

Based on the results of the experiment, and the analysis of each method used, this study recommends the following:

- Orienting the windows towards the North while increasing the WWR to 70% and using double glazing with low VLT percentages.
- Orienting towards the South should be added as an option when the North orientation is not a viable option.
- Glazing materials for the South orientation should have low Visual light transmittance. This should be combined with the use of shading systems.
- The WWR in the South orientation should follow the current building standards without any increase in its percentage.
- Light shelves are recommended to be used in deep spaces, especially facing the South orientation to avoid high glare issues and allow more daylight in the space.

- Imperceptible annual glare percentage should be above 60% to ensure that the space is tolerable.
- An average of 40-50% of analyzed useful hours/ year is recommended to ensure the existence of efficient daylight year-round.
- Furniture layout should be placed near windows to allow occupants access to adequate daylight.

CHAPTER 5: DISCUSSION, FUTURE RESEARCH, AND CONCLUSIONS

5.1 Discussion and Future Work

5.1.1 Discussion

This research presented a brief explanation of elderly experiences and complications accompanied by aging. It provided an understanding of the available research regarding lighting metrics needed for circadian entrainment for elderly and dementia individuals. Though this research might act as a piece of the puzzle to assist with the needed research in this field, it remains in need of development and advancement to provide a further detailed design framework.

The experiment undergone provided an initial understanding and analysis of one standard nursing room. Point-in-time illuminance was analyzed with windows facing the four different orientations, North, South, East, and West which are considered the baseline analysis. However, the analysis was limited to two points in the standard room only. Also, the design proposal and investigation extended to the North and South only which could be limiting to the design options as we did not investigate other orientations.

In addition, the experiment was in one location with prevailing clear skies. Thus, to fully understand and propose a more thorough design recommendation, other locations with different sky conditions should be investigated.

The aim of this research was to investigate a single bed bedroom in a standard nursing home to analyze the daylight entering the space which promotes circadian entrainment. The focus was on daylighting only, therefore, this research did not include the addition of electric lighting that could work together with daylighting to compensate for the hours where the daylighting was in-adequate.

Finally, the experiment was mainly focused on using basic materials for simulations in both software used. Though the use of these materials allowed a better understanding of the quality of space and its geometry, the change of materials is encouraged for further research and investigation.

5.2 Conclusions

5.2.1 Limitations, Challenges, and Future Research

The main challenge in this research was to identify the appropriate lighting metrics that are needed for elderly and dementia experiences. Though there were several types of metrics mentioned in the literature, focusing on illuminance values was recommended due to several points:

1- It was the most reviewed in the literature.

2- Daylighting software simulation tools were available and easy to access.

3- Metrics for the Circadian Stimulus and Short Wavelength bluish-white light focused on electric lighting which made it difficult when using daylighting.

4- EML has no reference in the literature. However, it is assumed that there is no difference between the EML values needed for elders and individuals with dementia.

The second challenge was the difficulty to give a definite statement about the acceptable percentage of useful daylight within the space given that each simulation has room for improvement in all orientations. It could be investigated to extend the research to an existing nursing home, measure the daylight illuminance values with appropriate tools, and compare it to software simulation results. This could provide a better understanding of the accuracy and deviation of the results from real life. However, this needs more time, equipment, and preparations that exceed this thesis's resources.

Finally, the experiment was limited to two locations only within the bedroom. Human behavior was not investigated nor analyzed. Thus, for future work, user behavior within the space should be accommodated and taken into consideration.

5.2.2 Conclusion

The effect of daylighting on health and well-being has been promoted through various research, all in support of its direct effect on circadian systems in human beings affecting sleep, alertness levels, and mood changes. This research focused on the effect of daylight on elderly and individuals with dementia along with the required metrics needed to entrain their circadian rhythms. It was assumed in this study the metrics which included point-in-time illuminance ranging between 2000-2500 lux, DGP experiences, and EML values at 450 or above. According to the literature review, it can be inferred that elders who are exposed to adequate daylight for a minimum of 1-2 hours per day should have a functional circadian system that acts towards the improvement of their overall health.

This research then developed an experiment through daylighting simulations investigating annual point in time illuminance, point in time and annual DGP. Though the results of the baseline case did not meet expected performance, the results of the design proposals for the North, and South orientations presented significant improvement at most locations. Through this research, design considerations can be recommended for architects to use when designing for the elderly population. Recommendations such as WWR, the orientation of the building, shading elements, and furniture layout are all considerations demonstrated in the research. However, it is crucial to mention that these recommendations are limited to the location of the investigation. Thus, the research recommends running daylight simulations in various climatic settings for further accuracy in design research.

Finally, this research is a preliminary investigation in a field that needs further explorations. Elderly experiences and challenges should become a priority for researchers and designers to accommodate their specific needs. Creating a healthy environment that promotes the overall well-being of individuals is a vital part of the built environment industry and should not be neglected.

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