THE IMPACT OF HUMAN-CENTRIC LIGHTING PARAMETERS ON OLDER ADULT'S PERCEPTION, AND COGNITIVE PERFORMANCE

by

NASRIN GOLSHANY

A DISSERTATION

Presented to the Department of Architecture
and the Division of Graduate Studies of the University of Oregon
in partial fulfillment of the requirements for the degree of Doctor of Philosophy

September 2023

DISSERTATION APPROVAL PAGE

Student: Nasrin Golshany

Title: The Impact of Human-Centric Lighting Parameters on Older Adult’s Perception, and Cognitive Performance

This dissertation has been accepted and approved in partial fulfillment of the requirements for the Doctor of Philosophy degree in the Department of Architecture by:

Ihab Elzeyadi	Chairperson
Margaret Sereno	Core Member
Virginia Cartwright	Core Member
Jun Hak Lee	Core Member
Habib Chaudhury	Institutional Representative

And

Krista Chronister	Vice Provost for Graduate Studies

Original approval signatures are on file with the University of Oregon Division of Graduate Studies.

Degree awarded September 2023

DISSERTATION ABSTRACT

Nasrin Golshany

Doctor of Philosophy

Department of Architecture

September 2023

Title:
The Impact of Human-Centric Lighting Parameters on Older Adult’s Perception, and Cognitive Performance

Population aging is a prominent demographic challenge. Older adults face increased risks of sleep dysfunctions, depression, and cognitive impairments due to physical, biological, and psychological factors associated with aging. These behavioral issues elevate safety risks at home, which necessitates the transition to assisted living facilities. Extensive research highlights the influence of healthcare environmental design, particularly related to architectural lighting impacts on residents' well-being and quality of life. To optimize older adults' health and well-being, it is essential to consider both the visual and non-visual effects of architectural lighting. Visual impacts include parameters related to task performance and visual acuity, while non-visual impacts may include outcomes such as circadian rhythm regulation, sleep quality, mood enhancement, and cognitive performance, thereby emphasizing the importance of implementing a holistic conceptual approach to human-centric lighting in indoor environments.

While existing gerontology studies have primarily focused on light-level attributes, such as radiant flux, illuminance, and equivalent melanopic lux, there has been limited exploration of spectral and spatial pattern parameters in indoor lighting. The primary objective of this research is to investigate the impact of both quantitative and qualitative aspects of lighting design, including spatial layout characteristics such as uniformity, direction, centrality, and spectral attributes like correlated color temperature (CCT), on the visual perception, preference, mood, cognitive performance, and overall well-being of older adults in assisted living facilities. The study employed a multi-method approach across three main research phases. In phase I, a Q-sort survey involving 60 participants assessed the impact of diverse spatial light patterns on visual perception and preference. In phase II, a within-subject design evaluated the cognitive performance of 32 older adults in similar lighting scenarios within real and virtual environments. Lastly, in phase III, the study examined the relationship between spatial and spectral light patterns and cognitive performance through virtual reality testing with 32 participants.

Results revealed significant effects of different spatial light patterns on older adults' environmental impressions, including visual preference, stress levels, and cognitive performance. Uniform and indirect lighting were preferred, with no substantial differences between peripheral and central spatial arrangements of light layers. Non-uniform lighting induced a relaxed impression, while uniform lighting heightened perceived stress. Furthermore, the study demonstrated the suitability of virtual reality environments (VR) for assessing cognitive performance and subjective perception. The findings underscore the substantial influence of spatial and spectral light patterns on the cognitive performance of older adults in assisted living facilities. This research contributes to the understanding of the visual and non-visual effects of human-centric lighting on the well-being of older adults. By considering spatial and spectral light attributes, designers can enhance cognitive function, reduce impairments, and cultivate healthier and more efficient living environments.

ACKNOWLEDGEMENTS

First and foremost, I thank my advisor, Dr. Ihab Elzeyadi with the deepest gratitude, for his exceptional guidance, mentorship, and the opportunities he has provided me during my research journey. Dr. Elzeyadi's multidisciplinary perspective in architecture has been a constant source of inspiration, pushing me to explore diverse areas within the field. His unwavering support, kindness, and insightful feedback have been instrumental in my growth as a researcher and academician. I am truly grateful for the joy and fulfillment he has brought to my path toward obtaining my Ph.D.

Second, I extend my heartfelt thanks to my husband for his unwavering support, understanding, and encouragement. His constant belief in my abilities and dedication to my aspirations have been invaluable throughout this endeavor. I am truly grateful for his patience, love, and motivation, which have provided me with the strength and determination to overcome challenges and excel in my studies. Additionally, I would like to express my profound gratitude to my dear mother for her unwavering love, guidance, and unwavering belief in my potential. Her continuous encouragement, wisdom, and sacrifices have shaped me into the person I am today. I am truly blessed to have her unwavering support and guidance in all aspects of my life, including my academic pursuits.

Furthermore, I would like to express my gratitude to Dr. Sereno, Dr. Chaudhury, Professor Cartwright, and Professor Lee for their invaluable contributions to this research. Their extensive knowledge and expertise in the areas of psychology, aging and gerontology, lighting design, and data analysis have enriched my understanding and shaped the direction of this study. Their guidance, critical insights, and constructive comments have broadened my horizons and assisted in the development of research ideas, refining research procedures, and overcoming obstacles. I deeply admire their dedication and consider them as role models for professional success.

Lastly, I would like to express my profound gratitude to the senior living community and the residents who generously participated in this study. Their willingness to contribute their time and insights has been vital to the data collection process. Without their participation and cooperation, this study would not have been possible.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

Table Page

CHAPTER 1: GENERAL INTRODUCTION

1.1. Background to the Problem

The aging population is increasing fast and by 2030, 20% of the US population will be 65 or older (Brawley, E. C. 2006) (Regnier, V.,2003). Therefore, there is a crucial need for increased research on factors and attributes which support late-life health and well-being and guarantee more independence for this vulnerable population. One of the problems of the aging population is that older adults are at higher risk for sleep dysfunctions, depression, and cognitive impairments as aging is associated with several physical, biological, and psychological challenges. These challenges often lead to behavioral impairment in older adults that results in unmanageable risks at home or a danger to the individual. This is the point at which the elderly are forced to move to senior living facilities. The architecture of elderly environments can be considered a therapeutic modality to promote health, well-being, and functionality for elderly residents. Knez, I. (1995) argues that different attributes of the natural and artificial environment may influence different moods and cognitive processes in humans. Studies have shown that design characteristics of healthcare environments might directly affect the residents' quality of life and health outcomes (Fontana Gasio, P., 2003; Sun, R., & Gu, D, 2008; Hygge, S., 2001). Appropriate lighting design is one of the significant indoor environmental qualities that could potentially play an important role in improving the living environment and enhancing health and well-being in older adults (Lu, Park, & Ahrentzen, 2019). However, lighting design for the aging population has not received much attention from researchers and designers. Furthermore, the limited number of studies that investigated the impact of light on elderly outcomes have mainly focused on the relationship between light and circadian rhythm and sleep quality while there is a significant gap in the literature regarding the relationship between lighting design and cognitive performance of older adults. Therefore, there is a crucial need for increased research on factors and attributes of lighting design that support late-life health, improve cognitive performance and guarantee more independence for this vulnerable population.

1.2. Research Problem

Appropriate lighting condition is one of the significant indoor environmental qualities that could potentially play an important role in improving the living environment and enhancing health and well-being in older adults (Lu et al., 2019). Lighting design for elderly settings, however, has not received much attention from researchers and designers. Elderly residents in assisted living facilities spend 90% of their time in indoor spaces (Klepeis, N. E., et al, 2001; Beyer, K. M. et al, 2018), therefore, they are experiencing dimmer days and brighter nights than they need to experience in nature (Wright Jr, K. P., et al, 2013; Chen, S. et al 2019). Many studies reported older adults suffering from poor lighting conditions in assisted living facilities in terms of light level and light spectrum (Buntinx, 2007; Eilertsen, Horgen, Kvikstad, & Falkenberg, 2016; Hegde & Rhodes, 2010). According to these studies, lighting design in senior living facilities does not even meet older adults' visual needs.

Furthermore, increasing age causes a reduction in circadian rhythm amplitude and causes impairment in the internal biological clock in humans, especially after the age of 80 (Swaab, D. F., et al, 1985, Hofman, M. A., & Swaab, D. F., 2006). These deficiencies in the biological clock and poor lighting conditions in the indoor environment can increase sleep time during the day and wakefulness during the night in the aging population. This disorder not only increases stress and agitation among older adults but also negatively impacts cognitive performance (Bliwise, 1993; Okawa et al., 1991; Tractenberg et al., 2003). Appropriate lighting quality and quantity is one of the indoor environmental qualities that plays a significant role as a non-pharmacological solution in improving health and well-being in older adults. While an increasing body of knowledge exists on indoor lighting for older adults for improving their circadian rhythm, sleep quality, stress, mood, and behavior, there is a lack of integrated and consistent resources in the literature that investigates the role of lighting conditions on the cognitive functioning of older adults.

Human-centric lighting is a relatively new approach to lighting design. It focuses on lighting solutions related to occupants' visual needs and incorporates new insights into the non-visual, biological, and behavioral impacts of light on humans (Houser, K. W., et al, 2020). Human-centric lighting for older adults who are suffering from many age-related visual and non-visual impairments also has recently received significant interest from healthcare workers and light designers. There are four categories of lighting variables in human-centric lighting that contribute independently to the non-visual outcomes of older adults. These categories are temporal pattern, light level, light spectrum, and spatial pattern (Houser, K. W., et al, 2020). Among these four attributes of light, quantitative attributes of light such as light level (Radiant flux(w), Illuminance(lux) and Equivalent melanotic lux EML) and temporal patterns (Timing of exposure and Duration of exposure), have been almost addressed in previous studies involved with the cognitive function of elderlies, while there are not enough studies showing a systematic relationship between cognitive function, the light spectrum and spatial patterns of light (Satlin, A. et al.,1992; Knez, I., & Kers, C, 2000; Riemersma et al, 2008; Yamadera, et al,2000).

According to the literature, there is a critical need for investigating the relationship between Human-centric light parameters and the cognitive performance of elderly residents in assisted living facilities. To address that, this study particularly, (1) investigates the impact of human-centric parameters on older adult's perception and preference (2) examines the influence of different spectrum and spatial patterns of Human-Centric light on older adults' cognitive function. Studies in this area can complement previous research efforts presenting both visual and non-visual effects of Human-Centric lighting on elderly residents' health and well-being.

1.3. Research Questions

This study aims to find answers to the following questions: (1) Do spatial and spectral patterns of light impact older adults' perception and preference of the environment? (2) Is there any significant difference between cognitive performance, mood, and behavioral outcomes of older adults in real environment lighting scenes compared to virtual reality lighting scenes? (3) How do spatial light patterns and arrangement of electric light sources impact the cognitive performance of elderly residents? And (4) Does Correlated Color Temperature (CCT) impact older adults' mood, behavioral outcomes, and cognitive performance?

Previous studies have revealed that the quantity and quality of light can impact a human's subjective impression. For instance, higher intensity and CCT of light, using task lighting and visual cues improve human perception in an environment (Yamagishi, et al, 2008; Janosik & Marczak, 2016; Cheng, 2016; Aarts, et al. 2019; Geerdinc, 2009; Kundur aci, 2017; Sawyer, 2014; Figuerio, 2011). However, in these studies there are some limitations, Firstly, the number of studies exploring the impact of light on older adults' perception is limited, Secondly, most of these studies are using computer-based methods that could not provide an interactive and immersive experience for the participants, Lastly, there is a lack of sufficient studies about the impact of lighting variables on cognitive performance of humans especially older adults. This dissertation utilizes an interdisciplinary approach that combines insights and techniques from both Psychology and Architecture to examine the impact of spatial lighting patterns on older adults' perception, mood, and preference, and to investigate whether spatial and spectral patterns of light can impact older adults' cognitive performance. Findings from this research are expected to provide new insights into the scope of lighting design of assisted living facilities.

1.4. Research Aim and Hypothesis

This study intends to evaluate the impacts of variable spatial light patterns and Correlated Color Temperature (CCT) on improving mood, perception, and cognitive functions, and consequently quality of life in older adults. The project focuses on defining optimum spatial lighting patterns and CCT of light, that provide a better quality of life for the aging population in assisted living facilities.

It is hypothesized that the different spatial light patterns and CCTs impact older adults' perception, preference, and cognitive performance. Applying a uniform, central, and direct spatial pattern with a higher level of CCT will result in better outcomes for perception, mood, cognitive performance, and thus the quality of life. In this regard,the specific aims of this study are as follows:

1.4.1. Aim 1: To investigate the impact of spatial light patterns on older adults' perception, mood, and preference

Aim 1 proposes to evaluate subjective impressions such as perception, mood, and preference of various spatial patterns among older adults. The goal is to build upon existing studies, which demonstrated that nonuniform, indirect, peripheral light is more pleasant, favorable, and relaxing for older adults (Flynn et al., 1973; Flynn et al., 1979; Yearout & Konz, 1989; Clijsters, Andre, 2015).

The main questions to be answered are (1) which attributes of spatial and spectral patterns of light are more favorable among the aging population? And (2) which are the most dominant variables that have the highest impact on the perception, mood, and preference of the participants?

These questions will be investigated in the first experiment to establish a lighting model according to the subjective impression of elderlies to measure cognitive performance in the next experiments.

Hypothesis: There is a statistically significant relationship between different spatial patterns (uniform/non-uniform, central/perimeter, and direct/indirect) and older adults' subjective impressions such as perception, mood, and preference.

1.4.2. Aim 2: Comparing the subjective impression and cognitive performance of older adults between a real and a virtual reality display

Aim 2 proposes to compare the mood, preference, and cognitive performance of older adults under similar lighting conditions in a real environment and a virtual reality environment. The findings from this experiment help us to understand if the VR environment can be a reasonable surrogate for real-world lighting environments when evaluating spatial patterns and CCT of electric lighting scenes on subjective impressions and cognitive performance in the final experiment.

It is hypothesized that cognitive performance ratings and subjective impression results are similar in a real environment and VR environment and the VR environment can be a reasonable surrogate for real-world lighting environments.

1.4.3. Aim3: Investigating the relationship between spectral and spatial patterns and cognitive performance in a virtual reality environment

Aim 3 proposes to measure the impact of the overall preferred and dominant characteristics of the spatial patterns and spectrums of light obtained from experiment 1 and literature on older adults' cognitive performance in a virtual environment. Cognitive performance in this experiment refers to the Trail Makin Cognitive Task which is mainly involved with visual navigation (Dobbs, B. M., & Shergill, S. S.,2013). In addition to cognitive tasks, the behavioral outcomes of the participants will be assessed as additional indicators of their performance and mood.

The question to be answered is, whether there is a relationship between the cognitive performance of the aging population and spectral and spatial patterns of light. And how do these attributes of light impact the cognitive performance of older adults?

It is hypothesized that there is a statistically significant relationship between different spatial patterns (uniform/non-uniform, central/perimeter, and direct/indirect) and spectrums of light (CCT) and older adults' cognitive performance and there are certain characteristics of human-centric light that result in better cognitive performance among older adults.

1.5. Significance and Innovation

Findings from this research are expected to provide new insights into the scope of lighting design of assisted living facilities. This Study will complement previous research efforts presenting both visual and non-visual effects of Human-Centric lighting on elderly residents' health and well-being.

While most previous studies have focused on quantitative variables of light such as light level and temporal pattern, in this study in addition to the exploration of the effect of CCT as a significant quantitative attribute of light we have focused on qualitative attributes of light which will lay the groundwork for a new generation of health care design. The main contribution of this research is the creation of a proposed model based on a subjective and objective assessment of residents' cognitive function. This model not only identified which variables of the light spectrum and spatial pattern impact residents' cognitive performance, but also evaluated the relative importance of all factors and their impact on cognitive function. The innovation of this study refers to three different phases of the study: first an online survey, second a comparative study between the real environment and virtual reality environment, and finally a completely immersive experience in VR that provides a holistic approach to evaluate cognitive performance with different tools both subjectively and objectively.

The second and third phases of the study can provide the opportunity to collect more accurate data and eliminate bias that might occur in a laboratory context. As most elderly residents in assisted living facilities spend a large portion of their time indoors and using electric lighting conditions, the findings of this study can provide a guideline for appropriate lighting design for improving cognitive impairment as a significant problem among this population. This also increases the architects' and lighting designers' awareness and encourages them to consider human-centric lighting design as one of the significant components of design in a residential building, especially for the older population.

1.6. Dissertation Overview

This dissertation is organized into multiple chapters that investigate different topics related to the research questions. The following section outlines the main topics and research questions covered in each chapter.

Chapters 1 and 2 serve as a comprehensive introduction and overview of the existing literature on human-centric lighting design. These chapters summarize the research related to lighting design and its impact on both visual and non-visual outcomes of humans. Furthermore, these two chapters highlight the current research gap in the area of lighting design and its impact on the aging population's perception, mood, and cognitive performance. At the end of the second chapter, a conceptual framework is presented that explains how different variables of the study are interconnected. Lastly, various research methods found in the literature are discussed and the research method framework employed in this study is outlined.

Chapter 3 provides an in-depth overview of two principal pilot studies conducted as pre-experimental assessments. The primary aims of these pilot studies were twofold: firstly, to establish a well-defined conceptual framework or assessment protocol for quantifying the sensitivity of various cognitive tests in evaluating the influence of the physical environment; and secondly, to identify and formulate a spatial pattern framework that can serve as a design pattern for guiding spatial light patterns associated with the preferences and moods of elderly individuals.

Chapter 4 summarizes the findings of the study's first experiment that investigated the subjective impressions among older adults under exposure to different spatial patterns of light in an environment. In the first step, we mainly focused on developing a spatial pattern framework, and in the next step, we used an online survey method to evaluate older adults' subjective impressions of different lighting conditions. This chapter will be submitted as a paper to Leukos, The Journal of the Illuminating Engineering Society. Selected portions of this paper were previously presented and published at the 2021 Architectural Research Centers Consortium (ARCC) International conference on April 7-10 in Tuscan (Virtual), the 2022 ARCC-EAAE International conference on March 2-5 in Miami, and ARCC 2023 International Conference in Dallas on April 12th to 15th.

Chapter 5 reports on the results of a within-subjects experiment conducted in a real space and Virtual Reality (VR) environment to investigate if VR can be a reasonable surrogate for real-world lighting environments. The paper titled "Comparing the Cognitive Performance of Older

Adults in a Lighting System Between a Real Space and a Virtual Reality Display" was co-authored with Professor Ihab Elzeyadi and is planned to be published in the Journal of Environmental Psychology.

Chapter 6 reports on the results of a within-subjects design study where 32 residents of the assisted living facility who participated in the previous study, were subjected to four lighting conditions (2 spatial patterns x 2 CCT) in a VR environment of an assisted living facility in Springfield, OR. Differences in visual perception and cognitive performance were examined across different conditions. The paper titled "The Impacts of Electric Lighting Spectrum and Spatial Patterns on The Cognitive Performance of Older Adults in an Immersive Virtual Environment" will be submitted to the Journal of Environment and Behavior.

In conclusion, Chapter 7 provides a summary of the key findings and suggests areas for future research that are necessary.

CHAPTER 2: REVIEW OF LITERATURE ON HUMAN-CENTRIC LIGHTING DESIGN FOR OLDER ADULTS

This Chapter provides an overview of the literature concerning human-centric lighting and its impact on visual and non-visual outcomes of older adults. Studies investigating human-centric lighting for older adults are limited and they are mainly focusing on the impact of quantitative attributes of lighting on older adults. To better understand how lighting might impact different visual and non-visual outcomes of older adults there is a crucial need for reviewing the literature.

2.1. Human-centric Lighting

Before Lewy's (1980) investigation of electric light's intensity impact on the decrease in nocturnal melatonin secretions, there was no evidence to show light also has a biological impact on the human body (Byerley et al, 1989). In 1984, Dr. Rosenthal and colleagues investigated the biological and therapeutic effect of light on 29 patients with Seasonal affective disorder (SAD). The finding of this study suggested that bright light therapy has an antidepressant effect.

In the 1990s and 2000s by discovering the intrinsically photosensitive retinal ganglion cells (ipRGCs) as the third type of photoreceptors in the eye, firm evidence was found that lighting can impact physiological, behavioral, and psychological outcomes of humans in addition to visual performance (Lucas et al, 2014). In this era before the LED's inventions, a higher scotopic to photopic ratio was an indicator of the potential benefits of light sources, while there was a controversy about the correlated color temperature (CCT) of light. Some studies were arguing higher CCT can improve visual acuity and brightness perception, while other studies were showing CCT of light should be determined according to different design factors, such as preference, mood, and aesthetics. Therefore, in the age of fluorescent lighting these two terms, "high CCT" or "high S/ P ratio" were used as an objective attribute of the light spectrum for lighting design according to users' needs. For the first time, the HCL term was used as a substitute for "high CCT" lighting to rebrand a new and arguable trend in lighting design (Houser, 2018).

Lighting Europe defines HCL as a type of lighting that improves the biological, emotional, health, and well-being of humans (Pei-Ting Chou, 2014; Boyce, 2016) in a study that explores human-centric lighting, argues that it is lighting that takes into consideration both the visual and non-visual effects of light on human outcomes such as visual performance and comfort, sleep quality, alertness, mood, and behavior as well as long term results for human health, learning, and spending.

Houser in 2018 proposed a more comprehensive definition for HCL that covers almost all the previous definitions: “Evidence-based lighting solutions optimized for vision, performance, concentration, alertness, mood, and general human health and well-being. Houser, K. W., et al (2020) have defined four main categories of lighting variables that contribute independently through designing lighting systems for the built environment: Temporal pattern (i.e. the timing and duration of exposure), Light level (i.e. quantity of light in radiometric and photometric units), Light spectrum (SPD) (i.e. spectral power distribution that governs color quality) and spatial patterns (i.e. luminance distribution of the three-dimensional light field) (see Figure 1)

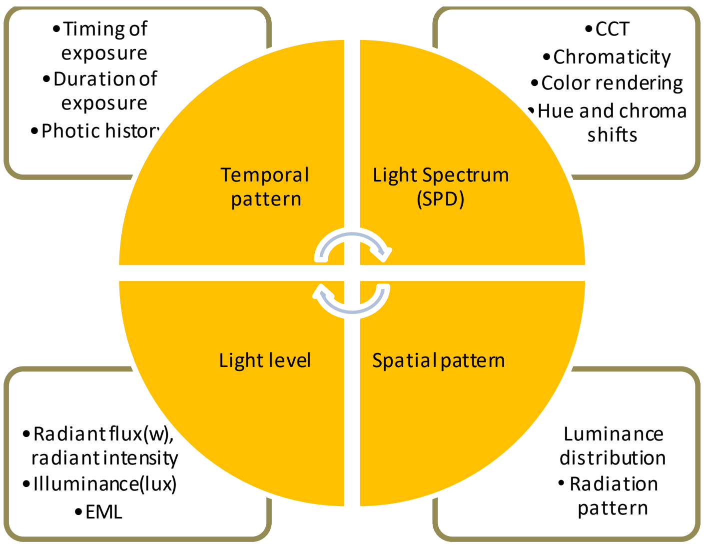


Figure 1. Human-centric lighting variables Houser, K. W., et al (2020)

2.2. Implications of HCL on the Aging Population

Existing literature on the topic has approached the light design for elderlies from two different areas: visual outcomes and non-visual outcomes of human-Centric light on the elderly population. Shikder and colleagues’ (2012) investigated the relationship between lighting design and the physical and mental health of the elderly through a comprehensive review of published literature. Shikder’s review provided a valuable research framework for analyzing lighting quantity and quality and their effect on visual and nonvisual outcomes in the aging population. It considered two important sub-domains of lighting for the elderly studies; first: visual performance-related aspects such as task performance, navigation, and wayfinding and safety, and second: psychophysiological aspects such as depression, circadian sleep-wake cycle disorder, and restless behavior among patients with dementia. (see Figure 2)

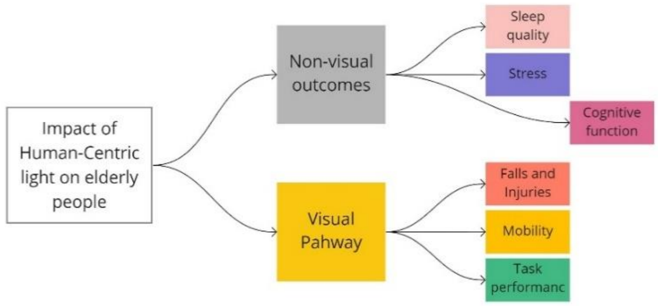


Figure 2. Sub-domains of lighting for the elderly studied. Shikder and colleagues (2012)

2.2.1 Visual Outcomes

With increasing age, people encounter visual impairment such as a gradual decrease in accommodation; yellowing pigmentation of the lens; a decrease in pupil diameter; and increased absorption and scatter of light in the ocular media because of the optical system. All these ophthalmological changes cause various problems in visual performance, such as reduced contrast sensitivity, poor night vision, slowed light-dark adaptation, decreased visual acuity, visual field loss, lack of color perception, etc. (Shikder, S., et al, 2012)

Brooke-Wavell, K., et al (2002) indicated among different lighting quantity, Dim lighting levels appears to be associated with poorer postural stability in older people and hence might be associated with an increased risk of falls while normal laboratory lighting (186 lx) improved Anteroposterior sway. Sinoo, M, M, (2010) results showed higher illuminances (>2500 lx) can provide a safer environment for older adults. Figuerio, M.G, (2011) showed 650 lux at the cornea was the most efficient illumination in comparison to night light providing 0.015 lux, and a night light and laser lines along a pathway providing 0.015 lux Kundura ci, A. C. (2017) also suggested providing (100-150 lux) for areas close to floor can prevent falls and accidents. In terms of lighting, quality studies recommend using task lighting and visual cues in addition to ambient lighting for increasing clarity and contrast in the environment and reducing the risk of falls among the aging group. (Kundur aci, A.C. 2017) (Sawyer, J., 2014) (Figuerio, M.G, 2011).

Dimmed ambient light affects stepping behavior and gait in older adults with a higher risk of falling, while just reducing the speed of walk-in healthy people (Kesler, A., et al, 2005) (Zietz, D., et al, 2011). There are some studies revealed there is a correlation between the low intensity of light and abnormal gait patterns and postural sway. These studies indicate elderlies have better mobility at 100 lumens in comparison to 5 lumens (Paul, S., & Liu, Y, 2012) and 250 lux than 0.25 lux (Rugeli, D., et al, 2014). There is also another study by Ellis, E. V. et al, which shows fully diurnal changing color spectrum and light intensity can provide a healthier environment for the aging population not only in terms of psychological effects but also in regards to their limited mobility.

Literature shows in addition to quantitative attributes of light such as illuminance, CCT, and spectrum wavelength, qualitative attributes of lighting such as glare and luminance distribution and contrast ratio are critical factors for visual task performance of the aging population. The evidence shows higher illumination in the environment can lead to better visual task performance (Geerdinc, 2009; Cheng, 2016). Yamagishi, et al (2008), Janosik & Marczak (2016), Cheng (2016), and Wang (2020) results revealed that elderlies perform better under CCT 5000, 6500, 6000, and 6500 respectively, while, only Geerdinc K, L (2009) showed there is no relationship between CCT and visual acuity and task performance.

2.2.2. Non-Visual Outcomes

While in visual outcomes, Retinal ganglion cells (RGCs) are more active in carrying signals from rods and cones to the visual cortex (yellow path in figure 3), in nonvisual outcomes, a distinct photoreceptor in the eye, intrinsically photosensitive retinal ganglion cells (ipRGCs) are responsible in carrying signals (Blue path in figure 3) (Lucas, R. J, 2014).

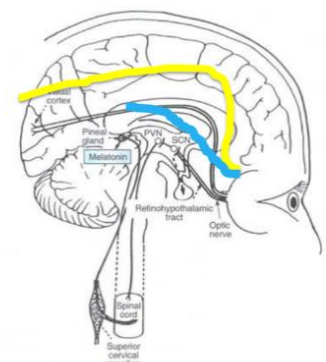


Figure 3. Visual pathways and nonvisual pathways in the brain

While the spectral response of the visual system is more sensitive to higher wavelengths (555nm, yellow-green light), the spectral response of the ipRGCs has a higher sensitivity to short light wavelength with a peak at approximately 490nm (blue light) (Corbett et al., 2012). Studies have shown both monochromatic short-wavelength light and blue-enriched polychromatic light is more effective than longer wavelengths of light at suppressing melatonin (Brainard, G. C., 2001), regulating the circadian clock (Gooley, J. J., et al, 2010; Revell, V. L., et al, 2005) and enhancing alerting effects and cognitive function (Chellappa, S. L., et al, 2011; Cajochen, C., et al, 2005; Vandewalle, G., et al, 2007).

Reviewing literature investigating the role of light on visual and nonvisual outcomes of elderlies indicates while there are many different approaches and methods adopted by multiple studies in this area, there is no general agreement between these studies on lighting quantity and quality to improve nonvisual outcomes among elderlies. Altogether, most of the studies suggest that elderlies biological lighting needs are different from visual lighting needs, an inadequate amount of light for biological stimulation can result in psychological problems. Studies regarding sleep quality indicate that higher illuminance of light (range between 1500 to 1000lux), with a wavelength range of 440 nm to 500 nm, and higher CCT (more bluish light) have a more positive impact on circadian rhythm and quality of sleep (Shikder et al, 2012*;* Satlin, et all, 1992*;* Kohsaka, 2000; Sinoo, 2016; Munch et al, 2017).

many older adults do not receive adequate light in assisted living facilities because of interior light design and the short period of time spent outdoors (Kuijsters, 2015; van Hoof, 2009). Lighting design can play an important role in ameliorating stress and depression in assisted living facilities. Ulrich et al (2008) indicate that exposure to bright electric light and daylight helps reduce depression and improve mood among adult patients. In general retina after receiving light influences the activity of the pineal gland which causes suppression or delay secretion of melatonin, thereby reducing depression, increasing daytime alertness, and fostering better sleep quality (Martiny,2004). Most of the studies indicate light treatment can play an important role in enhancing psychological impairment especially stress and depression in the elderly population (Lovell et al, 1995; Ichimori et al, 2013). Riemersma et al, (2008) also indicated whole day bright light (1000 lux) relieves depressive symptoms. There are also studies showing a higher level of illuminance is more efficient in controlling agitation. burns (2009) argues bright light therapy (10000 lux) in comparison to low illumination (100lux) can have some effect in reducing agitation (as measured by an actigraphy) and improving sleep in people with dementia.

Although there are many studies in the field of lighting design exploring the impact of light on the non-visual of humans, there are not sufficient studies in the gerontology discipline to measure the effects of different qualitative and quantitative attributes of lighting on elderlies' cognitive function. While among existing literature, some pieces of evidence demonstrate a higher level of illuminance can positively impact cognitive function among elderlies, there is still a need for further studies to measure the impact of other quantitative and qualitative attributes of lighting. (see Figure 4)

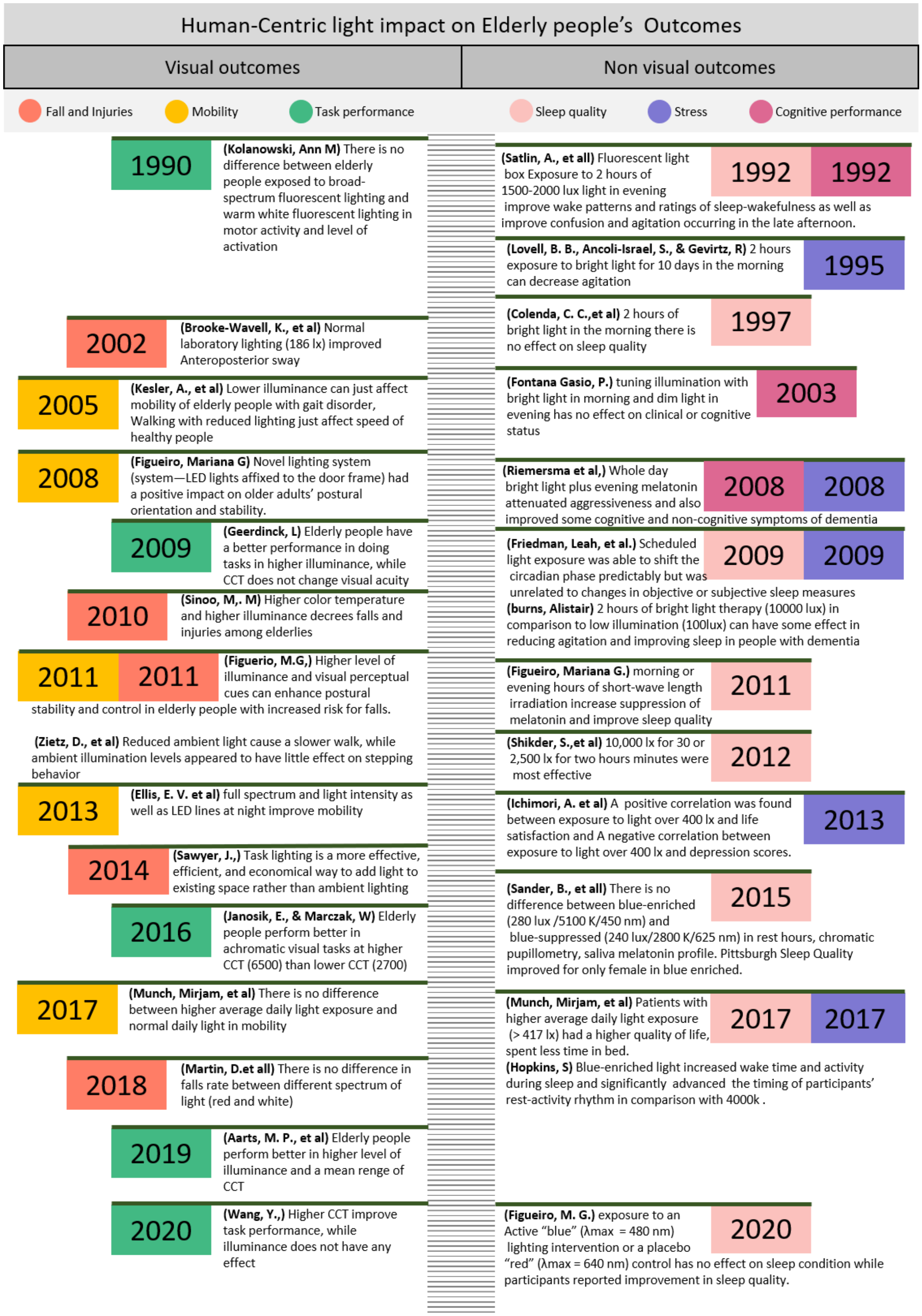


Figure 4. Human-centric light impact on Older adult's visual and non-visual outcomes

2.3. Lighting and Older Adult's Mood and Behavior (Stress, Anxiety, and Depression)

In the 1970s, John Flynn published a series of articles (Flynn & JE, F.,1977; Flynn et al., 1979; Flynn et al., 1973); conducted fundamental research about the role of the distribution of light and resulting patterns of the light on human subjective impressions. Flynn argues that environmental lighting is a vehicle that can alter and modify the information content of the visual field and consequently impact the behavior and sensation of well-being (Flynn, Spencer, Martyniuk, & Hendrick, 1973).

Disruption in the circadian system and Sleep disturbance are common impairments among elderlies especially those with Alzheimer's disease. These problems can stimulate aggressive behavior or agitation during the day (Cohen-Mansfield et al,1989). seasonal changes in the length of daylight can be another reason for agitation and stress (Foster & Roenneberg, 2008). The aging population might also experience anxious and stress because they are in the last stage of their life, or feel sad because they are not living with their family. Many stressors for the aging population are unavoidable because of aging impairments, illnesses, and medical treatment. Another kind of stress is produced by a poorly designed built environment and different attributes of the built environment such as acoustic, thermal, air, light condition, view, and even access to nature can affect user impression and behavior (Ulrich, R. S., et al, 2008). many older adults do not receive adequate light in assisted living facilities because of interior light design and the short period of time spent outdoors (Kuijsters, 2015; van Hoof, 2009). Lighting design can play an important role in ameliorating stress and depression in assisted living facilities. Ulrich et al (2008) indicate that exposure to bright artificial light and daylight helps reduce depression and improve mood among adult patients. In general retina after receiving light influences the activity of the pineal gland which causes suppression or delay secretion of melatonin, thereby reducing depression, increasing daytime alertness, and fostering better sleep quality (Martiny,2004).

Most studies investigating the impact of lighting quality and quantity on stress, agitation, and depression show a correlation between a higher level of illumination and psychological health and wellbeing, Lyketsos et al. (1999) and Wallace-Guy (2002) argue there is no relationship between bright light condition and low evening light level with depression. Most of the studies indicate light treatment can play an important role in enhancing psychological impairment especially stress and depression in the elderly population. Lovell et al (1995) showed people who received 2500 lx of light for 2 hours in the morning for two 10-day periods were less agitated than on normal days. Riemersma et al, (2008) also indicated whole day bright light (1000 lux) relieves depressive symptoms. There are also studies showing a higher level of illuminance is more efficient in controlling agitation. burns (2009) argues bright light therapy (10000 lux) in comparison to low illumination (100lux) can have some effect in reducing agitation (as measured by an actigraphy) and improving sleep in people with dementia. Ichimori et al (2013) also found there is a negative correlation between time exposed to light over 400 lx and depression scores.

There are some studies investigating the impact of CCT of light on the mood and behavior of elderlies. Kuijsters (2015) argued cozy ambient lighting with lower CCT (2700 k) and lower illuminance (120 lux) are more helpful In reducing a high arousing negative mood state (i.e., anxiety) than the neutral ambiance (3400k, 150 lux), while activating ambient lighting with higher CCT (4000k) and higher illuminance(325 lux) increase the physiological arousal of sad elderly more than the neutral ambiance. However, Hopkins, S (2017) indicated that Blue-enriched (17000 K) light can increase daytime activity and reduce anxiety and also negatively increase night-time activity, reducing sleep efficiency and quality in older people by more than 4000 k. On the other hand, van Hoof. j (2009) by proving that there is no difference between 17000k and 2700k at prolonged exposure to low-intensity light, i.e., E < 500 lx showed that higher illuminance levels are more important than color temperature in improving circadian rhythm and behavior in elderlies.

2.4. Lighting and Older Adults' Perception

"The perception Function is in charge of representing and discriminating objects based on their visual features, thus it integrates the input of visual processing with feedback from monitoring and memory systems." (González-Casillas et al, 2018). González-Casillas, A., and his colleagues presented a model that describes the process of visual recognition and perception in the human brain. This modular modeling approach by integrating the biological and neuroscientific evidence describes the process of perception and cognition in the human brain which occurs in V1, V2, V4, and ITC. According to this Theory ,the way that we perceive the surrounding environment is significantly related to the way that visual stimuli from the environment reach the retina in our eyes (González-Casillas et al, 2018).

Light is one of the significant environmental attributes that play a significant role in human perception and mood in interior spaces. Previous study indicates that light-correlated color temperature can significantly impact spatial brightness perception, visual comfort, satisfaction, and self-reported productivity (Wei et al., 2014). Richard Kelly used lighting design to influence human sensation in the environment. He defined three types of lighting that are associated with certain sensations: ambient luminescence, e.g. twilight haze; focal glow, e.g. a pool of light; and play of brilliants, e.g. sunlight on a fountain (Cialdella & D. Powerll, 1993). For example, he argued that the play of brilliants had the potential to excite the optic nerves and stimulate the body. The way that lighting impacts the elderly's perception of the environment is through the visual pathway and it mostly impacts the visual outcomes.

The literature shows that higher intensity of light and a higher level of CCT improve the elderly's perception of the environment and increase their task performance (Yamagishi, et al, 2008; Janosik & Marczak, 2016; Cheng, 2016; Aarts, et al. 2019; Geerdinc, 2009). IESNA also suggested controlling the glare in high-luminance situations, especially for elderlies suffering from cataracts is very important to improve their perception of the environment. Luminance distribution and contrast ratio are two main qualitative attributes of lighting affecting perception and task performance, especially for the aging population. IESNA recommends using a 2.5 times higher contrast ratio for a normal 65-year-old person to perceive equally as a 20-year-old person (Shikder, et al, 2012). In terms of lighting, quality studies recommend using task lighting and visual cues in addition to ambient lighting for increasing clarity and contrast in the environment and reducing the risk of falls among the aging group. (Kundur aci, A.C. 2017) (Sawyer, J., 2014) (Figuerio, M.G, 2011). Sinoo, M, M, 2010 argued a combination of quantitative and qualitative attributes of lighting such as an adequate amount of light, higher correlated color temperature (CCT), and a combination of electric light and daylight can provide a better perception and safer environment for older adults in their environment.

2.5. Lighting and Older Adults' Cognitive Performance

Cognitive performance in elderlies refers to multiple mental abilities, including learning, thinking, reasoning, remembering, problem-solving, decision-making, and active working memory as the aging population shows a greater impairment in this area in comparison to other populations (Fisher, G. G., et al,2019). There is firm evidence suggesting that older adults encounter greater challenges when learning new information, demonstrate less efficient reasoning abilities, exhibit slower response times across various cognitive tasks, and show heightened susceptibility to being disrupted by interfering with information compared to their younger counterparts. (Craik & McDowd, 1987; Park, D. C., et al, 2001;

The Literature shows previous studies investigating the impact of Human-Centric light on the cognitive performance of elderlies have mainly focused on the impact of light level on cognitive function.

Illuminance, an important quantitative attribute of lighting, has been shown to have a great impact on individuals' alertness and vitality, and task performance (Phipps-Nelson, Redman, Dijk, & Rajaratnam, 2003; Rüger, Gordijn, Beersma, de Vries, & Daan, 2003). As mentioned before, ipRGCs containing the photopigment melanopsin is responsible for the non-visual effect of light and are more sensitive to higher light level (Ru, T., et al, 2019). Some studies are showing a higher level of illuminance has a significant impact on the cognitive performance of elderlies. Satlin, Aa., et al (1992) and Graf, A., Wallner, C., et al. (2001) results show that two-hour exposure to evening bright light (1500-2000) and (3000) lux respectively not only improve sleep quality but also decrease sundowning (state of confusion and agitation) among elderlies and it has a beneficial effect on a patient with dementia. Other studies investigating the impact of intensity of light on non-visual and psychological impact, have shown although melanopsin phototransduction is only sensitive to moderate to high irradiance, ipRGCs and their downstream responses can be responsive to much lower levels of illumination. For example, it was originally thought, for activating nocturnal melatonin suppression we need at least 2500 lux, while later studies indicated even 1 lux or less illuminance can suppress melatonin in humans. (Lucas, R. J.2012).

In addition to Illuminance, researchers have proposed different metrics for quantifying the effectiveness of the non-visual and psychological impact of light on the human body. Equivalent Melanopic Lux (EML) is a more recent metric developed after Enezi et al. (2011) and Lucas et al. (2014) to measure the biological impacts of light on human bodies. EML measures the light impact on the human circadian cycle and indicates how much the spectrum of light source stimulates ipRGCs. This metric can be calculated at a point and in a given direction by multiplying the visual illuminance (in lux) by the mealnopic ratio which depends on the spectrum of incident light. Therefore, different light sources that create the same visual effect, might have a completely different non-visual impact. EML is used by WELL Building Standard to measure sufficient lighting for circadian stimulus. WELL requires exposure above various EML thresholds depending on the space type, ranging from 125 EML (learning areas) to 200 EML (work areas), to 250 EML (break rooms), for at least 4 hours a day for a 32-year-old individual (International Well Building Institute, 2018) Konis, K. (2018) is also a study evaluated circadian stimulus potential of daylit and non-daylit spaces in dementia care facilities, shows circadian stimulus potential ranging from 147 EML to 291 EML depending on closeness to windows and view orientation in care facilities.

The temporal pattern of light is also one of the most significant attributes in non-visual responses because the brain can perceive and understand time by observing a daily pattern of light and dark (Roenneberg, T., 2007). A specific light stimulus can be beneficial at one time of the day, while harmful at another time. For day-active people—that is, people who are active during the day, relatively less active in the evening—a bright light in the morning and during the day would help improve health, whereas bright light in the evening may delay sleep time and negatively impact health and wellbeing (Houser, K. W., & Esposito, T., 2021). There are also a vast majority of studies that have investigated the impact of temporal patterns such as timing and duration of exposure on cognitive performance. Yamadera, et al (2000) indicates 3000 lux bright light therapy from 9 to 11 am can improve circadian rhythm and cognitive state in the early stage of Alzheimer's. Riemersma et al, (2008) also argued a whole-day bright light therapy (1000 lux) improves some cognitive and non-cognitive symptoms of dementia (Figure 5).

Literature shows Previous studies have almost addressed the gap regarding light level variables and temporal pattern, while there are no studies that show a systematic relationship between cognitive function and light spectrum and spatial pattern of light (Satlin, A. et al.,1992; Knez, I., & Kers, C, 2000; Riemersma et al, 2008; Yamadera, et al,2000).

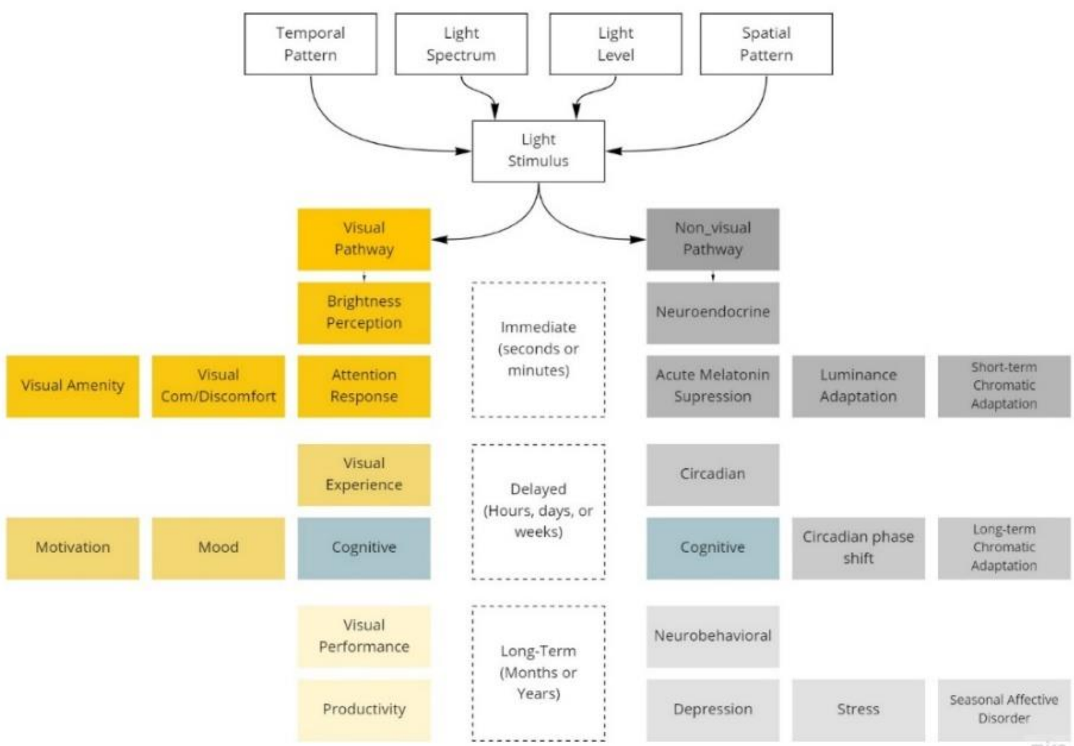


Figure 5. Schematic overview of light's impact on cognitive performance, considering visual and non-visual responses across three time periods. Inspired by Houser & Esposito (2021) and de Kort & Veitch (2014)

2.6.Visual perceptions and cognitive performance

To understand how light in an environment can impact the human's cognitive performance we first need to define how visual sensory information can be interpreted and perceived by the human brain. José E. Capó-Aponte and his colleagues in a study argue that" Visual Perception is defined as the mental organization and interpretation of the visual sensory information with the intent of attaining awareness and understanding of the local environment, e.g., objects and events" they also mentioned that" Cognition refers to the faculty for the human-like processing of this information and application of previously acquired knowledge (i.e., memory) to build understanding and initiate responses. González-Casillas, A., et al (2018) also argue that "Visual processing involves mechanisms to generate internal abstract representations, by applying multiple transformations to the light of environmental objects that reaches photoreceptors in the eye" while "Recognition refers to giving a meaning to such representations, regardless of simplicity, and it is shaped by the current sensory".

In a recent study González-Casillas, A., and his colleagues presented a model that describes the process of visual recognition and perception in the human brain. This modular modeling approach by integrating the biological and neuroscientific evidence describes the process of perception and cognition in the human brain which occurs in V1, V2, V4, and ITC (Figure 6)

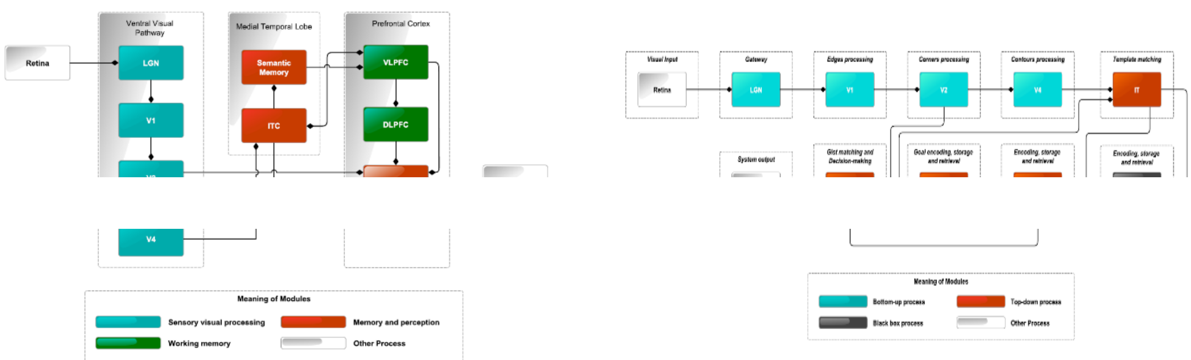


Figure 6. Conceptual Architecture: This figure depicts the interconnected brain structures involved in the visual identification process, along with their respective functions and associations with both bottom-up and top-down processes (González-Casill, et al, 2018)

Visual navigation is a cognitive task that involves processing the visual stimuli which are two-dimensional light patterns in the retina and analyzing them in the brain to obtain information to move through a three-dimensional environment (Therrien & Collin, 2010). This is where spatial vision meets spatial cognition. Spatial vision performance refers to the collaboration between the eye and the brain for encoding and representing spatial patterns of light. Studies have shown that changes in spatial vision can impact human spatial cognition. For instance, there is a large body of work investigating the impact of spatial frequency on face and object recognition (Collin et al, 2004; Ruiz-Soler & Beltran, 2006; Collin, 2006). Spatial frequency indicates the periodic distributions of light and dark in an image and evidence shows that higher spatial frequency which corresponded to sharp edges and fine details provides better spatial recognition. One of the most significant tasks which involve both spatial vision and spatial cognition is wayfinding. Aging cognitive spatial skills impairment such as mental spatial representation affects spatial orientation and wayfinding in older adults (Bates & Wolbers, 2014; Liu et al., 1991). This internal representation of the physical environment and space which is beyond visual perception is called cognitive maps (Marquardt, 2011). A cognitive map is a mental visual representation of different spaces, environments, places, and routes that are created by an area in the brain called the precuneus or mind's eye (Fletcher et al., 1995). In older adults with cognitive impairment and dementia, the cognitive map deforms and breaks apart, causing deficiencies in orientation and wayfinding (Marquardt, 2011). Gupta, et al (2017) represented a model which shows that our visual navigation needs cognitive mapping and planning (CMP). CMP consists of two main modules: mapping and planning modules. Mapping modules that are dependent on a latent spatial memory record the layout of the environment and create an egocentric map of the environment. The planner module used the memory and received information to conduct navigational actions (Figure 7).

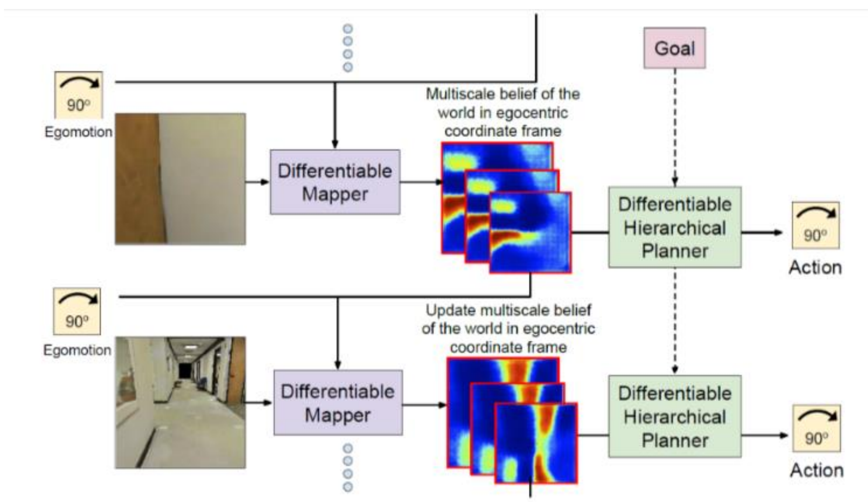


Figure 7. The navigation network consists of mapping and planning modules. The mapper creates an egocentric map in a latent spatial memory, which is then used by the planner to generate navigational actions based on the goal. The map emerges organically from the learning process (Gupta, et al., 2017).

According to the literature describing the process of visual perception and cognition in the human brain Figure 8, summarized this process from the initial step when the visual stimuli reach the retina in the human eye to the final step in the cognitive process which is decision making. To address the primary question of the study that how the spatial pattern of light in an assisted living facility could impact the cognitive performance of older adult residents, we first needed to examine the impact of lighting patterns on participants' perception, mood, and preference.

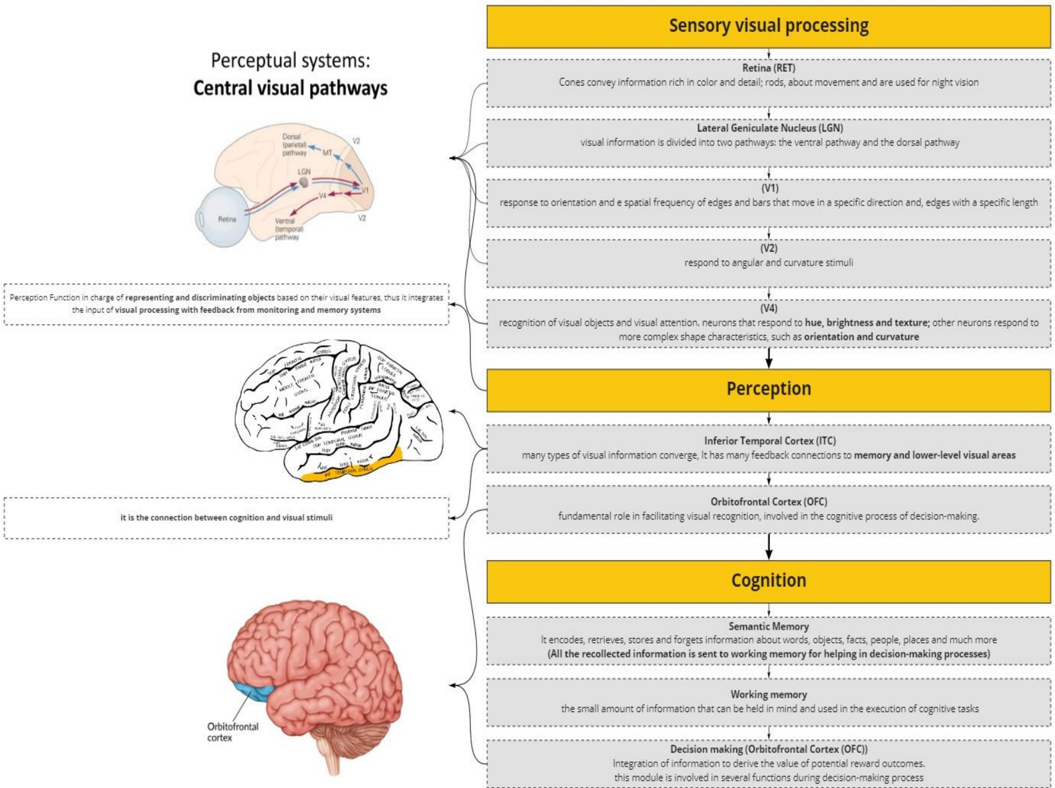


Figure 8. Different sequences of visual perception and cognition from eye receptors to brain processors according to (González-Casillas, et al, 2018)

2.7. Conceptual framework

In summary, existing literature shows that older adults' cognitive performance is influenced by visual perception. Spatial vision is where the human eye and brain collaborate to perceive and recognize spatial patterns of light. Several lighting variables such as light intensity, duration and period of light, light spectrum, and spatial pattern of light are the main attributes of light that impact the visual process and spatial vision and consequently spatial cognition. While the impact of light level and temporal pattern of light on cognitive performance have been sufficiently addressed, there are not enough studies to delineate relationships between spectral and spatial patterns of light and the cognitive performance of older adults.

This study conceptualizes the relationship between visual perception and cognitive performance from a systemic epistemological perspective. This model hypothesizes that human cognitive performance is impacted by sensory visual processing and perception. This is where spatial vision meets spatial cognition (Figure 9).

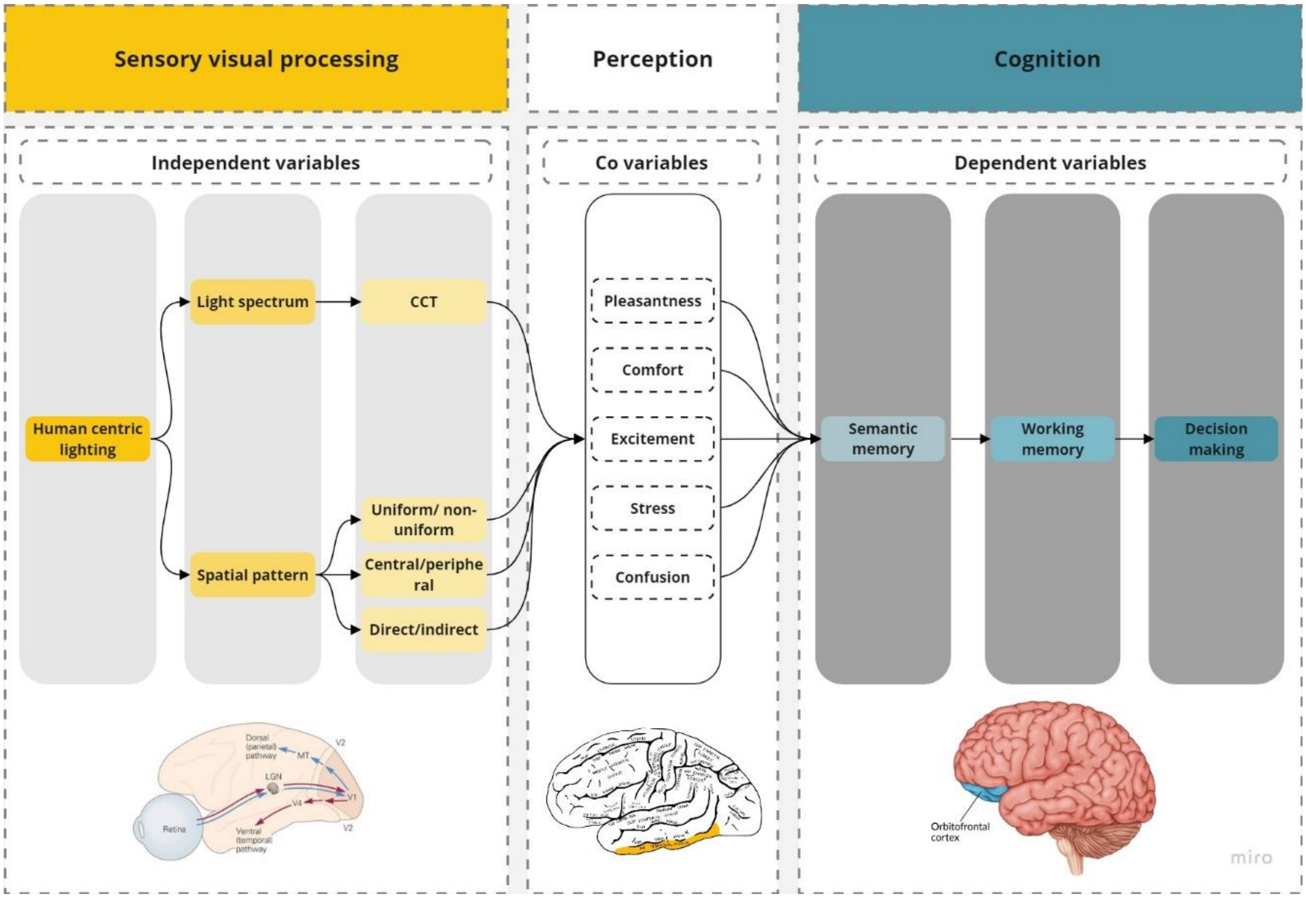


Figure 9. Cognitive performance as the main dependent variable of the study is impacted by sensory visual processing and perception in the human eye and brain. The list of variables influencing cognitive performance is meant to highlight the main variables involved in the current study.

To address the research questions of this study (outlined in Chapter 1), this proposal is broken down into three experiments. The goals of the first experiment are to investigate the impact of spectral and spatial patterns of light on older adults' perception, mood, and preference. The second experiment will assess the impact of the most favorable ad most dominant variables of lighting patterns from the first step on the cognitive performance of older adults in a virtual environment. A final experiment would be a field study, we will examine the impact of spectral and spatial patterns of light on the cognitive performance of older adults in a real environment through visual navigational tasks.

2.8. Summary of Methods

Evidence-based design as a relatively new trend in architectural studies has provided many promising results, while still dealing with many challenges in creating scientifically valid studies (Hamilton & Watkins, 2008; Edelstein & Macagno, 2012). A neurocognitive direction is an approach in evidence-based healthcare studies that not only investigate the impact of the physical environment on human behavior and performance but also seek information that shows brain mechanisms in response to the architectural environment. Neuroscientific data plays an important role in environmental behavioral studies and in bridging the gap between architecture and psychology (Vartanian et al., 2013). Current knowledge about the basic mental process such as visual perception, spatial navigation, and memory which addresses our responses to the architecture and surrounding environment supports this argument more than before (Sternberg & Wilson, 2006). Evidence-based design studies, by providing evidence on how our feeling, behavior, and mental function are influenced by different environmental attributes can be helpful to optimize the design of space and improve health and well-being (Goldstein, 2006).

The answer to question 3 consists of three sections. In the first section, we will discuss different methods for evaluating environmental attributes on human brain function and cognitive performance. After that in the second section, we will investigate the relationship between these three methods, including subjective assessment, task Performance-based cognitive tests, and physiological response-based evaluation through different studies evaluating the impacts of different environments on mental function. In the final section, we will propose a comprehensive assessment method that covers both subjective and objective evaluation of brain performance.

2.8.1. Cognitive Assessment in the Evidence base Studies

Evidence base studies revolving around environmental behavior and neuroarchitecture use different methods for investigating the impact of different environmental qualities and architectural attributes on brain responses and cognitive functions. Haapalainen, et al (2010) defined three assessment approaches for evaluating cognitive performance in humans according to literature: Subjective rating-based methods (self-reporting), Task Performance-based methods, and Physiological response-based methods (Figure 10).

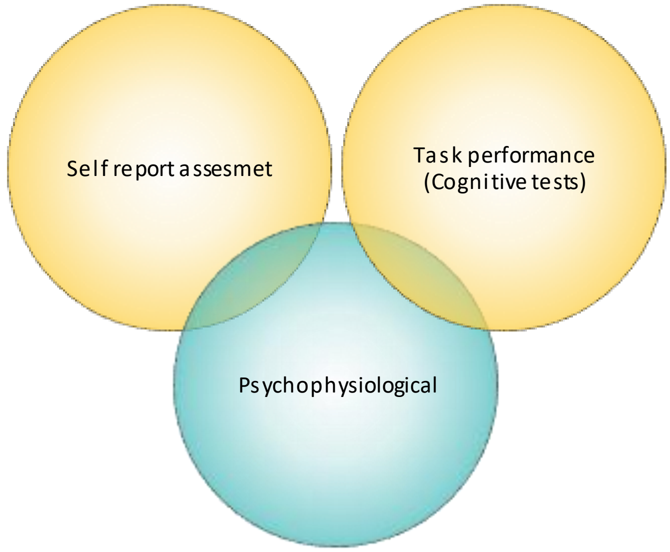


Figure 10. Three main approaches in assessing cognitive performance in psychophysiological studies based on Haapalainen (2010)

2.8.1.1. Subjective rating-based methods (self-reporting)

Lighting quality in a space is a result of interaction between lighting, environment, and human. While in most studies lighting evaluations are based on detailed photometric measures, this kind of assessment does not consider the role of the "human" component in lighting quality. There are studies evaluating human outcomes by subjective assessment tools. Cajochen et al. (2005) assessed the alertness sensitivity of participants to light wavelength by subjective Karolinska Sleepiness Scale and a visual analog scale. In another research, a field study was conducted to measure the affective impressions of 854 university students on the luminous environment in their classroom according to the different tasks they are doing there. This study used questionnaires as a subjective evaluation scale (Castilla et al., 2018). In Chellappa et al., (2011), 16 young men were studied to investigate the impact of different CCT of light on their Melatonin, Alertness, and Cognitive Performance. This balanced cross-over study also used subjective assessment of alertness, well-being, and visual comfort. In this study, the alertness of participants was measured by Subjective sleepiness on the Karolinska Sleepiness Scale (KSS), while for assessing the mental effort and visual comfort of participants they used the Mental Effort Rating Scale (MERS) which evaluates mental strain, concentration, and tiredness. Most previous studies investigating the impact of lighting variables on human outcomes mainly focused on comfort and satisfaction subjective assessment. while when residents are doing cognitive tasks; evaluating stress, mental fatigue and confusion can play a more important role in subjective assessment

(Kalantari, S., et al, 2021)

2.8.1.2. Task Performance-based methods

Although this approach is less common among different studies, it can provide the most objective data according to the task performance of the subjects. In this approach, subjects need to be involved enough with the task to be able to evaluate their performance (Haapalainen, 2010)

There are a variety of cognitive tests that measure the cognitive function of the human through a series of questions and/or performing tasks. To evaluate and assess the cognitive performance of elderly residents, we need the most sensitive cognitive tests to the physical environment. Therefore, we have done a sensitivity analysis among different cognitive tests in the literature to analyze their relation and sensitivity to the environment. This review found that there are cognitive tests in the field of psychology which might have the potential to assess the impact of physical environmental attributes on cognitive function. Among these tests in addition to MMSE which is the most common test in the field of environmental psychology, MOCA, TMT, CDT, and MINI-COG are the tests that have the highest rate of sensitivity to the physical environment. The physical environment mainly influences cognitive functioning tests which involve visuospatial and constructional praxis cognitive domains such as Montreal Cognitive Assessment (MOCA) and Trail Making Test (TMT). The Trail Making Test is a neuropsychological test of visual attention and task switching. It consists of different parts in which the subject is asked to mark and connect numbers and letters in a meaningful order as quickly as possible while trying to keep accuracy. This test can evaluate visual search speed, scanning, speed of processing, mental flexibility, as well as executive functioning. (Arnett, J. A., & Labovitz, S. S., 1995) it also is sensitive to detecting cognitive impairment associated with dementia, such as Alzheimer's disease (Cahn, D. A., et al, 1995). For the Current study, we designed a visual navigational-cognitive task that has been inspired by Trail making test. this test and its details will be discussed in the upcoming chapters.

2.8.1.3. Physiological response-based methods

Measuring the psycho-physiological signals of the human body is another approach to assessing cognitive performance (Paas et al., 2003; Ryu & Myung, 2005). In this approach different psycho-physiological signals have been influenced by variations in environmental qualities and task difficulty will be measured to assess the cognitive performance of humans. These psychophysiological signals include pupillary responses, eye movements, and blink interval (Ikehara& Crosby, 2005; Iqbal et al., 2005; Wilson, 2002), heart rate (HR), and heart rate variability (HRV) (Mulder, 1992; Wilson, 2002;

Fredericks et al., 2005), electroencephalogram (EEG or brainwave levels) (Wilson, 2002; Ryu & Myung, 2005), electrocardiogram (ECG) (Ryu & Myung, 2005), galvanic skin response (GSR) (Ikehara& Crosby, 2005; Shi et al., 2007), and respiration (Mulder, 1992).

Studies investigating lighting quality's impact on the physiological aspect of the human body mainly take into account melatonin suppression, heart rate, body temperature, and eye motion records. For example, Brainard et al., (2001) in a field study to measure the impact of lighting quality on melatonin regulation in the human body tested blood samples of participants before and after light exposure to quantify melatonin on them. In another study for assessing human melatonin sensitivity to short-wavelength, they used A direct double-antibody RIA, while for recording heart rate they used Standard electrocardiogram leads on the lateral thorax and the sternum (Cajochen et al., 2005).

2.8.2. Research setting

We obtained written consent from the managers of a senior living facility situated in Springfield, Oregon. Figure 11 presents visual documentation of this senior living facility. The decision to conduct our study at this particular facility was driven by the managers' expressed interest in participating in a research project aimed at enhancing the quality of life for their residents. In the selection process, no specific inclusion or exclusion criteria were imposed with regard to the assisted living facilities or the types of accommodations provided to the participants. The Senior Living facility offers a range of housing options, including independent and assisted living studios, one-bedroom apartments, and two-bedroom apartments, with sizes spanning from 427 to 977 square feet. The three main experiment of this dissertation were conducted in the main living room of facility (Figure 12)

To recruit participants for the study, we organized presentations and distributed flyers to the residents residing within the aforementioned senior living facility. The study sought to include residents aged 57 years or older, including individuals residing in various amenity types within the senior living facility.

Figure 11. Timber Pointe senior living facility, Springfield, OR

Figure 12. Main living room of the senior living facility where three main experiment of this dissertation were conducted

Based on previous studies, we propose a comprehensive method in three different phases that cover both self-reported assessment and task performance-based method (Figure 13).
In this study, physiological response-based methods were not included due to operational considerations such as the need for specialized equipment and trained personnel, which could pose practical challenges and potential discomfort. In addition, study's focus on cognitive, perception, and, behavioral aspects, rather than physiological responses, guided the decision to prioritize alternative variables of interest. Additionally, ethical considerations regarding the well-being and safety of vulnerable populations such as older adults led researchers to utilize non-invasive measures, emphasizing cognitive and perceptual assessments.

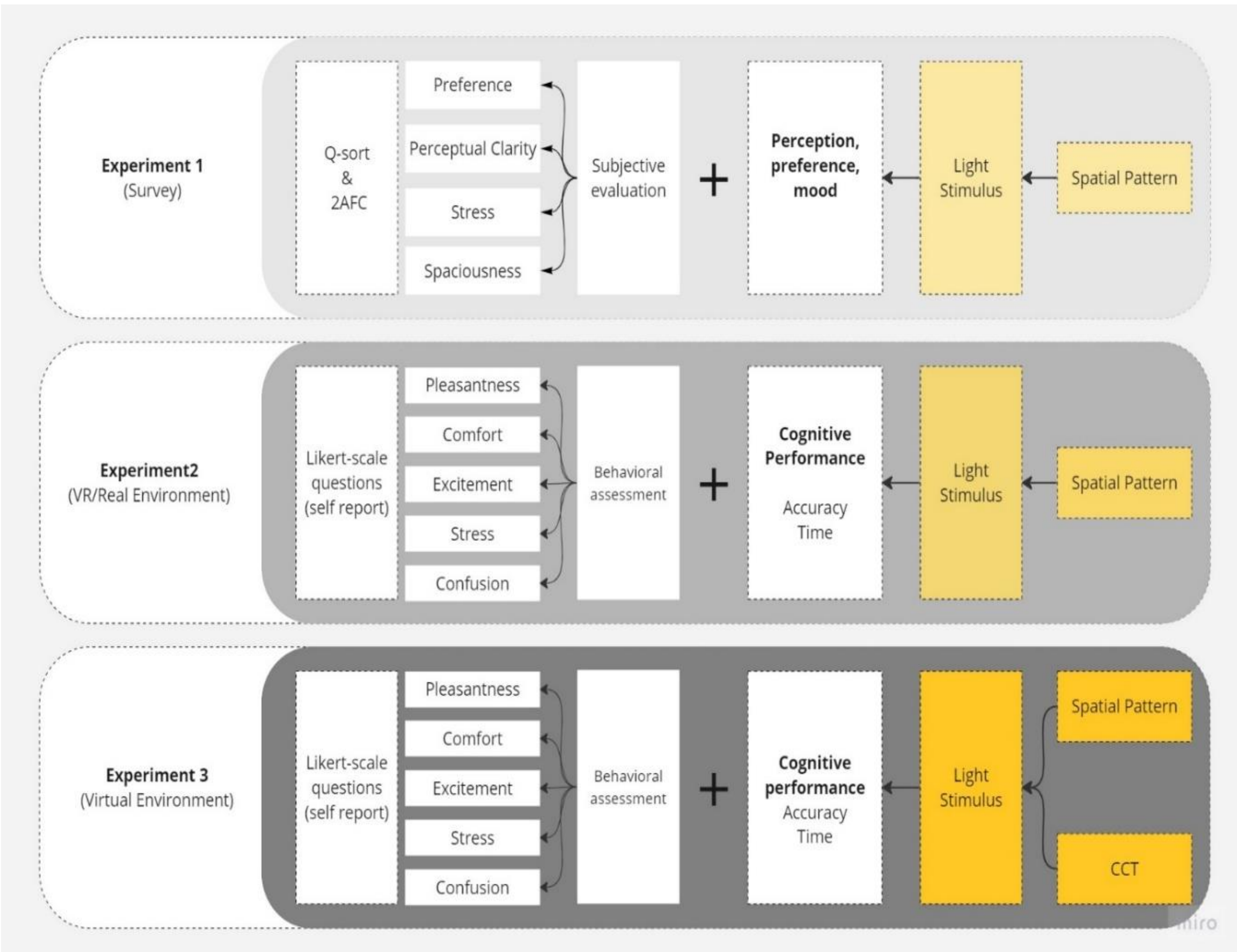


Figure 13. Overview of a three-step experimental procedure utilizing self-reporting and task performance-based methods

CHAPTER 3: PILOT STUDIES

This chapter offers a comprehensive overview of two primary pilot studies undertaken as pre-experimental tests. The primary objectives of these pilot studies were to first define a conceptual framework or assessment protocol to measure the sensitivity of different cognitive tests in assessing the impact of the physical environment; second to recognize and developed a spatial pattern framework that can be used as a design pattern to guide spatial light patterns relating to elderly people's preferences and moods. These two papers were presented in 2021 Architectural Research Centers Consortium (ARCC) International conference on April 7-10 in Tuscan (Virtual), the 2022 ARCC-EAAE International conference on March 2-5 in Miami. These two conference papers are a prologue to the three main experiments of the current dissertation that will be published in three different journals.

3.1. Measuring the Impact of Environmental Quality on Elderly Residents' Cognitive Functioning – A Critical Review

Cognitive impairment is a critical issue among the aging population. For elderly population it includes diseases, such as Dementia, Alzheimer, stress, and anxiety that are growing dramatically worldwide in recent years. Previous studies reported that different attributes of the physical environment could affect participant’s mood and affect cognitive performance. Currently, a variety of cognitive tests are used to assess an occupant's response to changes in their physical environment. These cognitive tests are frequently used in environmental psychology and gerontology studies, however, their sensitivity to measuring impacts of the physical environment is still unverified. To address this problem, this study develops content analysis of the different cognitive tests through a critical review to determine which tests are more sensitive to measure the impact of the physical environment and spatial parameters on cognitive performance. This study utilized a systematic procedure of extensive keyword search and cross-search using combinations of keywords through the EBSCO research database. In addition, a supplemental search through Google Scholar and other architectural science related journals was conducted by analyzing studies investigating the impact of the physical environment on cognitive functioning. Next, we employed a systematic procedure of keyword search and crosstabs, using combinations of keywords through multiple databases, in the field of psychology to find the most used cognitive tests employed in previous studies and then we conducted a comparative analysis between test parameters to evaluate their sensitivity to the physical environment parameters. The analysis revealed that Mini Mental State Examination (MMSE) is the most widely used cognitive test in previous studies. Results of this analysis indicate that the physical environment mainly influences cognitive functioning tests which involve visuospatial and constructional praxis cognitive domains such as Montreal Cognitive Assessment (MOCA) and Trail Making Test (TMT).

3.1.2. Physical environmental impact on cognitive function

The architecture of elderly environments is regarded as therapeutic modality to promote well-being and functionality for elderly residents. Knez, I. (1995) argues that different attributes of the natural and artificial environment (biotope) may induce different moods in people and cognitive processes also can be affected by these changes (Figure 14). Cognitive functioning defines performance in different tasks that need conscious mental effort (Lamportetal.,2014). These tasks consist of memory (verbal, spatial, and working), attention, and executive function (Lezak, 2004).

In this study cognitive functioning refers to multiple mental abilities, including learning, thinking, reasoning, remembering, problem solving, decision making, and active working memory as the aging population shows a greater impairment in this area in comparison to other populations.

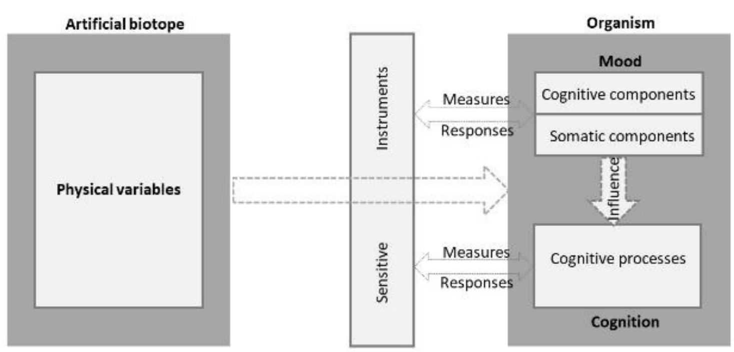


Figure 14.Relationship between physical environment and cognitive and mood (after Knez, I. ,1995).

There is conclusive evidence that the physical environment of elderly settings can influence social interactions and promote active lifestyles (Kelly et al., 2014). In addition, the physical environment can affect cognition directly through cognitive and sensory stimulation and indirectly, through lifestyle changes (Engineeret al., 2004; Kempermann, 2008). Different studies show bright light therapy can improve cognitive functions (Fontana Gasio, P., 2003; Satlin, A., et al, 1992; Yamadera, et al, 2000; Graf, A., et al., 2001). Environmental condition and air quality impact on cognitive performance have also been measured through many studies (Sun, R., & Gu, D, 2008). Taylor, L., (2016) indicated different thermal conditions can impact positively and negatively cognitive performance. Further studies reveal a positive relationship between acoustic and visual conditions on task performance and cognitive function of the elderly. (Hygge, S., 2001; Ranft, U., et al, 2009; Power, M. C., et al; 2011)

Despite the increasing body of knowledge related to the physical environment's impact on cognitive functioning in the field of environmental psychology, there is still a lack of a conceptual framework or assessment protocol to measure the sensitivity of different cognitive tests in assessing the impact of the physical environment. This is particularly important due to the fact that identifying the appropriate cognitive tests in evidence-based environmental design and psychology research play an essential role in providing insights and directions for researchers in the field to reach better outcomes. Additionally, measuring cognition, as one of the essential health factors, will be critical to investigate the impact of physical environment on health and well-being. Cognitive tests or tasks that have been used in these studies are mainly based on environmental psychology studies and their reliability and validity have not been accurately tested. Similarly, most cognitive tests have been developed to evaluate elderly cognitive performance but failed to acknowledge the assessment of physical environmental attributes of their settings. The objective of this review is to conduct a comparative analysis between existing cognitive tests and measures to identify that sensitive architectural research. This review followed a two-step process. First, an extensive series of cross-searches using combinations of keywords in two different fields of psychology and architecture was conducted. The search employed the EBSCO research database, which enabled the simultaneous search of multiple databases. The keyword search and crosstabs used combinations of keywords such as ‘cognitive performance’, ‘cognitive tests’, ‘cognitive assessment’, ‘cognitive screening’ and ‘cognitive impairment’ in the title or the abstract through Cinahl, Embase, Medline, and PsychINFO and PsycARTICLES databases to identify the most common cognitive tests in the field of psychological studies. After finding the ten most common cognitive tests, we conducted a content analysis of their parameters and used analytical charts in order to evaluate their sensitivity to the physical environment. In addition, a supplemental search through Google Scholar and specific architectural science related journals was conducted simultaneously. The next step involved a detailed analysis of selected articles that employed widely used cognitive tests and the protocols and research design used in them.

3.1.3. Literature review on articles of physical environment that adopted cognitive tests.

Cognitive tests stimuli employed in field studies to measure cognitive function were identified and categorized based on their application rates and the physical attributes measured in each study. The literature shows that among the 14 studies investigating the impact of different attributes of physical environment on cognitive performance of users, seven of them used MMSE test as the main test to evaluate cognitive performance. Three of these studies employed MMSE test to measure the impact of lighting quality and quantity on cognitive performance (Graf, A., et al, 2011, Riemersma-Van Der Lek, R. F.,2008, Most, E. I, et al). Two other studies used MMSE to investigate the impact of noise, heat and air quality on cognitive performance on users. (Power, M. C., et al, 2011, Sun, R., & Gu, D., 2008), and two studies compare the impact of urban and rural areas and natural environmental availability on cognitive performance of users (Cassarino, M., et al, 2016, Wu, Y. T. et al, 2017).

Eight studies among the articles reviewed have employed other cognitive tests to evaluate cognitive performance of subjects. Ranft, U., et al (2009) employed the Battery CERAD-Plus test to measure the impact of acoustics on cognitive performance. This test was originally developed as a screening tool for Alzheimer disease to test executive function and visuospatial understanding, language and memory function through 12 subtests (Schmid, N. S.,2014). Liebl, A, et al (2012) for measuring the impact of acoustic and visual distraction on attention and short-term memory has used two cognitive tests and two cognitive tasks. The Concentration Performance test applied for this study was a modified version of the original one that evaluates sustained attention or concentration through a calculation process. Other tests, such as Grammatical Reasoning were applied to investigate verbal-logical reasoning processes by measuring ability to reason about relationships among objects. In another study by Most, E. I, et al (2010) the impact of lighting quality and quantity was measured on different aspects of cognitive function by using a wide range of different cognitive tests and tasks. In this study, in addition to MMSE, Neuropsychological test battery (NTB), Stroop color/word test and Trail making test A&B, were applied in combination with other tasks. NBT covers different aspects of cognitive domains: short and long term verbal memory (the 15 Word List; the MIS+); semantic memory; working memory (Number Sequences; visual memory (the Visual Association Test) (Most, E. I.,et al, 2010). The Stroop Color and Word Test (SCWT) also are used in another study to evaluate the impact of air quality on processing speed and alertness, motor speed, inhibition and context, working memory (Schiavon, S, et al, 2017). SCWT is a neuropsychological test extensively used to assess the ability to inhibit cognitive interference that occurs when the processing of a specific stimulus feature impedes the simultaneous processing of a second stimulus attribute, well-known as the Stroop Effect. The Stroop effect is a phenomenon that occurs when you must say the color of a word but not the name of the word (Scarpina, F., & Tagini, S., 2017). Trails Making Test (Trails) is also a neuropsychological test of visual attention and task switching. It can provide information about visual search speed, scanning, speed of processing, mental flexibility, as well as executive functioning (Delbaere, K.,2013). The Montreal Cognitive Assessment (MOCA) is a widely used screening assessment for detecting cognitive impairment which is only used in one study with MMSE to assess whether and how geographical and physical characteristics of lived environments contribute to cognitive aging. These two tests are related to global cognition, memory, speed of processing, attention, and executive functions (Cassarino, M., et al, 2016)

In addition, studies investigating the impact of physical parameters on cognitive function were also reviewed. Each cognitive test involves answering a series of questions and/or performing tasks. These tasks are mainly a part of a cognitive test which is modified or redesigned to evaluate the impact of physical environmental attributes on cognitive function based on specific aims and purposes. Simple cognitive (underlining nouns and subtracting numbers), Memory-load search, Long and short-term recall and recognition, Serial recall, Text comprehension, Match to sample visual search (MTS), Choice reaction time (CRT), Pattern recognition memory (PRM), Rapid visual information processing (RVP), Spatial span (SSP), Simple reaction time, Numerical vigilance, Category Fluency, Finger tapping and 2-Back (2B) are some of these cognitive tasks were applied to assess cognitive performance in these studies.

3.1.4. Cognitive functioning tests review

The top-ten most employed cognitive tests in the field of environmental psychology and medicine screening for cognitive impairments are summarized below (Woodford, H. J., & George, J. ,2007). This brief summary aims at categorizing the sensitivity of standardized cognitive tests to measure the impacts of the physical environment on elderly cognitive abilities.

3.1.4.1. Mini Mental State Examination (MMSE)

The Mini Mental State Examination (MMSE) is the most used cognitive screening tool in the USA, Canada and the UK by some distance (Woodford, H. J., & George, J. ,2007). The Mini-Mental State Exam (MMSE) is an interviewer-administered 30-point assessment tool to assess cognitive performance and track cognitive impairment or recovery over time. This test consists of 30 questions with 30 points which are categorized as follows: orientation to time and place, registration, attention and calculation, recall, and language. The MMSE is typically administered in 5–10 min, and administration procedures are clearly explained (Schatz, P. ,2011).

3.1.4.2. Standardized Mini Mental State Examination (SMMSE)

The standardized Mini-Mental State Examination (SMMSE) was developed in 1997 to reduce inter-rater variability in scores and increase reliability. The SMMSE incorporates the same questions as MMSE with clearer guidance on the administration, scoring and time allocation. This test is an appropriate tool for family doctors who are the first medical professionals in identifying cognitive impairments in patients. The SMMSE needs a short time to conduct it and plays an important role in detecting dementia in early stages and it is important because effective medications can be beneficial if started early (Woodford, H. J., & George, J. ,2007, Molloy, W., 2014).

3.1.4.3. Abbreviated Mental Test (AMT)

The Abbreviated Mental Test (AMT) is a short, 10-item scale used commonly for assessing elderly patients for the possibility of dementia. It is also used for mental confusion and other cognitive impairments. This cognitive test involves short- and long-term memory as well as attention and orientation. The validity of this test is less than the MMSE test, but it is simpler to perform. The validity of the test has deteriorated over time (Oxford medical education, 2015, Woodford, H. J., & George, J.

,2007).

3.1.4.4. Six-Item Screener (SIS)

This Six-Item Screener (SIS) consists of three questions regarding time orientation and three questions about the recall task of MMSE test. Each question scores one point, and a lower score indicating more cognitive impairment (Woodford, H. J., & George, J. ,2007).

3.1.4.5. Six-Item Cognitive Impairment Test (6CIT)

The six-item cognitive impairment test (6CIT) also known as the Short Orientation-Memory-Concentration Test is a brief cognitive test for use in primary care settings. 6CIT is an acceptable and accurate test for cognitive impairments with higher sensitivity in performance than MMSE which can be considered as a viable alternative to MMSE in the secondary care setting (Abdelaziz and Larner, 2015).

3.1.4.6. Clock Drawing Test (CDT)

The Clock-drawing Test (CDT) is a simple and quick exam in the neuropsychiatric assessment of patients. It assesses different cognitive domains such as attention, language skills, frontal lobe function, auditory, processing, motor programming, frustration tolerance and visuospatial skills. The patient is asked to draw a circle and then put the numbers on. Incorrect space of numbers shows visuospatial impairment, neglect, or a planning deficit. The advantage of using this test is independence from bias due to intellect, language or cultural factors. (Eknoyan, D., 2012, Woodford, H. J., & George, J. ,2007).

3.1.4.7. Mini-Cog

It is a complementary version of the CDT test which has a three-word recall test in addition to the drawing clock task which improves memory testing. The cognitive assessment is based on a present absence of impairment and there is no numeric scale for the test. Although it makes the test easier to conduct, the test is not able to rate the severity of impairment and its progression. (Woodford, H. J., & George, J. ,2007).

3.1.4.8. General Practitioner Assessment of Cognition (GPCOG)

The GPCOG stands for the General Practitioner assessment of Cognition. This test is one of the three screening tools recommended by the Alzheimer's Association for use at the Medicare annual wellness visit. This test also consists of a recall task as well as historical questions and components testing memory of recent events and orientations.

3.1.4.9. Montreal Cognitive Assessment (MOCA)

The Montreal Cognitive Assessment (MOCA)Test was used as an assessment for mild cognitive impairment (MCI), and after that adapted in numerous clinical settings. This test sensitivity for detecting MCI is 90%, compared to 18% for other cognitive tests such as the MMSE. MOCA can assess a variety of cognitive domains such as: short term memory, visuospatial abilities, executive functions, Attention, concentration and working memory, Language as well as Orientation to time and place. (Rosenzweig, A. S., 2020)

3.1.4.10. Trail Making Test A&B (TMT-A&B)

The TMT is a timed test of visual conceptual and visuo-motor tracking. TMT-A mainly focuses on attention, visual search and motor function, while TMT-B measures executive functioning, speed of attention, visual search and motor function. Both parts of the Trail Making Test consist of 25 circles distributed over a sheet of paper. The results of both tests are evaluated based on time to completion and number of errors; therefore, higher scores reveal greater impairment (Dobbs, B. M., & Shergill, S. S.,2013). The difference of scores in TMT-A and TMT-B (B– A) indicates cognitive flexibility (Vazzana et al., 2011)

3.1.5. Content analysis of cognitive tests

Empirical studies in the fields of psychology, medicine and therapeutics investigated the impacts of different variables on cognitive performance, using different outcomes for evaluating and assessing diagnostic tests. Most meta-analysis studies in this area have shown sensitivity and positive/negative likelihood ratios as the main critical values for assessing tests (Korsten, M. A., 2007) (Tsoi, K. K., 2015). This study has conducted a content analysis of different cognitive tests based on different criteria in order to measure their sensitivity to the physical environment. This is a comparative content analysis based on these main attributes: time, number of questions, points, cognitive domains, impact of physical environment, inventory of physical environment and physical environmental attributes involved in each test. Information regarding time for conducting studies, the number of questions, and scoring points for each test was derived from previous studies and recorded as important attributes for evaluating tests. Woodford, H. J., & George, J., (2007) used qualitative evaluation of the main cognitive domains as a tool for defining the areas of cognitive impairment. Each cognitive test assesses a particular aspect of cognition in the brain called cognitive domains. Memory, visuospatial/constructional praxis, orientation, attention/calculation, and other aspects were selected as main domains assessed within cognitive tests. The authors compared commonly used assessment tools relative to cognitive domains in a table which shows the efficiency of each cognitive test for evaluating these domains. In this study These Cognitive domains have been used as one of the criteria to evaluate the sensitivity of tests to the physical environment. Cognitive tests involve visuospatial and orientation domains and will get a higher score in terms of sensitivity to the physical environment. The score for each test has been obtained directly from the study Woodford, H. J., & George, J., (2007).

In addition, a comparative analysis of the contents of the questions was conducted to measure the impact and inventory of the physical environment. By evaluating each question, direct and indirect mentioning of the physical environment were considered as an indicator of sensitivity for each test. This indicator was tabulated and rated as impact and inventory of physical environments of a numeric scale based on the points of each question and the whole number of questions in each test. According to the contents of the questions and the exam’s requirement, sensation and physical environmental attributes involved in each test were identified (Table 1).

Table 1. Content analysis of cognitive tests

Test	Time	Number of questions	Points	Cognitive domain					Impact of physical environment	Inventory of physical environment	Involved Sensations/ physical environmental attributes
				Memory	Visuospatial/ constructional praxis	Orientation (time and place)	Attention/calculati on	Other aspect			
MMSE	8	11	30	1	1	3	2	2	12/30= 0.4	1/11= 0.09	Vision (Light, spatial ergonomic) Auditory (acoustic)
AMT	3	10	10	3	0	2	2	0	1/10=0.1	0	Vision (Light, spatial ergonomic) Auditory (acoustic)
SIS	2	6	6	1	0	1	0	0	0	0	Auditory (acoustic)
6CIT	5	6	28	2	0	2	2	0	0	0	Auditory (acoustic)
CDT	1.5	1	3	1	2	0	1	1	3/3=1	0	Vision (Light) Auditory (acoustic)
Mini-Cog	3	4	-	2	2	0	1	1	3/6=0.5	0	Vision (Light) Auditory (acoustic)
GPCOG	5	5	9	3	2	1	1	1	2/9=0.2	0	Vision (Light) Auditory (acoustic)
MOCA	11	12	30	3	3	2	3	1	10/30=0. 33	4/30=0.1 3	Vision (Light) Auditory (acoustic)
TMT-A&B	(A=29s, B=75s)1.73 min	2	- time	1	3	3	3	1	2/2=1	0	Vision (Light) Auditory (acoustic)

3.1.6. Comparative analysis and findings

Comparative analysis of different cognitive tests indicates MMSE and MOCA tests consists of the highest number of questions and will require an average of 8 and 11 minutes to complete, respectively., The overage duration to complete the other tests is five minutes or less. All cognitive tests have numeric scales for assessing cognitive impairment, except MINI-COG and TMT tests that evaluate cognitive functioning based on presence/absence of impairment and the required time to answer a question. Although it makes these tests more convenient to conduct, they are not able to rate the severity of impairment and its progression (see figure 15). Cognitive impairment is associated with at least one of the cognitive brain domains (Reger, M. A., 2004). Each cognitive test can assess a specific range of cognitive domains. In this analysis, the involvement of cognitive domains was measured and compared (memory, visuospatial/constructional praxis, orientation, attention/calculation, and other aspects) based on Woodford, H. J., & George, J., (2007). It can be concluded that processing of spatial, temporal, and social relations relies on mental cognitive maps, on which the behaving self is oriented relative to different places, events, and people (Peer, M., 2015). The ability to see an object or picture as a set of parts and then to construct a replica of the original from these parts is known as visuospatial constructive cognition (Mervis, C. B.,et al, 1999). Therefore, among different cognitive domains, orientation and visuospatial/ constructional praxis are considered as an indicator to the sensitivity of different tests to measure the impacts of the physical environment. In addition, comparative analysis of cognitive domains reveals MMSE and TMT are assessing orientation domains more than other cognitive tests, while CDT and MINI-COG cannot provide any information regarding orientation domain. Among different tests investigating impairment in visuospatial/ constructional praxis domain MOCA and TMT have the highest scores. TMT among all the tests can perform better in assessing orientation and visuospatial domains with 6 scores, which renders it as an appropriate measure for the impact of the physical environment on cognitive functioning (see figure 16). In order to measure the sensitivity of each test to the physical environment the impact and inventory of the physical environment were then compared. The analysis indicates that the physical environment can impact TMT and CDT tests more than any other tests because the questions of both tests are mostly related to visual conceptual and visuo-motor tracking. Although CDT test sensitivity to physical environment is more than any other tests, this test consists of one question only, which makes it less sensitive in early stages of cognitive impairment and it should be used in combination with other tests. MINI-COG and MMSE are the other tests that have the highest sensitivity to physical environments impacts. There is no evidence, however, that shows the impact of the physical environment on SIS and 6CIT tests (see figure 17). In addition, the inventory of the physical environment for each test was also measured. This indicator shows that only MOCA and MMSE have some questions that provide an inventory list of the physical environment attributes in their content (see figure 18).

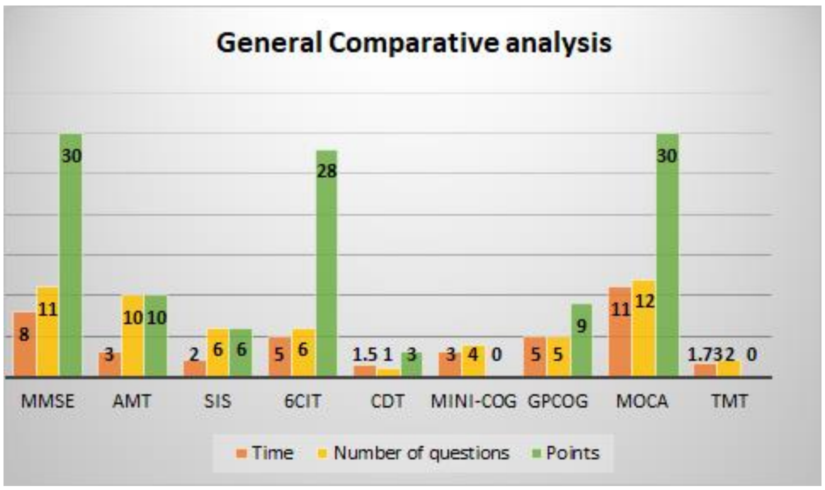


Figure 15.Comparative analysis of time, number of questions and points of different tests

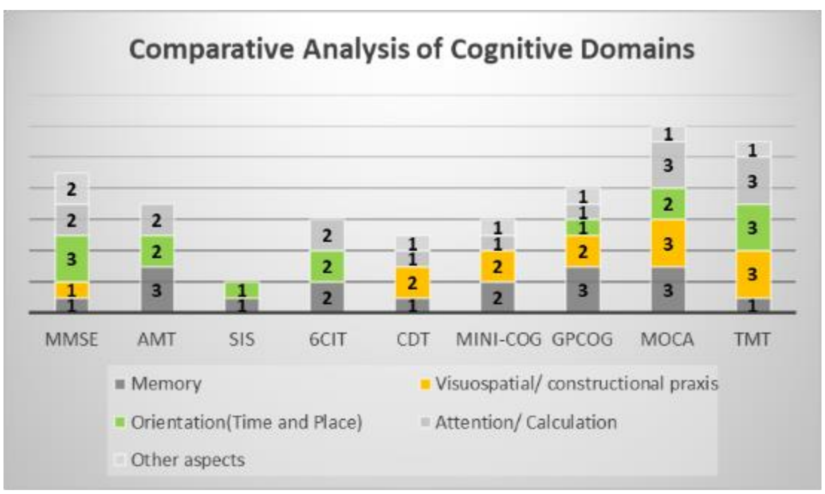


Figure 16. Comparative analysis of cognitive domains between different tests

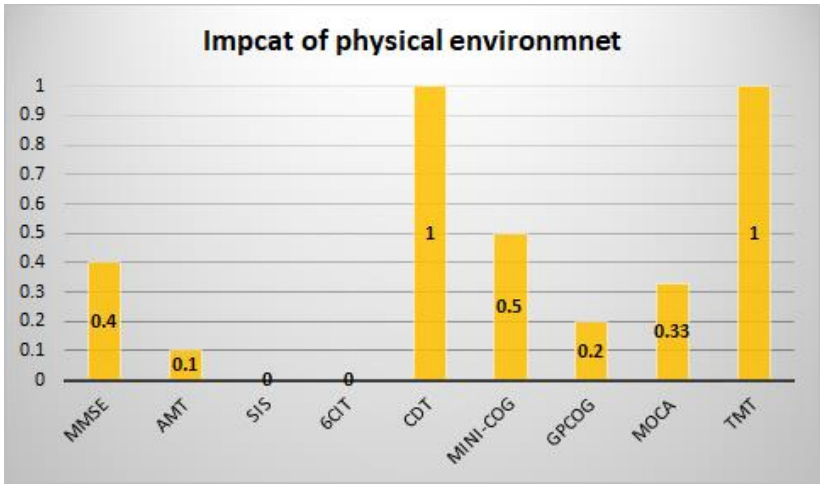


Figure 17. Comparative analysis of the impact of the physical environment on cognitive tests

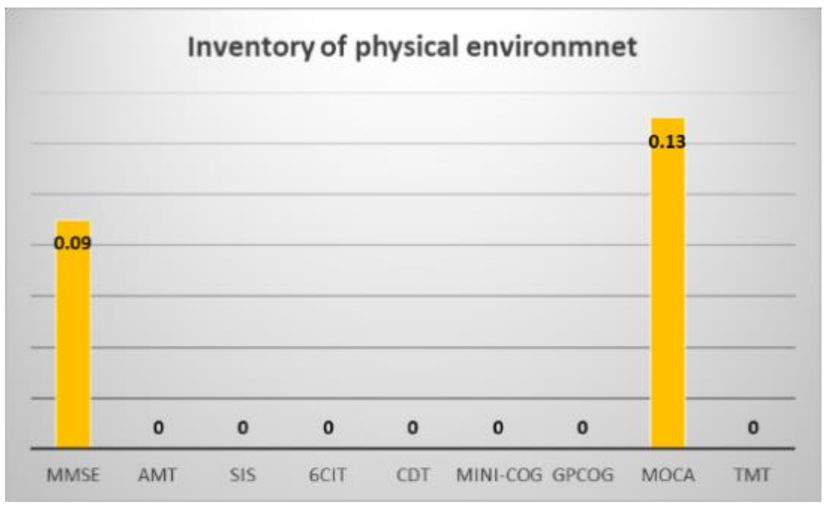


Figure 18. Comparative analysis of Inventory of physical environment in different tests

3.1.7. Conclusions and limitations

The analysis reviewed studies of the physical environment mostly adopting cognitive tests and tasks without considering their sensitivity to the physical environment. This critical review indicated there are cognitive tests in the field of psychology which might have potential to assess the impact of physical environmental attributes on cognitive function. Among these tests in addition to MMSE which is the most common test in the field of environmental psychology, MOCA, TMT, CDT and MINI-COG are the tests that have the highest rate of sensitivity to physical environment. Researchers in Environmental psychology studies investigating the impact of different physical environmental attributes can combine and customize these tests according to the requirement of the experimental study. In addition to defined criteria in this study for assessing cognitive tests, there are other attributes in psychological studies which assess the accuracy of these cognitive tests such as sensitivity and specificity. Sensitivity is the ability of a test to correctly identify patients with a disease and specificity is the ability of a test to correctly identify people without the disease. These two factors also play an important role in assessing cognitive tests and should be considered for choosing the appropriate cognitive test for different studies. This critical review takes the first step to identify the most sensitive and applicable cognitive tests in relationships with the physical environmental attributes to be adopted in environmental psychology and evidence-based healthcare design research. Future studies in the field are needed to investigate the applicability of the cognitive tests based on the research settings and the special populations of the study. The findings of such studies can be beneficial for evidence-based design researchers to address the impact of the physical environment on cognitive functioning and subsequently create environments that promote health outcomes.

3.2. Exploring the Impacts of Human-Centric Lighting Spatial Patterns on Elderly Residents mood and preference – An Architectural Content Analysis

The aging population is growing rapidly. The population is aged 65 and older increasing from 9 percent in 2019 to 16 percent by 2050, which means one in every six people in the world will be aged 65 or older. One of the problems of an aging population is that older adults are at higher risk for sleep dysfunctions, anxiety disorders, and depression leading to mental stress and cognitive impairments. Studies have shown that lighting parameters are among the most significant indoor environmental qualities that can potentially play an important role in improving health and wellbeing in older adults. Human-Centric light is an approach in lighting design, which investigates the impact of different variables of lighting such as temporal pattern, light level, the light spectrum and spatial pattern on both visual and non-visual outcomes of humans. While previous studies have investigated the impact of different light variables on elderly visual and non-visual outcomes, there is a critical need to identify the impact of spatial patterns of light on elderly residents' outcomes.

This study is an initial effort in recognizing and developing a spatial pattern framework that can be used as a design pattern to guide spatial light patterns relating to elderly people's preferences and moods. This paper aims to identify spatial patterns of light according to literature and apply them to the most common typologies of existing senior living facilities' interior spaces. After a picture content analysis of 36 images of assisted living facilities living rooms and bedrooms, the Visual Attention Software (3M-VAS) was used to predict the human engagement with the image scene and reveal the most efficient visual hierarchy in the images according to lighting elements and furniture arrangements. The main contribution of this study is the creation of a proposed spatial pattern framework that can be used as a design pattern to guide spatial light patterns relating to elderly people's preferences and moods. Findings from this research will provide new insights into the scope of human-centric lighting design of assisted living facilities.

3.2.1. Introduction

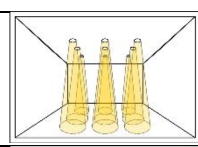
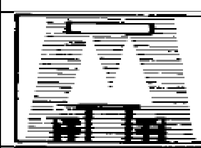
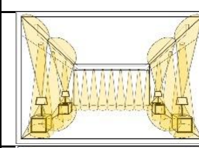
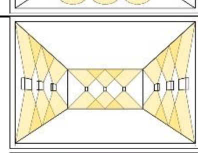
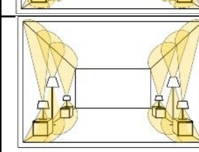
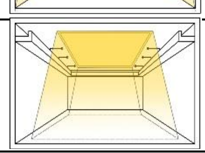
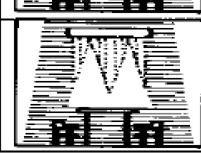
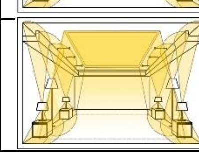
Appropriate lighting condition is one of the significant indoor environmental qualities that could potentially play an important role in improving the living environment and enhancing health and well-being in older adults (Lu et al., 2019). However, lighting design for the aging population has not received much attention from researchers and designers. Human-Centric light is a new approach in lighting design, which focuses not only on the visual impact of light, but also on its non-visual aspects that influence circadian rhythms, sleep, mood, and cognitive performance. Houser, K. W., et al (2020) have defined four main categories of lighting variables that contribute independently through designing lighting systems for the built environment: Temporal pattern (i.e., the timing and duration of exposure), Light level (i.e., the quantity of light in radiometric and photometric units), Light spectrum (SPD) (i.e., spectral power distribution that governs color quality) and spatial patterns (i.e., the luminance distribution of the three-dimensional light field). Illuminance, an important quantitative attribute of lighting, has been shown to have a positive impact on individuals' alertness, vitality, task performance, agitation, depression, sleep quality, and cognitive performance (Satlin et al.,1992; *Yamadera et al.,2000;* Riemersma et al., 2008). In addition to Illuminance, researchers have proposed different metrics for quantifying the effectiveness of the non-visual and psychological impact of light on the human body. Equivalent Melanopic Lux (EML) is a more recent metric developed after Lucas et al (2014) to measure the biological impacts of light on humans' bodies. Studies investigating the impact of the light spectrum have shown both monochromatic short-wavelength light and blue-enriched polychromatic light are more effective than longer wavelengths of light at suppressing melatonin (Brainard et al., 2001), regulating the circadian clock (Revell et al., 2005), and enhancing alerting effects and improving mood (Chellappa et al., 2011). There is firm evidence among the literature that the temporal pattern of electric light in the indoor environment that follows the same natural pattern of daylight (morning bright light, dim evening light) provide a better non-visual outcome for human, especially for elderly people (Yamadera et al., 2000; Riemersma et al., 2008; Figueiro, 2008).

Existing studies in the field of human-centric lighting for elderly people have mainly focused on quantitative attributes of light such as light level (Sinoo, 2010; Figuerio, 2011); light spectrum (Janosik& Marczak, 2016; Cheng, 2016; Sean et al., 2020); and temporal patterns of light (Gasio et al., 2003; Figueiro, 2008), while there are not enough studies showing a systematic relationship between qualitative attributes of light such as the spatial pattern and luminance distribution with nonvisual outcomes of elderlies *(*Knez, I., & Kers, C, 2000; Riemersma et al, 2008; Yamadera, et al,2000*).* A vast majority of gerontology studies have addressed the visual impacts of indoor lighting on wayfinding, mobility, and task performance, while there is a significant gap in understanding the impact of indoor lighting on the nonvisual outcomes of elderly people as mood, behavior, and preference. To address the research gaps in this area and particularly investigate the impact of spatial patterns on mood and preference, this study aims to initially identify the most common spatial patterns of light in existing elderly facilities. Next, the patterns will be modified and combined with the extracted spatial pattern attributes of light from the literature to provide a more holistic approach towards the creation of a proposed lighting spatial pattern framework.

3.2.2. Flynn's theory (spatial pattern of light and human subjective impression)

There is some evidence in the literature that show inferior retinal light exposure is more effective than superior retinal exposure in suppression melatonin (Glickman et al., 2003) and light exposure on the nasal side of the retina is more effective in biological responses than the temporal side of the retina (Visser,1999). Therefore, the way that light radiation reaches the human eye is very important in its effect on visual and non-visual outcomes. Lighting designs for visual outcomes are at task locations and are often oriented horizontally (DiLaura, D. L., et al, 2011), while non-visual lighting designs are at the plane of the occupant’s eyes and are oriented vertically (Houser & Esposito, 2021; Brown et al., 2020). The spatial pattern of light refers to the spatial distribution of light in the three-dimensional light field and it depends on many parameters of light and environment. In the 1970s, John Flynn published a series of articles (Flynn & JE, F.,1977; Flynn et al., 1979; Flynn et al., 1973); conducted fundamental research about the role of the distribution of light and resulting patterns of the light on human subjective impressions. Flynn et al (1979) defined four main lighting modes in space, which make various impressions in humans. These four lighting modes are the basic attributes that designers consider when they are creating an environment for different purposes: bright/dim, uniform/non-uniform, central / perimeter, and warm/cool. Flynn particularly examined how different “lighting modes” affect Spaciousness / Confinement, Visual Clarity / Haziness, Relaxation / Activation, and Private/ Public. Flynn et al (1973) defined six different light arrangements which had their specific uniformity, centrality, and brightness value so that each arrangement corresponds to a specific point in a dimensional space of the different lighting characteristics. The results of this study indicated that there is a significant difference in human subjective impression between different lighting arrangements. According **to** Flynn’s theory of lighting and mood in the 1970s we have defined six main spatial patterns of light that contribute to humans’ moods and preferences. These six spatial patterns of light have been created according to three main attributes including Spatial arrangement (uniform/non-uniform, centrality (central/perimeter), and direction**.** (Table 2)

Table 2. Spatial lighting patterns according to Flynn's theory of lighting and mood (Flynn, 1973)

	Spatial arrangement	**Flynn’s theory arrangement**	Proposed spatial lighting arrangement		Spatial arrangement	**Flynn’s theory arrangement**	Proposed spatial lighting arrangement
1	Uniform Central Direct			4	Nonuniform Peripheral Direct/indirect		
2	Nonuniform Peripheral Indirect			5	Nonuniform Peripheral Indirect		
3	Uniform Central Indirect			6	Nonuniform Central/Peripheral Direct/indirect		

Previous studies regarding the spatial pattern of light have mainly focused on the relationship between the control parameters of light and the spatial distribution of light and how it impacts human outcomes. In this section, we have reviewed and discussed spatial arrangement (uniform/non-uniform, centrality (central/perimeter) and, the direction of light as three main independent variables of the spatial pattern of light and their impacts on mood, preference, perception, behavior, performance, and other outcomes of the human according to the literature.

3.2.2.1. Spatial Arrangement (Uniformity)

Light fixtures in an environment can be arranged in two different ways: Uniform and Non-uniform. In a uniform arrangement, all the lighting fixtures in a room are placed in maximum height and uniform spacing without considering the location of furniture and other architectural elements to illuminate the environment at about the same level. In a non-uniform lighting system, all the fixtures are located at a high level and close to the ceiling, but with irregular spacing. The exact location of each fixture depends on the place of the workstations and machinery and the task that will be performed in that space.

Hawkes et al. (1979) argued two main attributes of light define the perception of light in a scape, namely brightness, and interest. Brightness refers to the perceived intensity of light while interest is related to perceived uniformity. There is evidence that shows that task lighting can increase attention to desk work, which improves task performance (Rea et al.,1990). Taylor et al. (1975) found that nonuniform desktop illumination improved task performance. This study shows adults perform better in arithmetic calculations (on paper) in office spaces with nonuniform lighting in comparison to uniform fluorescent lighting or very nonuniform colored lighting. On the other hand, some other studies are indicating there is no correlation between uniformity of light and task performance. McKennan & Parry. (1984) shows different illuminance levels on the desk-based on different lighting distribution does not impact (paper-based) clerical task performance in a comparison of 10 different general and local/general combined lighting installations. Lighting design in theatres shows that areas of high luminance could help to attract the audience’s attention, but there is no firm evidence to show how this mechanism can be implemented to provide appropriate conditions for different tasks in other settings (Veitch, 2001). There is a study that investigated the impact of position and number of the light source on a perceived atmosphere of light in space. The position of the light in this study refers to the distribution of light (symmetrically, left-right, and front-back). The results indicate that adjacent luminaires to walls create a less uniform atmosphere *(*Stokkermans et al., 2018). In another study, affective impressions of university students were evaluated concerning spatial patterns and luminous environments in their classrooms. They defined six different axes of effective impressions of students including Surprising-amazing; Clear-efficient; Cheerful-colorful; Uniform; Intense brilliant and Warm-cozy. The result showed that Writing-reading tasks need a positioning of light that generate Clear-efficient, Intense-brilliant, and Uniform pattern, Reflecting-discussing tasks require a positioning of light that generates a Warm-cozy atmosphere and Paying attention task needs a light positioning that creates Clear-efficient, Uniform, and Surprising-amazing atmospheres (*Castilla et al., 2018)*. There are also other studies investigating the impact of spatial arrangement and uniformity on human perception, behavior, and preference *(*Flynn et al.,1973; Flynn et al, 1979; Chraibi, et al., 2017; Stokkermans et al., 2018). Flynn et al. (1973) and Flynn et al. (1979) as indicated in table 1 showed that uniformity in the spatial pattern of light increases clarity in space, while non-uniformity contributes to more relaxing feelings. Yao et al. (2017) that argues uniformity is a critical attribute of indoor lighting in work efficiency and comfort, have investigated different methods for evaluating uniformity of light in space. These methods include: (Min: Avg), the coefficient of variance (CV), entropy uniformity (EU, introduced in the article), and a pattern vision-based indicator (U_{HVS}). According to the literature, it seems that illuminance distribution in a space can direct attention in useful ways, and impact visual and non-visual performance, however, there is no integrated evidence to show how uniform or nonuniform light can impact the mood and preference of a human.

3.2.2.2. Centrality (central/ peripheral)

Light sources in a space can be arranged to emphasize horizontal surfaces (central, overhead), or vertical surfaces (perimeter). Flynn et al. (1973) also revealed that in addition to light intensity (dim – bright dimension of light) and interest (uniform and non-uniform dimension of light), there is another factor that impacts the perception of light in a space, namely peripheral – overhead. Flynn showed central arrangement with Higher light levels on horizontal surfaces such as work plane provide more visual clarity, and Uniform peripheral lighting make the space more spacious, while peripheral non-uniform lighting is more helpful in increasing relaxation and privacy (Flynn et al., 1973; Flynn et al., 1979). Another study investigating the impact of the different spatial patterns of light in university classrooms on students' performance showed that each pattern of light (central or peripheral) should be modified according to the specific task taking place in the class (Castilla et al, 2018).

3.2.2.3. Lighting direction

A fixture can be designed to focus light in one of the following ways: Direct Lighting, Semi-Direct Lighting, General Lighting, Semi-Indirect Lighting, and Indirect Lighting. In direct lighting, 90 to 100 percent of light radiation from the luminaire reaches the work surface. This type of lighting is a very common lighting design specially for task lighting. The main problem of direct lighting is that it causes glare and unfavorable shadows. In a semi-direct lighting system, 60 to 90 percent of light sources reach the working surface and the remainder of the light is reflected toward the ceiling or wall. In general lighting, the light will be distributed equally in both upper and lower areas of space (Lighting methods, 2017). Semi-indirect lighting, unlike semi-direct, reflects 60 to 90 percent of light toward the ceiling, while 30 to 40 percent only reach the working surface. In indirect lighting, 90 to 100 of light reflects toward the ceiling that increasing diffusion and even distribution. Studies have shown that people prefer indirect lighting in comparison with systems providing direct lighting (Veitch et al., 2008;). Yearout & Konz (1989) found that indirect direct lighting is more favorable than direct lighting among participants doing tasks in the workstation. Operators also prefer brighter illumination in office space and spotlights on walls. Katzev (1992) also showed office employees prefer direct/indirect lighting more than other lighting systems, while there were no significant differences between participants' performance in cognitive/intellectual tasks**.** A recent study investigating the impact of direct and indirect light on health, well-being, and cognitive performance of office workers also demonstrates except for a relationship between reduced job stress severity and direct lighting, there is no meaningful correlation between direct and indirect lighting and cognitive performance (Fostervold & Nersveen, 2008). Another study that investigated the impact of light direction on office workers' satisfaction, visual health, and productivity demonstrates that satisfaction and other subjective lighting rates were higher in an indirect lighting system, while productivity was less influenced by the direction of light (Hedge, et al,1995). Another study that investigated the impact of lighting positioning in workstations has found that two different spatial patterns (varies in terms of number, direction, and position of the light) create different views while do not impact the performance of the users. This study shows that a combination of direct and indirect light is more favorable for the users. They also preferred a non-uniform spotlight on wall painting (Yearout & Konz, 1989).

Literature shows most previous studies investigating the impact of the spatial patterns of light on elderly outcomes have mainly focused on one or two attributes of spatial pattern. However, there is a critical need for a comprehensive investigation of the impact of the spatial pattern of light on elderly outcomes. Furthermore, most of the previous studies have not sufficiently addressed the architectural and design perspective of the spatial patterns of light and have mainly examined the spatial pattern of light in an experimental room. To address this critical gap this study has used a multi-method approach to investigate spatial patterns of light in senior residence facilities.

3.2.3. Multi-method approach to investigate spatial light patterns.

In this study, architectural content analysis has been conducted by an inductive approach through three main phases. In phase 1, a Picture Content Analysis (PCA) was conducted for surveyed facilities' websites to determine the most common layout arrangements and properties for Bedrooms and Living Rooms of Assisted living facilities in the US. This phase resulted in the most common typologies of each of the two rooms. In phase 2, Visual Attention Software (3M-VAS) software analyzed the most common room typologies from phase 1 to determine which typology is the most attractive to users and can generate the most viewing interest. In phase 3, the two most likable views of each room were selected to implement spatial lighting patterns according to Flynn's theory of lighting and mood.

3.2.3.1. Picture Content Analysis

In the first phase of the study, to identify the most common layout arrangement, interior lighting quality, and spatial patterns of light in existing senior residence facilities, we conducted a picture content analysis of the online image stocks from surveyed assisted living facilities website.

Quantitative or formal content analysis is an empirical method for systematic analysis of different media content such as audio, textual, visual, and/or audiovisual (Krippendorf, 2004; Rössler, 2005). This systematic observational method aims to examine hypotheses about the representation of an event, people, and situations in different media (Fielding et al., 2008). To conduct a picture content analysis the main unit, sample unit, unit of analysis, and codebook should be defined. In this study, the main unit of analysis consists of all the images of 50 elderly residents' facilities websites in the US. In the first step, we selected 36 images of assisted living facilities' living rooms (18) and bedrooms (18) as the sample unit of the analysis. Images were selected based on the type of facilities (assisted living facilities), interior space (living room and bedrooms), areas of the spaces (living room<1000 sq ft; bedroom< 450 sq ft), and lighting quality of spaces (including the different spatial patterns of light). The images including the human figures were also excluded from the sample unit to decrease distraction in content analysis. In the second step, five different subjective categories were defined for coding the images of the first phase. These categories include the possibility of having daylight, home likeness, including colorful furniture, the existence of natural elements, and warmness. (Figure 1 and 2). Five images with the highest score of these coding categories were selected for the final visual content analysis via 3M VAS software in phase 2.

3.2.3.2.Visual Attention Analysis – (3M VAS)

In phase 2 five final images were analyzed by 3M VAS software to investigate which image has met the visual hierarchy goals for our study. 3M-VAS (Visual Attention Software) is a biometric tool that collected and clustered 30 years of eye-tracking data (Salingaros and Sussman, 2020). This software is mostly applied in website and signage design, analyses the images according to three different attributes: heatmap, hotspots, and gaze sequences. The results of analyzing the five final images of the bedroom and living rooms have been indicated in Figures 19.

- **Heatmap**

This attribute shows the probability that a part of visual content is seen within 3-5 seconds of seeing a picture. Among 5 selected images of the living room, room number four with more attention on lighting fixtures and seating area rather than other elements of the room get the higher scores in this analysis. Between 5 images of the bedrooms room, number five with the focus of heating map on lighting fixtures and bed shows the most attractive typology.

- **Hotspots**

This criterion is a simplified version of the heatmap results which shows the areas of the image that is most likely to be seen. The probability of being seen by a person will be shown by a numeric score on each region of the image. Hotspot analysis among living rooms indicated that Image number 1 and number 4 by 85% and 92% focus on seating areas and 51% and 85% on lighting elements have the highest scores among five different images. Comparative analysis among bedrooms images hotspots revealed that room number 2 and number 4 by 69% and 42% attention on lighting fixtures and 77% and 97% focus on beds can generate the most viewing interest.

- **Gaze sequence**

This parameter shows the four most-likely gaze locations, in their most-probable viewing order. This criterion is important because it shows the visual hierarchy of the scene. For this study, we are looking for a gaze sequence in a scene that attracts the users' attention to lighting fixtures and the significant elements of the room (seating area in the living room and bed in bedrooms). Among five images of living rooms, room number four's gaze sequence shows the most rational sequence: 1- desk light, 2- ceiling light, 3- desk light and, 4- seating area. The gaze sequence analysis among bedroom images also indicated that image number 2 by a gaze sequence from bed to desk light and then to ceiling light and window has a most reasonable hierarchy among room's elements in the scene.

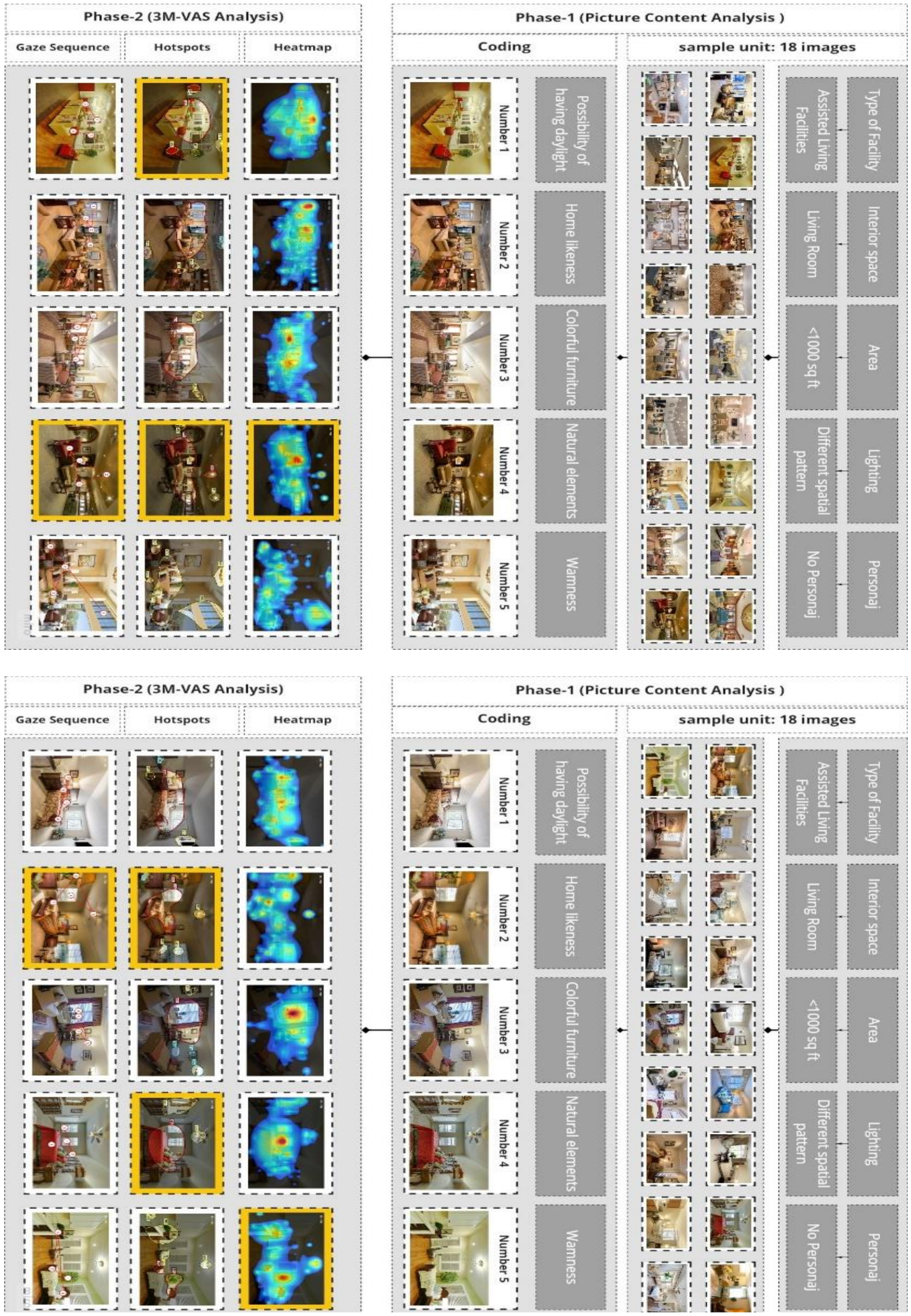


Figure 19. (Top): Picture content analysis and visual attention analysis of the Livingroom's images (Bottom): Picture content analysis and visual attention analysis of the bedroom's images.

3.2.4. Proposed Spatial Lighting Patterns

In the final phase, the two most likable typologies of each room were selected to implement spatial lighting patterns according to Flynn's theory of lighting and mood. First, the virtual space of the living room and bedroom was simulated according to these two most attractive typologies in Autodesk 3ds Max software. Light level and light spectrum in each space were simulated according to the recommended amounts based on the literature (illuminance: 500 lux for living room and 300 lux for bedrooms; CCT:4500 k). Second, six main spatial patterns of light according **to** Flynn's theory of lighting and mood were implemented in each room to create the final proposal spatial pattern framework in assisted living facilities living rooms, and bedrooms (Figure 20).

The results of this architectural content analysis show that the dominant lighting fixtures in living rooms of assisted living facilities are chandeliers, recessed lighting, and table shade lamps, while in bedrooms ceiling fans and bedside lamps are more common. Although we have included the images of spaces by the possibility of having daylight, there are a vast majority of facilities without any access to daylight. Elderly residents in assisted living facilities spend 90% of their time in indoor spaces therefore, they are experiencing dimmer days and brighter nights than what they need to experience in nature. The results of visual attention analysis indicated that spatial patterns of light in many of these facilities have created a glare that can be seen in the images. Although glare can create discomfort for all age groups, it takes more time for elderly people to recover glare effect and can impact their efficiency and activation. The final spatial pattern framework can be implemented in future studies to investigate the impact of different attributes such as centrality, uniformity, and direction of light on both visual and non-visual outcomes of elderly people.

Figure 20. Spatial pattern framework in assisted living facilities living rooms and bedrooms.

3.2.5. Conclusions and future studies

Literature shows that the spatial pattern of light has a significant impact on the way that light radiation reaches our eyes, however, there is not sufficient evidence about the influence of the spatial pattern of light on both visual and non-visual outcomes of elderly people.

This study is an initial effort in recognizing and developing a spatial pattern framework that can be used as a design pattern to guide spatial light patterns relating to elderly people's preferences and moods. The findings of the study can play an important role in providing new insight into the field of human-centric lighting. To address the existing gap regarding the influence of the spatial pattern of light on elderlies' non-visual outcomes especially mood, behavior and cognitive performance, the final simulated images of this study can be used as a valid and replicable reference of spatial patterns of light in senior living facilities. The finding of this study can be combined with the results of previous studies regarding the light level, light spectrum and, temporal patterns of light to provide a more integrative resource of lighting design in assisted living facilities that can be used in experimental studies in the future.

CHAPTER 4: THE IMPACT OF SPATIAL LIGHT PATTERNS ON PERCEPTION, MOOD, AND PREFERENCE OF OLDER ADULTS IN ASSISTED LIVING FACILITIES

This paper will be submitted to Leukos, The Journal of the Illuminating Engineering Society. Selected portions of this paper were previously presented and published at the 2021 Architectural Research Centers Consortium (ARCC) International conference on April 7-10 in Tuscan (Virtual), the 2022 ARCC-EAAE International conference on March 2-5 in Miami, and ARCC 2023 International Conference in Dallas on April 12th to 15th. Professors Ihab Elzeyadi contributed to these papers by helping to develop the structure, the research questions and scope, the study design, analyses, and interpretations. I was the primary contributor to the studies, conducted data collection, and analyses, and wrote the draft manuscript. Professor Elzeyadi provided editorial review and additions to the manuscript structure and contributed to the discussion, and the data analysis and interpretations. This chapter summarizes the findings of the study's first experiment that investigated the subjective impressions among older adults under exposure to the different spatial patterns of light in an environment.

Previous studies show that light-level variables and temporal patterns significantly impact human perception, mood, and preference. However, there are not sufficient studies that investigate the qualitative aspect of lighting design such as the spatial pattern of light on older adults' moods, preferences, and perceptions. The main goal of this study is to investigate the impact of different spatial patterns of light on the perception, mood, and preference of older adults. The research question that is specifically addressed is, "Are there any consistent and shared patterns of subjective impressions among the aging population under exposure to the different spatial patterns of light in an environment?" This paper consists of two sections. The first section represents an earlier attempt to identify and construct a framework for spatial light patterns that can serve as a design model for examining the impact on older adults' outcomes. In the second section, we conducted a preference experiment utilizing multiple sorting task techniques (Q-sort method) as well as forced-choice questions in a survey experiment. The findings of this study show that different spatial light patterns have a substantial impact on older adults' perceptions and preferences related to the environment. The results demonstrate a clear preference among older adults for uniform lighting over non-uniform lighting, as well as a preference for indirect lighting compared to direct lighting. Notably, our study did not observe significant differences in visual preferences between peripheral and central light arrangements among older adults. We also found that non-uniform lighting tended to create a more relaxed impression, while uniform lighting increased the sense of stress perceived in the environment.

4.1. Introduction

Appropriate lighting conditions are one of the significant indoor environmental qualities that could potentially play an important role in improving the living environment and enhancing health and well-being in older adults (Lu et al. 2019). However, lighting design for the aging population has not received much attention from researchers and designers. Human-Centric light is a new approach in lighting design, which focuses not only on the visual impact of light, but also on its non-visual aspects that influence circadian rhythms, sleep, mood, and cognitive performance. Houser, K. W et al. (2020) defined four main categories of lighting variables that contribute independently through designing lighting systems for the built environment: Temporal pattern (i.e., the timing and duration of exposure), Light level (i.e., the quantity of light in radiometric and photometric units), Light spectrum (SPD) (i.e., spectral power distribution that governs color quality) and spatial patterns (i.e., the luminance distribution of the three-dimensional light field). Illuminance, an important quantitative attribute of lighting, has been shown to have a positive impact on individuals' alertness, vitality, task performance, agitation, depression, sleep quality, and cognitive performance (Satlin et al.1992; Yamadera et al.2000*;* Riemersma et al. 2008). In addition to illuminance, researchers have proposed different metrics for quantifying the effectiveness of the non-visual and psychological impact of light on the human body. Equivalent Melanopic Lux (EML) is a more recent metric developed after Lucas et al. (2014) to measure the biological impacts of light on human bodies. Studies investigating the impact of the light spectrum have shown both monochromatic short-wavelength light and blue-enriched polychromatic light is more effective than longer wavelengths of light at suppressing melatonin (Brainard et al. 2001), regulating the circadian clock (Revell et al. 2005), and enhancing alerting effects and improving mood (Chellappa et al. 2011). There is firm evidence in the literature that the temporal pattern of electric light in the indoor environment that follows the same natural pattern of daylight (morning bright light, dim evening light) provides a better non-visual outcome for humans, especially for older adults (Yamadera et al. 2000; Riemersma et al. 2008; Figueiro, 2008).

Existing studies in the field of Human-Centric lighting for older adults have mainly focused on quantitative attributes of light such as light level (Figuerio, 2011); light spectrum (Janosik and Marczak, 2016; Cheng, 2016); and temporal patterns of light (Gasio et al. 2003; Figueiro, 2008), while few studies are showing a systematic relationship between qualitative attributes of light such as the spatial pattern and luminance distribution with nonvisual outcomes of elderlies (Knez, I and Kers, C, 2000; Riemersma et al. 2008; Yamadera, et al. 2000). The vast majority of gerontology studies have addressed the visual impacts of indoor lighting on wayfinding, mobility, and task performance, while there is a significant gap in understanding the impact of indoor lighting on the nonvisual outcomes of older adults such as mood, behavior, and preference.

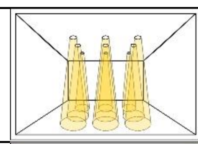
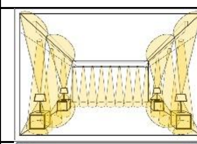
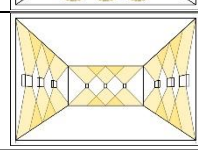
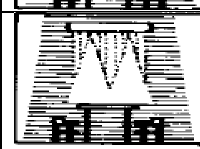
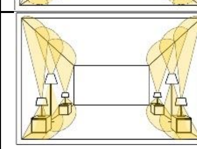
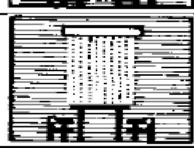
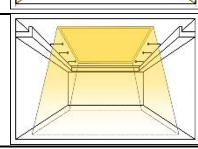
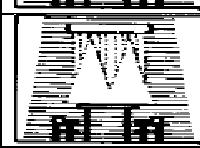
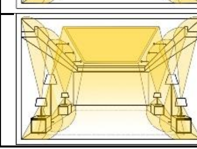
4.2. Flynn's Theory (Spatial Pattern of Light and Human Subjective Impression)

There is some evidence in the literature that shows inferior retinal light exposure is more effective than superior retinal exposure in the suppression of melatonin (Glickman et al. 2003) and light exposure on the nasal side of the retina is more effective in biological responses than the temporal side of the retina (Visser,1999). Therefore, the way that light radiation reaches the human eye is very important in its effect on visual and non-visual outcomes. Lighting designs for visual outcomes are at task locations and are often oriented horizontally (DiLaura, D. L. et al, 2011), while non-visual lighting designs are at the plane of the occupant’s eyes and are oriented vertically (Houser and Esposito, 2021; Brown et al. 2020).

The spatial pattern of light refers to the spatial distribution of light in the three-dimensional light field and it depends on many parameters of light and environment. In the 1970s, John Flynn published a series of articles (Flynn & JE, F.,1977; Flynn et al. 1979; Flynn et al. 1973) conducting fundamental research about the role of the distribution of light and resulting patterns of the light on human subjective impressions. Flynn et al. (1979) defined four main lighting modes in space, which make various impressions on humans. These four lighting modes are the basic attributes that designers consider when they are creating an environment for different purposes: bright/dim, uniform/non-uniform, central/perimeter, and warm/cool. Flynn particularly examined how different “lighting modes” impact spaciousness/confinement, visual clarity/haziness, relaxation/activation, and private/ public.

Flynn et al. (1973) defined six different light arrangements which had their specific uniformity, centrality, and brightness value so that each arrangement corresponds to a specific point in a dimensional space of the different lighting characteristics. The results of this study indicated that there is a significant difference in human subjective impressions among different lighting arrangements. According to Flynn’s theory of lighting and mood in the 1970s we have defined six main spatial patterns of light that contribute to humans’ moods and preferences. These six spatial patterns of light have been created according to three main attributes including spatial arrangement (uniform/non-uniform), centrality (central/perimeter), and direction (direct/indirect)**.** (Table 3).

Table 3. Spatial lighting patterns according to Flynn's theory of lighting and mood (Flynn, 1973).

	Spatial arrangeme nt	**Flynn’s theory arrangement**	**Proposed spatial lighting arrangement**		**Spatial arrangement**	**Flynn’s theory arrangement**	**Proposed spatial lighting arrangement**
1	Uniform Central Direct			4	Nonuniform Peripheral Direct/indirec t		
2	Nonuniform Peripheral Indirect			5	Nonuniform Peripheral Indirect		
3	Uniform Central Indirect			6	Nonuniform Central/Perip heral Direct/indirec t		

Previous studies regarding the spatial pattern of light have mainly focused on the relationship between the control parameters of light and the spatial distribution of light and how it impacts human outcomes. In this section, we have reviewed and discussed spatial arrangement (uniform/non-uniform, centrality (central/perimeter), and the direction (direct/indirect) of light as three main independent variables of the spatial pattern of light and their impacts on mood, preference, perception, behavior, performance, and other outcomes on of the humans according to the literature.

4.2.1. Spatial Arrangement (Uniformity)

Light fixtures in an environment can be arranged in two different ways: uniform and non-uniform. In a uniform arrangement, all the lighting fixtures in a room are placed at maximum height and uniform spacing without considering the location of furniture and other architectural elements to illuminate the environment at about the same level. In a non-uniform lighting system, all the fixtures are located at a high level and close to the ceiling, but with irregular spacing. The exact location of each fixture depends on the place of the workstations and machinery and the task that will be performed in that space.

Hawkes et al. (1979) argued that two main attributes of light define the perception of light in a space, namely brightness, and interest. Brightness refers to the perceived intensity of light while interest is related to perceived uniformity. There is evidence that shows that task lighting can increase attention to desk work, which improves task performance (Rea et al.1990). Taylor et al. (1975) found that nonuniform desktop illumination improved task performance. This study shows adults perform better in arithmetic calculations (on paper) in office spaces with nonuniform lighting in comparison to uniform fluorescent lighting or very nonuniform colored lighting. On the other hand, some other studies indicate there is no correlation between uniformity of light and task performance. McKennan and Parry (1984) showed that different illuminance levels on the desk based on different lighting distribution does not impact (paper-based) clerical task performance in a comparison of 10 different general and local/general combined lighting installations. Lighting design in theatres shows that areas of high luminance could help to attract the audience’s attention, but there is no firm evidence to show how this mechanism can be implemented to provide appropriate conditions for different tasks in other settings (Veitch, 2001). There is a study that investigated the impact of position and number of light sources on the perceived atmosphere of light in space. The position of the light in this study refers to the distribution of light (symmetrically, left-right, and front-back). The results indicated that adjacent luminaires to walls create a less uniform atmosphere (Stokkermans et al. 2018). In another study, the affective impressions of university students were evaluated concerning spatial patterns and luminous environments in their classrooms. They defined six different axes of affective impressions of students including surprising-amazing; clear-efficient; cheerful-colorful; uniform; intense brilliant and warm-cozy. The results showed that writing-reading tasks need a positioning of light that generates a clear-efficient, intense-brilliant, and uniform pattern, reflecting-discussing tasks require a positioning of light that generates a warm-cozy atmosphere, and paying attention tasks need a light positioning that creates clear-efficient, uniform, and Surprising-amazing atmospheres (Castilla et al. 2018). There are also other studies investigating the impact of spatial arrangement and uniformity on human perception, behavior, and preference (Flynn et al.1973; Flynn et al. 1979; Chraibi et al. 2017; Stokkermans et al. 2018). Flynn et al. (1973) and Flynn et al. (1979) showed that uniformity in the spatial pattern of light increases clarity in space, while non-uniformity contributes to more relaxing feelings. Yao et al. (2017) argue that uniformity is a critical attribute of indoor lighting in work efficiency and comfort, and have investigated different methods for evaluating uniformity of light in space. These methods include (Min: Avg), the coefficient of variance (CV), entropy uniformity (EU, introduced in the article), and a pattern vision-based indicator (U_{HVS}).

According to the literature, it seems that illuminance distribution in a space can direct attention in useful ways, and impact visual and non-visual performance. However, there is no integrated evidence to show how uniform or nonuniform light can impact the mood and preferences of a human.

4.2.2. Centrality (central/ peripheral)

Light sources in a space can be arranged to emphasize horizontal surfaces (central, overhead), or vertical surfaces (perimeter). Flynn et al. (1973) also revealed that in addition to light intensity (dim – bright dimension of light) and interest (uniform and non-uniform dimension of light), there is another factor that impacts the perception of light in a space, namely peripheral – overhead. Flynn showed central arrangement with higher light levels on horizontal surfaces such as a work plane provides more visual clarity, and uniform peripheral lighting makes the space more spacious, while peripheral non-uniform lighting is more helpful in increasing relaxation and privacy *(*Flynn et al. 1973; Flynn et al.1979). Another study investigating the impact of the different spatial patterns of light in university classrooms on students' performance showed that each pattern of light (central or peripheral) should be modified according to the specific task taking place in the class (Castilla et al. 2018).

4.2.3. Lighting Direction

A fixture can be designed to focus light in one of the following ways: direct lighting, semi-direct Lighting, general Lighting, semi-indirect lighting, and indirect lighting. In direct lighting, 90 to 100 percent of light radiation from the luminaire reaches the work surface. This type of lighting is a very common lighting design specially for task lighting. The main problem of direct lighting is that it causes glare and unfavorable shadows. In a semi-direct lighting system, 60 to 90 percent of light sources reach the working surface and the remainder of the light is reflected toward the ceiling or wall. In general lighting, the light will be distributed equally in both upper and lower areas of space (Lighting Methods, 2017). Semi-indirect lighting, unlike semi-direct, reflects 60 to 90 percent of light toward the ceiling, while 30 to 40 percent only reaches the working surface. In indirect lighting, 90 to 100 of light reflects toward the ceiling that increasing diffusion and even distribution. Studies have shown that people prefer indirect lighting in comparison with systems providing direct lighting (Veitch et al. 2008;). Yearout and Konz (1989) found that indirect/direct lighting is more favorable than direct lighting among participants doing tasks in the workstation. Operators also prefer brighter illumination in office space and spotlight on walls. Katzev (1992) also showed that office employees prefer direct/indirect lighting more than other lighting systems, while there were no significant differences between participants' performance in cognitive/intellectual tasks. A recent study investigating the impact of direct and indirect light on the health, well-being, and cognitive performance of office workers also demonstrates that except for a relationship between reduced job stress severity and direct lighting, there is no meaningful correlation between direct and indirect lighting and cognitive performance (Fostervold and Nersveen, 2008). Another study that investigated the impact of light direction on office workers' satisfaction, visual health, and productivity demonstrates that satisfaction and other subjective lighting rates were higher in an indirect lighting system, while productivity was less influenced by the direction of light (Hedge, et al.1995). Another study that investigated the impact of lighting positioning in workstations has found that two different spatial patterns (varying in terms of number, direction, and position of the light) create different views but do not impact the performance of the users. This study showed that a combination of direct and indirect light was more favorable for the users. They also preferred a non-uniform spotlight on a wall painting (Yearout and Konz, 1989).

Most previous studies show that most previous studies investigating the impact of the spatial patterns of light on elderly outcomes have mainly focused on one or two attributes of spatial patterns. However, there is a critical need for a comprehensive investigation of the impact of the spatial pattern of light on elderly outcomes. Furthermore, most of the previous studies have not sufficiently addressed the architectural and design perspective of the spatial patterns of light and have mainly examined the spatial pattern of light in an experimental room. To address this critical gap this study has used a multi-method approach to investigate spatial patterns of light in senior residence facilities.

4.3. Overview of the Related Research

4.3.1. Spatial Light Patterns and Perception

"The perception Function is in charge of representing and discriminating objects based on their visual features, thus it integrates the input of visual processing with feedback from monitoring and memory systems." (González-Casillas et al. 2018). González-Casillas and his colleagues (2018) presented a model that describes the process of visual recognition and perception in the human brain. This modular modeling approach by integrating the biological and neuroscientific evidence describes the process of perception and cognition in the human brain which occurs in visual areas V1, V2, V4, and ITC. According to this theory, the way that we perceive the surrounding environment is significantly related to the way that visual stimuli from the environment reach the retina in our eyes (González-Casillas et al. 2018).

Flynn et al. (1973) and Flynn et al. (1979) for the first time studied the impact of the spatial light pattern on different subjective impressions of humans. They found that uniform lighting provides a clearer and more understandable environment while non-uniform lighting mode reinforces a sense of relaxation. Hawkes et al. (1979) argued that brightness and interest are two main attributes of light that impact the human perception of an environment. Brightness represents the intensity of light while interest refers to the uniformity of light in space. In another study, Stokkermans and his colleagues explore the impact of the positioning of the light (symmetrically, left-right, and front-back) and the number of lights on human perception of the atmosphere. They found that luminaires close to walls created a less uniform atmosphere in space (Stokkermans et al. 2018). Flynn's studies revealed that the central arrangement of light on horizontal surfaces provides more visual clarity, while peripheral uniform lightings make the space more spacious, and peripheral nonuniform lighting creates a more relaxed and private space (Flynn et al. 1973; Flynn et al. 1979). The results of a study in a university setting indicate that positioning and centrality of the light in classrooms should be modified according to the tasks and activities of students in each space because each lighting pattern might reinforce a different impression (Castilla et al. 2018). In another study, Fostervold and Nersveen (2008) also found that direct lighting can reduce job stress severity while there is no other correlation between the direction of light and the cognitive performance of office workers (Fostervold and Nersveen, 2008). Some evidence shows that uniform lighting reinforces the impression of spaciousness while nonuniform lighting can evoke a feeling of relaxation and improve task performance (Flynn et al. 1979; Taylor et al. 1975; Rea et al.1990).

Previous studies also have shown that there is a more significant relationship between the direction of light and perception, satisfaction, visual health, and general visual outcomes in comparison to non-visual outcomes such as cognitive performance and productivity in office workers (Yearout and Konz, 1989; Katzev,1992; Hedge et al.1995).

4.3.2. Spatial Light Patterns and Visual Preference

There are not adequate research studies available that examine the impact of spatial light patterns on human visual preference. In a recent study, different affective impressions (surprising-amazing; clear-efficient; cheerful-colorful; uniform; intense brilliant, and warm-cozy) of university students were evaluated under different spatial patterns and luminous environments. The results show each lighting condition fits best for a specific task. For example, lighting condition with clear-efficient, Intense-brilliant, and uniform pattern fits are best for writing-reding tasks, while students prefer their reflecting-discussing tasks in a lighting condition that provide a warmer-cozier atmosphere (Castilla et al. 2018). There are some pieces of evidence in the literature indicating that people prefer indirect lighting more than direct lighting. These studies indicate that office workers prefer indirect lighting or a combination of direct and indirect lighting more than direct lighting, while the direction of light does not impact their cognitive performance and productivity (Yearout and Konz, 1989; Katzev,1992; Hedge et al.1995).

The literature shows the number of studies investigating the impact of the spatial light pattern on human perception is very limited and most of the studies have been conducted in office spaces. Therefore, there is a critical need to understand how the uniformity, centrality, and direction of light in space might impact older adults' perceptions, moods, and preferences.

4.4. Rationale and Hypotheses

Participants in this study were asked to participate in an experiment where they needed to answer q-sort and dual forced-choice questions to evaluate the lighting condition in terms of visual preference, stress, clarity, and spaciousness. Q-methodology is an inverted technique of factor analysis (R-method), this technique is a scientific approach in human subjectivity studies (Stephenson, W, 1953).

Different spatial patterns of light might impact perceived detail and, hence, visual interest and preference. Therefore, we propose the following hypotheses: first, we expect that patterns with higher complexity and a combination of direct and indirect lighting will be more visually interesting and preferable; second, it is expected that peripheral patterns compared to central patterns provide a better enhancement in terms of relaxation; third, it is expected that uniformity, Centrality and direction of light, influence the perception of the participant of the clarity and spaciousness of the environment.

4.5. Methods

Although lighting evaluations in most studies are based on detailed photometric measurements, such assessments often fail to account for the impact of the "human" component in determining lighting quality. For the first time, Flynn (1973) explores the potential value of subjective qualitative assessment in lighting research to examine the impact of various lighting decisions on human subjective impressions. The current study used a multi-method approach to extend the results of Flynn et al. (1973) by investigating the impact of different spatial patterns of light based on the same lighting modes on older adults' perceptions and preferences. The initial phase of our study involved conducting an architectural content analysis with an inductive approach in three main steps to identify and develop a Spatial Lighting Pattern Framework. Firstly, a Picture Content Analysis

(PCA) was carried out on the websites of surveyed facilities to determine the most common layout arrangements and properties of the bedrooms and living rooms in assisted living facilities across the US. Secondly, the Visual Attention Software (3M-VAS) was utilized to analyze the most common room typologies identified in Step 1, to determine the most attractive typology that generates the most viewing interest. Finally, in step 3, based on Flynn's theory of lighting and mood, the two most preferred views of each room were chosen to implement spatial lighting patterns to construct the final spatial pattern framework. This framework was utilized in the second phase of our research to experimentally investigate the impact of different spatial patterns of light on older adults' perceptions and preferences (Figure 21)

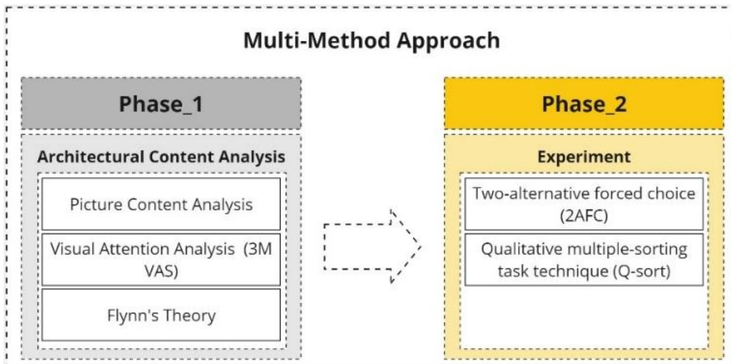


Figure 21. Multi-method approach overview

4.5.1. Phase 1_ Developing Spatial Pattern Framework through Architectural Content Analysis

4.5.1.1. Picture Content Analysis

In the first step, to identify the most common layout arrangement, interior lighting quality, and spatial patterns of light in existing senior residence facilities**,** we conducted a picture content analysis of the online image stocks from surveyed assisted living facilities' websites. Quantitative or formal content analysis is an empirical method for systematic analysis of different media content such as audio, textual, visual, and/or audiovisual (Krippendorf, 2004; Rössler, 2005). This systematic observational method aims to examine hypotheses about the representation of an event, people, and situations in different media (Fielding et al. 2008). To conduct a picture content analysis, the main unit, sample unit, unit of analysis, and codebook should be defined. In this study, the main unit of analysis consists of all the images of 50 elderly residents' facilities websites in the US. In the first step, we selected 36 images of assisted living facilities' living rooms (18) and bedrooms (18) as the sample unit of the analysis. Images were selected based on the type of facilities (assisted living facilities), interior space (living room and bedrooms), areas of the spaces (living room<1000 sq ft; bedroom< 450 sq ft), and lighting quality of spaces (including the different spatial patterns of light). Images that included human figures were also excluded from the sample unit to decrease distraction in content analysis. In the second step, five different subjective categories were defined for coding the images of the first phase. These categories include the possibility of having daylight, home likenesses, including colorful furniture, the existence of natural elements, and warmness. The results of analyzing the five final images of the bedroom and living rooms have been indicated in Figure 22.

4.5.1.2.Visual Attention Analysis – (3M VAS)

Five final images were analyzed with 3M VAS software to investigate which image met the visual hierarchy goals for our study. 3M-VAS (Visual Attention Software) is a biometric tool that collected and clustered 30 years of eye-tracking data (Salingaros and Sussman, 2020). This software, which is mostly applied in website and signage design analyzes the images according to three different attributes: heatmap, hotspots, and gaze sequences.

- **Heatmaps**

This attribute shows the probability that a part of visual content is seen within 3-5 seconds of viewing a picture. Among the 5 selected images of the living room, room number four with more attention to lighting fixtures and seating area rather than other elements of the room received the higher scores in this analysis. Among 5 images of the bedrooms, number five with the focus of the heating map on lighting fixtures and bed shows the most attractive typology. (Figure 22)

- **Hotspots**

This criterion is a simplified version of the heatmap results which shows the areas of the image that are most likely to be fixated. The probability of being seen by a person will be shown by a numeric score on each region of the image. Hotspot analysis among living rooms indicated that Image number 1 and number 4 by 85% and 92% focus on seating areas and 51% and 85% on lighting elements have the highest scores among the five different images. Comparative analysis among bedroom image hotspots revealed that in room number 2 and number 4 by 69% and 42% attention on lighting fixtures and 77% and 97% focus on beds can generate the most viewing interest.

- **Gaze Sequence**

This parameter shows the four most-likely gaze locations, in their most-probable viewing order. This criterion is important because it shows the visual hierarchy of the scene. For this study, we are looking for a gaze sequence in a scene that attracts the users' attention to lighting fixtures and the significant elements of the room (seating area in the living room and bed in the bedrooms). Among five images of living rooms, room number four’s gaze sequence shows the most rational sequence: 1- desk light, 2- ceiling light, 3- desk light, and 4- seating area. The gaze sequence analysis among bedroom images also indicated that image number 2 by a gaze sequence from bed to desk light and then to ceiling light and window has the most reasonable hierarchy among room elements in the scene. (Figure 15). In the final step, the two most likable typologies of each room were selected to implement spatial lighting patterns according to Flynn's theory of lighting and mood. First, a 3d model of the living room and bedroom was simulated according to the two most attractive typologies in Autodesk 3ds Max software. Light level and light spectrum in each space were simulated according to the recommended amounts based on the literature (illuminance: 500 lux for living room and 300 lux for bedrooms; CCT:4500 k). Next, according to Flynn’s theory of lighting and mood, six main spatial patterns of light were implemented in each room to create the final proposal spatial pattern framework in assisted living facilities, living rooms, and bedrooms. (Figure 23)

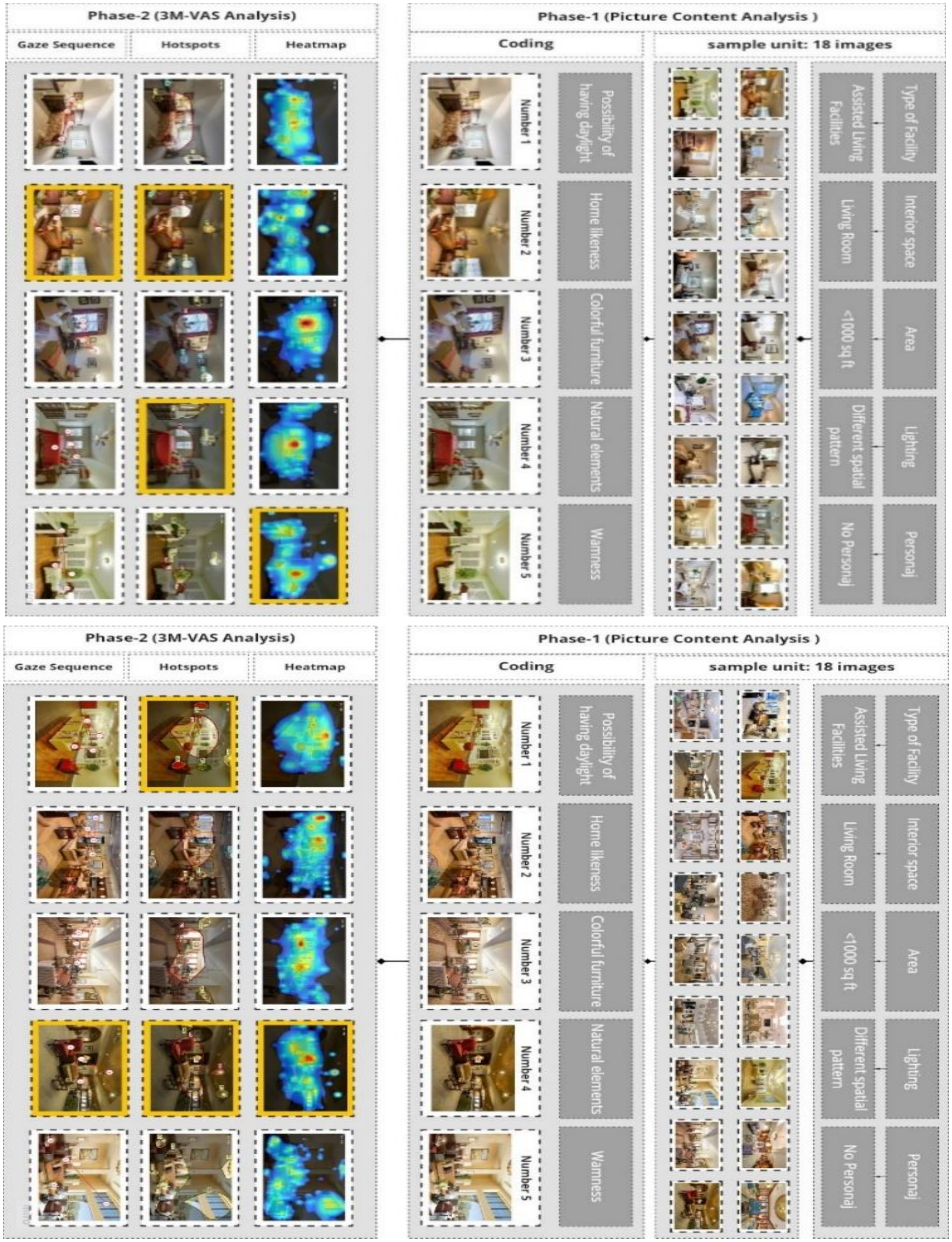


Figure 22. Picture content and visual attention analysis of the Livingroom and bedroom images

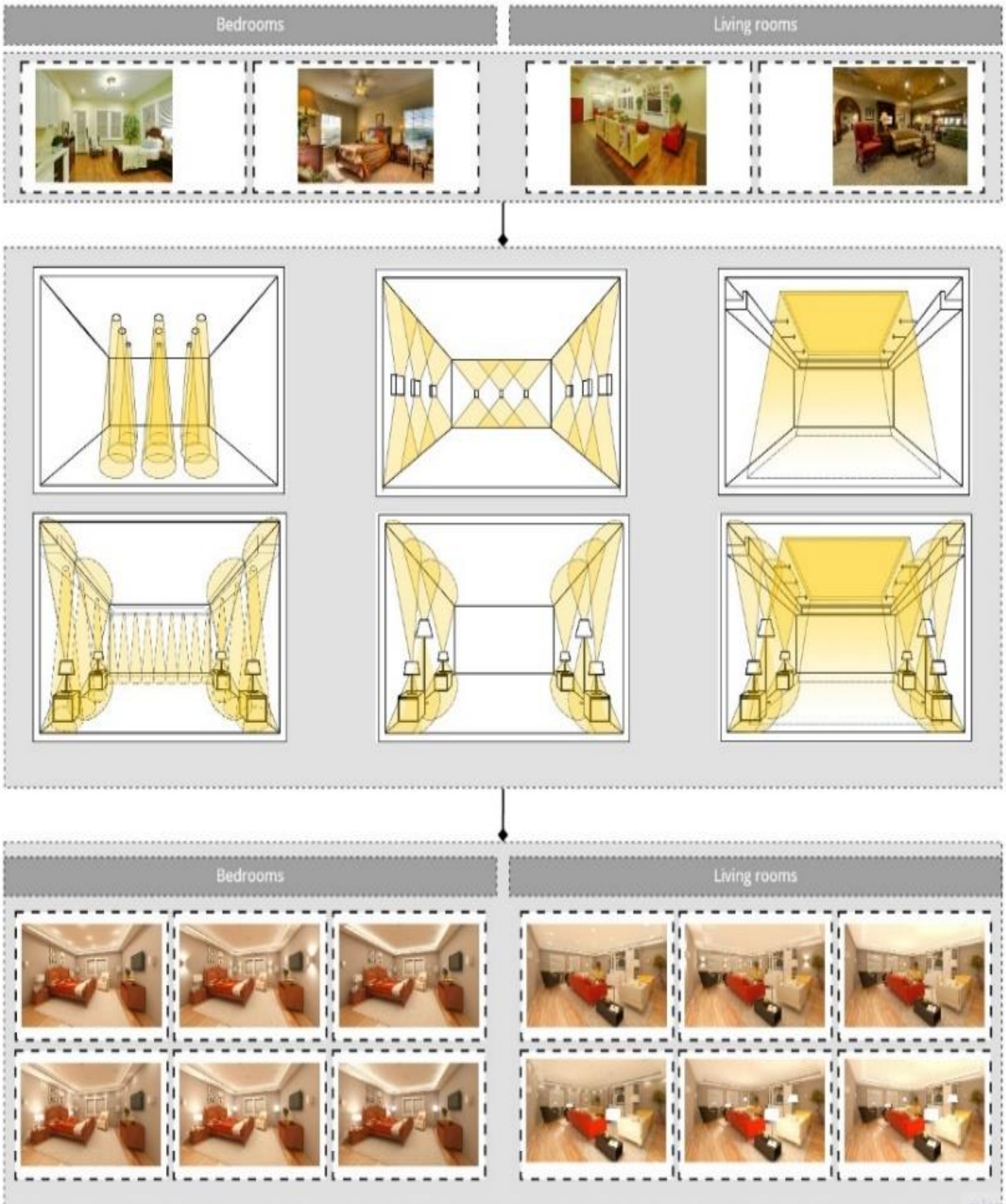


Figure 23. Spatial pattern framework in assisted living facilities living rooms and bedrooms

The final spatial pattern framework for the living room was utilized in the preference experiment in the next phase to investigate the impact of different attributes such as centrality, uniformity, and direction of light on older adults' perception and preference. (Figure 24)

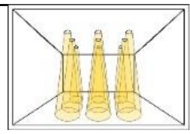
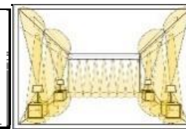
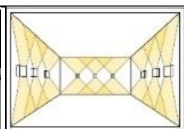
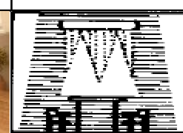
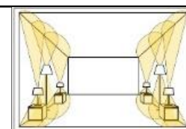
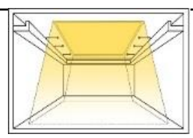
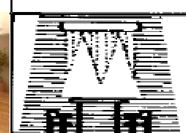
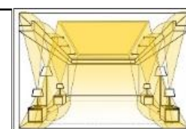
Flynn's lighting modes	Spatial pattern framework	The final lighting scenes	Flynn's lighting modes	Spatial pattern framework	The final lighting scenes
Uniform, Central, Direct (A)			Nonuniform, Peripheral, Direct/indirect (D)		
					
Uniform, Peripheral, Indirect (B)			Nonuniform, Peripheral, Indirect (E)		
					
Uniform, Central, Indirect (C)			Nonuniform, Central/Peripheral, Direct/indirect (F)		
					

Figure 24. Different lighting design senses were used in the online survey simulated based on Flynn et al. (1979)

4.5.2. Phase 2_ Experiment

4.5.2.1. Experiment Design

During the second phase of the study, we used the final proposed spatial pattern framework consisting of six distinct lighting patterns to investigate the preferences and perceptions of older adults towards different lighting scenes (A, B, C, D, E, F) in the living spaces of assisted living facilities. These lighting scenes were simulated according to a proposed spatial pattern framework that was designed in the first phase of the study. Each lighting scene is a combination of different lighting modes including Image A (Uniform, Central, Direct), Image B (Uniform, Peripheral, Indirect), Image C (Uniform, Central, Indirect), image D (Nonuniform, Peripheral, Direct/indirect), Image E (Nonuniform, Peripheral, Indirect), and image F (Nonuniform, Central/Peripheral, Direct/indirect)

4.5.2.2. Participants

Following an IRB-approved protocol, participants for the experiment were recruited through an in-person presentation to residents of an assisted Senior living facility in the Pacific Northwest in the US. The facility has 176 residents who are living in independent and assisted living spaces. A total number of 74 residents aged 60 to 90 participated in the survey. Only 60 (N=60) participants (39 female, 21 male) were eligible to answer the survey question according to their mental, physical, and visual condition. The researcher met the interested participants in the facility and instructed the participants regarding the details of the study and asked them to approve and sign the informed consent form.

Participants were asked to rate their cognitive performance, physical health, mental health, and visual condition in questions that were administered using a 5-point response scale (poor, fair, good, very good, excellent). Exclusion criteria were any evidence of moderate to major cognitive impairment, blindness or severe eye disease, severe depression and agitation, and physical impairment. Participants who had poor conditions in any of these criteria were excluded from the study and were not able to continue the survey questions. At the end of the survey, participants could elect to write their names to enter a separate drawing for one of the three $25 Amazon gift cards. The entry into this drawing did not compromise their anonymity and is not linked to their responses in any possible way.

4.5.2.3. Study Setting

The participants answered the Q-sort test questions on a laptop that was provided by the researcher. All participants' screen brightness was set at the highest intensity to allow better visibility. Participants were seated in the living room of the facility when answering the survey questions (Figure 25).

Figure 25. Older adults answering the online surveys in the living room of the assisted living facility.

The room's lighting condition was set to a similar condition for all the participants. A two-alternative forced-choice (2AFC) and qualitative multiple-sorting task technique (Q-sort) were used to assess the visual perception and preference of the participants. The online Q-sort test includes 10"x17" familiar-looking pictures of interior spaces which have been simulated based on 6 spatial lighting patterns. After signing the consent form and answering health assessment questions, participants were asked to answer four categories of questions. First, for assessing the visual preference for light patterns, a two-alternative forced-choice (2AFC) procedure was used in which pairs of images were presented simultaneously. The 2AFC procedure has been successfully used in previous studies of visual interest and preference (Spehar et al. 2015). Participants needed to choose the more visually preferable environment between the 15 pairs of images that were presented on the screen. A preferable environment was defined as an environment that has many similarities to other spaces you have experienced. The high degree of familiarity elicits a pleasant feeling as you immediately can make sense of the setting. In the second, third, and fourth questions, participants were asked to sort the images according to the level of stressfulness, spaciousness, and clarity through a rating procedure. A stressful environment was defined as 'an environment where you have no control over it and that you are not able to construct the conditions deemed satisfactory'. A spacious environment was defined as 'an environment that appears larger for you.' A clear environment was defined as 'an environment that has a crispy and distinct visual appearance and you can do your desired task very easily on it.' In the Q-sort questions, participants were asked to categorize the images into 3 main groups including 'the most', 'the least', and 'moderate', and then ranked them in each category according to the level of stress, spaciousness, and clarity they are perceiving in each environment and their degree of preference. (Figure 26)

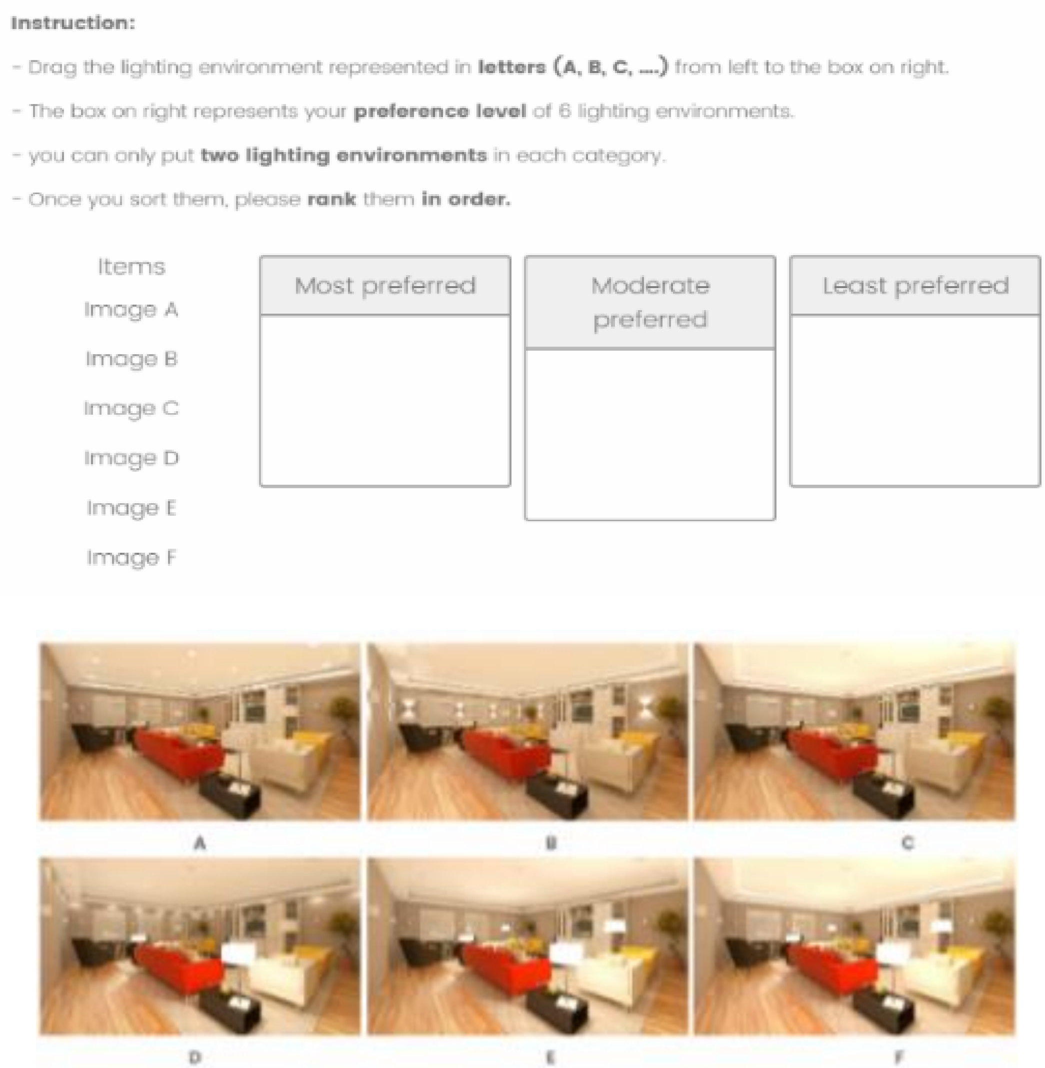


Figure 26. Q-sort question assessing the visual preference of the participants.

4.6.Results

The results of architectural content analysis show that the dominant lighting fixtures in living rooms of assisted living facilities are chandeliers, recessed lighting, and table shade lamps, while in bedrooms ceiling fans and bedside lamps are more common. Although we have included images of spaces with the possibility of having daylight, there are a vast majority of facilities without any access to daylight. According to picture content analysis, five images with the highest score of the coding categories (including the possibility of having daylight, home likeness, including colorful furniture, the existence of natural elements, and warmness) were selected for the final visual content analysis via 3M VAS software. The results of visual attention analysis indicated that spatial patterns of light in many of these facilities have created a glare that can be seen in the images. Although glare can create discomfort for all age groups, it takes more time for older adults to recover from the glare effect, and can impact their efficiency and activation.

Questionnaire data from the 60 participants were analyzed to investigate 1) the impact of gender, age, and cognitive performance on older adult's perception and preference under different lighting conditions, and 2) differences in the degree of visual preference, Clarity, stressfulness, and spaciousness of the environment: and 3) the correlation between the mood, perception, and preference of older adults among the 6 spatial light patterns. The differences were investigated using box plots, and the Freidman test, whereas the relationships were examined using Kendalls's coefficients. The Friedman test, an extension of the Wilcoxon signed rank test, is a nonparametric alternative to repeated measures. ANOVA is appropriate for more than two correlated sample designs that are not normally distributed (Zimmerman and Zumbo, 1993).

4.6.1. Sample Statistics

A total number of 87 residents aged 60 to 90 participated in the study. Only 60 (39 female, 21 male) were eligible to participate in the experiment according to their mental, physical, and visual condition. As reported by the participants at the time of the experiment, 36 participants were wearing glasses and 24 were not. Participants were encouraged to wear their glasses when they were answering survey questions.

A multivariate test was used to analyze the correlation among gender, age, overall health, cognitive performance, and various perceptual and preference questions. The results show there is no significant ($p<0.05$) effect of gender, age, overall health, and cognitive performance on any of the perceptual and preference data. (Table 4)

Table 4. Wilks' lambda P-values

	Gender	Age	Overall health	Cognitive performance
Visual preference	.277	.635	.952	.873
Stress	.244	.523	.389	.576
Clarity	.952	.452	.814	.941
Spaciousness	.966	.936	.721	.115

4.6.2. Visual preference

To examine differences in visual interest among the different patterns, the Friedman test was used, as a Shapiro-Wilk test confirmed a violation of the T-test normality assumption. The result of the analysis indicates that there is a significant effect of the type of spatial pattern of light on participants' visual preference for the different lighting scenes (p=.004). The Size of the effect is 0.058 which is a relatively small effect size (0.2= small effect size, 0.5= Medium, 0.8= Large). (Table 5)

Table 5. Summary of related samples Kendall's coefficient for visual preference

Summary	
Total N	60
Kendall's W	.058
Test Statistic	17.377
Degree of Freedom	5
Asymptotic Sig. (2-sided test)	.004

The mean ranks represent the average of the ranks for all observations within each sample. By comparing the mean rank among different lighting patterns, it is evident that visual interest ratings peaked for pattern B, (Mean Rank =4.12). The results also show that older adult participants preferred pattern C over D, D over F, F over A, and A over E (Figure 27).

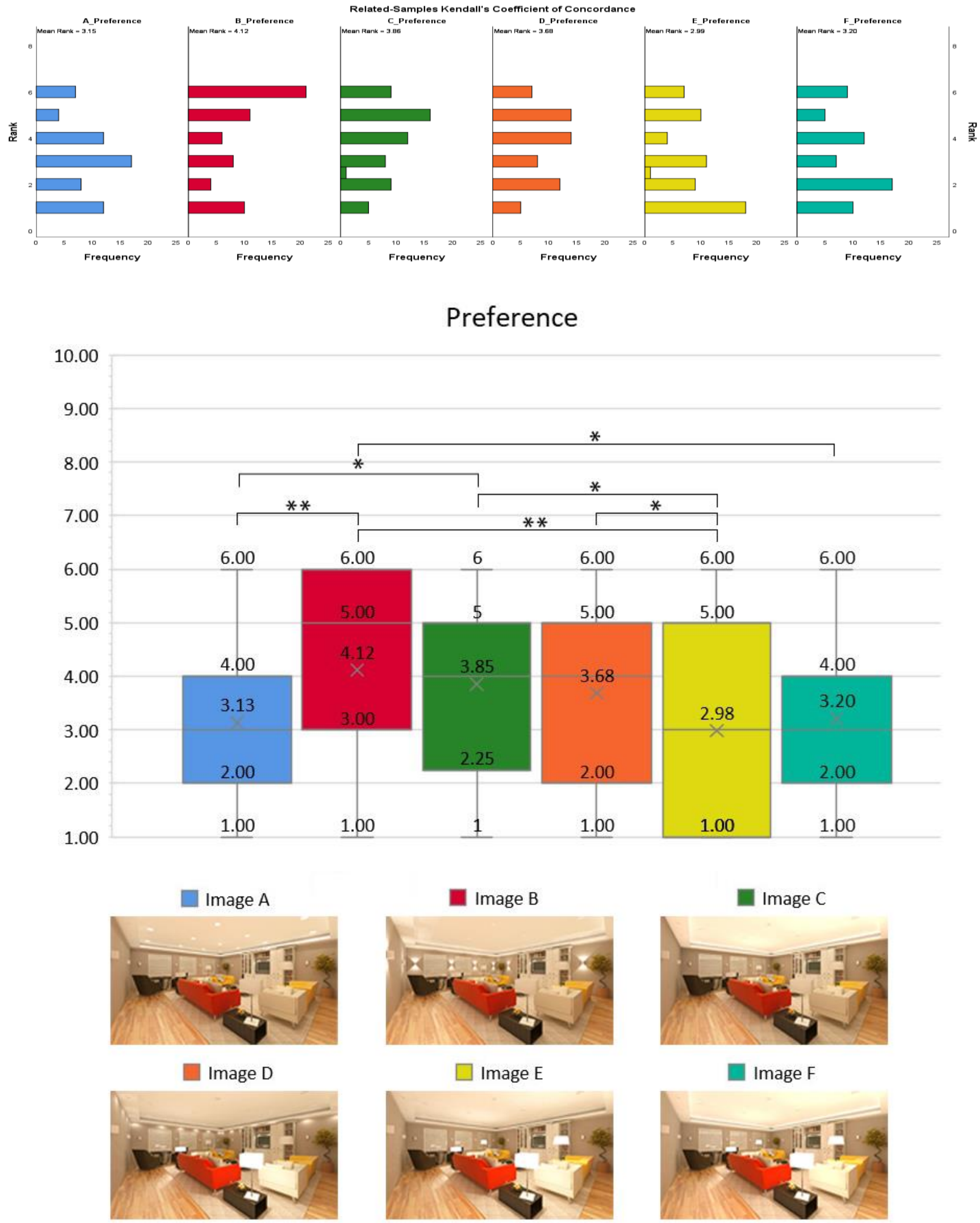


Figure 27. The Friedman test results of visual preference (* represents p<0.05, ** represents p<0.01)

To better understand if there are any significant differences in visual preference between different lighting patterns, we also conducted a pairwise comparison. The results indicate that there is a statistically significant difference between patterns D and E, C and E, B and E, C and A, B, and A, and B and F (D>E, C>E, B>E, C>A, B>A, B>F). This comparison reveals that older adults prefer uniform over nonuniform, and indirect over direct while there is no significant difference between the peripheral and central arrangement in older adults' visual preference. (Table 6)

Table 6. Comparative analysis of different spatial patterns' attributes on visual preference

Direct	**Indirect**	**Central**	**Peripheral**	**Uniform**	**Non-uniform**	**Direct/Indirect**	**Central/Peripheral**	**Uniform/Non-uniform**
-	3	1	2	3	-	1	-	-
Image B (Uniform, Peripheral, Indirect) > Image A (Uniform, Central, Direct)								
Image B (Uniform, Peripheral, Indirect) > Image E (Nonuniform, Peripheral, Indirect)								
Image B (Uniform, Peripheral, Indirect) > Image F (Nonuniform, Central/Peripheral, Direct/indirect)								
Image C (Uniform, Central, Indirect) > Image A (Uniform, Central, Direct)								
Image C (Uniform, Central, Indirect) > Image E (Nonuniform, Peripheral, Indirect)								
Image D (Nonuniform, Peripheral, Direct/indirect) > Image E (Nonuniform, Peripheral, Indirect)								
Significantly different: B>A, B>F, B>E, C>E, C>A, D>E								

4.6.3. Stressfulness

Data were analyzed to compare the stressfulness of the various light patterns. To examine the differences in stressfulness among the different lighting patterns, the Friedman test was used, as a Shapiro-Wilk test confirmed that the data are not normally distributed. The result of the analysis indicates that there is a significant effect of the type of spatial pattern of light on the relaxation or stress level that people perceive in the environment (p=.000). The size of the effect is 0.126 which is relatively a small effect size (0.2= small effect size, 0.5= Medium, 0.8= Large). (Table 7)

Table 7. Summary of related samples Kendall's coefficient for stressfulness

Summary	
Total N	60
Kendall's W	.126
Test Statistic	37.738
Degree of Freedom	5
Asymptotic Sig. (2-sided test)	.000

The mean rank comparison indicates that C is the most stressful pattern while E is the least stressful pattern for the older adult participants (C>A>B>F>D>E). The analysis indicates that patterns E (Nonuniform, peripheral, indirect) and D (Nonuniform, Peripheral, Direct/indirect) are significantly less stressful than patterns A, C, and B. C pattern (Uniform, central, indirect) is the most stressful pattern among all lighting patterns, and it is significantly more stressful than F, D, and E patterns with 0.01, 0.000, and 0.000 *p*-values respectively (Figure 28).

According to Table 8, the final analysis compares the impact of each variable in each lighting pattern, the relaxation implies non-uniform lighting while uniformity and centrality in the spatial pattern of light contribute to a more stressful impression in the environment. It also shows that having more peripheral light, especially on the walls, induces a sense of relaxation in the environment.

Table 8. Comparative analysis of different spatial patterns' attributes on stress

Direct	**Indirect**	**Central**	**Peripheral**	**Uniform**	**Non-uniform**	**Direct/Indirect**	**Central/Peripheral**	**Uniform/Non-uniform**
3	3	6	-	8	--	-	-	-

Image C (Uniform, Central, Indirect) > Image F (Nonuniform, Central/Peripheral, Direct/indirect)
Image C (Uniform, Central, Indirect) > Image D (Nonuniform, Peripheral, Direct/indirect)
Image C (Uniform, Central, Indirect) > Image E (Nonuniform, Peripheral, Indirect)
Image A (Uniform, Central, Direct) > Image F (Nonuniform, Central/Peripheral, Direct/indirect)
Image A (Uniform, Central, Direct) > Image D (Nonuniform, Peripheral, Direct/indirect)
Image A (Uniform, Central, Direct) > Image E (Nonuniform, Peripheral, Indirect)
Image B (Uniform, Peripheral, Indirect) > Image D (Nonuniform, Peripheral, Direct/indirect)
Image B (Uniform, Peripheral, Indirect) > Image E (Nonuniform, Peripheral, Indirect)
Significantly different: C>F, C>D, C>E, A>F, A>D, A>E, B>D, B>E

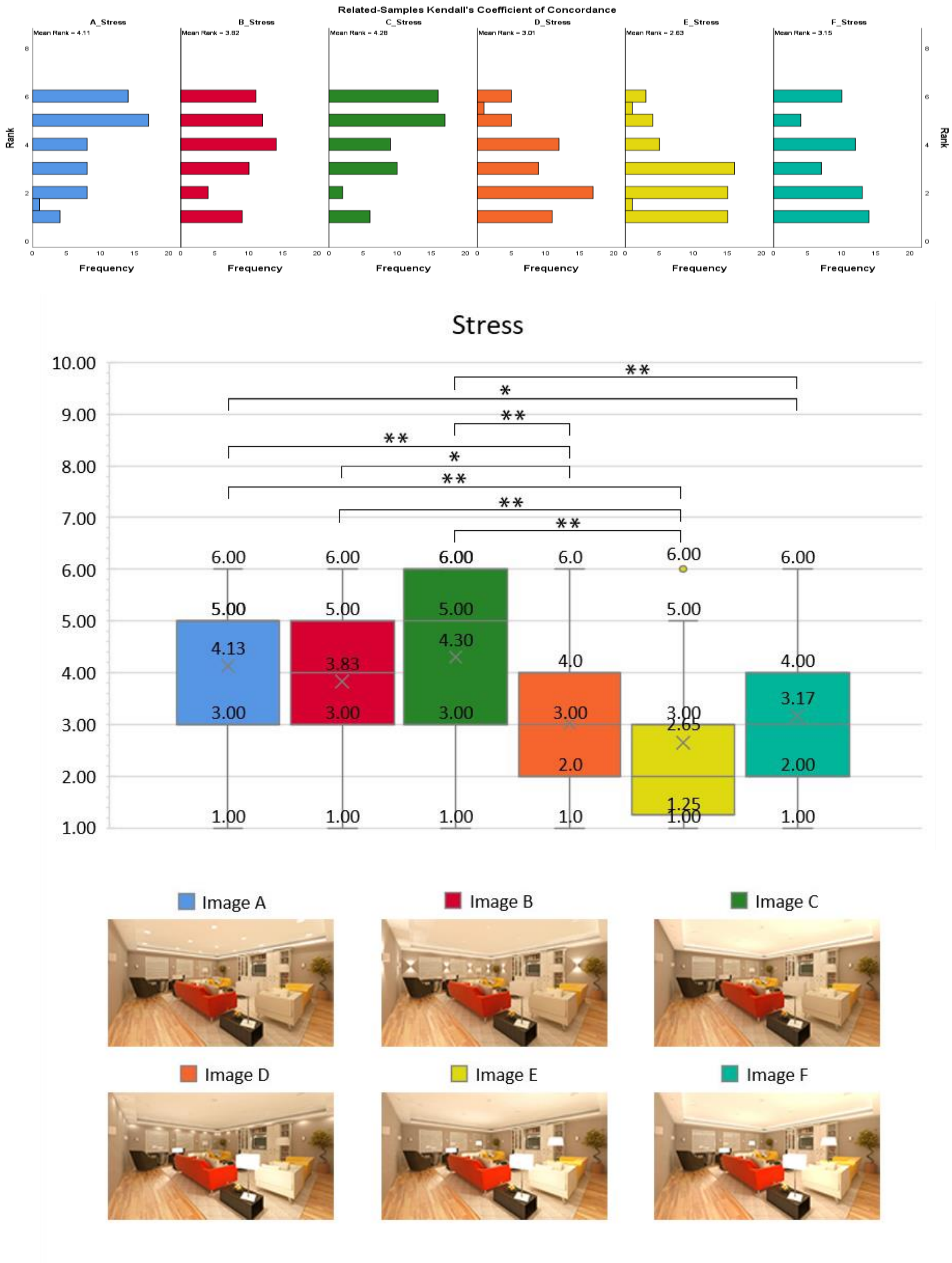


Figure 28. The Friedman test results of Stressfulness (* represents p<0.05, ** represents p<0.01)

4.6.4. Clarity

To examine differences in visual clarity among the different lighting patterns, the Friedman test was used, as a Shapiro-Wilk test confirmed a violation of the t-test normality assumption. The result of the analysis indicates that there is a significant effect of the type of spatial pattern of light on the perception of people of the Clarity of the environment ($p < 0.000$). The Size of the effect is 0.180 which is relatively a small effect size (0.2= small effect size, 0.5= Medium, 0.8= Large) (Table 9)

Table 9. Summary of related samples Kendall’s coefficient for clarity

Related-Samples Kendall's Coefficient of Concordance Summary	
Total N	60
Kendall's W	.180
Test Statistic	53.922
Degree of Freedom	5
Asymptotic Sig. (2-sided test)	.000

The mean rank comparison indicates that people perceive the A lighting pattern as the clearest pattern while B is the least clear pattern for the older adult participants (A>D>F>E>C>B).

The A (Uniform, Central, Direct), D (Nonuniform, Peripheral, Direct/indirect), and F (Nonuniform, Central/Peripheral, Direct/indirect) are significantly clearer than the E (Nonuniform, Peripheral, Indirect), C (Uniform, Central, Indirect), and B (Uniform, Peripheral, Indirect) lighting patterns. A pattern (Uniform, Central, Direct) is perceived as the clearest pattern among all lighting patterns, and it is significantly clearer than B, C, and E patterns with 0.00, 0.000, and 0.006 P values respectively. B and C patterns are significantly less clear than the A, D, and F patterns (Figure 29)

According to Table 10, the final analysis compares the impact of each variable in each lighting pattern, non-uniform lighting pattern is the most common attribute that significantly impacts the Clarity of the environment. It also shows that Direct lighting and a combination of direct/indirect lighting can significantly impact the Clarity of the space, while there is no significant correlation between the Clarity of the space and the centrality of the lighting patterns.

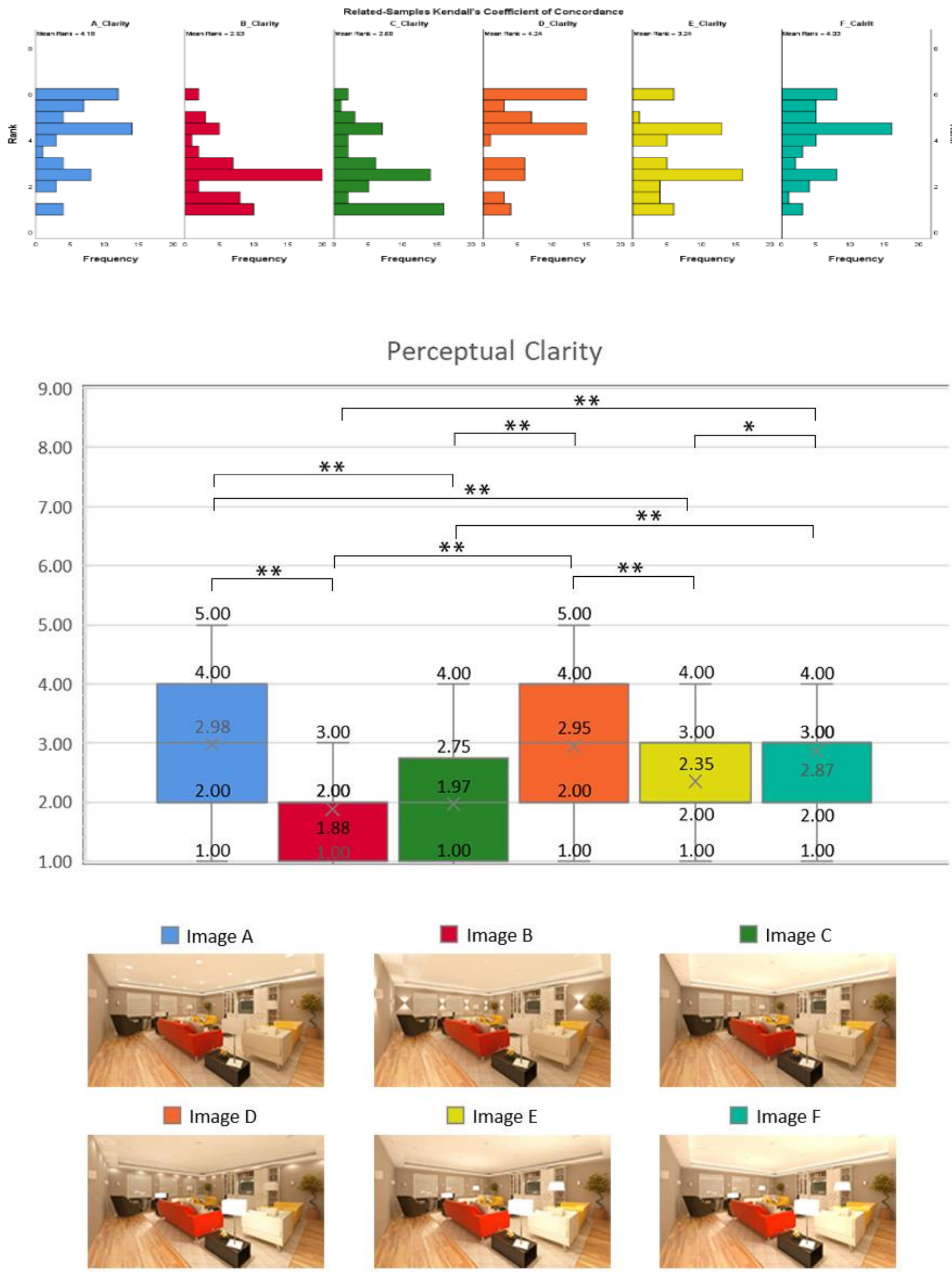


Figure 29. The Friedman test results of clarity (* represents p<0.05, ** represents p<0.01)

Table 10. Comparative analysis of different spatial patterns' attributes on clarity perception

Direct	Indirect	Central	Peripheral	Uniform	Non-uniform	Direct/Indirect	Central/Peripheral	Uniform/Non-uniform
3	-	2	1	1	4	3	1	1

Image A (Uniform, Central, Direct) > Image B (Uniform, Peripheral, Indirect)
Image A (Uniform, Central, Direct) > Image C (Uniform, Central, Indirect)
Image A (Uniform, Central, Direct) > Image E (Nonuniform, Peripheral, Indirect)
Image F (Nonuniform, Central/Peripheral, Direct/indirect) > Image B (Uniform, Peripheral, Indirect)
Image F (Nonuniform, Central/Peripheral, Direct/indirect) > Image C (Uniform, Central, Indirect)
Image F (Nonuniform, Central/Peripheral, Direct/indirect) > Image E (Nonuniform, Peripheral, Indirect)
Image D (Nonuniform, Peripheral, Direct/indirect) > Image B (Uniform, Peripheral, Indirect)
Image D (Nonuniform, Peripheral, Direct/indirect) > Image C (Uniform, Central, Indirect)
Image D (Nonuniform, Peripheral, Direct/indirect) > Image E (Nonuniform, Peripheral, Indirect)
Significantly different: F>B, A>B, D>B, F>C, A>C, D>C, F>E, A>E, D>E

4.6.5. Spaciousness

To examine the differences in spaciousness among the different lighting patterns, the Friedman test was used, as a Shapiro-Wilk test confirmed a violation of the T-test normality assumption. The result of the analysis indicates that there is a significant effect of the type of spatial pattern of light on the perception of people of the spaciousness of the environment (P=.000). The Size of the effect is 0.137 which is relatively a small effect size (0.2= small effect size, 0.5= Medium, 0.8= Large).

Table 11. Summary of related samples Kendall's coefficient for spaciousness

Related-Samples Kendall's Coefficient of Concordance Summary	
Total N	60
Kendall's W	.137
Test Statistic	41.190
Degree of Freedom	5
Asymptotic Sig. (2-sided test)	.000

The mean rank comparison indicates that people perceive the C lighting pattern as the most spacious pattern while A is the least spacious pattern for the older adult participants (C>B>F>E>D>A). The B (Uniform, Peripheral, Indirect) and C (Uniform, Central, Indirect) are significantly more spacious than the A (Uniform, Central, Direct), D (Nonuniform, Peripheral, Direct/indirect), and F (Nonuniform, Central/Peripheral, Direct/indirect), and E (Nonuniform, Peripheral, Indirect). C pattern (Uniform, Central, Indirect) is perceived as the most spacious pattern among all lighting patterns, and it is significantly more spacious than A, D, E, and F patterns with 0.00, 0.00, 0.00, and 0.004 P values respectively (Figure 30)

According to Table 12, the final analysis compares the impact of each variable in each lighting pattern, uniform and indirect lighting patterns are the most common attributes that significantly impact the spaciousness of the environment. It also shows that lighting patterns with indirect and non-uniform lighting can be perceived as significantly more spacious than the other lighting patterns. It also indicates that central patterns of light are perceived as more spacious than the peripheral patterns.

Table 12. Comparative analysis of different spatial patterns' attributes on spaciousness perception

Direct	**Indirect**	**Central**	**Peripheral**	**Uniform**	**Non-uniform**	**Direct/Indirect**	**Central/Peripheral**	**Uniform/Non-uniform**
-	6	3	2	6	-	-	-	-
Image C (Uniform, Central, Indirect) > Image A (Uniform, Central, Direct)								
Image C (Uniform, Central, Indirect) > Image D (Nonuniform, Peripheral, Direct/indirect)								
Image C (Uniform, Central, Indirect) > Image E (Nonuniform, Peripheral, Indirect)								
Image C (Uniform, Central, Indirect) > Image F (Nonuniform, Central/Peripheral, Direct/indirect)								
Image B (Uniform, Peripheral, Indirect) > Image A (Uniform, Central, Direct)								
Image B (Uniform, Peripheral, Indirect) > Image D (Nonuniform, Peripheral, Direct/indirect)								
Image B (Uniform, Peripheral, Indirect) > Image E (Nonuniform, Peripheral, Indirect)								
Image B (Uniform, Peripheral, Indirect) > Image F (Nonuniform, Central/Peripheral, Direct/indirect)								
Significantly different: **C>A, C>E, C>F, C>D, B>A, B>D, B>E, B>F**								

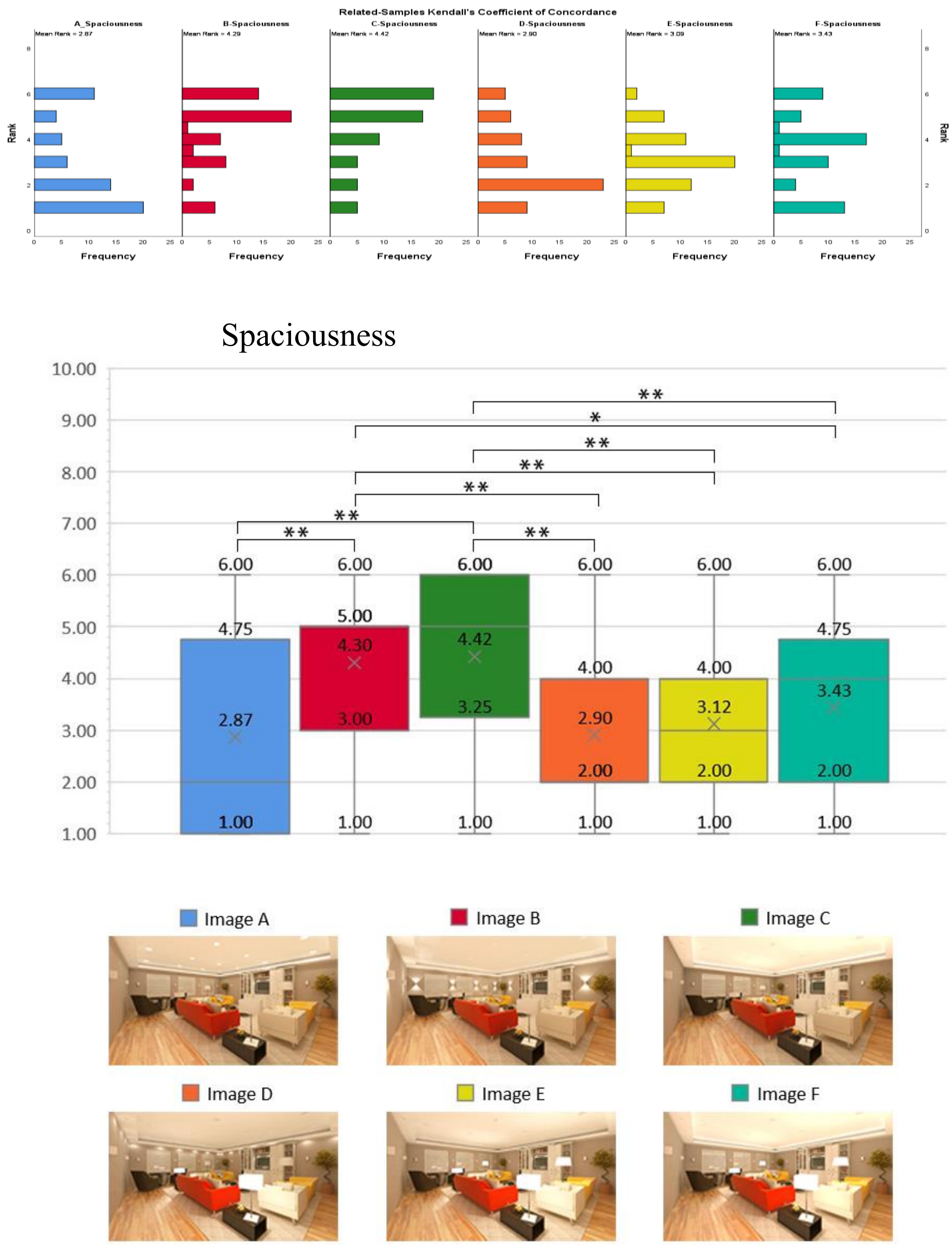


Figure 30. The Friedman test results of Spaciousness (* represents p<0.05, ** represents p<0.01)

4.7.Discussion

The present study represents a significant initial stride toward understanding the impact of spatial lighting patterns on the cognitive performance of older adult residents. To address this question, the study aimed to investigate the relationship between lighting patterns and human perception and preference. To achieve this, the study examined the participants' visual preference, stress, and perception of the environment in terms of clarity and spaciousness based on different lighting scenes. In the initial phase of the study, the two most frequent and favored typologies of bedrooms and living rooms in assisted living facilities across the United States were identified using a combination of picture content analysis and visual attention software. Subsequently, the study obtained six distinct spatial patterns of light from Flynn's theory and implemented them into the previously identified typologies of bedrooms and living rooms. In the second phase, an experiment using forced-choice and q-sort questions was conducted to investigate how different lighting patterns in the living room could impact the perception and preferences of older adults. It was hypothesized that the experience of a lighting scene is to some extent a shared experience among different occupants who had a similar perception of the environment. Furthermore, this paper seeks to test Flynn's theory concerning the aging population, which suggests that lighting can act as a vehicle that impacts the information data of the visual field and alters mood, behavior, well-being, and subjective impression.

The findings of this study confirm some of the previous research regarding the impact of different lighting modes on human subjective impressions. It revealed that different spatial patterns of light can significantly impact older adults' impression of the environment including visual preference and perception. We found that older adults show a preference for uniform lighting as opposed to non-uniform lighting. Although the investigation into the influence of lighting in residential buildings is limited, there are some studies that indicated that the preference for non-uniform and peripheral lighting tends to be higher in office spaces (Flynn, 1988). Additionally, indirect lighting was preferred over direct lighting. However, there were no significant variations between the peripheral and central arrangement regarding older adults' visual preferences. This findings are also light with the findings of Veitch et al (2008), Yearout and Konz (1989), and Katzev (1992) that found people prefer indirect lighting or a combination of direct/indirect in comparison to lighting conditions that provide direct lighting. The findings of this study also revealed a notable correlation between spatial patterns of light and the mood of older adults. It was found that non-uniform lighting tended to create a more relaxed impression, while uniform lighting increased the sense of stress perceived in the environment. Additionally, the results indicated that peripheral lighting, particularly on the walls, reinforced the sense of relaxation in the environment. This finding is consistent with previous studies that have demonstrated the contribution of non-uniform and peripheral lighting to creating a more relaxing atmosphere in an environment (Flynn et al., 1973; Flynn et al., 1979).

The finding of this study also demonstrates that the spatial patterns of light can significantly impact the perception of the lighting environment. In particular, the clarity and spaciousness of the environment can be perceived significantly differently under different spatial patterns of light. Providing non-uniform lighting with a combination of direct/indirect lighting can significantly improve the clarity of the environment, while there is no significant relationship between the Clarity of the space and the centrality of the lighting patterns. This observation is in line with the results of a prior study that examined the influence of various lighting arrangements on human perception of space. The study also discovered that nonuniform light on walls enhanced the perception of clarity (Manav & Yener, 1999).

Although the previous studies have shown a positive correlation between the uniformity of light and perceived spaciousness this study's results show that lighting patterns with indirect and non-uniform lighting were perceived as significantly more spacious than the other lighting patterns (Flynn & JE, F.,1977; Flynn, J. E., et al, 1979; Flynn, J. E., et al, 1973). Additionally, the analysis revealed that central patterns of light were perceived as more spacious than peripheral patterns.

4.8.Conclusion

We summarize the conclusions of this study with the following points:

- The findings indicate that gender, age, overall health, and cognitive performance do not have a statistically significant ($p<0.05$) effect on any of the perceptual and preference data.
- The spatial pattern of light can significantly impact the visual preference of older adults. The analysis demonstrates that older adults exhibit a preference for uniform lighting over non-uniform lighting, as well as a preference for indirect lighting over direct lighting.

- The analysis reveals a statistically significant impact of the spatial pattern of light on the perceived level of relaxation or stress in the environment (p = .000). The findings suggest that non-uniform lighting is associated with a sense of relaxation, whereas uniformity and centrality in the spatial pattern of light tend to contribute to a more stressful impression in the environment.
- The analysis reveals a statistically significant influence of the spatial pattern of light on people's perception of the clarity of the environment (p = .000). The findings demonstrate that both direct lighting and a combination of direct/indirect lighting have a significant impact on the clarity of the space. However, no significant correlation was observed between the clarity of the space and the centrality of the lighting patterns.
- The analysis reveals a statistically significant impact of the spatial pattern of light on people's perception of the spaciousness of the environment (p = .000). The results indicate that lighting patterns featuring indirect and non-uniform lighting are significantly associated with a greater perception of spaciousness compared to other lighting patterns. Additionally, the findings suggest that central lighting patterns are perceived as more spacious than peripheral patterns.

4.9. Limitations and future studies

This study also had some limitations. First, the sampling size of the study is relatively small (60 participants) which makes it harder to generalize the findings. In addition, only 30 percent of assisted living facility population are men while women make up 70% of the population. This imbalance also impacted our sampling in the experiment (39 females and 21 males). The present study is subject to another limitation in that extracting in-depth information from images featuring complex scenes displayed on a laptop screen is a challenging task for the aging population. To address this issue, an alternative solution may be to incorporate virtual reality (VR) technology, which would allow older adults to be immersed in a simulated environment to obtain in-depth information. This approach may serve as a valid alternative for the aging population in accessing and interpreting visual information in a lit scene.

Considering the restrictions and limitations associated with image-based studies, it is recommended that future research endeavors aim to provide participants with a more immersive and interactive experience with the lighting design conditions. This approach would enable participants to better extract depth information and contribute to a more impactful assessment of lighting effects. Furthermore, to expand upon the implications of the current study's findings and to better understand the impact of lighting patterns on older adults' perception and cognition, it is critical to conduct further research using objective measures rather than relying on subjective assessments. To obtain a more comprehensive assessment of the impact of light on the outcomes of older adults, it is recommended to incorporate physiological data collection alongside subjective data obtained through perceptual and behavioral self-report measures in future studies. This integration of multiple data sources would enhance the understanding of the physiological responses and provide a more holistic evaluation of the effects of light on older adults.

CHAPTER 5: COMPARING THE COGNITIVE PERFORMANCE OF OLDER ADULTS IN A LIGHTING SYSTEM BETWEEN A REAL SPACE AND A VIRTUAL REALITY DISPLAY.

This paper will be submitted to the Journal of Environmental Psychology*. Co-authored material (with Professor Ihab Elzeyadi and Professor Margaret Sereno). The excerpt to be included was written entirely by me, with my coauthors contributing to the development of the structure of the paper, assisted with the methods and measurement verifications, stimuli design, data analysis methods, interpretations of the findings, and the discussion sections. They provided editorial review and feedback on the manuscript as well as Chapter reports on the results of a within-subjects design conducted in real space and Virtual Reality (VR) environment to investigate if VR can be a reasonable surrogate for real-world lighting environments.*

This Chapter reports on the results of a within-subjects design conducted in a real space and Virtual Reality (VR) environment to investigate if VR can be a reasonable surrogate for real-world lighting environments. In recent decades the use of virtual reality (VR) head-mounted displays (HMDs) as an alternative media for visual settings has increased in indoor lighting studies. VR technology is a good representation of visual stimuli that can provide a comparable field of view to the real environment where subjects are immersed in an environment and can see and perceive the visual stimuli on the same scale as the original environment (Kort. et al, 2003; Field & Hole, 2002). Although previous studies investigating the subjective and objective visual responses and participants' perception and interaction in VR have shown a high level of perceptual accuracy regarding appearance and higher-order perceptions, there is not enough evidence regarding the mood, behavior, and cognitive performance of participants in a VR environment. In addition, most of the previous studies investigating the impact of the VR environment on human responses have mainly focused on the younger population, while there is a critical need to assess the validity and accuracy of the VR environment in gerontology studies. This leaves a gap in our understanding of the behavioral and cognitive responses of older adult participants in VR HMDs lighting scenes in comparison to real lighting scenes. The questions to be answered here are: Is there a difference in subjective behavioral assessments of older adults between a real lighting environment and a virtual lighting environment? Does the virtual lighting environment impact the cognitive performance of the aging population? If so, How might the virtual environment alter the cognitive performance of older adults?

To address this gap, this Chapter employed a within-subjects design where 32 assisted living facility residents were presented with similar lighting conditions: A real lighting environment and a virtual lighting environment according to the existing lighting condition of a living room in an assisted living facility in Springfield, OR. Multiple data types were collected and analyzed, including self-reported and behavioral data as participants were doing different cognitive tasks.

5.1. Introduction

The development of Virtual reality (VR) technology have provided researchers with a variety of options for experimenting in numerous fields. (VR) have been used in medical (John, N. W., 2007), psychotherapy (Rothbaum & Hodges, 1999), educational (Pan, Z., et al, 2006), and design fields (Wu, et al, 2009). Within the design field, virtual environments have become an active means of experimentation. VR has also been suggested to be beneficial to researchers who are interested in examining spatial abilities, wayfinding, and cognitive mapping (Richardson, A. E., et al, 1999; Sharlin, E., et al, 2009; Wu, A., et al, 2009).

VR technology also provides stereoscopic (3-dimensional) which provides depth perception that cannot be perceived in mesoscopic two-dimensional scene assessments (Lambooij et al, 2011). In addition, it provides a great opportunity for participants to interact with the scene and improve the realism of user-experience studies (Bishop & Rohrmann, 2003; Kort et al, 2003).

VR also allows for controlling physical environmental attributes (Abd-Alhamid et al, 2019). For instance, the VR environment can control the sky condition and provide constant daylight conditions for setups using windows (Chamilothori et al, 2019). Using a VR environment makes it possible to maintain the level of illumination coming through the window and easily switch out different light variables such as spatial pattern and light spectrum and therefore evaluate human responses to different scenes in immersive environments. This provides a great opportunity for researchers to replicate the same experimental lighting setup in a virtual environment without the limitation of the real environment and investigate the impact of visual stimuli which is the independent variable of the study.

Existing studies investigating the impact of physical environmental attributes on human outcomes in VR have mainly focused on visual perception of the environment and also are limited to passive experiences. In a study by Chamilothori et al. (2019), four subjective impressions of lighting including pleasantness, interest, excitement, and complexity as well as satisfaction regarding the window view were evaluated in a VR environment under different stereoscopic physically based renderings. The results indicated that there was no significant difference between VR and the real environment in terms of visual perception. In a recent study, the perceptual impressions of 40 participants were compared between a 23 immersive 360-video displayed smartphone VR and a real environment. Three correlated color temperatures (CCT) including warm white (3000 K), neutral white (4000 K), and cool white (5500 K) were used in a scene with average illuminance of 800 Lux on the work plane. The two lighting attributes (open/close and diffuse/glaring) and overall satisfaction were perceived as significantly similar to the real environment (Chen et al, 2019). In another study, the task performance of office workers was evaluated and compared in a bright and dark environment in a real office and a simulated rendered 3-dimensional environment. The results showed that there was no statistically significant difference between the two environments. However, in that study, the exact illuminance of the two environments that play an important role in task performance was not mentioned (Heydarian et al, 2015)

While previous studies found VR to9 be a reasonable substitute for the real environment in environmental design research regarding visual perception, they leave an incomplete understanding of the limitations of VR HMD for assessing and evaluating the behavioral and cognitive performance of the participants. In addition, most of the previous studies investigating the impact of lighting design using a VR environment mainly provide a passive experience that does not allow for an engagement and exploration of the environment. Therefore, we first need to replicate the result of previous studies to further confirm the applicability of VR in lighting research and then investigate the validity of VR environments in assessing the cognitive performance of older adults.

5.2. Background

Various studies have compared the perceptual performance and preference between real and virtual environments (Heydarian et al, 2015; Chamilothori et al, 2019; Kuş, B, 2019; Wong et al, 2019; Omidfar Sawyer & Chamilothori, 2019). In one study, Abd-Alhamid et al. (2019) developed a new method called quasi-stereoscopic HDR imaging to evaluate visual perception in a virtual reality environment. The results showed that the VR environment can provide a very accurate and reliable measurement of brightness, distribution, interest, excitement, and color variety. They also found there is a significant difference in task completion time between real and VR environments. The finding of the study indicates that although the VR environment is a good replication of the real environment in terms of subjective evaluation, it cannot match the task performance results (Abd-Alhamid et al, 2019). In another study, Chen et al. (2019) compared the participant's subjective evaluation and objective measurements such as visual acuity, color perception, and brightness between a real environment, VR environment, video, and photographs. While significant differences were observed for several attributes between real and VR environments, VR provided the most similar perception to the real environment in comparison to video footage and photographs (Chen et al, 2019). Chamilothori et al. (2019) investigated the accuracy of an immersive virtual environment in daylight perception by recruiting 30 participants including architecture students and professionals. The results showed no significant difference between real and VR environments, indicating a high level of perceptual accuracy in the VR environment. The finding of this study revealed that VR can be used as a promising method for architectural lighting design research. However, there is a critical need for calibration of the VR system and tone mapping procedure to improve perceptual accuracy (Chamilothori et al, 2019). There are also other studies highlighting the importance of tone-mapping and image processing in studies related to lighting in a virtual reality environment. Tone mapping is a crucial step that should be implemented to improve the perceptual accuracy of the VR environment and replicate a similar luminance to the real environment (Raffin et al, 2008; Murdoch et al, 2015; Chamilothori et al, 2019; Melo et al, 2015)

There are also other studies that investigated cognitive performance in real and virtual environments. In these studies, Grealy et al. (1999) investigated the impact of exercise and a VR environment on improving the cognitive function of people with brain injuries. Participants were randomly assigned to a VR group with four weeks of exercise in VR or a no-exercise control condition. The results show a significant improvement in the cognitive function of the participant in the VR environment (Grealy et al, 1999). Lee et al, (2018) the authors conducted a comprehensive literature review to examine the impact of VR on the cognitive function of various groups of people including healthy individuals, older adults, stroke patients, and individuals with Parkinson's disease. The results of this study indicated that the VR environment can improve cognitive performance, especially in tasks that involve spatial memory and attention. In another review article, Nolin et al. (2019) investigated the potential, validation, benefits, and limitation of VR as a tool for cognitive assessment. They found that VR-based cognitive assessment is a promising tool for evaluating cognitive performance in individuals with neurological conditions. However, the study highlighted the critical need for further research to establish the reliability and validity of cognitive assessment tests in the VR environment for a diverse group of populations. Zhu et al. (2021)conducted a systematic review to examine the effectiveness of VR intervention on the cognitive function of older adults with cognitive impairment. After analyzing 11 studies including 359 participants, they found that the VR environment, as a non-pharmacological approach, can improve and enhance overall cognition, memory, and motor function of older adults, while not impacting visuospatial ability and gait performance. In a current study, Plotnik et al. (2021) investigated the feasibility and validity of the Multimodel Immersive Trail Making (MITM task) to evaluate cognitive-motor interaction in different groups of people. They asked 25 healthy adults and 24 individuals with cognitive impairments to complete a series of cognitive tasks involving memory, attention, and motor function while wearing a VR headset. Although VR completion times for the test were longer in comparison to a pencil-and-paper format the results indicated that MITM is an effective tool for assessing cognitive-motor interactions and also has a good potential in diagnosing and treating cognitive impairment.

In Summary, there is a lack of consistency between the results of previous studies which compared the perceptual accuracy, preference, and cognitive performance between real and VR environments using different methods. Previous research investigating the applicability of VR in lighting research has shown that despite limitations in the VR scenes regarding the range of luminance, color, and light spectrum compared to real environments, it is still a valid and reliable tool for conducting lighting research. However, there is a lack of studies comparing the behavioral and cognitive performance of the users in real and VR environments. Previous studies in this area have primarily utilized the VR environment as a therapeutic approach to improve cognitive performance, rather than examining the differences between VR and real environment. Furthermore, most of the previous studies exploring the impact of lighting design in VR environments have primarily offered a passive experience that limits the user's interactive and engaging experience in VR. Lastly, although there are some studies that include older adults in their experiments, there is still an incomplete understanding of the performance of older adults' performance in VR in comparison to the real environment. This paper examines three main topics 1- the applicability of VR in lighting research, 2- the effectiveness of VR in evaluating cognitive performance, and 3- the validation and limitation of using VR environments in studies involving the older adult population.

5.3. Hypotheses

In this study, participants were tasked with completing a cognitive test in both a real environment and a virtual reality (VR) environment, each featuring a similar lighting condition characterized by direct, central, and uniform lighting. Cognitive performance measures, such as completion time and error count, along with self-reported subjective perceptual data, were collected from the participants. Statistical analysis was conducted to compare these variables between the real and VR conditions, aiming to test the following hypotheses: First, it is hypothesized that the lighting condition in both the real and VR environments would similarly impact participants' perception of the environment. Second, it is expected that the impact of the lighting condition on participants' cognitive performance would be consistent between the real and VR environments.

5.4. Methods

To assess the research objectives, we selected a living room with specific lighting conditions in an assisted living facility in Eugen, Oregon. The physical and photometric conditions of this room were replicated and presented in a virtual reality environment.

All the lighting parameters including light intensity, light spectrum, and correlated color temperature (CCT) of the real environment were measured and simulated in the VR environment. To provide a constant spectrum of light between the real environment and VR, both tests were conducted on a winter day in an overcast sky condition while all the blinds of the exterior windows were down, and the penetration of the daylight was controlled. Other extraneous variables (e.g., noise, temperature, and humidity) were measured and controlled for between the real and virtual environments. This section will introduce the facility design condition, the methods used to capture HDR images and lighting condition measurement, the image post-processing, VR development, and the design and delivery of the experiment.

5.4.1. Facility Design Condition

A living room located in Timber Pointe Senior assisted living facility in Springfield, Oregon was selected. This assisted living facility is selected because of 1) strong working relationships; 2) free technical assistance and services (e.g., lighting setups, control commissioning, moving); 3) the importance of electric lighting in this climate zone. The room had an internal dimension of 22' x 42' 6" and a floor-to-ceiling height of 9' 6" – 14' 5". The walls and ceiling are painted bright yellow and white, with reflectance (ρ) properties: ρwall≈ 0.8, and ρceiling≈ 0.85, and the floor is carpeted (ρfloor≈ 0.3). A standard office desk chair was placed in the corner of the room with a wide view of the cognitive task and acted as a viewing position (Figure 31).

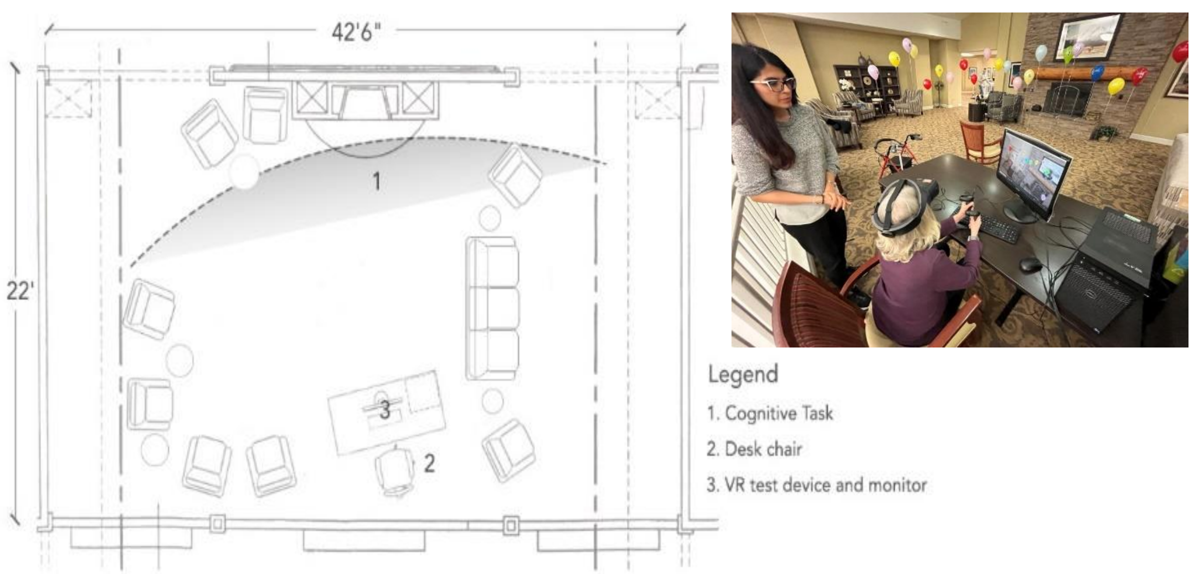


Figure 31. Left: layout of the experimental room 2, right: Internal view of the experimental room

5.4.2. HDRI scene capture, Photometric measurements, and Image-processing workflow

The following photometric equipment was used to capture images for display on our VR.
HMD and measure the luminous environment of the test room: 1) Insta360 ONE X2 360 Degree Camera (Dual-lens 5.7K 360° video with H.265 encoding) mounted on a tripod; 2) Li-Cor LI-250A Light meter; 3) Lighting Passport Essence Pro Spectrometer (Figure 32). The Camera was mounted on a tripod at 1.20 m from the floor corresponding to the subject's seated eye level and toward the location of the task scene. According to standard photometric methods, the pixel values of an HDR image are corresponding to the luminance measures of the real environment (Inanici, 2006)

Figure 32. Photometric equipment was used in the study.

Insta360 camera can capture a large range of luminance values of different points of the scene and store them within the image pixels. A high dynamic range image (HDRI) was created using seven low dynamic range images (LDRI) with different exposure values by varying the camera shutter speed. The camera settings are shown in Table 13.

Table 13. Insta360 camera settings for capturing the seven LDRI.

Image	White balance	Sensitivity (ISO)	Exposure time (1/s)	Aperture (f/n)
1			1/500	
2			1/240	
3			1/100	
4	3000K	100	1/30	2
5			1/2	
6			1	
7			2.5	

The camera sensitivity (ISO) was set to 100 to minimize the noise in the HDRI image. To keep the color temperature of the HDRI images consistent with the real environment, the mean correlated color temperature of the lighting scene in the real environment was measured by Lighting Passport Essence Pro Spectrometer and was used as the camera white balance (3000K). The photosphere software was used to combine the seven LDRI images into an HDRI image (Ward, 2005). This software also was used to calibrate the luminance values in the HDRI image based on the corresponding point luminance measurement within the actual visual scene. The luminance value of the corresponding point in the actual scene was measured by a Li-Cor LI-250A Light meter.

Insta360 Studio and Adobe Photoshop were used to combine the seven LDRI images into one single HDRI image. (Figure 33)

Figure 33. Seven LDRI images with different exposure values were captured by Insta360.

At the time of capture, the physical illuminance measurement of a gray and white card mounted on two different walls behind the cognitive test was also measured. The white card was located on the left wall behind the cognitive task and was centered 2.1 m from the ground. The gray card was mounted on the fireplace wall exactly in front subject's seated eye level and behind the task scene (Figure 27). The HDRI image was calibrated using Photosphere according to the grey-card measurements. The percentage error between grey and white cards was also calculated and the resulting error was 7.5 %, which is aligned with the acceptable margin previously reported for the HDR capture method (Inanici, 2006). The Evalglare software (Wienold, J., & Fraunhofer Institute for Solar Energy Systems ISE, 2010) also was used to measure the average luminance of the HDRI scene across the 180° field-of-view facing forward from the participant's viewpoint. This illuminance was compared with the illuminance level measured by the Lighting Passport Essence Pro mounted to the right part of the participant's head at a height of 1.2 m facing the direction of the cognitive task. The measured illuminance in real space and HDRI image was 233 lux and 231 lux respectively. The minimum, maximum, and average luminance of the HDRI image calculated in the photosphere were 5.59, 320.3, and 267.9 cd/m2, respectively.

In addition, to provide an integrative and consistent luminous condition of the actual lighting scene in the VR environment, a 1.2 m horizontal grid of lux measurements across the whole space of the living room was captured using a Li-Cor LI-250A Light meter. Figure 34 shows the location of the measurements taken in the space. The average illuminance of the real environment was 252.7, with a min of 162 lux and a max of 355 lux. The average correlated color temperature measured with the Lighting Passport Essence Pro was 3000K. The average illuminance level in the living room is lower than IESNA's (1998) recommended light in the living room for the aging population (300 lux) while meeting the CIBSE (2009) suggested levels of illumination in living rooms for older adults (150 lux). The color temperature of light is also in the range of IES recommendations for the living rooms (higher than 2700K).

Figure 34. The location of white and gray cars within the experimental space and a 1.2 m horizontal grid of lux measurements

5.5.3. Image processing workflow:

Chamilothori et al (2019) argue that an HDRI image cannot be directly displayed in the virtual environment due to the limited luminance range in VR display (~216 cd/m2). To make the HDRI image lighting readable for the VR display, we need to do a tone-mapping process and compress the large range of luminance in the HDRI image into a lower dynamic range (Abd-Alhamid et al, 2019). According to the literature, there are different ton-mapping operators (TMOs) that can be used to optimize the color matching of HDR images and represent a photometrically accurate and immersive HDR image that replicates the real lighting condition (Rockcastle et al, 2021). In this study, the Reinhard tone-mapping operator was applied using Luminance-hdr software (Guiuseppe et al, 2006). The Calibrated and tone mapped HDRI image was saved as a .bmp file with a gamma correction of 2.2. To obtain the appropriate gamma curve for our device the procedure outlined in Abd-Alhamid et al (2019) and Díaz-Barrancas et al (2020) was used and the results indicated that Oculus Rift also uses a 2.2 correction value.

In this process, we used the Lighting Passport Essence Pro spectrometer to measure and compare the relationship between the digital-to-analog converter (DAC) of each RGB channel and eight different shades of gray with their corresponding values of luminance in a dark room (Figure 35).

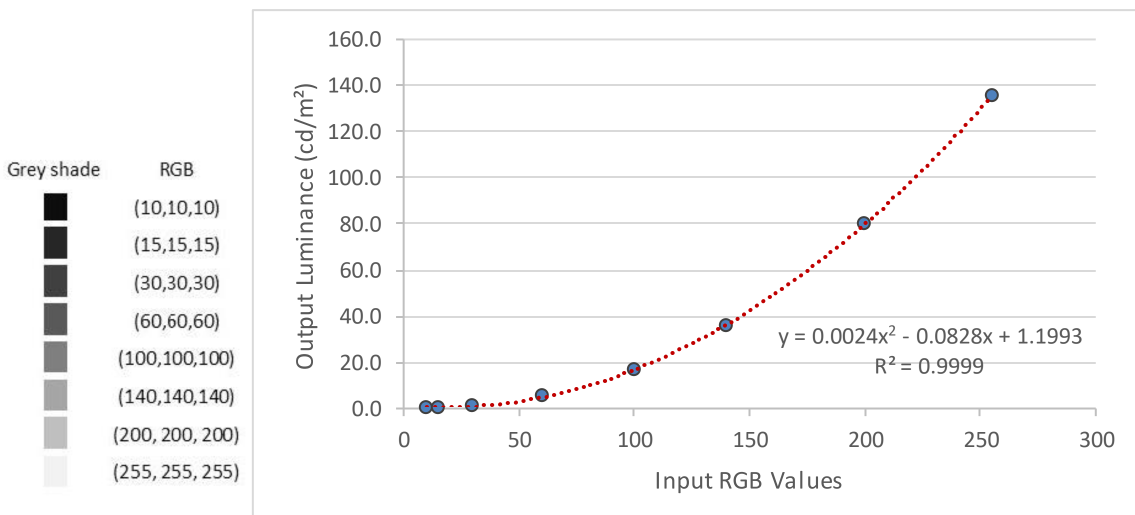


Figure 35. Gamma curve (luminance response curve for the used VR headset as measured in the middle of the lens) using Lighting Passport Essence Pro spectrometer.

5.5.4. Virtual Environment

The Oculus Rift S was used in this study based on advances in pixel resolution (2560×1440), the field of view (115º), and "next generation" lens technology that almost eliminates god rays. The Rift S uses a DisplayPort 1.2 port and one USB 3.0 port, as opposed to the HDMI and USB 3.0 port used on the Rift CV (Wikipedia contributors, 2021). A Core ™ i7 computer with two 2.50 GHz possessors and 1 NVIDIA GeForce RTX 3070 card was used along with Unreal Engine software to display the final HDRI image as an immersive 360º image. The virtual environment was created by importing the HDRI image of the assisted living facility to Epic Games' Unreal Engine (www.epicgames.com) and assigning it to a spherical skybox. The height for the camera was set at 1.02 cm, while the participants can change the angle by looking around and rotating their heads.

5.5.5. Cognitive Tasks (Trail Making Test (TMT))

The Trail Making Test is a neuropsychological test of visual attention and task switching. It consists of different parts in which the subject is asked to mark and connect numbers and letters in a meaningful order as quickly as possible while trying to keep accuracy. This test can evaluate visual search speed, scanning, speed of processing, mental flexibility, as well as executive functioning. (Arnett, J. A., & Labovitz, S. S., 1995) it also is sensitive to detecting cognitive impairment associated with dementia, such as Alzheimer's disease (Cahn, D. A., et al, 1995). For this experiment, we have designed a visual navigational-cognitive task that has been inspired by Trail making test. Plotnik et al., (2021) showed that the result of a three-dimensional VR-based format of Trail making test is feasible and valid as the two-dimensional pencil-and-paper format (See figure 36).

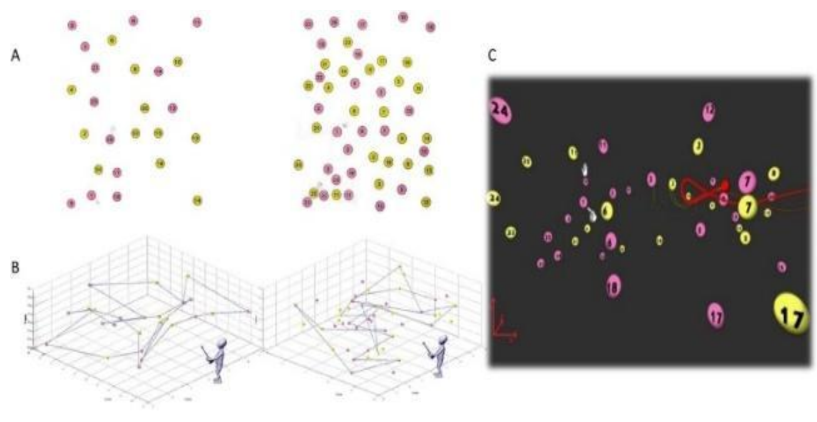


Figure 36. Conducting the trail-making task in a virtual environment for assessing the cognitive task of the participants (Plotnik et al., 2021)

In the VR version of the Trail Making Test (TMT), the two-dimensional (2D) page is replaced by a three-dimensional (3D) VR space. This test consists of two Trails and both Trails include 25 balloons distributed over a 3D environment. In Trail A, 25 target balls are distributed in a 3d space in the real environment or VR environment, and the participants should select the balloons in ascending order. In Trail B, the balloons include both numbers (1-13) and the letter (A-L); as in Trails A, the participants connect the balls in an ascending pattern, with the added task of alternating between the numbers and letters (i.e., 1-A-2-B-3-C, etc.). The cognitive task will assess the participants' cognitive performance by objectively evaluating their answers' time allocation and accuracy. After conducting Trails A and Trails B in both real and virtual environments, 5 subjective perceptual rating questions were delivered in random order

and asked participants:

- How pleasant is the light in space, with 1 being unpleasant and 5 being pleasant?
- How visually comfortable is the light in this space, with 1 being uncomfortable and 5 being comfortable.
- How exciting is the light in this space, with 1 being unexciting and 5 being exciting?
- How stressful is the light environment, with 1 being non-stressful and 5 being stressful?
- How confusing is the task in space, with 1 being clear and 5 being confusing?

5.5.7. Design and delivery of experiment

After obtaining the IRB approvals the researcher presented the goal and procedure of the research project in the targeted senior living facilities in Springfield (we collaborated with this facility in the previous phase). An a-priori analysis was conducted using G*Power (Version 3.1.9.7.) to determine the required sample size for this study. Based on an effect size of dz = 0.50, a significance level of 0.05, and a power of 0.8, a sample size of 18 participants was determined to be necessary. A total of 37 participants were recruited for the study by presenting an online invitation to residents of the assisted living facility and requesting volunteers to take part. Interested participants filled out a form at the end of the presentation or contacted the researcher through phone/email to show their interest and provided their email and phone number. After receiving emails or phone calls from the interested participants of the study, the researcher contacted the participants and notified them about their health assessment appointment.

Participants who attended their health assessment appointment (one day before the experiment) were asked to review the consent form in advance of their arrival then they were directed to fill out a brief demographic questionnaire on gender, age, and visual condition, 12-item Short Form Survey (SF-12). The 12-item Short Form Survey (SF-12) is a general health questionnaire that assesses both mental and physical health based on the mental component score (MCS-12) and physical component score (PCS-12) (Ware et al, 1996). We used an online version of the test which uses Z-scores (difference compared to the population average, measured in standard deviations) to evaluate the participant's health scores (Ortho Toolkit website ("SF-12"), 2023). The United States population average PCS-12 and MCS-12 are both 50 points with a 10 points standard deviation. Scores greater or lower than 50 represent better or worse physical and mental health in the US general population (Vilagut et al, 2013). Furthermore, the cognitive function of potential subjects was assessed by the Mini-Mental State Examination (MMSE) (Smith et al, 2007). Exclusion criteria were any evidence of moderate to major cognitive impairment (scores less than 23 for MMSE), and severe physical and mental health problems (PCS-12 and MCS-12 < 40). Participants who had poor conditions in any of these criteria were excluded automatically from the experiment. After the screening process was completed, 32 qualified participants were notified about their two confirmed appointments, the first for the next day and the second one for the next week, and were asked to contact the researcher with any questions.

In this experiment, we employed a within-subject design (the same group experienced both real and virtual environments) to remove the individual variation between the two groups. It also allows us to conduct the study with the same senior living facility's residents that we did in the previous phase of the study. Both the real and VR test experiments were conducted in the living room of a nursing home to control the climate condition between the two experiments. The experiment was carried out on a Winter afternoon under overcast sky conditions with closed blinds with limited access to daylight.

The real environment in this study is a living room with an internal dimension of 22' x 42' 6" and a floor-to-ceiling height of 9' 6" – 14' 5". Six surface-mounted fluorescent ceiling lights and six recessed fluorescent lights were in the suspended ceiling. A standard office desk chair was placed in the corner of the room with a wide view of the cognitive task and acted as a viewing position.

Thirty-two participants were randomly assigned to two separate groups; Group 1: includes 16 participants who were assigned to the real environment in week 1 and then were assigned to a virtual environment in the second week, group2: includes 16 participants who conducted the cognitive task in VR in the first week and then were assigned to the real environment in the second week. The experimental procedure and duration for each step are shown in Table 14.

Table 14. Experiment with detailed procedure and duration

Time progress in minutes	**Activity**	**Duration in minutes**
One day before the experiment	Signing the consent, demographic questionnaire, visual condition, 12-item Short Form Survey (SF-12), MMSE test	15
0-2	Welcoming and introduction	2
2-7	Explanation of experiment 1 (VR or real environment) *	5
7-13	Participants complete the Trails A (connecting numbers) of the task in the Real or VR environment	6
13-18	Participant rest outside the experiment room and the experimenter prepare for the Trail B of the task (connecting numbers and letters)	5
18-23	Explanation of experiment 2 (VR or real environment)	5
23- 33	Participants complete the second part of the task in the same environment and complete behavioral assessment questionnaires and the experimenter records responses	10
33-35	The end of the experiment. The participant will be thanked for their time, led to the door, and told they are free to leave	2

* These two steps can be conducted interchangeably

5.5.7.1.Real environment experiment:

In the real environment, 25 target colorful balloons with numbers and letters were distributed at the time that the first group of participants entered the room (Figure 37). Upon entering the real space, participants were asked to sit down on the test station's rotating chair while the researcher explained the TMT test procedure. The Trails A of the TMT test (connecting the numbers in ascending order) was conducted and data regarding the total time of the test, and success/failure data were collected. After finishing the Trails, A of the test, the participants were directed outside the room to set up the room for Trails B of the test. After a 5-minute break, participants were returned to the room to conduct Trail B of the test, with the added task of alternating between the numbers and letters (i.e., 1-A-2-B-3-C, etc.). After finishing the Trails, A and Trail B of the test behavioral assessment was conducted and pleasantness, comfort, excitement, stress, and confusion were evaluated by using Likert-scale questions in Qualtrics.

Figure 37. Participants engaging in the cognitive test within the real environment.

5.5.7.2. Virtual environment experiment

Participants in this group were assigned to the VR test station to do the same procedure and complete the task in a VR environment (Figure 38). Participants in the VR test were asked to be seated on a chair when they were using VR sets. They also became more familiar with the VR system and interacted with it through a tutorial session (about 5 minutes). In this tutorial, participants experienced a simple and small environment (10*10 feet) surrounded by walls, while there are 5 interactive balloons in the space that can be selected with joysticks while they were looking around. After the tutorial session, participants were asked to start the cognitive tasks in the virtual environment. After finishing the Trails A of the experiment and collecting the data, participants waited for 5 minutes outside the room to get prepared for the Trail B of the experiment. The time it took for participants to finish the first and Trails B of the test and the number of errors were recorded by a code developed in the blueprint Unreal Engine. Self-reported behavioral data including pleasantness, comfort, excitement, stress, and confusion were also collected at the end of the Trails B cognitive task using the integrated Likert-scale widgets.

Figure 38. Participants engaging in the cognitive test within the real environment.

After finishing the first round of data collection in week one, participants had a 1-week break to get ready for the second round of the experiment. In the second week, 15 participants who conducted the test in the real environment in the first week were assigned to the VR environment, while the 14 people in the VR group were required to complete the task in the real environment.

5.6. Results

5.6.1. Sample statistics

A total number of 37 residents aged 62 to 84 participated in the study. Only 32 (17 female, 15 male) were eligible to participate in the experiment according to their mental, physical, and visual condition. The female mean age was 73 years, while Men's average age was 75. As reported by the participants at the time of the experiment, 18 participants were wearing glasses and 14 were not. Participants were encouraged to wear their glasses inside the VR HMD while conducting the cognitive task. Tables 15 and 16 show t-test results for gender for each self-reported behavioral data (pleasantness, comfort, excitement, stress, and confusion) in the real environment and virtual environment. The results show there is no significant ($p<0.05$) effect of gender on the means of any rating scales in the real or VR environment. However, our analysis is constrained by the limited sample sizes for gender within our participant population. The t-tests conducted exhibit a mean power of 0.1864, falling short of the desired power of 0.80, thereby indicating a small effect size. To achieve a power of 0.80, we would need a population of at least 18 for each gender. This topic could be interesting in future studies to investigate the impact of gender on human lighting perception in a virtual reality environment.

Table 15. t-test results for the effect of gender on mean ratings in the real environment

	Gender	Mean	Std. Deviation	Std. Error Mean	t	p-value	Cohen's d
Pleasantness	F	3.82	.636	.154	.355	.725	.126
	M	3.73	.799	.206			
Comfort	F	3.82	.636	.154	-.503	.619	-.178
	M	3.93	.594	.153			
Excitement	F	2.47	.800	.194	1.026	.313	.363
	M	2.20	.676	.175			
Stress	F	1.24	.437	.106	-.600	.553	-.212
	M	1.33	.488	.126			
Confusion	F	1.76	.752	.182	-.149	.883	-.053
	M	1.80	.561	.145			

Table 16. t-test results for the effect of gender on mean ratings in the VR environment

	Gender	Mean	Std. Deviation	Std. Error Mean	t	p-value	Cohen's d
Pleasantness	F	3.59	.939	.228	.314	.756	.111
	M	3.47	1.246	.322			
Comfort	F	3.71	.686	.166	-.741	.465	-.262
	M	3.87	.516	.133			
Excitement	F	3.94	.827	.201	1.614	.117	.572
	M	3.47	.834	.215			
Stress	F	2.76	.664	.161	-.753	.457	-.267
	M	2.93	.594	.153			
Confusion	F	3.18	.951	.231	.156	.877	0.55
	M	3.13	.516	.133			

Note: The sample is 17 females and 15 males.

In this study, the Pearson correlation coefficient was utilized to examine the potential relationship between participants' visual condition and their self-reported behavioral data.

The results revealed a significant ($P<0.05$) negative correlation between the visual condition and both confusion rate and stress level experienced by participants in real-life environments, indicating that individuals with better visual conditions experienced lower levels of confusion and stress in the real environment. The Pearson correlation test results also showed there was a significant ($p<0.05$) effect of visual condition on the excitement rate of the participants in the VR environment. Participants with better visual conditions perceived more excitement in the VR environment (Tables 17 and 18)

Table 17. t-test results for the effect of visual conditions on mean ratings in the real environment

	Pearson Correlation	p-value	N
Pleasantness	.247	.174	32
Comfort	.060	.743	32
Excitement	.111	.546	32
Stress	-.502	**0.003****	32
Confusion	-.681	**0.000****	32

Correlation is significant at the 0.05 level (2-tailed).

Table 18. t-test results for the effect of visual condition on mean ratings in the VR environment

	Pearson Correlation	p-value	N
Pleasantness	.247	.174	32
Comfort	.347	.052	32
Excitement	.355	**.046****	32
Stress	.073	.691	32
Confusion	-.299	0.097	32

Correlation is significant at the 0.05 level (2-tailed).

5.6.2. Self-reported subjective perceptual data

5.6.2.1. Mean rating and distribution

Figure 39 shows the boxplot and mean rating scores for each subjective perceptual question. The solid green represents the real space while the solid pink represents the VR screen. The box plot shows mean rating and overall response trends for pleasantness and comfort are similarly independent of the environmental condition. In other words, participants rated the scenes both in the real and VR environments relatively high in terms of pleasantness and comfort. However, participants involved in the study experienced more excitement, stress, and confusion in the VR environment with average scores of 3.72, 2.84, and 3.16, compared to 2.34, 1.28, and 1.78 in the real environment. It is also helpful to note those questions that produced a wider spread in subjective perceptual rating. Both pleasantness and excitement show a broad distribution of ratings, while the ratings for comfort were closely clustered between the range of 3 to 5, indicating a high level of consistency in people's responses regarding comfort in both real and virtual environments. The distribution of ratings for stress is also more spread in the VR environment compared to the real space.

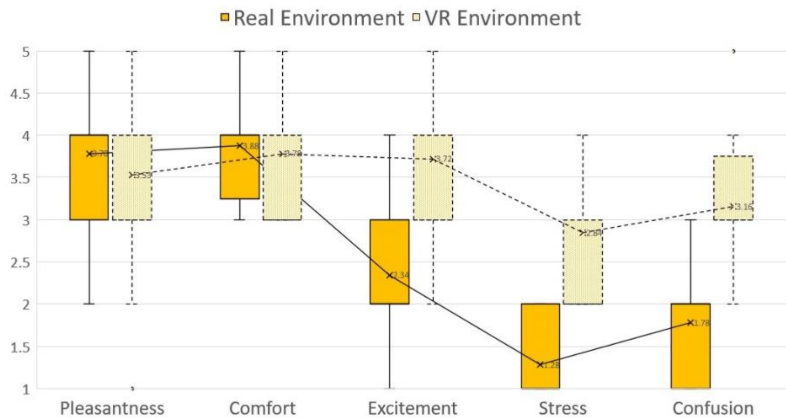


Figure 39. Self-report data distributions and mean scores are depicted in box plots.

According to the Shapiro-Wilk test and Table 19, the participants' responses were not normally distributed between real and VR environments in all self-reported data. For the last three questions, including excitement, stress, and confusion there is a shift in distribution for the frequency of ratings. A higher frequency of participants rated the VR environment as more exciting, stressful, and confusing. However, the frequency distribution chart indicates that participants rated the pleasantness and the comfort of the scene as relatively similar in both environments (Figure 40).

Table 19. Shapiro-Wilk test results

Perceptual question	Environment	Mean	Std.Dev	Shapiro-Wilk (Sig.)
Pleasantness	Real Environment	3.78	.706	.000
	VR Environment	3.53	1.077	.003
Comfort	Real Environment	3.87	.609	.000
	VR Environment	3.78	.608	.000
Excitement	Real Environment	2.34	.745	.000
	VR Environment	3.72	.851	.000
Stress	Real Environment	1.28	.457	.000
	VR Environment	2.84	.628	.000
Confusion	Real Environment	1.78	.659	.000
	VR Environment	3.16	.767	.000

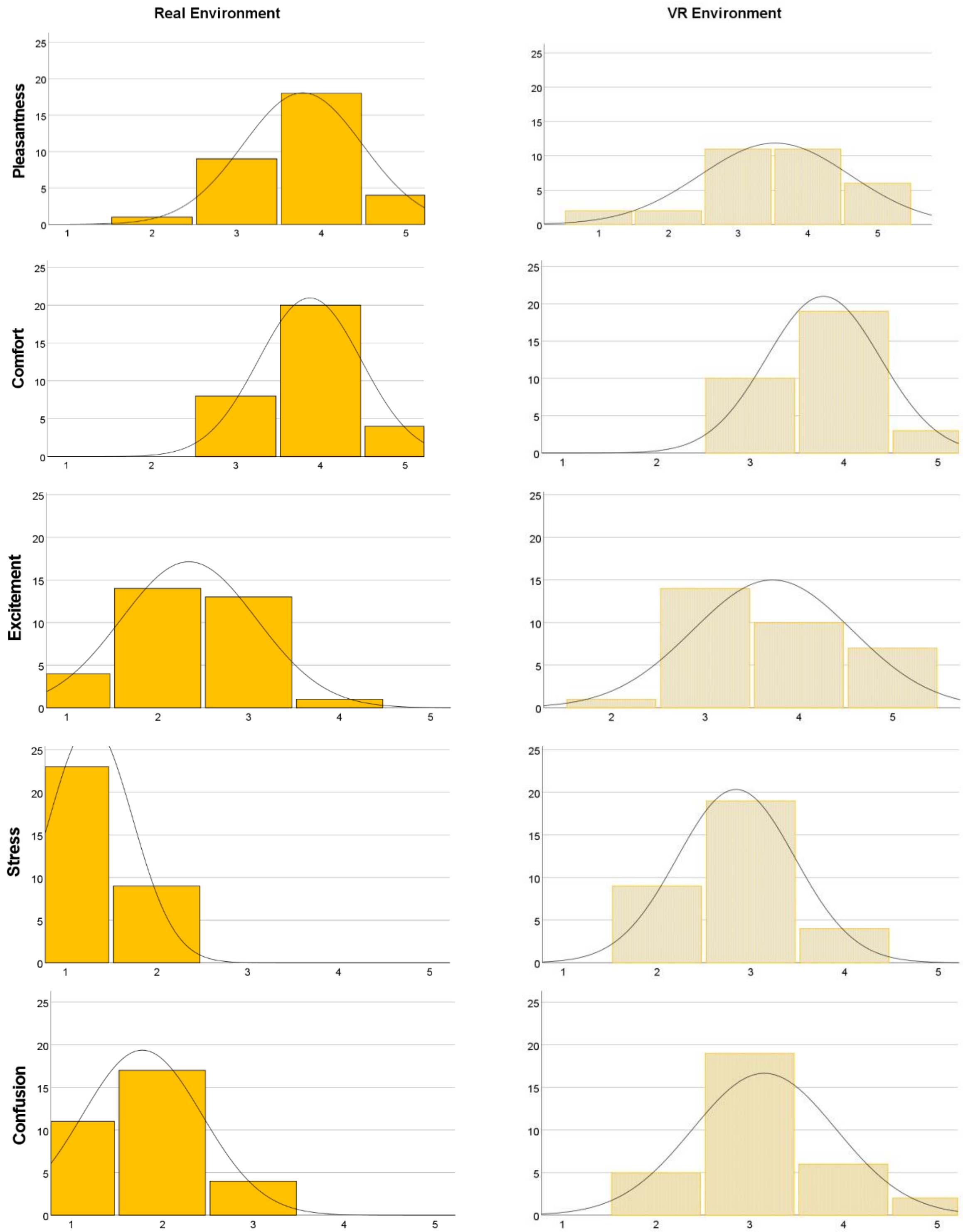


Figure 40. Frequency distribution plots for ratings in real (gold yellow) and VR (bright yellow)

5.6.2.2.Mann-Whitney test

To examine differences in subjective perceptual ratings between real and VR environments, a nonparametric test was used, as a Shapiro-Wilk test confirmed a violation of the t-test normality assumption. Table 20 shows the Mann-Whitney Test results of each subjective rating question from the real and VR environments, treated as two independent samples. The table includes associated. U-values, median values, p-values (for a two-tail analysis), effect size (effect_r), and z-scores for each question. Questions with significant *p*-values are indicated in bold $*p \leq 0.05$ or $**p \leq 50.01$. Effect sizes are explained based on the work of Cohen (1988). The results indicate no significant difference in pleasantness and comfort level between the two conditions, while significant differences were observed in excitement, stress, and confusion level between the real environment and VR environment. The question about excitement resulted in a significant difference ($p \leq 0.00$) with a medium effect (r= 0.458) between real and VR environment. The stress question also indicated a significant difference ($p \leq 0.00$) between real and VR environments with a relatively large effect size (r= 0.702). The confusion question also revealed that participants experienced significantly ($p \leq 0.00$) higher level of confusion in the VR environment in comparison with the real environment with medium effect (r= 0.534).

Table 20. Mann-Whitney non-parametric test for two independent samples: Real (N=32) and VR (N=32) groups.

	Environment	Median	U-value	z.score	Effect_r	p-value (2-tails)
Pleasantness	Real	4	450	-.884	.012	.377
	VR	4				
Comfort	Real	4	472	-.62	.006	.535
	VR	4				
Excitement	Real	2	131	-5.376	.458	**.000****
	VR	4				
Stress	Real	1	40.5	-6.654	.702	**.000****
	VR	3				
Confusion	Real	2	100.5	-5.801	.534	**.000****
	VR	3				

*p-values of ≤ 0.05, **p-values of ≤ 0.01.

5.6.3. Performance on the Cognitive task (Trail Making Test (TMT))

5.6.3.1. Time Required for cognitive task completion.

The time required for cognitive task completion was averaged across the first and the second task in real and virtual environments. A one-way ANOVA test was used to compare the time taken to complete the cognitive task in real and virtual reality environments as the Shapiro-Wilk test confirmed the t-test normality assumption (Table 21).

Table 21. Shapiro-Wilk test results

	Environment	Mean	Std.Dev	Shapiro-Wilk (Sig.)
Trails A_Time	Real Environment	2.216	.154	.066
	VR environment	2.422	.168	.341
Trails B_Time	Real Environment	3.923	.222	.299
	VR environment	4.497	269.	.223

No statistically significant differences were found for task completion time in Trails A (p=0.371) and Trails B (p= 0.106) of the cognitive task between real and VR environments. All participants completed Trails A and B of the Trail-making test in both environments. Time for completing Trails A and Trails B of the test varied between participants, however, the total time for Trails A and B did not exceed 9.72 minutes and 11.46 minutes in the real and virtual reality environments, respectively. On average, it took participants 2.216 minutes to complete Trails A of the task in a real environment and 3.923 minutes in a VR environment. Similarly, the mean time for completing the Trails B of the task in the real environment was 2.422 minutes, while it took an average of 4.497 minutes to complete the same task in the virtual reality environment (Figure 41).

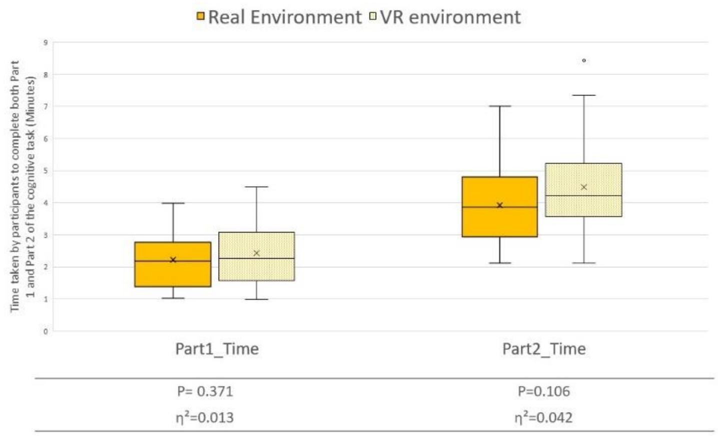


Figure 41. Box plots and ANOVA tests comparing the time distribution for Trails A and Trails B of the experiment in real and VR environments.

5.6.3.2. Number of errors in the cognitive task

The Mann-Whitney test was used to compare the number of errors made by participants during the Tarils A and Trails B of the cognitive task in both the real and VR environments, as the Shapiro-Wilk test confirmed a violation of the t-test normality assumption (Table 22). The study found no significant variations in the number of errors made by participants during Trails A (p=0.069) and Trails B (p=0.201) of the cognitive task between the real and VR environment**.** (Figure 42 and Table 23)**.** The average error rate for the Tarils A of the experiment was 1.56 errors in real and 2.41 in the VR environment. The average number of errors in Trails B increased from 12.41 in the real environment to 15.06 in the VR environment.

Table 22. Shapiro-Wilk test results

	Environment	**Mean**	**Std.Dev**	**Shapiro-Wilk (Sig.)**
Trails A_Error	Real Environment	1.56	1.544	**.000**
	VR environment	2.41	1.949	**.003**
Trails B_Error	Real Environment	12.41	7.259	**.045**
	VR environment	15.06	7.649	.362

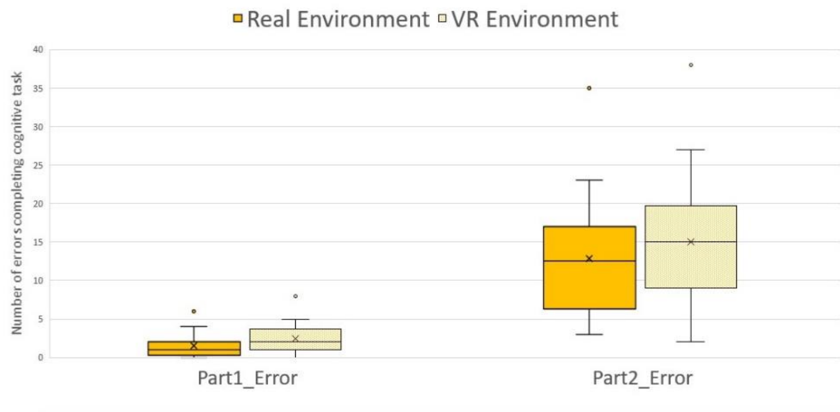


Figure 42. Box plots comparing the number of errors made by participants during the Trails A and B of the experiment in real and VR environments.

Table 23. Mann-Whitney non-parametric test for error comparison.

	Environment	Median	U-value	z.score	Effect_r	p-value (2-tails)
Trails A_Error	Real	1	380	-1.818	0.052	.069
	VR	2.41				
Trails B_Error	Real	12.5	417	-1.277	0.025	.201
	VR	15				

*p-values of ≤ 0.05, **p-values of ≤ 0.01.

In this study, the Pearson correlation coefficient was used to investigate whether there was any potential relationship between participants' MMSE scores, the time taken by participants to complete the cognitive task, and the number of errors made by them during the task completion.

The results revealed a significant ($p \leq 0.000$) negative correlation between the MMSE scores and the time for completing the Trails A of the test in real and VR environments. The Pearson correlation test results also showed there was a significant (p=0.033) effect of MMSE scores on the time required for the Trails B of the test in the VR environment. The findings indicated that individuals with higher MMSE score tests took significantly less time to complete Trails A of the test in both real and VR environments, as well as the Trails B of the test in the VR environment (Table 24).

The findings from the Pearson correlation test also show a significant negative relationship between MMSE scores and the number of errors made by participants in both the real and virtual reality (VR) environment. Participants with higher MMSE scores had fewer errors on the test in both environments with p-values of 0.000, 0.002, 0.000, and 0.000 for the Trails A and B of the test, respectively (Table

25).

Table 24. t-test results for the effect of MMSE scores on time required for cognitive task completion.

	Pearson Correlation	p-value	N
Trails A_Time (Real)	**-.810****	.000	32
Trails A _Time (VR)	-.333	.063	32
Trails B_Time (Real)	**-.747****	.000	32
Trails B_Time (VR)	**-.379***	0.033	32

Table 25. t-test results for the effect of MMSE scores on the number of errors made by participants.

	Pearson Correlation	p-value	N
Trails A _Error (Real)	**-.628****	.000	32
Trails A _ Error (VR)	**-.635****	.000	32
Trails B _ Error (Real)	**-.536****	.002	32
Trails B _ Error (VR)	**.550****	.001	32

*. Correlation is significant at the 0.05 level (2-tailed).

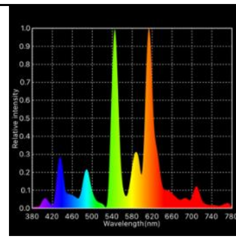
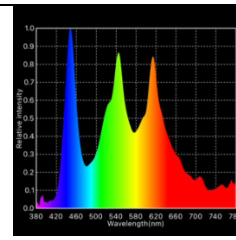
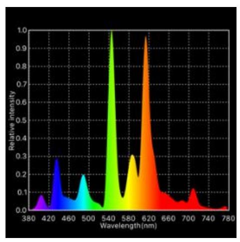
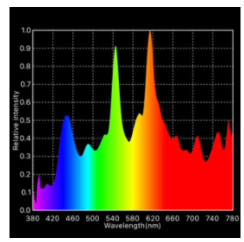
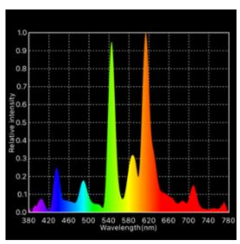
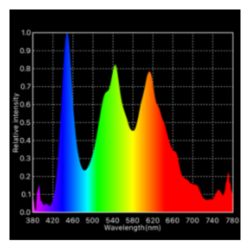
**. Correlation is significant at the 0.01 level (2-tailed).

5.6.4. Light intensity, spectral power distribution, and CCT

Although the final HDRI image used in the VR environment was calibrated and tone mapped precisely according to the real environment condition, we also wanted to monitor and compare the light intensity and light spectrum received at eye level in both the real and VR scenes during the test experiment. The Lighting Passport Essence Pro Spectrometer was mounted to the right part of the participant's head at a height of 1.02 m and measured the light intensity and spectrum in different locations of the room. The device was then used to read the same information in the same direction of the scene from the inside right eye of Oculus Rift S, in a completely dark environment. This procedure was conducted to verify that the lighting condition in the VR display represents a similar lighting condition as the real environment lighting condition in terms of light intensity and light spectrum.

Table 26 shows the comparison between light intensity, wavelength, CCT, and spectral power distribution between the real environment and the VR environment. The comparison of light intensity and color temperature (CCT) measurements between real and VR environments reveals a negligible distinction, while the spectral power distribution demonstrates measurable variances. The VR headset's screen consistently exhibits peaks at 455nm, 545nm, and 610nm, regardless of the camera's positioning, while real lighting condition shows peaks at 545 nm and 610 nm. In all three camera positions, it shows higher spectral power in the VR headset than in the real environment.

Table 26. Measurements were captured in both the real space and VR environment.

Light intensity, Wavelength, CCT	**Lighting Passport Essence Pro Spectrometer location**	**Spectral Power Distribution in the Real Environment**	**Spectral Power Distribution in the VR Environment**	**Spectral Power Distribution in the VR Environment**
Illuminance= 193 lux λp= 614 nm CCT= 3142 K			Illuminance= 215 lux λp= 448 nm CCT=3150K	
Illuminance= 89 lux λp= 545 nm CCT= 3210 K			Illuminance= 101 lux λp= 614 nm CCT=3008 K	
Illuminance= 34 lux λp= 614 nm CCT= 3017 K			Illuminance=17 lux λp= 448 nm CCT= 3012 K	

5.7. Discussion

The finding of this study revealed that for questions regarding pleasantness and comfort, there was no significant difference between the real environment and the VR environment. However, questions regarding excitement, stress, and confusion showed a significant difference between the real and VR environment. Despite experiencing higher levels of excitement, stress, and confusion in the VR environment, no significant variations were found in cognitive performance including the amount of time they spent completing the task and the number of errors between the real and VR environment.

It also needs to be noted that even though there was no significant difference in cognitive performance between real and VR environments, the average time required for completing the cognitive test and the average number of errors were both higher in the VR environment. It might be attributed to the participant's unfamiliarity with VR technology and issues related to working with the controllers. This study's results indicate that participants' visual abilities can affect their stress and confusion levels in the real environment, as well as their excitement in the VR environment. However, their gender does not have an impact on their responses to the subjective perceptual questions. We also used the Pearson correlation test to investigate the correlation between MMSE test scores and the cognitive performance of the participants. Our findings revealed a significant correlation between MMSE scores and both the duration of the test and the number of errors in all conditions, except for Trail A of the test in the virtual reality environment.

Although image processing and tone mapping helped to provide a more similar light intensity in the VR environment, there is still a discrepancy in spectral power distribution between real and VR environments. The measurements inside the lens of Oculus show a higher spectral power with consistent peaks at 455nm, 545nm, and 610nm while the real environments measurement shows lower spectral power with peaks at 545 nm and 610 nm. All these observations highlight the importance of further investigation into tone mapping and image processing techniques for HDRI images in VR, to improve perceptual accuracy.

5.7.1. Limitations

Virtual reality in design provides a great opportunity to evaluate the effectiveness of design strategies before their construction, and it also enables comparative testing which is not feasible to conduct in the real environment. However, there are some limitations in the use of VR in studies, especially in studies related to lighting and its relationship with human behavioral outcomes. Firstly, using HDRI images in a VR headset has some limitations in terms of lighting quality and quantity, and may not be able to exactly replicate the same lighting condition as a real environment. When using a calibrated and tone-mapped HDRI image in a VR environment, the resulting color and light intensity may closely replicate those of the real environment. However, this method has some limitations in accurately reproducing the same spectral power distribution of light. This limitation might be addressed by creating the lighting scene in 3D modeling software such as 3Ds Max and Unreal

Engine and incorporating real-world lighting fixtures. Secondly, the limited field of view of the VR headset may impact the visual acuity, which is a critical aspect in conducting the Trail Making test. Furthermore, some features of the VR environment, such as the absence of noise and visual distraction, may have a positive impact on participants' performance in comparison to the real environment. Another limitation of this study was that participants in the VR test had a 5-minute tutorial session to become more familiar with the VR system before their actual test, which could have potentially improved their performance compared to a real environment where had no prior experience with the task.

Designers and researchers who are using virtual reality environments in the area of lighting design need to be aware of these limitations and use caution if they are investigating the impact of quantitative attributes of light such as light intensity, chromaticity, and spectral power distribution. Future work is needed to seek innovative methods for replicating and representing the same spectral power distribution of the real-life lighting condition in the VR environment. It is also important to explore the impact of different lighting variables including lighting spatial patterns and color of light on the cognitive performance of older adults in the VR environment to assess if using a VR environment could be a successful strategy in studies investigating the impact of qualitative and quantitative attributes of lighting on human cognitive performance.

5.8. Conclusion

The findings of this study reveal that the VR environment can serve as a viable alternative to real-world lighting conditions when assessing cognitive performance and subjective perception among older adults. Despite older adult participants experiencing higher levels of excitement, stress, and confusion in the VR environment compared to the real environment, their cognitive performance did not exhibit significant differences between the two environments.

Importantly, this research demonstrates the feasibility and validity of converting a 3D cognitive test from a real-world format to a 3D virtual reality (VR) format, without compromising the essential features of the test or affecting its evaluation. These results build upon the work of Plotnik et al. (2021), who demonstrated the feasibility and validity of using VR-based neuropsychological tests to evaluate participants' cognitive-motor interactions. Plotnik et al.'s study reported significantly higher completion times and a greater number of errors on the VR-based version of Trails A and Trails B compared to the real environment. In contrast, although the current study observed higher mean completion times and error rates in the VR environments, these differences did not reach statistical significance.

CHAPTER 6: INVESTIGATING THE IMPACT OF SPATIAL PATTERNS AND COLOR OF LIGHT ON THE COGNITIVE PERFORMANCE OF OLDER ADULTS_ IN AN IMMERSIVE VIRTUAL ENVIRONMENT

This paper is being prepared to be submitted to the <u>*Journal of Environment and Behavior*</u>*. Co-authored material (with Professor Ihab Elzeyadi and Professor Margaret Sereno). The excerpt to be included was written by me, with my coauthors contributing to the development of the structure of the paper, assisted with the methods and measurements verifications, stimuli design, data analysis methods, interpretations of the findings, and the discussion sections. They provided editorial review and feedback on the manuscript as well.*

This Chapter reports on the results of a within-subjects design conducted in a Virtual Reality (VR) environment to investigate the impact of different spatial patterns and color of light on the cognitive performance of older adults. Four experimental settings were created in the virtual reality version of an assisted living facility living room using two different correlated color temperatures (2700 k and 5000 k) and two spatial patterns of light (least stressful: non-uniform, peripheral, direct/indirect and most clear: uniform, central, direct)
This study builds upon a previous within-subjects experiment where the 32 participants completed a series of cognitive tasks in both real and virtual reality environments. In this study, the same 32 residents will complete a cognitive task and questionnaire in four different lighting conditions in VR.

Human-centric light is a new approach in lighting design, which focuses not only on the visual impact of light, but also on its non-visual aspects that influence circadian rhythms, sleep, mood, and cognitive performance. While an increasing body of knowledge exists on indoor lighting for older adults for improving their circadian rhythm, sleep quality, stress, mood, and behavior, there is a lack of integrated and consistent resources in the literature which investigate the role of lighting conditions on the cognitive performance of elderly people. Furthermore, these studies have mainly focused on some quantitative attributes of light such as light level and temporal pattern while other attributes of light such as spatial patterns of light and light spectrum have been neglected in these studies. Research suggests that a higher level of lighting, task lighting, and visual cues can increase clarity and contrast, reduce fall risk, and improve postural orientation and mobility. While previous studies have focused on the impact of light level and temporal pattern in human-centric lighting, the impact of light spectrum and spatial pattern has not been fully addressed. Thus, further studies are needed to establish more comprehensive human-centric lighting design guidelines in senior living facilities. The questions to be answered in this paper are: (1) Is there a difference in the subjective perception of older adults under different spatial patterns and correlated color temperature (CCT) of light? (2) Do spatial patterns and color of light impact the cognitive performance of older adults?

6.1. Introduction

The aging population is growing very fast in the US. Today, about one in every seven Americans is over the age of 65, and by 2040 that number will swell to one in five (Gabriel, 2018). In 2017, 13% of the world's population are people aged 60 or more and by 2050 the number of people aged 80 or more will triple (425 million), this number will increase seven times by 2100 (909 million) (UN 2017).

Age-related impairment in the human body causes a lot of problems in the daily life of elderly people such as falls and injuries, becoming lost and wandering, sleep disorders, anxiety, depression, agitation, stress, etc (Shikder et al., 2012; Chien et al., 2020).

Older adults with increasing age encounter many age-related visual impairments: gradual decrease in accommodation, less sensitivity to blue light and yellowing pigmentation in their lens shrinking eye pupils, light scatter, and absorption within the eye. In addition to these impairments, eye diseases such as macular degeneration (AMD), cataracts, and glaucoma are also more prevalent in Older Adults because of pathological transformation in their visual system (Boyce, 2014). Diabetic retinopathy is also another eye disease that can affect the visual condition of the aging population (Sturnieks et al, 2008). Age-related visual impairment can affect spatial contrast sensitivity, prolonged dark adaptation, and decreased visual processing speed. Aging eyes can affect the visual condition and increase physical problems, for example, elderly people with visual impairment cannot see clearly under low illumination or at night and it can increase the fall and injuries in this aging group. On the other hand, they need more time to adapt to a dark environment in comparison to younger people, especially in transitions from outside to inside which is an important threat to their safety (Oweley, 2016). These ophthalmological changes and impairments can also decrease contrast sensitivity, reduce visual acuity, decline visual field and minimize color perception (Sturnieks, et al, 2008). Aging populations also suffer from a reduction in their visual field which means they can just see a portion of the environment around them, and it can bring a lot of problems in their tasks. Yellowing in the eye is another problem that can impact elderly people's color discrimination. On the other hand, as older adults might have more absorption and scatter in their eyes, they would require more lighting to do the same task that other aging groups do with a lower light level. One other factor that plays an important role in the vision condition of elderly people is glare. Although glare can create discomfort for all age groups, it takes more time for elderly people to recover from the glare effect which can impact their efficiency and activation (Sinoo et al., 2010).

In addition to visual impairment, aging eyes cause nonvisual impairment in elderly people. Studies have shown increasing age is associated with a reduction in neural activity in suprachiasmatic nuclei (SCN) in the elderly, especially after the age of 80, and a reduction in circadian rhythm amplitude after the age of 50 (Hofman and Swaab, 2006). These deficiencies in the biological clock and circadian rhythm in the aging population can increase their sleep time during the day and wakefulness during the night which is a significant symptom of the insufficiency of sleep/wake rhythm in elderly AD patients. This disorder not only increases stress and agitation among elderlies but also affects the cognitive functions of the patients which is one of the main reasons for caregiver distress in assisted living facilities (Bliwise, 1993; Tsuzuki et al, 2015; Singer et al, 2003).

These challenges often lead to behavioral impairment in elderly people that result in unmanageable risks at home or a danger to the individual. This is the point at which the elderly is forced to move to assisted living facilities or other elderly living settings. Design decisions and strategies of the built environment can slow down and even prevent many of these negative outcomes. Knez (1995) argues that different attributes of the natural and artificial environment may influence different moods and cognitive processes in humans. Studies have shown that design characteristics of healthcare environments might directly affect the residents' quality of life and health outcomes (Gasio et al., 2003; Sun& Gu, 2008; Hygge, 2001). Lighting quantity and quality are two main important attributes of the built environment affecting elderly health and well-being and have recently attracted the attention of healthcare designers and architects. Human-centric lighting design is a new approach to lighting that addresses both visual and non-visual aspects of light and plays a critical role in the health and well-being of the aging population. Houser et al., (2020) have defined four main categories of lighting variables that contribute independently to designing lighting systems for the built environment: Temporal pattern (i.e., the timing and duration of exposure), light level (i.e., the quantity of light in radiometric and photometric units), light spectrum (SPD) (i.e., spectral power distribution that governs color quality) and spatial patterns (i.e., the luminance distribution of the three-dimensional light field) (Figure 43).

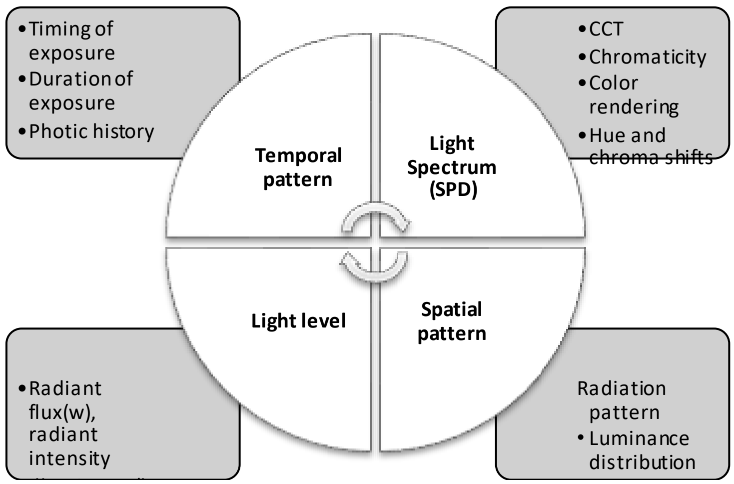


Figure 43. A schematic of the lighting variables impacts Cognitive performance as one of the non-visual responses to light (based on a schematic representation by Houser et al. (2020)

Existing studies in the field of human-centric lighting for elderly people have mainly focused on quantitative attributes of light such as light level (Sinoo, 2010; Figuerio, 2011) and temporal patterns of light (Gasio et al., 2003; Figueiro, 2008), while there are not enough studies showing a systematic relationship between spatial pattern, luminance distribution, and light spectrum with nonvisual outcomes of elderlies (Knez & Kers 2000; Riemersma et al, 2008; Yamadera, et al,2000). A vast majority of gerontology studies have addressed the visual impacts of indoor lighting on wayfinding, mobility, and task performance, while there is a significant gap in understanding the impact of indoor lighting on the cognitive performance of elderly people. Thus, further studies are needed to establish more comprehensive human-centric lighting design guidelines in senior living facilities. The current research project aimed to address the gap by developing an efficient evaluation approach that can be used during the design development process to assess and optimize particular lighting design characteristics in senior living facilities. The goal was to evaluate the impact of different spatial patterns and CCT of light on older adults' perception and cognitive performance using an immersive virtual environment as a novel-testing method.

6.2. Overview of the related research (Flynn's Theory)

In the 1970s, John Flynn published a series of articles (Flynn & JE,1977; Flynn et al., 1979; Flynn et al., 1973); conducting fundamental research about the role of the distribution of light and resulting patterns of the light on human subjective impressions. Flynn defined four main lighting modes in space, which make various impressions on humans. These four lighting modes are the basic attributes that designers consider when they are creating an environment for different purposes: bright/dim, uniform/non-uniform, central / perimeter, and warm/cool. Flynn particularly examined how different "lighting modes" affects spaciousness/confinement, visual clarity/haziness, relaxation/activation, and private/ public.

6.2.1. Spatial patterns (Uniformity, Centrality, Direction)

The existing literature on the spatial pattern of light has primarily concentrated on examining the association between light control parameters and its spatial distribution, and how this affects human outcomes. Flynn et al (1973) defined six different light arrangements which had their specific uniformity, centrality, and brightness value so that each arrangement corresponded to a specific point in a dimensional space of the different lighting characteristics. The results of this study indicated that there is a significant difference in human subjective impression between different lighting arrangements. This section provides a comprehensive review and discussion of the three primary independent variables of the spatial pattern of light: spatial arrangement (uniform/non-uniform), centrality (central/perimeter), and direction of light (direct/indirect).

Light fixtures in an environment can be arranged in two different ways: uniform and non-uniform. A uniform arrangement entails placing all the lighting fixtures in a room in maximum height and uniform spacing, regardless of the location of furniture and other architectural elements to illuminate the environment at about the same level. In a non-uniform lighting system, all the fixtures are located at a high level and close to the ceiling, but with irregular spacing. The precise position of each lighting fixture depends on factors such location of the workstations and machinery and the task that will be performed in that particular area. According to Hawkes et al. (1979), the perception of light in an environment is determined by two key attributes: brightness and interest. Brightness refers to the perceived intensity of the light, whereas interest is linked to the perceived uniformity of the light. There is evidence that shows that task lighting can increase attention to desk work, which improves task performance (Rea et al.,1990). Taylor et al. (1975) found that nonuniform desktop illumination improved task performance. This study shows adults perform better in arithmetic calculations (on paper) in office spaces with nonuniform lighting in comparison to uniform fluorescent lighting or very nonuniform colored lighting. In contrast, some other studies indicate that there is no correlation between the uniformity of light and task performance. For instance, McKennan and Parry (1984) found that varying illuminance levels on a desk, based on different lighting distributions, did not have an impact on paper-based) clerical task performance across ten distinct lighting installations. Lighting design in theatres shows that areas of high luminance could help to attract the audience's attention, but there is no firm evidence to show how this mechanism can be implemented to provide appropriate conditions for different tasks in other settings (Veitch, 2001). Another study was conducted to examine the impact of the position and number of light sources on the perceived lighting atmosphere in a given space (Stokkermans et al. 2018). The position of the light sources in this study refers to their distribution, including symmetric, left-right, and front-back arrangements. According to the findings, adjacent luminaires to walls resulted in a less uniform lighting atmosphere. Castilla et al. (2018) conducted a study to evaluate the affective impressions of university students regarding the spatial patterns and luminous environments in their classrooms. Six different axes of affective impressions were identified, including surprising-amazing, clear-efficient, cheerful-colorful, uniform, intense brilliant, and warm-cozy. The results of the study showed that clear-efficient, intense-brilliant, and uniform patterns were necessary for writing and reading tasks, while warm and cozy lighting was more suitable for reflecting and discussing tasks. For paying attention to tasks, lighting that generated clear and efficient, uniform, and surprising-amazing atmospheres was found to be the most effective. There are also other studies exploring the impact of spatial arrangement and uniformity on human perception, behavior, and preference (Flynn et al.,1973; Flynn et al, 1979; Chraibi, et al., 2017; Stokkermans et al., 2018). Flynn et al. (1973) and Flynn et al. (1979) showed that uniformity in the spatial pattern of light increases clarity in space, while non-uniformity contributes to more relaxing feelings. Yao et al. (2017) who have argued that uniformity is a critical attribute of indoor lighting in work efficiency and comfort, have investigated different methods for evaluating uniformity of light in space. These methods include (Min: Avg), the coefficient of variance (CV), entropy uniformity (EU, introduced in the article), and a pattern vision-based indicator (U_{HVS}). The available literature suggests that the illuminance distribution in each environment can effectively direct attention and impact both visual and non-visual performance. However, there is currently no integrated evidence to support the notion that uniform or non-uniform lighting can significantly influence the perception, preference, and cognitive performance of older adults.

Light sources in a space can be arranged to emphasize horizontal surfaces (central, overhead), or vertical surfaces (perimeter). Flynn et al. (1973) revealed that in addition to light intensity (dim – bright dimension of light) and interest (uniform and non-uniform dimension of light), there is another factor that impacts the perception of light in a space, namely peripheral – overhead. Flynn showed central arrangement with higher light levels on horizontal surfaces such as a work plane provides more visual clarity, and uniform peripheral lighting makes the space more spacious, while peripheral non-uniform lighting is more helpful in increasing relaxation and privacy (Flynn et al., 1973; Flynn et al., 1979). In another study, the impact of the different spatial patterns of light in university classrooms on students' performance was examined. The results showed that each pattern of light (central or peripheral) should be modified according to the specific task taking place in the class (Castilla et al, 2018).

A fixture can be designed to focus light in one of the following ways: direct lighting, semi-direct lighting, general lighting, semi-indirect lighting, and indirect lighting.

Based on research, people prefer indirect lighting over systems providing direct lighting (Veitch et al., 2008;). Yearout & Konz (1989) found that indirect lighting is more favorable than direct lighting among participants doing tasks in the workstation. Operators also prefer brighter illumination in office space and spotlight on walls. Additionally, Katzev (1992) found that office employees prefer direct/indirect lighting more than other lighting systems, while there were no significant differences between participants' performance in cognitive/intellectual tasks. A recent study examined the impact of direct and indirect light on the health, well-being, and cognitive performance of office workers. The findings demonstrate there is no significant correlation between direct or indirect lighting and cognitive performance, except for a relationship between direct lighting and reduced job stress severity (Fostervold & Nersveen, 2008). A study by Hedge et al. (1995) examined the impact of light direction on office workers' satisfaction, visual health, and productivity. The findings showed that satisfaction and other subjective lighting rates were higher in an indirect lighting system, while the direction of light had a lesser impact on productivity. Another study that investigated the impact of lighting positioning in workstations has found that two different spatial patterns (vary in terms of number, direction, and position of the light) resulted in a different visual experience without impacting the users' performance. The study suggests that a combination of direct and indirect light is more favorable for the users, and they also preferred a non-uniform spotlight on wall painting (Yearout & Konz, 1989).

In the previous study by the authors (under review), Flynn’s theory has been expanded to investigate the impact of spatial lighting patterns on older adults’ perceptions and preferences. According to Flynn’s theory of lighting and mood in the 1970s, we defined 6 main spatial patterns of light that contribute to humans’ moods and preferences. These 6 spatial patterns of light were created according to three main attributes including Spatial arrangement (uniform/non-uniform), centrality (central/perimeter), and direction. The result of this study suggested that Pattern_1 (uniform, central, and direct) provides a clearer lighting scene, while pattern_2 (Nonuniform, peripheral, Direct/indirect) contributes to a more relaxed impression in the lighting environment (Figure 44). In this paper, we will implement these two highly promising patterns that potentially can impact the cognitive performance of older adults.

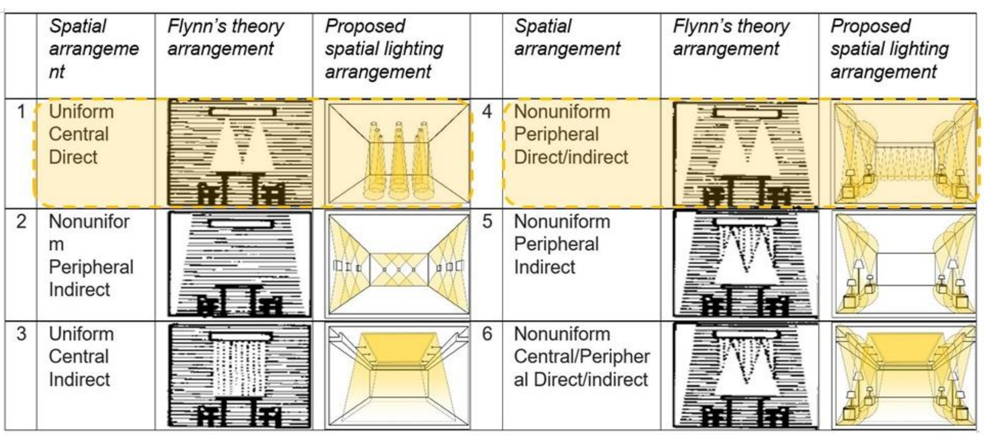


Figure 44. The six spatial light patterns were tested in the previous study, with selected patterns highlighted.

6.2.2. Correlated color temperature (Warm/Cool)

The correlated color temperature (CCT) of polychromatic light is associated with the light spectrum and it increases when the light contains more power in the blue part of the spectrum. According to the study by Flynn and Spencer (1977), the color of the light source can have an impact on users' impressions and satisfaction. The researchers conducted an experiment where they varied the color of the light source and asked participants to rate their impression of the light quality and overall satisfaction with the lighting. The results showed that participants' impressions of the light quality were affected by the color of the light source, with warmer colors (e.g., reddish-orange) receiving more favorable ratings than cooler colors (e.g., bluish-white). Additionally, participants reported greater satisfaction with the lighting when the light source was warmer in color (Flynn & Spencer, 1977).

Studies investigating the impact of the light spectrum on visual outcomes have mainly focused on the wavelength and CCT of light. Martin et al. (2018) found there is no relationship between spectrum wavelength and frequency of falls in elderly people. Ellis et al. (2013) showed that full diurnal changing color spectrum and light intensity not only enhance psychological outcomes but also improve limited mobility. Yamagishi et al. (2008), Janosik & Marczak, (2016), Cheng et al. (2016), and Wang et al. (2020) findings revealed that elderlies perform better under CCT 5000, 6500, 6000, and 6500 K respectively, while Geerdinck et al. (2009) showed there is no relationship between CCT and visual acuity and task performance. While the spectral response of the visual system is more sensitive to higher wavelengths (555nm, yellow-green light), the spectral response of the ipRGCs has a higher sensitivity to short light wavelength with a peak at approximately 490nm (blue light) (Corbett et al., 2012). Studies have shown both monochromatic short-wavelength light and blue-enriched polychromatic light is more effective than longer wavelengths of light at suppressing melatonin (Brainard et al., 2001), regulating the circadian clock (Gooley et al., 2010; Revell et al., 2005), and enhancing alerting effects and cognitive function (Chellappa et al., 2011; Cajochen et al., 2005; Vandewalle et al., 2007). Several studies have examined the impact of CCT on the mood and behavior of older adults. Kuijsters (2015) suggested that cozy ambient lighting with lower CCT (2700 k) and lower illuminance (120 lux) can effectively reduce a highly arousing negative mood state, specifically anxiety, than the neutral ambiance (3400k, 150 lux). Conversely, activating ambient lighting with higher CCT (4000k) and higher illuminance (325 lux) increases the physiological arousal of sad elderly individuals more than the neutral ambiance. Another study conducted by Hopkins, S (2017) revealed contrasting results, revealing that blue-enriched light with a CCT of 17000 K can enhance daytime activity and reduce anxiety in older individuals. The result of this study also highlighted the negative impact of high-CCT light on nighttime activity, sleep efficiency, and sleep quality when compared to light with a CCT of 4000 K. Another study by van Hoof. j (2009) indicated that there is no difference between 17000k and 2700k at prolonged exposure to low-intensity light, i.e., E < 500 lux. This finding suggests that higher illuminance levels play a more important role than the color temperature in improving the circadian rhythm and behavior of elderly individuals.

Studies investigating light spectrum effects on cognitive performance also reveal divergent outcomes. While some studies argue that long-wavelength maintain subjective alertness and improve cognitive performance (Papamichaelet al., 2012), others indicate that older adults can perform better in cognitive tasks under cool white lighting with lower wavelengths (Knez & Kers, 2000). Although higher CCT has a positive impact on sustained attention and subjective measurement of performance (Keis et al., 2014), the specific advantage of CCT on cognitive performance remains uncertain. These contrasting findings emphasize the need for further investigation and a comprehensive understanding of the impact of color temperature and its effects on the well-being of older adults. In this paper, we will implement two warm (2700K) and cool (5000K) lighting modes according to the literature, to investigate the impact of correlated color temperature on older adults' cognitive performance.

6.3. The Conceptual model

To understand how light in an environment can impact the human's cognitive performance we first need to define how visual sensory information can be interpreted and perceived by the human brain. José E. Capó-Aponte and his colleagues in a study argue that" Visual Perception is defined as the mental organization and interpretation of the "visual sensory information with the intent of attaining awareness and understanding of the local environment, e.g., objects and events" They also mentioned that "Cognition refers to the faculty for the human-like processing of this information and application of previously acquired knowledge (i.e., memory) to build understanding and initiate responses. González-Casillas, A., et al (2018) also argue that "Visual processing involves mechanisms to generate internal abstract representations, by applying multiple transformations to the light of environmental objects that reaches photoreceptors in the eye" while "Recognition refers to giving a meaning to such representations, regardless of simplicity, and it is shaped by the current sensory".

This study conceptualizes the relationship between visual perception and cognitive performance from a systemic epistemological perspective. This model hypothesizes that human cognitive performance is impacted by sensory visual processing and perception. This is where spatial vision meets spatial cognition. Spatial vision performance refers to the collaboration between the eye and the brain for encoding and representing spatial patterns of light. Studies have shown that changes in spatial vision can impact human spatial cognition (Collin et al, 2004; Ruiz-Soler & Beltran, 2006; Collin, 2006, González-Casillas, et al, 2018) (Figure 45).

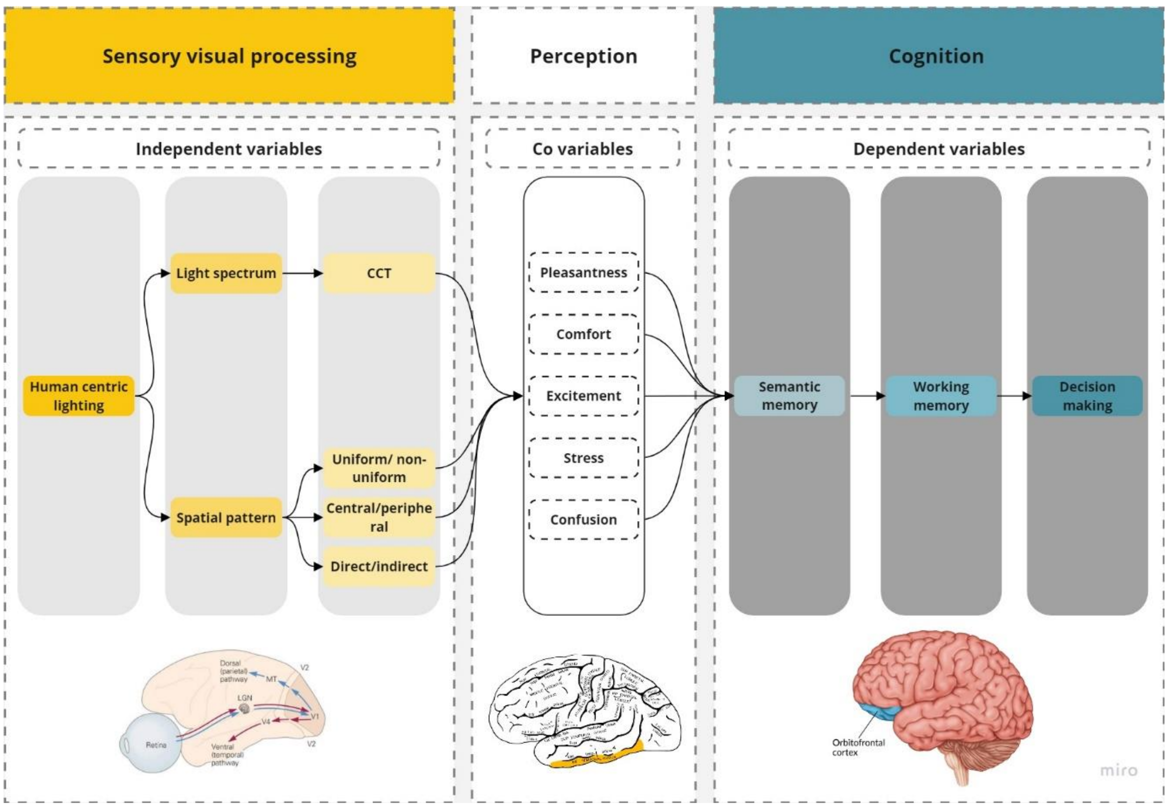


Figure 45. Cognitive performance as the main dependent variable of the study is impacted by sensory visual processing and perception in the human eye and brain. The list of variables influencing cognitive performance is meant to highlight the main variables involved in the current study.

6.4. Methods

6.4.1. Facility design condition

The VR testing environment was based on an actual assisted living facility in Springfield, OR. The living room of this facility was selected to be used in the study, and design details of that portion of the facility were modeled and imported into our virtual testing platform.

Based on existing literature and a previous study conducted by the authors (under review) we employed a 2×2 factorial design (Stampfer et al., 1985), to establish four unique lighting conditions, encompassing two levels of CCTs and spatial patterns. In the initial step of the experiment during the first week, participants were randomly assigned to two lighting conditions, namely A_1 and A_2. Subsequently, in the following week, they were assigned to another two lighting conditions, B_1 and B_2, to conduct cognitive tests within a virtual reality (VR) environment. Figure 46 shows the 2×2 factorial design matrix.

Step 1: Spatial pattern_1 with two different CCTs. The choice of selected spatial pattern for our experiment was derived from a previous study conducted by the author (under review), which focused on examining how spatial lighting patterns influence the perceptions and preferences of older adults. This spatial pattern was chosen due to its clarity and representation of the existing spatial patterns observed in assisted living facilities.

- **Condition A_1**: Existing spatial pattern (Uniform, central, direct) with a CCT of 2700K. The selected correlated color temperature of 2700 was based on existing literature that investigated the impact of warm color on human visual perception, behavior, and performance (Van Hoof et al., 2009; Janosik & Marczak, 2016; Geerdink et al., 2016).
- **Condition A_2**: Existing spatial pattern (Uniform, central, direct) with a CCT of 5000k. The selected correlated color temperature of 5000 was based on existing literature that investigated the impact of cool color on human visual perception, behavior, and performance (Yamagishi, et al, 2008; Sinoo et al, 2011, Sinoo, 2016)

Step 2: Spatial pattern_2 with two different CCTs. The selection of the spatial pattern for our study was guided by a previous investigation conducted by the author (under review), which specifically explored the effects of spatial lighting patterns on the perceptions and preferences of older adults. Among the various options considered, this spatial pattern was chosen as it was found to evoke the highest degree of relaxation among participants.

- **Condition B_1**: Spatial pattern_2(Nonuniform, peripheral, direct/indirect) with a CCT of 2700K.
- **Condition B_2**: Spatial pattern_2 (Nonuniform, peripheral, direct/indirect) with a CCT of 5000K.

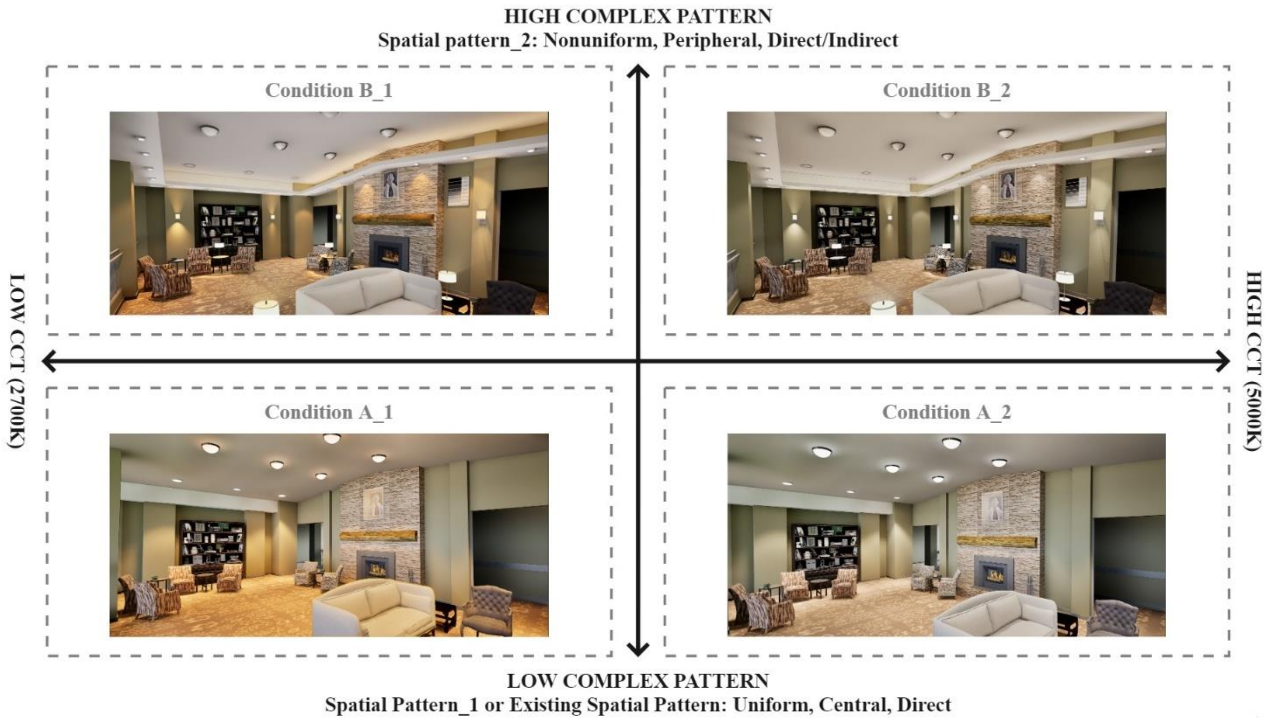


Figure 46. 2x2 factorial design matrix depicting independent variables: spatial pattern and CCTs with two levels each.

6.4.2. Hypotheses

In this study, participants were assigned to two sets of lighting design conditions in two different steps, including conditions A_1, A_2, B_1, and B_2. They were asked to complete a cognitive task in a virtual reality (VR) environment while self-reported subjective perceptual data were collected synchronously. The collected data were statistically compared between two design conditions within each step, to assess the following hypothesis: First, it was hypothesized that lighting conditions with low complex pattern and higher CCT are more beneficial in improving cognitive performance; second, it was expected that lighting condition with high complex pattern and lower CCT can contribute to a better mood and perception in older adults.

6.4.3. Virtual reality development

The virtually assisted living facility’s living room was developed by importing architectural design documents into Epic Games' Unreal Engine (www.epicgames.com). The Autodesk 3d Max (www.autodesk.com) was used as the primary software tool in the creation process for modeling and UV-mapping tasks. The lighting environment design in terms of incorporating lighting fixtures, and adjusting light intensities was conducted in 3Ds Max and then imported to Unreal Engine. The main independent variables including the color temperature, and spatial patterns of light were designed and modified in Unreal Engine. This decision helped us to improve consistency across various design conditions. To maintain consistent light intensity across all four lighting conditions, a two-step approach was employed. Firstly, the Vray Lighting Analysis element in 3ds Max was utilized to measure the light intensity in lux on a designated horizontal surface within the room for each lighting condition. Subsequently, in the Unreal scene, a grayscale card containing eight distinct gray cards was utilized to visually compare the appearance of the cards under the four different lighting conditions. This ensured an accurate and reliable assessment of light intensity consistency within the virtual environment (figure 47)

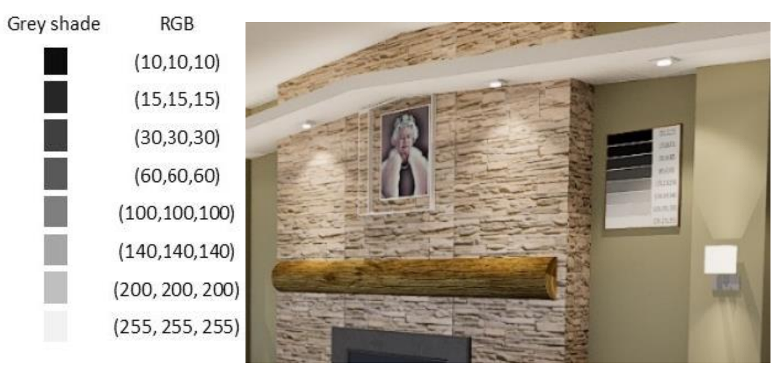


Figure 47. grayscale card containing eight distinct grays mounted on the wall of the test room in the VR environment

This study used the Blueprint scripting feature in the Unreal engine to design the interactive cognitive task in a virtual testing environment (the detail of the cognitive task will be discussed in the next section). The height for the camera was set at 1.02 cm (average human eye height in a seated position), while the participants can change the angle by looking around and rotating their heads. The Oculus Rift S was used in this study based on advances in pixel resolution (2560×1440), the field of view (115º), and "next generation" lens technology that almost eliminates god rays. The Rift S uses a DisplayPort 1.2 port and one USB 3.0 port, as opposed to the HDMI and USB 3.0 port used on the Rift CV (Wikipedia contributors, 2021). A Core ™ i7 computer with two 2.50 GHz possessors and 1 NVIDIA GeForce RTX 3070 card was used along with Unreal Engine software to display the final immersive 360º environment. The interactive widget was designed and implemented as Likert scale questions to collect the self-reported perceptual data directly in the VR environment.

6.4.4. Cognitive Tasks (Trail Making Test (TMT))

The Trail Making Test is a neuropsychological test of visual attention and task switching. It consists of different parts in which the subject is asked to mark and connect numbers and letters in a meaningful order as quickly as possible while trying to keep accuracy. This test can evaluate visual search speed, scanning, speed of processing, mental flexibility, as well as executive functioning (Arnett, J. A., & Labovitz, S. S., 1995). For this experiment, we have designed a visual navigational-cognitive task that has been inspired by Trail making test. Plotnik et al., (2021) showed that the result of a three-dimensional VR-based format of Trail making test is feasible and valid as the two-dimensional pencil-and-paper format. According to the previous study conducted by authors (under review) we found that VR environment can be a suitable alternative for real-world lighting conditions when evaluating the cognitive performance and subjective perception of older adults. The results of this study revealed that the VR version of the trail-making test can be a valid and feasible substitute for the 3D format in the real-world environment. It will help to replicate the test in the VR environment without losing the primary features of the lighting scene or impacting the cognitive test results (Figure 48)

Figure 48. Participants conducted the cognitive Trail Making Test in both the real environment and virtual reality (VR) environment in the previous study by authors (under review)

In the VR version of the Trail Making Test (TMT), the two-dimensional (2D) page is replaced by a three-dimensional (3D) VR space. This test consists of two Trails and both Trails include 25 balloons distributed over a 3D environment. In Trail A, 25 target balls are distributed in a 3d space in the real environment or VR environment, and the participants should select the balloons in ascending order. In Trails B, the balloons include both numbers (1-13) and the letter (A-L); as in Trails A, the participants connect the balls in an ascending pattern, with the added task of alternating between the numbers and letters (i.e., 1-A-2-B-3-C, etc.). In this study, we exclusively utilized Trails B of the test due to its greater efficiency in assessing executive functioning, attention speed, visual search, and motor function (Dobbs, B. M., & Shergill, S. S.,2013). Additionally, it requires less time to complete compared to both trials. The evaluation of the results is based on the time taken for completion and the number of errors made. Hence, higher scores indicate a greater degree of impairment.

6.4.5. Participants

The study participants provided informed written consent before participating, and the study protocol received approval from the Institutional Review Board at the University of Oregon. A priori analysis was conducted using G*Power (Version 3.1.9.7.) to determine the required sample size for this study. Based on an effect size of dz = 0.50, a significance level of 0.05, and a power of 0.95, a sample size of 30 participants was determined to be necessary. This study represents a continuation of our previous research, focusing on the comparison between real and virtual reality (VR) environments (under review). For participant recruitment, we included the same group of 32 older residents from the facility who had participated in the previous study. By including the same participants, we aimed to maintain consistency and facilitate direct comparisons between their experiences in both environments.

A total number of 37 residents were interested in participating in the study. Only 32 (17 female, 15 male) were eligible to participate in the experiment according to their mental, physical, and visual condition. This paper employed a within-subject study design involving 32 participants who were tasked with completing a cognitive test under a 2x2 factorial design. The first week consisted of two lighting design conditions, namely Condition A_1, and A_2, while the second week comprised two different lighting design conditions, specifically Condition B_1 and B_2. The age range of the participants in this study spans from 62 to 84 years old (*M* = 72.59, *SD* = 6.420). As reported by the participants at the time of the experiment, 18 participants were wearing glasses and 14 were not. Participants were encouraged to wear their glasses inside the VR HMD while conducting the cognitive task.

6.4.6. Procedure

The experiment sessions were conducted in the living room of a senior living facility in Springfield, OR, which served as research setting for our previous related studies. Thirty-two participants who met the criteria for visual conditions, general health-- assessed using the 12-item Short Form Survey (SF-12), cognitive performance (measured by MMSE scores), and had participated in the previous phase of the experiment, were informed about their two scheduled appointments. They were asked to reach out to the researcher if they had any questions. The first appointment was scheduled for the next day, and the second appointment was scheduled for the following week. In the first week experiment, 32 participants were randomly assigned to two separate groups; Group 1: includes 16 participants who were assigned to conduct the cognitive test in condition A_1 first and then were assigned to condition A_2, while the 16 other participants in the second group started to conduct the test in the A_2 and then were assigned to A_1 condition. Upon entering the living room of the facility, participants were instructed to take a seat on the rotating chair at the test station. (Figure 49). The researcher then explained the Trails B of the Trail Making Test (TMT) procedure. Before starting the test, participants were instructed to sit quietly with their eyes closed for a duration of 1 minute. Due to the participants' prior completion of the test in the previous phase of the study and their existing familiarity with the virtual reality (VR) environment, the tutorial session was excluded from this phase of the study. In the second week experiment, 32 participants were randomly assigned to two separate groups; Group 1: includes 16 participants who were assigned to conduct the cognitive test in condition B_1 first and then were assigned to condition B_2, while the 16 other participants in the second group started to conduct the test in the B_2 and then were assigned to B_1 condition. The experimental procedure and duration for each step are shown in Table 27.

Figure 49. Participants in the test station conducting the cognitive test in the VR environment.

Table 27. Experiment with detailed procedure and duration in weeks 1 and 2

Time progress in minutes	Activity	Duration in minutes
This took place in the previous phase of the experiment	Signing the consent, demographic questionnaire, visual condition, 12-item Short Form Survey (SF-12), MMSE test	15
0-3	Welcoming and explanation, 1-minute relaxation	3
3-13	Participants in the group1 complete the cognitive task under A-1 in week 1 and B-1 in week 2 Participants in group 2 complete the cognitive task under A-2 in week 1 and B-2 in week 2	10
13-18	Participant rest outside the experiment room and the experimenter prepare the VR environment for the second lighting condition	5
18-28	Participants in the group1 complete the cognitive task under A-2 in week 1 and B-2 in week 2 Participants in group 2 complete the cognitive task under A-1 in week1 and B-1 in week 2	10
28-30	The end of the experiment. The participant will be thanked for their time, led to the door, and told they are free to leave	2

6.4.7. Data collection

In this study, we collected three sets of data including demographic and health information, cognitive task performance, and self-reported perceptual data. For demographic information, participants were requested to complete a Qualtrics survey to provide details regarding their age, gender, and visual condition. Health condition data were collected using the 12-item Short Form Survey (SF-12) and the MMSE test. To collect data on cognitive task performance, a code was developed in Unreal Engine to automatically record the number of errors and task completion duration. During the Trail Making Test, instances where participants clicked outside the designated balloon and made an incorrect selection, were considered as one error and accurately recorded. Self-reported perceptual data including pleasantness, comfort, excitement, stress, and confusion were also collected at the end of the Trails B of the cognitive task employing the integrated Likert-scale widgets within the virtual reality (VR) environment:

- How pleasant is the light in space, with 1 being unpleasant and 5 being pleasant?
- How visually comfortable is the light in this space, with 1 being uncomfortable and 5 being comfortable?
- How exciting is the light in this space, with 1 being unexciting and 5 being exciting?
- How stressful is the light environment, with 1 being non-stressful and 5 being stressful?
- How confusing is the task in space, with 1 being clear and 5 being confusing?

The obtained data was exported to an MS Excel spreadsheet for further analysis.

6.5.Results

6.5.1. Sample Participants Demographics

In this phase of the study, a total of 32 residents (17 female, 15 male) ranging in age from 62 to 84 participated in the previous phase of the study. Selection criteria for these 32 participants involved assessing their mental, physical, and visual conditions from a pool of 37 volunteers. The average age of the female participants was 73 years, while the male participants had an average age of 75. During the experiment, 18 participants reported wearing glasses, whereas 14 did not. Participants were instructed to wear their glasses while performing the cognitive task inside the virtual reality (VR) head-mounted display (HMD). The t-test results in Table 28 indicate the influence of gender on the average ratings of self-reported perceptual data, including measures of pleasantness, comfort, excitement, stress, and confusion, across four distinct lighting conditions. Notably, the findings reveal that there is no statistically significant ($p < 0.05$) effect of gender on the mean scores of any of the rating scales.

Table 28. t-test results for the effect of gender on self-reported perceptual data under four different lighting conditions

	Gender	Mean	Std. Deviation	Std. Error Mean	t	p-value	Cohen's d
Pleasantness	F	4.43	.759	.092	2.938	.600	.520
	M	4.00	.883	.114			
Comfort	F	4.07	.698	.085	.057	.535	.010
	M	4.07	.660	.085			
Excitement	F	4.43	.676	.082	2.735	.418	.484
	M	4.08	.743	.096			
Stress	F	2.50	.872	.106	-.612	.316	-.108
	M	2.60	.978	.126			
Confusion	F	2.66	1.016	.123	-2.664	.884	-.472
	M	3.15	1.055	.136			

Note: The sample is 17 females and 15 males.

Pearson correlation coefficients were employed to investigate the potential association between participants' visual condition and the variables of pleasantness, comfort, stress, and confusion, considering the normal distribution of the data. However, since the data for excitement did not meet the assumption of normality based on the Shapiro-Wilk test, Spearman's rank correlation was utilized to assess the correlation between the visual condition and excitement.

In the preceding phase of the study (currently under review), a noteworthy negative correlation ($p < 0.05$) was observed between the visual condition and both the rate of confusion and stress levels. However, in the present phase of the study, the findings from the correlation analysis indicate no significant correlation ($p > 0.05$) between the visual condition of older adult participants and their self-reported mean rating perceptual data across four distinct lighting conditions. Refer to Table 29 for detailed results.

Table 29. Pearson and Spearman's rank test results for the effect of visual condition on self-reported perceptual data

	Correlation Coefficient	p-value	N
Pleasantness	.072	.696	32
Comfort	.272	.132	32
Excitement	.024	.894	32
Stress	.248	.172	32
Confusion	-.087	0.635	32

Correlation is significant at the 0.05 level (2-tailed).

6.5.2. Self-reported perceptual data (H1)

The analysis of the mean ratings for the question regarding pleasantness reveals that participants rated pleasantness higher in spatial pattern 2 compared to spatial pattern 1. Additionally, the mean ratings of pleasantness are higher in lower CCT in comparison to higher CCT conditions. This might be statistically significant as 95% of the confidence intervals do not overlap. The mean rating of comfort in the second spatial pattern is higher compared to the first spatial pattern. However, no constant pattern was observed in the mean rating of comfort between the two correlated color temperatures (CCTs). The participant's mean rating for the excitement question indicates that people reported experiencing higher levels of excitement in the lighting environment with a higher CCT in both spatial patterns, while no consistent pattern is observed in the mean ratings between the two different spatial patterns. The mean rating chart regarding stress reveals that participants reported experiencing lower levels of stress in the lighting condition with a lower CCT in both spatial patterns. Furthermore, the mean rating of stress indicates a decrease in the second spatial pattern compared to the first spatial pattern. The estimated marginal mean for the confusion question indicates that participants experienced a lower level of confusion in higher CCTs and the second spatial pattern, compared to higher CCTs and the first spatial pattern (Table 30 and Figure 50)

Table 30. presents the mean ratings and standard deviations provided by the participants.

		Pleasantness		Comfort		Excitement		Stress		Confusion	
Pattern	**CCT**	**Mean**	**Std. Error**	**Mean**	**Std. Error**	**Mean**	**Std. Error**	**Mean**	**Std. Error**	**Mean**	**Std. Error**
Spatial pattern_1	**2700K**	4.469	.134	3.875	.117	4.000	.119	2.438	.138	3.813	.153
	5000K	3.688	.134	3.938	.117	4.438	.119	3.156	.138	2.594	.153
Spatial pattern_2	**2700K**	4.688	.134	4.344	.117	3.969	.119	1.844	.138	3.031	.153
	5000K	4.063	.134	4.125	.117	4.656	.119	2.781	.138	2.125	.153

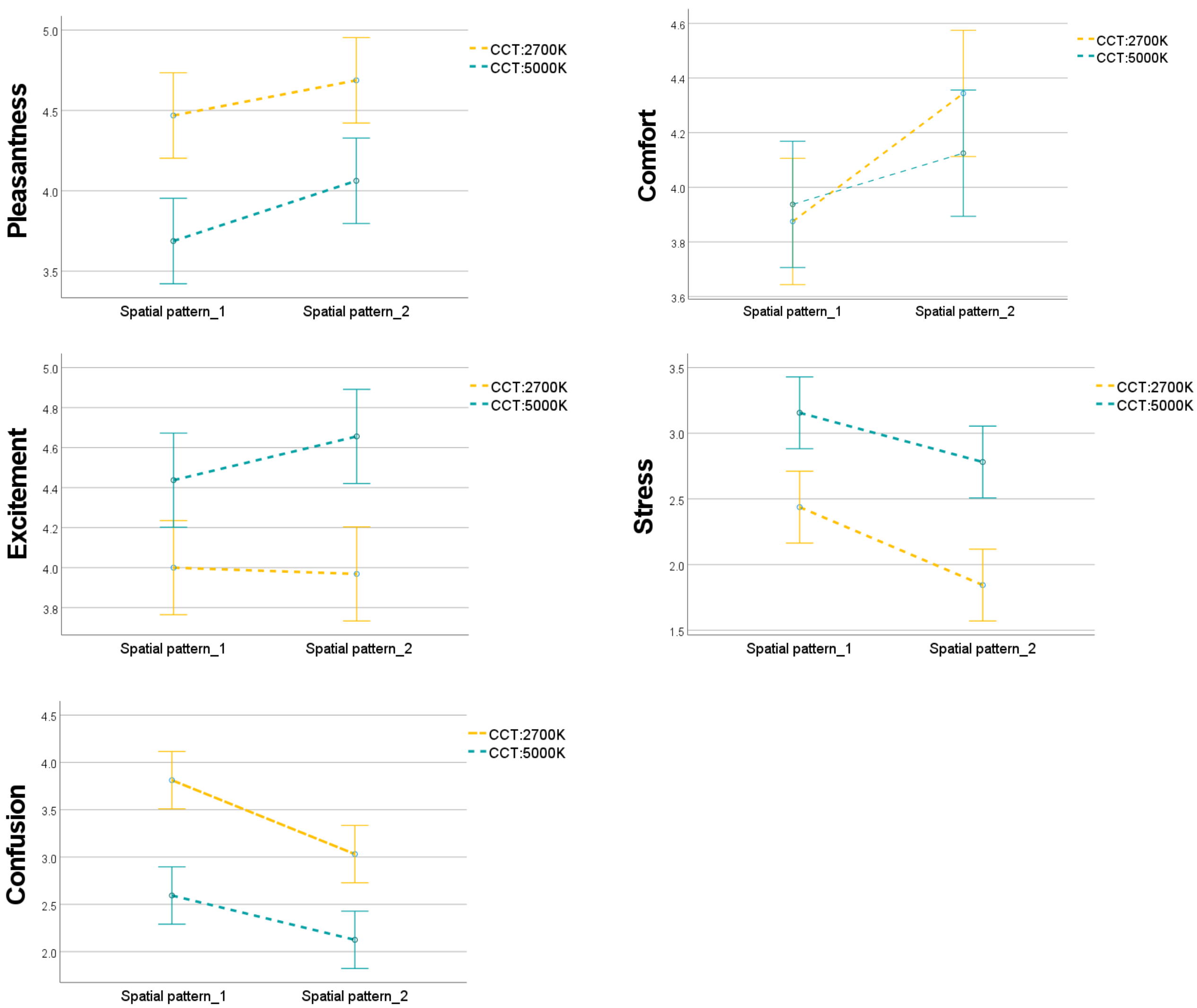


Figure 50. Mean ratings with standard deviations were given by participants for five self-reported perceptual data in four different lighting design conditions.

In this study, a 2x2 between-subject factorial ANOVA test was employed to evaluate the main effect of spatial pattern and CCT and their interaction impact on five self-reported perceptual questions, namely pleasantness, comfort, excitement, stress, and confusion. Table 31 provides a comprehensive summary of the results obtained from these mixed-model analyses. The mixed-model analysis results indicated that spatial patterns ($p=0.029$) and CCT ($p=0.000$) significantly influenced the pleasantness of participants in lighting environments. However, the two-way interaction between spatial pattern and CCT did not have a significant impact on pleasantness ($p=0.562$). Eta squared values revealed a relatively small effect size for the spatial pattern ($\eta^2 = 0.38$) and a large effect size for CCT ($\eta^2 = 0.181$) with pleasantness. The analysis results revealed a significant impact of the spatial pattern of light ($p=0.006$) on participants' comfort perception in the lighting environment. However, the main effect of CCT and the two-way interaction between CCT and spatial pattern were not significant ($p=0.505$ and $p=0.231$, respectively) with the comfort level. Participants reported significantly higher comfort in the second spatial pattern of light compared to the initial spatial pattern, with a medium effect size ($\eta^2= 0.060$). The ANOVA test revealed that the correlated color temperature (CCT) of light had a significant impact on the excitement level perceived by participants in the lighting environment ($P=0.000$). However, the spatial pattern of light ($p=0.432$) and the interaction between CCT and spatial pattern ($p=0.295$) did not significantly affect excitement. The effect size ($\eta^2=0.153$) indicated a moderate amount of variance explained in excitement between different levels of CCTs. The analysis of the stress questions revealed significant effects of both the spatial pattern of light ($p=0.001$) and correlated color temperature (CCT) ($p=0.000$) on participants' stress levels in the VR lighting environments. Participants reported significantly higher stress levels in the first spatial pattern and higher CCT of light. The effect sizes indicated a relatively moderate effect size for the spatial pattern ($\eta^2=0.90$) and a large effect size for CCT ($\eta^2=0.225$). The analysis of self-reported confusion levels demonstrated that both spatial patterns ($P=0.000$) and correlated color temperature (CCT) ($P=0.000$) significantly influenced the confusion levels experienced by participants under different lighting conditions. The effect sizes for the spatial pattern ($\eta^2= 0.118$) and CCT ($\eta^2= 0.280$) were relatively large, indicating substantial impacts on confusion levels. participants reported significantly higher levels of confusion in the first spatial pattern and lower CCT.

Table 31. Statistical significance (p-values), Eta-squared (η^2), and observed power for main effects and interaction items in linear mixed-model for self-reported perceptual data.

		Pleasantness			**Comfort**			**Excitement**			**Stress**			**Confusion**		
		p-value	**Eta-squared (η^2)**	**Observed Power**	**p-value**	**Eta-squared (η^2)**	**Observed Power**	**p-value**	**Eta-squared (η^2)**	**Observed Power**	**p-value**	**Eta-squared (η^2)**	**Observed Power**	**p-value**	**Eta-squared (η^2)**	**Observed Power**
Main effect	**Spatial pattern**	**.029***	.038	.592	**.006***	.060	.796	.432	.005	.123	**.001****	.090	.935	**.000****	.118	.982
	CCT	**.000****	.181	.999	.505	.004	.102	**.000****	.153	.997	**.000****	.225	1.000	**.000****	.280	1.000
2-Way interaction	**CCT × Spatial pattern**	.562	.003	.089	.231	.012	.223	.295	.009	.181	.430	.005	.123	.310	.008	.173

6.5.3. Cognitive Performance (H2)

The examination of participants' time allocation during the cognitive task reveals that participants expended a greater amount of time completing the task under the influence of the first spatial pattern compared to the second spatial pattern. Furthermore, when comparing two distinct color temperatures of light, it is evident that participants exhibited faster task completion rates in the lighting environment with a higher correlated color temperature (CCT: 5000) as opposed to the one with a lower CCT (CCT: 2700). The findings indicate that participants, on average, required 4.142 and 3.634 minutes to complete the cognitive task in the first spatial pattern under color temperature conditions of 2700K and 5000K, respectively. In contrast, when exposed to the second spatial pattern, participants exhibited reduced task completion times with averages of 3.897 and 3.380 minutes for color temperatures of 2700K and 5000K, respectively. The comparative analysis of the chart data further highlights a notable distinction in participants' error rates during the cognitive task between the two spatial patterns of light. Specifically, the number of errors observed in the second spatial pattern is lower than those observed in the first spatial pattern. The data analysis regarding the influence of color temperature on the number of errors reveals that participants demonstrated a lower number of errors in the lighting condition with a higher color temperature compared to the condition with a lower CCT. On average, participants committed 12.5 and 9.72 errors during the completion of the cognitive task in the first spatial pattern of light under a color temperature of 2700K and 5000K, respectively. Conversely, when exposed to the second spatial pattern of light, participants made 10.06 and 7.69 errors under color temperature conditions of 2700K and 5000K, respectively (Table 32 and Figure 51)

Table 32. Mean ratings and standard deviations of cognitive performance

		Time		Error	
Pattern	**CCT**	**Mean**	**Std. Deviation**	**Mean**	**Std. Deviation**
Spatial pattern_1	**2700K**	4.142	1.535	12.59	6.951
	5000K	3.634	1.440	9.72	5.958
Spatial pattern_2	**2700K**	3.897	1.377	10.06	5.494
	5000K	3.380	2.340	7.69	4.403

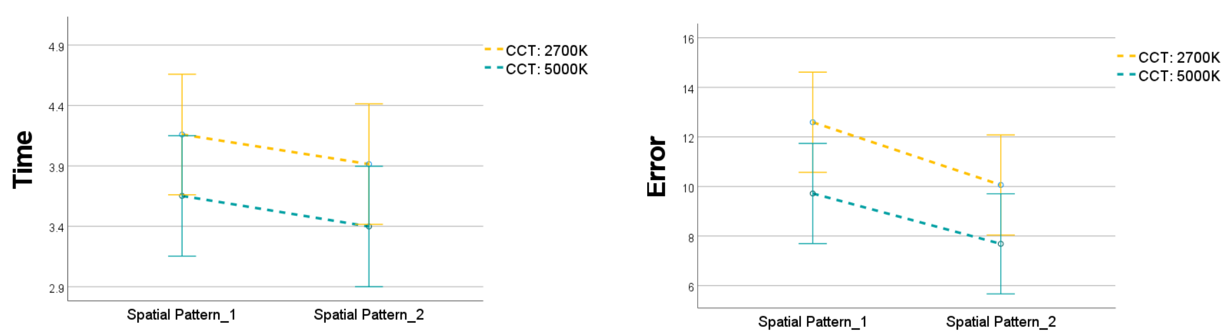


Figure 51. Mean ratings (with standard deviations) of time and number of errors during the cognitive task under four different lighting design conditions.

To assess the influence of spatial pattern, CCT, and their interaction on cognitive performance variables, namely the amount of time and number of errors, a 2x2 between-subject factorial ANOVA test was conducted. A comprehensive summary of the outcomes derived from these mixed-model analyses can be found in Table 33.

The results of the mixed-model analysis revealed that there was no significant correlation between spatial pattern ($p = 0.325$) and the time participants spent completing the cognitive test. However, the color temperature of light demonstrated a significant influence ($p = 0.044$) on the amount of time participants required to complete the cognitive test under different lighting conditions.

The results indicate that a higher correlated color temperature (CCT: 5000K) significantly reduces the completion time for participants during a cognitive task in a lighting environment, compared to a lower CCT (CCT: 2700K). However, it is important to note that the effect size of CCT on task completion time was relatively small, as indicated by the eta squared value ($\eta^2 = 0.032$). Furthermore, the two-way interaction between spatial pattern and CCT did not yield a significant impact on the amount of time required to complete the cognitive task ($p = 0.987$).

The ANOVA test results demonstrated significant effects of both the spatial pattern of light and CCT on the number of errors committed by participants across four different lighting conditions. Specifically, participants exhibited a significantly lower number of errors in the second spatial pattern ($p = 0.027$) compared to the first spatial pattern. Furthermore, participants made significantly fewer errors under higher CCT ($p = 0.011$) compared to lower CCT lighting conditions. The effect sizes of the spatial pattern ($\eta^2 = 0.039$) and CCT ($\eta^2 = 0.051$) on the number of errors were found to be relatively small. However, the results did not indicate any significant impact of the interaction between spatial pattern and CCT on the number of errors ($p = 0.807$).

Table 33. Statistical significance (p-values), Eta-squared (η^2), and observed power for main effects and interaction items in linear mixed-model for cognitive performance data.

		Time			**Error**		
		p-value	**Eta-squared (η^2)**	**Observed Power**	**p-value**	**Eta-squared (η^2)**	**Observed Power**
Main effect	**Spatial pattern**	0.325	0.008	0.165	**0.027***	0.039	0.602
	CCT	**0.044***	0.032	0.523	**0.011***	0.051	0.723
2-Way interaction	**CCT × Spatial pattern**	0.987	0.000	0.050	0.807	0.000	0.057

In this study, we employed the Pearson correlation coefficient to examine potential associations between participants' MMSE scores, the time taken to complete the cognitive task, and the number of errors made during task completion. The use of the Pearson correlation was justified by the normality of the data distribution, as indicated by the Shapiro-Wilk test.

The study revealed a significant correlation between MMSE scores and cognitive task performance under different lighting conditions. Specifically, a significant negative correlation (P = 0.017) was observed between MMSE scores, and the mean time required for completing the cognitive task in the VR environment. This suggests that individuals with higher MMSE scores exhibited significantly shorter completion times (see Table 32). Additionally, the Pearson correlation test showed a significant negative relationship between MMSE scores, and the number of errors made by participants in the VR environment. Participants with higher MMSE scores demonstrated a lower frequency of errors on the cognitive test (P = 0.001, see Table 34).

Table 34. Effects of MMSE scores on time and errors: Pearson correlation analysis

	Pearson Correlation	p-value	N
Time	**-.417****	.017	32
Errors	**-.570****	.001	32

*. Correlation is significant at the 0.05 level (2-tailed).

**. Correlation is significant at the 0.01 level (2-tailed).

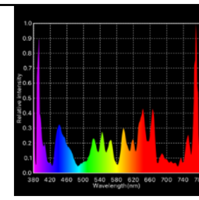
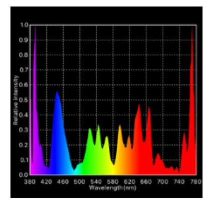
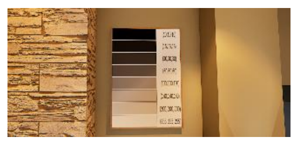
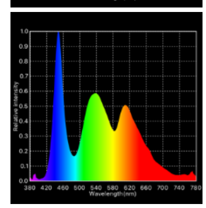
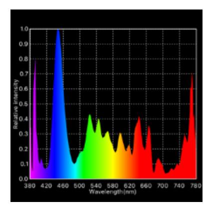
6.5.4. Light intensity, spectral power distribution, and CCT

In this study, we employed the Vray Lighting Analysis element within 3ds Max software to ensure consistent lighting intensity across all four distinct lighting conditions. Subsequently, we employed the Lighting Passport Essence Pro spectrometer to measure and compare the light intensity, spectral power distribution, and correlated color temperature (CCT) emitted from the inner right eye of the Oculus Rift S device while looking at eight different shades of gray in the VR environment. These measurements were taken within a controlled, completely dark environment (Table 35)

Table 33 illustrates the analysis of gray cards mounted on the walls, light intensity, wavelength, correlated color temperature (CCT), and spectral power distribution across four distinct lighting conditions within the virtual reality (VR) environment. The visual evaluation of the gray card scale under four distinct lighting conditions reveals that Condition B_2 exhibits the highest visual clarity in terms of the contrast between different shades of gray and the intensity of light illuminating the scale. In contrast, Condition A_1 produces a uniform and warm lighting environment, thereby posing challenges for participants in terms of observation and perception.

The measurements show consistency in terms of lighting intensity and spectral power distribution. While there were some discrepancies in terms of CCT.

Table 35. Measurements captured in different lighting conditions in the VR environment.

	Light intensity, Wavelength, CCT	**Gray scale card appearance**	**Spectral Power Distribution**
Condition A_1	Illuminance= 100 lux λp= 770 nm CCT= 4369 K K		
Condition A_2	Illuminance= 100 lux λp= 770 nm CCT= 5976 K K		
Condition B_1	Illuminance= 200 lux λp= 448 nm CCT= 6187 K		
Condition B_2	Illuminance= 100 lux λp= 447 nm CCT= 12084 K		

6.6.Discussion

This study aimed to investigate the perception and cognitive performance of older adults in various lighting conditions. The study examined the impact of two different spatial patterns and correlated color temperatures (CCTs) of light using a 2X2 factorial within-subject design.

To counterbalance the order of four lighting conditions, we designed a two-week experimental procedure. During the first week, participants were randomly assigned to complete the cognitive task in conditions A_1 and A_2. In the subsequent week, they were then instructed to participate in the experiment under the B_1 and B_2 conditions. This careful arrangement ensured that the order of the lighting conditions was counterbalanced, thereby minimizing any potential biases or confounding factors in the study. Participants with any evidence of moderate to major cognitive impairment (scores less than 23 for MMSE), and severe physical and mental health problems (PCS-12 and MCS-12 < 40) were excluded from the experiment. Paired sample t-tests were utilized to examine the influence of gender and visual condition on the visual perception of participants in various lighting conditions. The analysis of the test results revealed no statistically significant relationship between gender and visual condition concerning the self-reported perceptual data.

An analysis of variance (ANOVA) was used to assess the primary influence of spatial pattern and correlated color temperature (CCT), as well as their interaction, on participants' responses to five perceptual questions. The analysis of the data revealed that the spatial pattern of light has a significant influence on the perceived levels of pleasantness, comfort, stress, and confusion among older adults. Through the examination of mean ratings and ANOVA tests, it was observed that participants found spatial pattern_2 (non-uniform, peripheral, direct/indirect) to be significantly more pleasant compared to spatial pattern_1 (uniform, central, direct). These findings align with the research conducted by Flynn (1988), which similarly demonstrated that individuals tend to prefer bright, non-uniform, and peripheral lighting in office environments. In addition to being perceived as more pleasant, the spatial pattern_2 was also found to be significantly more comfortable, less stressful, and less confusing compared to the spatial pattern_1. These findings align with Flynn's studies, which suggested that non-uniform lighting arrangements are more relaxing. However, it is worth noting that Flynn's research also highlighted the visual clarity of light in the central area of the room, particularly when combined with wall luminance (Flynn et al., 1979; Flynn et al., 1973). Furthermore, the analysis using ANOVA tests indicated that participants found lighting conditions with higher correlated color temperature (CCT) significantly less pleasant, more exciting, more stressful, and less confusing. These findings suggest that the CCT of light plays a crucial role in shaping subjective perceptions of various emotional and cognitive aspects. These findings also overlapped with the previous evidence in the literature that shows a higher level of CCT, or cooler light can create a more visually clear environment while warmer-toned light sources are more relaxing (Flynn et al., 1979; Flynn et al., 1973).

To examine how spatial pattern, color temperature (CCT), and their interaction impact cognitive performance variables (specifically, time and error rates), a 2x2 between-subject factorial ANOVA was utilized. Based on the analysis findings, it was observed that the spatial pattern of light had a significant effect on the number of errors in the cognitive task. Additionally, the color temperature (CCT) of light was found to impact both the time taken to complete the task and the number of errors made by participants under different lighting conditions.

The results revealed that participants in the second spatial pattern (non-uniform, peripheral, direct/indirect) made significantly fewer errors ($p=0.027$) compared to those in the first spatial pattern (uniform, central, direct). However, although participants spent less time completing the task in the lighting condition with the second spatial pattern compared to the first spatial pattern, the observed differences were not statistically significant ($p=0.325$). Despite previous studies examining the influence of spatial arrangement and uniformity on human perception, behavior, and preference (Flynn et al., 1973; Flynn et al., 1979; Chraibi et al., 2017; Stokkermans et al., 2018), there is a notable research gap in the field. To the best of our knowledge, no prior field study has utilized a full-factorial design to investigate the effects of the spatial distribution of light in the three-dimensional light field on the cognitive performance of older residents. The results of our study indicate that introducing nonuniformity and creating contrast between different areas within a room can improve cognitive performance, contrary to the findings of Flynn et al. (1973) and Flynn et al. (1979), which suggested that spatial uniformity in light patterns enhances spatial clarity.

Additionally, the findings indicated that the color temperature (CCT) of light significantly influenced the cognitive performance of the participants, impacting both the time taken to complete the task ($p=0.044$) and the number of errors made ($p=0.011$). Specifically, participants exhibited significantly improved performance in lighting conditions with higher CCT (5000K) or cooler light. The mean completion time decreased from 4.142 to 3.634 minutes in the first spatial pattern and from 3.897 to 3.380 minutes in the second spatial pattern as the CCT of light increased. The findings of this study align with most of the previous research in the field of human-centric lighting design, indicating that a higher correlated color temperature (CCT) of a light source can significantly enhance task performance in the elderly population. Several studies, including Yamagishi et al. (2008), Janosik and Marczak (2016), Cheng (2016), and Wang (2020), have demonstrated that elderly individuals perform better under CCT values of 5000, 6500, 6000, and 6500, respectively. However, the study conducted by Geerdinc K, L (2009) reported no significant relationship between CCT, visual acuity, and task performance. It is important to mention that, as per the ASHRAE report (2011), light sources with a color temperature of 4100K or 5000K are closer in resemblance to daylight compared to a 3500K source.

This study encompassed two categories of data: visual perception and cognitive performance. Participants reported that Spatial Pattern_2 was more pleasant, comfortable, and less confusing and stressful in self-reported perceptual questions. Additionally, this pattern significantly enhanced cognitive performance during the cognitive task. The use of a higher correlated color temperature (CCT) of light, which was found to be less confusing based on self-reported questions, also resulted in improved cognitive performance, demonstrated by reduced task completion time and fewer errors. The consistent alignment between the findings from both categories of data adds to the reliability of the results obtained in this study.

The utilization of virtual reality (VR) environments offers the advantage of conducting a comprehensive evaluation of outcomes using a 2X2 factorial design, which may not be feasible in real-world settings. However, it is important to acknowledge that VR environments also have certain limitations. First and foremost, it is worth noting that while we employed VRay lighting analysis in 3ds Max to maintain consistent light intensity across all four lighting design conditions, the utilization of lighting fixtures within the Unreal Engine does not provide an accurate measurement of light intensity. This may lead to minor variations between the different lighting conditions. Furthermore, reproducing the exact spectral power distribution of a light source within a VR headset is not feasible due to the presence of a digital-to-analog converter (DAC) for each RGB channel in the headset itself.

Furthermore, it is important to consider the constrained field of view associated with VR headsets, as it can potentially affect visual acuity, a crucial factor in conducting the Trail Making test. Although we meticulously designed all interactive components and widgets within the maximum field of view of 115º provided by the headset, it remains narrower compared to the broader field of view experienced in real-world environments, which typically ranges from approximately 160 to 200 degrees horizontally and 135 to 160 degrees vertically. When employing virtual reality (VR) environments for lighting design research, designers and researchers must be aware of the limitations associated with such platforms. Specifically, It is important to be cautious when examining the effects of quantitative light attributes, including light intensity, chromaticity, and spectral power distribution. Furthermore, it is crucial that future studies focus on developing novel methodologies to accurately replicate and represent the authentic spectral power distribution of real-life lighting conditions within VR environments. Addressing these challenges will enhance the reliability and validity of investigations conducted in the VR environment regarding lighting design.

6.7. Conclusion

This field study aimed to investigate the impact of different lighting conditions on the self-reported visual perception and cognitive performance of older adults. The study employed a 2 × 2 factorial design, incorporating two levels of the spatial pattern (i.e., Spatial Pattern_1: uniform, central, direct; Spatial Pattern_2: non-uniform, peripheral, direct/indirect) and two levels of correlated color temperature (CCT) (i.e., 2700K and 5000K). A total of 32 participants (17 female, 15 male) within the age range of 62 to 84 were recruited for this study. The average age of the female participants was 73 years, while the male participants had an average age of 75. Out of the participants, 18 reported wearing glasses, while 14 did not during the experiment. Two types of data were collected and analyzed in this study: self-reported perceptual data obtained through interactive widgets in the virtual environment and cognitive performance assessment data, which included the time taken to complete the trail-making test and the number of errors made. Based on the analysis of these data, we draw the following conclusions:

- Participants rated the lighting condition with non-uniform, peripheral, direct/indirect lighting, and lower CCT (2700K) as the most pleasant. Both spatial pattern and color temperature significantly influenced the pleasantness of the environment, while their interaction did not have a significant impact.
- Participants felt more comfortable in the non-uniform, peripheral, direct/indirect lighting condition with lower CCT. The spatial pattern of light significantly influenced comfort perception, while the color of light had no significant impact.
- Participants experienced more excitement in the lighting condition with non-uniform, peripheral, direct/indirect lighting, and higher CCT (5000K). The color had a significant impact on excitement, while the spatial pattern did not show a significant effect.

- Color temperature and spatial pattern significantly impacted participants' stress levels. The lighting condition with non-uniform, peripheral, direct/indirect lighting, and lower CCT was perceived as the least stressful lighting condition.
- Color temperature and spatial pattern significantly impacted participant confusion. The lighting condition with non-uniform, peripheral, direct/indirect lighting, and higher CCT was perceived as the least stressful lighting condition.
- The spatial pattern of light was found to have a significant impact on participants' cognitive performance, specifically influencing the number of errors made. On the other hand, color temperature affected cognitive performance in terms of both the time taken to complete the test and the number of errors made.
- The lighting condition characterized by non-uniform, peripheral, direct/indirect lighting, and a higher CCT demonstrated the highest efficacy in enhancing participants' cognitive performance. Conversely, uniform, central, direct lighting with a lower CCT was found to be the least effective in improving cognitive performance.

CHAPTER 7: SUMMARY OF CONTRIBUTIONS AND FUTURE WORK

This dissertation aimed to achieve two primary objectives. Firstly, it sought to explore the influence of spatial patterns on the perception, mood, and preference of older adults. Secondly, it aimed to investigate variations in visual perception and cognitive performance among older adults under different spatial patterns and correlated color temperatures of light. To accomplish these objectives, a series of three experiments were conducted, each addressing different aspects relevant to these goals. By examining the collective findings of these studies, valuable insights regarding the impact of spatial pattern and light color on the visual perception, preference, and cognitive performance of older adults in assisted living facilities were obtained. The subsequent sections provide a summary of the key contributions of each objective.

7.1. The Impact of Spatial Light Patterns on Perception, Mood, and Preference of Older Adults in Assisted Living Facilities

Study 1 (Chapter 4) aimed to explore this objective by evaluating the visual perception, mood, and preferences of older adults in response to six different spatial light patterns. These patterns were characterized by variations in the direction, centrality, and uniformity of light.

This study employed a multi-method approach to expand upon the findings of Flynn et al. (1973) by examining the influence of various spatial patterns of light, using the same lighting modes, on the perceptions and preferences of older adults. The initial phase involved an architectural content analysis conducted in three steps to establish a Spatial Lighting Pattern Framework. This framework was developed through a Picture Content Analysis (PCA) of Assisted Living Facilities' websites to identify common room layouts and properties. Subsequently, the Visual Attention Software (3M-VAS) was utilized to determine the most visually appealing room typology. Finally, based on Flynn's theory of lighting and mood, the two most preferred room views were selected to construct the final spatial pattern framework. In the second phase of the study, this framework was used to experimentally investigate how different spatial patterns of light affected the perceptions and preferences of older adults.

This study confirms that different lighting modes have a significant impact on older adults' subjective impressions. Preferences lean towards uniform and indirect lighting, while non-uniform lighting creates a more relaxed atmosphere and uniform lighting increases perceived stress. Findings align with studies by Veitch et al. (2008), Yearout and Konz (1989), and Katzev (1992) indicating a preference for indirect or combined direct/indirect lighting over direct lighting. The spatial patterns of light also influence mood, with peripheral lighting on the walls reinforcing relaxation. This discovery aligns with earlier research that highlights the role of non-uniform and peripheral lighting in establishing a calming ambiance within an environment (Flynn et al., 1973; Flynn et al., 1979). Additionally, these patterns influence the perception of clarity and spaciousness. Non-uniform lighting with a combination of direct and indirect lighting improves clarity, while there is no significant relationship between clarity and the centrality of lighting patterns. This observation is consistent with a previous study that investigated the impact of diverse lighting arrangements on human spatial perception. Additionally, the study revealed that nonuniform light on walls improved the perception of clarity (Manav & Yener, 1999). Despite previous studies indicating a positive relationship between light uniformity and perceived spaciousness, our findings demonstrate that lighting patterns featuring indirect and non-uniform lighting are perceived as notably more spacious compared to other patterns (Flynn & JE, F., 1977; Flynn, J. E., et al., 1979; Flynn, J. E., et al., 1973). Furthermore, our analysis reveals that central light patterns are perceived as more spacious than peripheral patterns.

Overall, this research emphasizes the importance of considering spatial patterns of light in designing environments for older adults, as they impact perception, mood, and preferences. The study findings indicate that Pattern_1 (uniform, central, and direct) creates a clearer lighting scene, while Pattern_2 (non-uniform, peripheral, direct/indirect) generates a more relaxed impression in the lighting environment (figure 52). Based on these promising outcomes, both patterns were selected for the final experimental study, which aimed to explore the influence of spatial patterns on the cognitive performance of older adults.

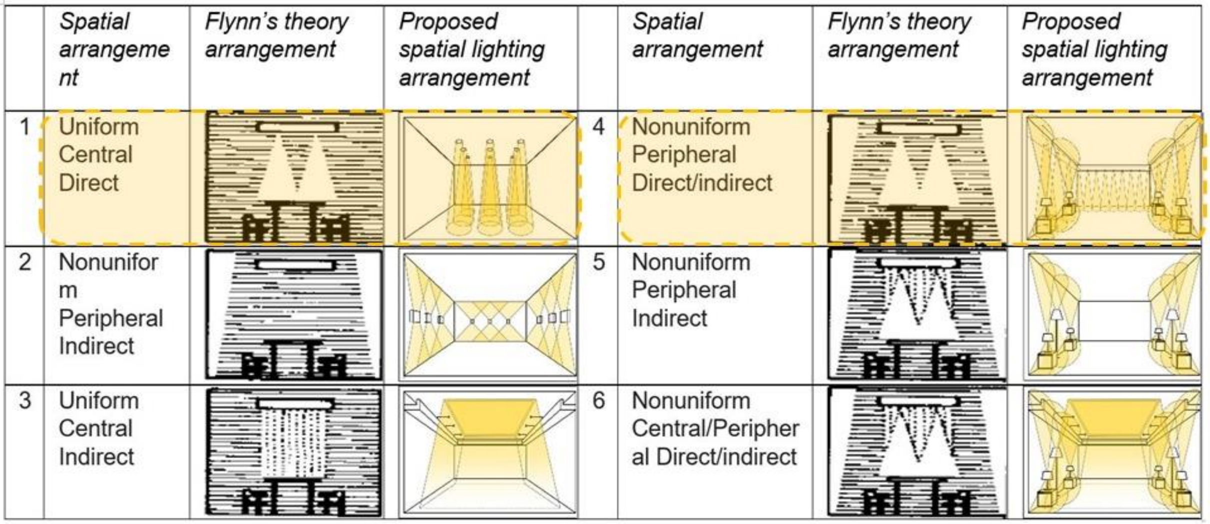


Figure 52. Highlighted spatial patterns among the six tested in Study 1

7.2. Investigating the Impact of Spatial Patterns and Color of Light on the Cognitive Performance of Older Adults_ In an Immersive Virtual Environment

This goal was investigated through two studies described in Chapter 5 and Chapter 6. In Study 2 (Chapter 5), a within-subjects design was utilized to examine the impact of two lighting conditions, namely the Real Lighting Environment and the Virtual Lighting Environment, on 32 residents of an assisted living facility. The Virtual Lighting Environment was designed to replicate the existing lighting conditions of a living room in an assisted living facility located in Eugen, OR. The results of this study suggest that the VR environment can be considered a valid substitute for real-world lighting conditions when evaluating cognitive performance and subjective perception in older adults. While participants experienced increased levels of excitement, stress, and confusion in the VR environment compared to the real environment, there were no significant differences in their cognitive performance between the two environments. The primary goal of study 3 (Chapter 6) was to investigate the effects of different spatial patterns and color temperature (CCT) of light on the perception and cognitive performance of older adults. To accomplish this objective, a 2×2 factorial design was implemented within an immersive virtual environment, serving as a novel and advanced testing methodology. The participants were assigned randomly to distinct lighting conditions over two separate weeks, during which cognitive assessments were administered within a virtual reality setting.

Generally, the results revealed that spatial pattern significantly influenced participants' perceptions of pleasantness, comfort, stress, and confusion, with non-uniform, peripheral, and direct/indirect lighting being preferred over uniform, central, and direct lighting, aligning with previous research. Additionally, higher correlated color temperature (CCT) was found to be less pleasant, more exciting, more stressful, and less confusing, supporting the idea that cooler light is visually clearer and warmer-toned light is more relaxing. The study found that the spatial pattern of light influenced error rates, while color temperature affected completion time and error rates, with non-uniform, peripheral, direct/indirect lighting and higher CCT showing the highest efficacy in enhancing cognitive performance.

7.3. Applications

The research presented in this dissertation holds promising implications for enhancing visual comfort, perception, and cognitive performance among older adults in various settings, particularly in living rooms within assisted living facilities, nursing homes, and care facilities. Moreover, the study's insights extend beyond these specific environments and can be adapted for application in diverse spaces based on their unique requirements and the tasks carried out within them. By considering the lighting patterns and their impact on subjective impressions and mood, designers and planners can optimize the spatial lighting arrangements to better accommodate the needs and preferences of the occupants, ultimately promoting well-being and an enhanced living experience for older adults across a wide range of settings.

The study's compelling findings underscore the significance of incorporating a tunable and layered lighting design to cater to the diverse needs and preferences of older adults throughout their daily routines. By considering the impact of different correlated color temperatures (CCTs) and spatial patterns on various outcomes, a dynamic lighting approach can be implemented. During the morning when older adults engage in daily tasks that require focus and alertness, cooler and more direct lighting can be employed to enhance their cognitive performance and visual comfort. This energizing lighting setup can positively influence their productivity and overall well-being during the active hours of the day. As the day progresses and older adults transition to more relaxed activities in the afternoon and evening, a shift to warmer and indirect lighting can be employed to create a soothing and calming atmosphere. This warmer light temperature aligns with the body's natural circadian rhythm, promoting relaxation and preparing the occupants for a restful sleep later in the evening. The layered lighting design, with its adaptability to different times of the day and activities, offers an opportunity to enhance the overall living experience of older adults in various environments, such as assisted living facilities, nursing homes, and care facilities, where their comfort, mood, and cognitive performance are essential components of their daily life quality. By catering to the specific lighting needs of older adults during different stages of the day, the tunable and layering lighting approach serves as a valuable tool for creating supportive and age-friendly environments that foster positive outcomes for this population.

This study also complements existing research endeavors by providing comprehensive insights into both the visual and non-visual effects of Human-Centric lighting on the health and well-being of elderly residents. While previous studies have predominantly focused on quantitative variables of light, such as light levels and temporal patterns, this study goes a step further by investigating the qualitative attributes of light, particularly the effect of correlated color temperature (CCT). These qualitative attributes serve as essential components for the development of a new generation of healthcare lighting design. However, future advancements in lighting design standards must integrate considerations for non-visual aspects, including light spectrum, corneal illuminance levels, and the timing and duration of exposure.

This dissertation primarily focuses on examining the influence of color and spatial patterns of electric lighting in indoor environments. While the findings have implications for windowless rooms, they are also applicable to rooms with direct access to daylight. This is particularly relevant for elderly residents in assisted living facilities, as they typically spend a significant amount of their time indoors, with studies indicating that they spend around 90% of their time in indoor spaces (Klepeis, N. E., et al., 2001; Beyer, K. M. et al., 2018). Consequently, they may experience variations in lighting conditions, with dimmer days and brighter nights compared to what they would naturally encounter in an outdoor setting (Wright Jr, K. P., et al., 2013; Chen, S. et al., 2019). Therefore, it is crucial that lighting design standards, as well as guidelines for nursing homes and senior living facilities, place significant emphasis on the incorporation of daylighting strategies and electric lighting to facilitate regular exposure to both indoor light and outdoor daylight for older adults. Architects must recognize that daylighting and electrical lighting systems are interconnected entities that work in conjunction, influencing and complementing one another. Therefore, a well-executed lighting design should integrate both electrical lighting and daylighting elements.

While architects place a higher emphasis on daylighting design and overlook the significant influence and potential of electrical lighting systems, lighting designers also neglect the importance of daylight in indoor environments. These two extreme approaches lead to incomplete and suboptimal lighting solutions in residential units of not only older adults but also other populations. To address this gap and have a comprehensive design strategy, future architectural design and lighting design guidelines, and standards should strongly emphasize the integration of lighting and daylighting systems. This transformative shift would prompt architects to recognize electrical lighting design as a vital and integrated component of the overall architectural design process. It will ensure a comprehensive and harmonious approach to lighting design in a residential setting.

7.4. Research Limitations

There are several limitations to the approach, methods, and findings that should be considered when interpreting the studies reported.

Conducting research related to elderly individuals poses several significant challenges, starting with the recruitment and selection of subjects, which demand careful consideration. Firstly, ethical considerations come into play as many older adults may lack the autonomy to independently decide about their participation in scientific studies. Secondly, the presence of various physical and psychological impairments among elderly participants further complicates the recruitment process. Such limitations necessitate the development of specialized methods and instruments tailored to accommodate the functional performance and abilities of the subjects. Overcoming these challenges provided beneficial lessons that would be beneficial for future gerontology studies:

First, the importance of ensuring the validity of healthcare research by considering the diversity of health status and socio-economic backgrounds of the aging population involved in the study. Selecting an appropriate sub-population from the heterogeneous group of elderly subjects is essential, and using the senior protocol for immunological aging studies, while strictly excluding all diseases, may not align with the current theory on aging and disease correlation. Loosening exclusion criteria and including elderly subjects with co-morbidities can enhance the study's validity, even though it may lead to some attrition due to increased frailty. To increase the participation rate of elderly subjects in this research, various strategies were utilized based on the literature. These include using simple language and explaining the study's aims and contributions to the subjects, employing visual tools to assess their mental and sensory capabilities, establishing partnerships with family members, and assisted living facilities. The recruitment of this study was carried out at the living room of the assisted living facility, which served as a natural gathering place for seniors facing similar issues and engaging in social interactions. The approach involved conducting shorter interview sessions and being flexible with the timing and location of interviews. These strategies have been found to be effective in encouraging elderly participation in research, as supported by previous studies (Adams et al., 1997; Peel & Wilson, 2008; Faes et al., 2007; Crawford et al., 2010; Marcantonio et al., 2008; Stineman et al., 2011).

One of the main limitations of this study is the exclusive focus on electric lighting, neglecting to address human-centric variables related to daylight. While the research conducted in this dissertation provided valuable insights into the impact of electric lighting on human outcomes, it is essential to acknowledge that daylighting, in conjunction with electric lighting, can significantly affect the perception of the environment and cognitive performance among older adults. The inclusion of windows that provide views of nature adds another dimension to the lighting environment, potentially influencing mood, well-being, and overall cognitive engagement. Prior research has traditionally separated investigations into either electric lighting or daylighting, but a holistic approach considering both lighting sources may offer a more comprehensive understanding of the complex interactions between light and human cognition. Therefore, future studies should aim to explore the interactive effects of both electric lighting and daylighting, considering the combination of these lighting sources in creating age-friendly environments for older adults.

In the first study, extracting in-depth information from images featuring complex scenes displayed on a laptop screen was a challenging task for the aging population. To address this issue, an alternative solution was to incorporate virtual reality (VR) technology, which would allow older adults to be immersed in a simulated environment to obtain in-depth information. In addition, although in study 1 we employed a consistent light intensity and color temperature in all the lighting scenes via 3Ds Max, the picture comparison method could capture all the technical aspects of lighting such as light level, color temperature, distribution, and direction of light. As the design of lighting in any environment is multifaceted and complex, relying solely on static images may not accurately represent the dynamic and intricate nature of lighting attributes. To tackle this challenge, a potential solution lies in the integration of virtual reality (VR) technology, enabling older adults to immerse themselves in a simulated environment to gain comprehensive insights. This innovative approach presents a compelling alternative for the aging population, facilitating their access to and comprehension of visual information within a given lighting scene. The second and third studies also encountered limitations in terms of utilizing virtual reality (VR) technology. While VR can serve as a viable substitute for real-world environments in environmental design research, there are still constraints associated with VR head-mounted displays (HMDs) when it comes to assessing and evaluating lighting design conditions. In the second study, the implementation of a high dynamic range imaging (HDRI) image within the VR environment allowed for a close replication of the color and light intensity found in the real environment through calibration and tone-mapping. However, it is important to acknowledge that this approach has certain limitations in accurately reproducing the precise spectral power distribution of light and light intensity. In the final experiment, despite meticulously modeling the entire scene and electric lighting fixtures using 3ds Max and Unreal Engine and assigning specific quantitative and qualitative parameters to each lighting fixture, certain limitations persisted in terms of maintaining a consistent CCT across the four distinct lighting conditions. To address this challenge effectively, it is recommended that future studies consider the implementation of a synergistic approach combining virtual reality and augmented reality technologies. By leveraging the strengths of both these immersive technologies, researchers can explore new possibilities and gain deeper insights into the subject matter. This integrated approach has the potential to enhance the overall research experience and provide more comprehensive and valuable findings for addressing the identified challenge. To address this challenge effectively, it is recommended that future studies consider the implementation of a synergistic approach combining virtual reality and augmented reality technologies. By leveraging the strengths of both these immersive technologies, researchers can explore new possibilities and gain deeper insights into the subject matter. This integrated approach has the potential to enhance the overall research experience and provide more comprehensive and valuable findings for addressing the identified challenge.

Lastly, a significant limitation of this study was its reliance on a cross-sectional design rather than a longitudinal approach. Previous literature has demonstrated that lighting design can alter human outcomes, including mood, behavior, and performance, across various time frames: immediate (seconds or minutes), delayed (hours, days, or weeks), and long-term (months or years). Considering that cognitive performance, as a human outcome, can be influenced by physical environmental attributes over an extended duration, it is crucial to not only examine the immediate effects of light on cognitive performance but also investigate how light may impact the cognitive performance of older adults over a longer period. Therefore, to gain a comprehensive understanding, future research should explore the long-term effects of lighting on cognitive performance in older adults. The Trail Making Test serves as a cognitive assessment tool for evaluating cognitive performance within the context of short-duration tasks. However, it is essential to acknowledge the existence of alternative tests, such as wayfinding, which can offer insights into cognitive performance concerning longer-duration cognitive tasks. Additionally, the inclusion of physiological data as an additional layer of information holds promise in providing a more comprehensive evaluation of cognitive tests, a facet that remains unexplored in this dissertation. By incorporating physiological data, a deeper understanding of cognitive processes and responses can be gained, augmenting the overall assessment of cognitive performance beyond the scope of the present study.

7.5. Suggestions for Future Research

7.5.1. Integration of Electric lighting and daylighting design approaches

Previous research has primarily focused on investigating the individual effects of either electric lighting or daylighting on human outcomes, as demonstrated in the studies conducted in this dissertation. However, to gain a more comprehensive understanding of the impact of lighting design on older adults' well-being and cognitive performance, it is essential to consider the integration of both electric lighting and daylighting. Future studies should undertake a multidimensional approach, examining various variables related to lighting design. These variables may include the type, location, dimension, and glazing specifications of windows, in conjunction with the spatial and spectral characteristics of electric lighting and daylighting.

By exploring the combined effects of these parameters, researchers can unveil valuable insights that can guide the selection of appropriate window types and lighting fixtures within facilities catering to older adults. This knowledge is instrumental in developing human-centric lighting designs aimed at enhancing the perception and cognitive experience of elderly residents. Additionally, considering the interaction between electric lighting and daylighting allows for a more holistic evaluation of lighting's impact on older adults, paving the way for innovative and tailored lighting strategies that promote their well-being and overall quality of life. Ultimately, the integration of electric lighting and daylighting research offers an exciting avenue to optimize lighting design for the unique needs of older adult populations in various environments.

7.5.2. Impact of light on Wayfinding behavior

Cognitive function encompasses a wide range of mental abilities crucial for daily functioning and problem-solving. These abilities include learning, thinking, reasoning, remembering, problem-solving, decision-making, and active working memory. In this study, we focused on evaluating the cognitive abilities of older adults using the Trail Making Test. This test was chosen due to its sensitivity to the physical environment, specifically targeting the visuospatial and constructional praxis cognitive domains, as evident from our sensitivity analysis. While the Trail Making Test served as an effective tool for assessing certain cognitive aspects influenced by lighting in a short period of time, it is important to explore additional cognitive tests in future studies to comprehensively evaluate the impact of light on cognitive performance. One such test is Wayfinding, which involves the entire process of cognitive tasks and is defined as a spatial problem-solving mechanism encompassing decision-making, decision execution, and information processing. By incorporating Wayfinding and other cognitive tests in subsequent research, a more thorough understanding of the intricate relationship between lighting and cognitive function in older adults can be gained. Additionally, the integration of eye tracking data and physiological data can offer valuable insights into the real-time cognitive responses of older adults under various lighting conditions, providing a deeper comprehension of the underlying mechanisms at play. The combination of these approaches will contribute to a more robust and holistic investigation of how lighting design influences cognitive performance in the aging population.

7.5.2. Blending Reality and Interactivity in Virtual Environments

Within the context of the current study's limitations, it is important to note that although Virtual Reality (VR) technology has provided researchers with numerous experimental possibilities across various fields, it still has certain limitations, particularly in the area of lighting design. The constraints of VR in replicating the exact quality and quantity of real-world lighting necessitate future studies to adopt a combination of both real-world and virtual environments to examine the impact of lighting variables on human outcomes.

Augmented Reality (AR) emerges as an innovative testing approach that facilitates this integration by overlaying virtual objects and information onto the real-world environment. This enables users to perceive and interact with virtual elements while still being fully aware of their physical surroundings through devices like smartphones or AR glasses. For instance, AR can be employed to substitute different lighting fixtures within a single physical environment without altering the existing conditions. Consequently, AR serves as a cost-effective, efficient, and flexible method, providing researchers with the opportunity to examine the impact of various lighting scenarios and their effects on human outcomes.

REFERENCES

Abd-Alhamid, F., Kent, M., Bennett, C., Calautit, J., & Wu, Y. (2019). Developing an innovative method for visual perception evaluation in a physical-based virtual environment. Building and Environment, 162, 106278.

Allan, A. C., Garcia-Hansen, V., Isoardi, G., & Smith, S. S. (2019). Subjective assessments of lighting quality: A measurement review. Leukos.

Arthur, P., & Passini, R. (1992). Wayfinding: People, signs, and architecture.

Bailes, H. J., & Lucas, R. J. (2013). Human melanopsin forms a pigment maximally sensitive to blue light (λ max≈ 479 nm) supporting activation of Gq/11 and Gi/o signalling cascades. Proceedings of the Royal Society B: Biological Sciences, 280(1759), 20122987.

Baker, J. (1987). The Role of Environment in Marketing Services: The Consumer Perspective in The Service.

Berman, S. (2000). The coming revolution in lighting practice. Energy Users News, 25, 24-26.

Bishop, I. D., & Rohrmann, B. (2003). Subjective responses to simulated and real environments: A comparison. Landscape and Urban Planning, 65(4), 261-277.

Beyer, K. M., Szabo, A., Hoormann, K., & Stolley, M. (2018). Time spent outdoors, activity levels, and chronic disease among American adults. Journal of behavioral medicine, 41(4), 494-503.

Boyce, P. (2016). Exploring human-centric lighting.

Boyce, P. R., Veitch, J. A., Newsham, G. R., Jones, C. C., Heerwagen, J., Myer, M., & Hunter, C. M. (2006). Lighting quality and office work: two field simulation experiments. Lighting Research & Technology, 38(3), 191-223.

Brainard, G. C., Hanifin, J. P., Greeson, J. M., Byrne, B., Glickman, G., Gerner, E., & Rollag, M. D. (2001). Action spectrum for melatonin regulation in humans: evidence for a novel circadian photoreceptor. Journal of Neuroscience, 21(16), 6405-6412.

Brown, T., Brainard, G., Cajochen, C., Czeisler, C., Hanifin, J., Lockley, S., ... & Wright Jr, K. (2020). Recommendations for healthy daytime, evening, and night-time indoor light exposure.

Beni, R. D., & Cornoldi, C. (1988). Imagery limitations in totally congenitally blind subjects. Journal of Experimental Psychology: Learning, Memory, and Cognition, 14(4), 650.

Boyce, P. R., & Cuttle, C. (1990). Effect of correlated colour temperature on the perception of interiors and colour discrimination performance. Lighting Research & Technology, 22(1), 19-36.

Braden, J. P. (1985). The structure of nonverbal intelligence in deaf and hearing subjects. American Annals of the Deaf, 130(6), 496-501.

Cajochen, C., Munch, M., Kobialka, S., Krauchi, K., Steiner, R., Oelhafen, P., ... & Wirz-Justice, A. (2005). High sensitivity of human melatonin, alertness, thermoregulation, and heart rate to short wavelength light. The journal of clinical endocrinology & metabolism, 90(3), 1311-1316.

Carrier, J., & Monk, T. H. (2000). Circadian rhythms of performance: new trends. Chronobiology international, 17(6), 719-732

Castilla, N., Llinares, C., Bisegna, F., & Blanca-Giménez, V. (2018). Affective evaluation of the luminous environment in university classrooms. Journal of Environmental Psychology, 58, 52-62.

Cernin, P. A., Keller, B. K., & Stoner, J. A. (2003). Color vision in Alzheimer's patients: Can we improve object recognition with color cues? Aging, Neuropsychology, and Cognition, 10(4), 255-267.

Chamilothori, K., Wienold, J., & Andersen, M. (2019). Adequacy of immersive virtual reality for the perception of daylit spaces: Comparison of real and virtual environments. Leukos, 15(2-3), 203-226.

Chellappa, S. L., Steiner, R., Blattner, P., Oelhafen, P., Götz, T., & Cajochen, C. (2011). Non-visual effects of light on melatonin, alertness and cognitive performance: Can blue-enriched light keep us alert? PloS One, 6(1), e16429.

Chen, S., Wei, M., Dai, Q., & Huang, Y. (2019). Estimation of possible suppression of melatonin production caused by exterior lighting in commercial business districts in metropolises. LEUKOS.

Chen, Y., Cui, Z., & Hao, L. (2019). Virtual reality in lighting research: Comparing physical and virtual lighting environments. Lighting Research & Technology, 51(6), 820-837.

Corbett, R. W., Middleton, B., & Arendt, J. (2012). An hour of bright white light in the early morning improves performance and advances sleep and circadian phase during the Antarctic winter. Neuroscience Letters, 525(2), 146-151.

Craik, F. I., & McDowd, J. M. (1987). Age differences in recall and recognition. Journal of Experimental Psychology: Learning, Memory, and Cognition, 13(3), 474.

De Boer, J. B. (1967). Visual perception in road traffic and the field of vision of the motorist. Public Lighting, 1967, 11-96.

de Kort, Y. A., & Veitch, J. A. (2014). From blind spot into the spotlight. Journal of Environmental Psychology, 39, 1-4.

Dickerson, B. C., Salat, D. H., Bates, J. F., Atiya, M., Killiany, R. J., Greve, D. N., ... & Sperling, R. A. (2004). Medial temporal lobe function and structure in mild cognitive impairment. Annals of Neurology, 56(1), 27-35.

Dickerson, B. C., & Sperling, R. A. (2008). Functional abnormalities of the medial temporal lobe memory system in mild cognitive impairment and Alzheimer's disease: Insights from functional MRI studies. Neuropsychologia, 46(6), 1624-1635.

DiLaura, D. L., Houser, K., Mistrick, R., & Steffy, G. R. (2011). The lighting handbook: Reference and application.

Do, M. T. H., Kang, S. H., Xue, T., Zhong, H., Liao, H. W., Bergles, D. E., & Yau, K. W. (2009). Photon capture and signalling by melanopsin retinal ganglion cells. Nature, 457(7227), 281-287.

Dobbs, B. M., & Shergill, S. S. (2013). How effective is the Trail Making Test (Parts A and B) in identifying cognitively impaired drivers? Age and Ageing, 42(5), 577-581.

Eklund, N. H., & Boyce, P. R. (1996). The development of a reliable, valid, and simple office lighting survey. Journal of the Illuminating Engineering Society, 25(2), 25-40.

Eknoyan, D., Hurley, R. A., & Taber, K. H. (2012). The clock drawing task: common errors and functional neuroanatomy. The Journal of Neuropsychiatry and Clinical Neurosciences, 24(3), 260-265.

Field, A., & Hole, G. (2002). How to design and report experiments. Sage Ltd ISBN, 28(9780761973836), 29.

Figueiro, M. G. (2008). A proposed 24 h lighting scheme for older adults. Lighting Research & Technology, 40(2), 153-160.

Flynn, J. E., & F., J. E. (1977). A study of subjective responses to low energy and nonuniform lighting systems.

Flynn, J. E., Hendrick, C., Spencer, T., & Martyniuk, O. (1979). A guide to methodology procedures for measuring subjective impressions in lighting. Journal of the Illuminating Engineering Society, 8(2), 95-110.

Flynn, J. E., Spencer, T. J., Martyniuk, O., & Hendrick, C. (1973). Interim study of procedures for investigating the effect of light on impression and behavior. Journal of the Illuminating Engineering Society, 3(1), 87-94.

Fostervold, K. I., & Nersveen, J. (2008). Proportions of direct and indirect indoor lighting—The effect on health, well-being and cognitive performance of office workers. Lighting Research & Technology, 40(3), 175-200.

Gasio, P. F., Kräuchi, K., Cajochen, C., van Someren, E., Amrhein, I., Pache, M., ... & Wirz-Justice, A. (2003). Dawn–dusk simulation light therapy of disturbed circadian rest–activity cycles in demented elderly. Experimental gerontology, 38(1-2), 207-216.

Geerdink, M., Walbeek, T. J., Beersma, D. G., Hommes, V., & Gordijn, M. C. (2016). Short blue light pulses (30 min) in the morning support a sleep-advancing protocol in a home setting. Journal of Biological Rhythms, 31(5), 483-497.

Glickman, G., Hanifin, J. P., Rollag, M. D., Wang, J., Cooper, H., & Brainard, G. C. (2003). Inferior retinal light exposure is more effective than superior retinal exposure in suppressing melatonin in humans. Journal of Biological Rhythms, 18(1), 71-79.

Glisky, E. L. (2007). Changes in cognitive function in human aging. In Brain Aging: Models, Methods, and Mechanisms (pp. 1-27).

Golshany, N. & Elzeyadi, E., (2021). Measuring the Impact of Indoor Environ-mental Quality on Elderly Residents Cognitive Functioning – A Critical Review., Architectural Research Centers Consortium (ARCC), Tucson, Arizona, USA.

Golshany, N., Elzeyadi, E., (2022). Exploring the Impacts of Human-Cen-tric Lighting Spatial Patterns on Elderly Residents Cognitive Performance – A Meta-Analysis, Architectural Research Centers Consortium (ARCC), Miami, Florida.

Golshany, N., Elzeyadi, E., (2023). The Impact of Human-Centric Lighting on Subjective Impression: A Quantitative Study of Older Adults' Experience in Different Spatial Patterns of Light, Architectural Research Centers Consortium (ARCC), Dallas, Texas.

González-Salvador, T., Lyketsos, C. G., Baker, A., Hovanec, L., Roques, C., Brandt, J., & Steele, C. (2000). Quality of life in dementia patients in long-term care. International Journal of Geriatric Psychiatry, 15(2), 181-189.

Gopal, S., Klatzky, R. L., & Smith, T. R. (1989). Navigator: A psychologically based model of environmental learning through navigation. Journal of Environmental Psychology, 9(4), 309-331.

Gooley, J. J., Rajaratnam, S. M., Brainard, G. C., Kronauer, R. E., Czeisler, C. A., & Lockley, S. W. (2010). Spectral responses of the human circadian system depend on the irradiance and duration of exposure to light. Science Translational Medicine, 2(31), 31ra33-31ra33.

Grealy, M. A., Johnson, D. A., & Rushton, S. K. (1999). Improving cognitive function after brain injury: The use of exercise and virtual reality. Archives of Physical Medicine and Rehabilitation, 80(6), 661-667.

Hattar, S., Liao, H. W., Takao, M., Berson, D. M., & Yau, K. W. (2002). Melanopsin-containing retinal ganglion cells: architecture, projections, and intrinsic photosensitivity. Science, 295(5557), 1065-1070.

Heydarian, A., Carneiro, J. P., Gerber, D., Becerik-Gerber, B., Hayes, T., & Wood, W. (2015). Immersive virtual environments versus physical built environments: A benchmarking study for building design and user-built environment explorations. Automation in Construction, 54, 116-126.

Hidayetoglu, M. L., Yildirim, K., & Akalin, A. (2012). The effects of color and light on indoor wayfinding and the evaluation of the perceived environment. Journal of Environmental Psychology, 32(1), 50-58.

Houser, K. W., Boyce, P. R., Zeitzer, J. M., & Herf, M. (2020). Human-centric lighting: Myth, magic, or metaphor. Lighting Research & Technology, 1477153520958448.

Houser, K. W., & Esposito, T. (2021). Human-Centric Lighting: Foundational Considerations and a Five-Step Design Process. Frontiers in Neurology, 12, 25.

International Energy Agency. (1999). Post occupancy evaluation of daylight in buildings. Galve (Sweden): Centre for Built Environment.

International Energy Agency. (2016). Monitoring protocol for lighting and daylighting retrofits. Stuttgart (Germany): Fraunhofer-Institut für Bauphysik.

International Well Building Institute. (n.d.). WELL Building Standard. Retrieved from https://www.wellcertified.com/en/explore-standard

Iwata, T., Shukuya, M., Somekawa, N., & Kimura, K. (1992). Experimental study on discomfort glare caused by windows. Journal of Architectural Planning and Environmental Engineering, 432, 21–33.

Jamshidi, S., & Pati, D. (2021). A narrative review of theories of wayfinding within the interior environment. HERD: Health Environments Research & Design Journal, 14(1), 290-303.

Janosik, E., & Marczak, W. (2016). The effect of warm and cool lighting on visual performance of elderly workers. Zeszyty Naukowe Politechniki Poznańskiej Organizacja i Zarządzanie, 51-67.

Jernigan, T. L., Archibald, S. L., Fennema-Notestine, C., Gamst, A. C., Stout, J. C., Bonner, J., & Hesselink, J. R. (2001). Effects of age on tissues and regions of the cerebrum and cerebellum. Neurobiology of Aging, 22(4), 581-594.

John, N. W. (2007). The impact of Web3D technologies on medical education and training. Computers & Education, 49(1), 19-31.

Kalantari, S., Tripathi, V., Rounds, J. D., Mostafavi, A., Snell, R., & Cruz-Garza, J. G. (2021). Evaluating wayfinding designs in healthcare settings through EEG data and virtual response testing. bioRxiv.

Keis, O., Helbig, H., Streb, J., & Hille, K. (2014). Influence of blue-enriched classroom lighting on students' cognitive performance. Trends in Neuroscience and Education, 3(3-4), 86-92.

Kirk-Sanchez, N. J., & McGough, E. L. (2014). Physical exercise and cognitive performance in the elderly: current perspectives. Clinical Interventions in Aging, 9, 51.

Klepeis, N. E., Nelson, W. C., Ott, W. R., Robinson, J. P., Tsang, A. M., Switzer, P., ... & Engelmann, W. H. (2001). The National Human Activity Pattern Survey (NHAPS): a resource for assessing exposure to environmental pollutants. Journal of Exposure Science & Environmental Epidemiology, 11(3), 231-252.

Knez, I. (1997). Changes in females' and males' positive and negative moods as a result of variations in CCT, CRI and illuminance levels. Right Light 4 Proceedings.

Knez, I., & Enmarker, I. (1998). Effects of office lighting on mood and cognitive performance and a gender effect in work-related judgment. Environment and Behavior, 30(4), 553-567.

Knez, I., & Kers, C. (2000). Effects of indoor lighting, gender, and age on mood and cognitive performance. Environment and Behavior, 32(6), 817-831.

Konis, K. (2018). Field evaluation of the circadian stimulus potential of daylit and non-daylit spaces in dementia care facilities. Building and Environment, 135, 112-123.

Kort, Y. A. D., Ijsselsteijn, W. A., Kooijman, J., & Schuurmans, Y. (2003). Virtual laboratories: Comparability of real and virtual environments for environmental psychology. Presence: Teleoperators & Virtual Environments, 12(4), 360-373.

Kuş, B. (2019). A comparative study on spatial perception in real and virtual office environments under different lighting conditions (Doctoral dissertation, Bilkent Universitesi (Turkey)).

Lambooij, M., IJsselsteijn, W., Bouwhuis, D. G., & Heynderickx, I. (2011). Evaluation of stereoscopic images: Beyond 2D quality. IEEE Transactions on Broadcasting, 57(2), 432-444.

Lee, H. B., & Lyketsos, C. G. (2003). Depression in Alzheimer's disease: Heterogeneity and related issues. Biological Psychiatry, 54(3), 353-362.

Lee, S., Yang, J. W., Kim, J. Y., & Kim, K. (2018). Cognitive function and virtual reality. Journal of Exercise Rehabilitation, 14(3), 321-327.

Lindenberger, U., & Baltes, P. B. (1994). Sensory functioning and intelligence in old age: A strong connection. Psychology and Aging, 9(3), 339.

Lin, C. N. (2013). Heat Transfer Enhancement Analysis of a Cylindrical Surface by a Piezoelectric Fan. Applied Therm. Eng, 50, 693-703.

Lin, M. Y., Gutierrez, P. R., Stone, K. L., Yaffe, K., Ensrud, K. E., Fink, H. A., ... & Mangione, C. M. (2004). Study of Osteoporotic Fractures Research Group. Vision impairment and combined vision and hearing impairment predict cognitive and functional decline in older women. J Am Geriatr Soc, 52(12), 1996-2002.

Lu, X., Park, N. K., & Ahrentzen, S. (2019). Lighting effects on older adults' visual and nonvisual performance: A systematic review. Journal of Housing for the Elderly, 33(3), 298-324.

Lucas, R. J., Lall, G. S., Allen, A. E., & Brown, T. M. (2012). How rod, cone, and melanopsin photoreceptors come together to enlighten the mammalian circadian clock. Progress in Brain Research, 199, 1-18.

Lucas, R. J., Peirson, S. N., Berson, D. M., Brown, T. M., Cooper, H. M., Czeisler, C. A., et al. (2014). Measuring and using light in the melanopsin age. Neurotoxins., 37(1), 1-9.

Lynch, K. (1960). The image of the city. MIT Press.

MacGregor, J. N., Ormerod, T. C., & Chronicle, E. P.

Manav, B., & Yener, C. (1999). Effects of different lighting arrangements on space perception. *Architectural Science Review*, *42*(1), 43-47.

McKennan, G. T., & Parry, C. M. (1984). An investigation of task lighting for offices. Lighting Research & Technology, 16(4), 171-186.

Melo, M., Bessa, M., Debattista, K., & Chalmers, A. (2015, December). Evaluation of Tone-Mapping Operators for HDR Video Under Different Ambient Luminance Levels. In Computer Graphics Forum (Vol. 34, No. 8, pp. 38-49).

Miller, N. J., & Irvin, A. L. (Year). M/P ratios-Can we agree on how to calculate them?

Moore, R. Y. (1996). Entrainment pathways and the functional organization of the circadian system. Progress in Brain Research, 111, 103-119.

Murdoch, M. J., Stokkermans, M. G., & Lambooij, M. (2015). Towards perceptual accuracy in 3D visualizations of illuminated indoor environments. Journal of Solid State Lighting, 2, 1-19.

Neten, A. (1989). The effect of design of residential homes in creating dependency among confused elderly residents: A study of elderly demented residents and their ability to find their way around homes for the elderly. International Journal of Geriatric Psychiatry, 4(3), 143-153.

Noell-Waggoner, E. U. N. I. C. E. (2006). Lighting in nursing homes-The unmet need. In Proceedings of the 2nd International Commission on Illumination Expert Symposium on Lighting and Human Health (pp. 7-8).

Nolin, P., Stipanicic, M., & Grange, J. A. (2019). Virtual reality and cognitive assessment: The state of the art. Neuropsychology Review, 29(2), 152-162.

Omidfar Sawyer, A., & Chamilothori, K. (2019). Influence of subjective impressions of a space on brightness satisfaction: An experimental study in virtual reality. In Proceedings of Symposium on Simulation for Architecture and Urban Design 2019 (No. CONF).

O'Neill, M. (1991). A biologically-based model of spatial cognition and wayfinding. Journal of Environmental Psychology, 11(4), 299-320.

Osterhaus, W. K., & Bailey, I. L. (1992, October). Large area glare sources and their effect on visual discomfort and visual performance at computer workstations. In Conference Record of the 1992 IEEE Industry Applications Society Annual Meeting (pp. 1825-1829). IEEE.

Pache, M., Smeets, C. H., Gasio, P. F., Savaskan, E., Flammer, J., Wirz-Justice, A., & Kaiser, H. J. (2003). Colour vision deficiencies in Alzheimer's disease. Age and Ageing, 32(4), 422-426.

Panda, S., Nayak, S. K., Campo, B., Walker, J. R., Hogenesch, J. B., & Jegla, T. (2005). Illumination of the melanopsin signaling pathway. Science, 307(5709), 600-604.

Pan, Z., Cheok, A. D., Yang, H., Zhu, J., & Shi, J. (2006). Virtual reality and mixed reality for virtual learning environments. Computers and Graphics, 30(1), 20-28.

Papamichael, C., Skene, D. J., & Revell, V. L. (2012). Human nonvisual responses to simultaneous presentation of blue and red monochromatic light. Journal of Biological Rhythms, 27(1), 70-78.

Park, D. C., Polk, T. A., Mikels, J. A., Taylor, S. F., & Marshuetz, C. (2001). Cerebral aging: integration of brain and behavioral models of cognitive function. Dialogues in clinical neuroscience, 3(3), 151.

Papamichael, C., Skene, D. J., & Revell, V. L. (2012). Human nonvisual responses to simultaneous presentation of blue and red monochromatic light. Journal of biological rhythms, 27(1), 70-78.

Phipps-Nelson, J., Redman, J. R., Schlangen, L. J., & Rajaratnam, S. M. (2009). Blue light exposure reduces objective measures of sleepiness during prolonged nighttime performance testing. Chronobiology International, 26(5), 891-912.

Plotnik, M., Ben-Gal, O., Doniger, G. M., Gottlieb, A., Bahat, Y., Cohen, M., ... & Beeri, M. S. (2021). Multimodal immersive trail-making-virtual reality paradigm to study cognitive-motor interactions. Journal of neuroengineering and rehabilitation, 18(1), 1-16.

Purandare, N., Burns, A., Craig, S., Faragher, B., & Scott, K. (2001). Depressive symptoms in patients with Alzheimer's disease. International Journal of Geriatric Psychiatry, 16(10), 960-964.

Raffin, M., & Guarnieri, G. (2008, February). Tone mapping and enhancement of high dynamic range images based on a model of visual perception. In Proc. of the Tenth IASTED International Conference on Computer Graphics and Imaging (pp. 190-195).

Rea, M. S., Ouellette, M. J., & Tiller, D. K. (1990). The effects of luminous surroundings on visual performance, pupil size, and human preference. Journal of the Illuminating Engineering Society, 19(2), 45-58.

Revell, V. L., Arendt, J., Terman, M., & Skene, D. J. (2005). Short-wavelength sensitivity of the human circadian system to phase-advancing light. Journal of Biological Rhythms, 20(3), 270-272.

Richardson, A. E., Montello, D. R., & Hegarty, M. (1999). Spatial knowledge acquisition from maps and from navigation in real and virtual environments. Memory & Cognition, 27(4), 741-750.

Riemersma-van Der Lek, R., Swaab, D., Twisk, J., Hol, E., Hoogendijk, W., & Van Someren, E. (2008). Effect of bright light and melatonin on cognitive and noncognitive function in elderly residents of group care facilities - A randomized controlled trial. JAMA-Journal of the American Medical Association, 299(22), 2642-2655.

Roenneberg, T., Kumar, C. J., & Merrow, M. (2007). The human circadian clock entrains to sun time. Current Biology, 17(2), R44-R45.

Rothbaum, B. O., & Hodges, L. F. (1999). The use of virtual reality exposure in the treatment of anxiety disorders. Behavior Modification, 23(4), 507-525.

Rüger, M., Gordijn, M. C., Beersma, D. G., de Vries, B., & Daan, S. (2003). Acute and phase-shifting effects of ocular and extraocular light in human circadian physiology. Journal of biological rhythms, 18(5), 409-419.

Ru, T., de Kort, Y. A., Smolders, K. C., Chen, Q., & Zhou, G. (2019). Non-image forming effects of illuminance and correlated color temperature of office light on alertness, mood, and performance across cognitive domains. Building and Environment, 149, 253-263.

Satlin, A., Volicer, L., Ross, V., Herz, L., & Campbell, S. (1992). Bright light treatment of behavioral and sleep disturbances. American Journal of Psychiatry, 149, 1028.

Schatz, P. (2011). Mini-Mental State Exam. Encyclopedia of Clinical Neuropsychology, 1640-1641.

Sharlin, E., Watson, B., Sutphen, S., Liu, L., Lederer, R., & Frazer, J. (2009). A tangible user interface for assessing cognitive mapping ability. International Journal of Human-Computer Studies, 67, 269-278.

Sinoo, M. M. (2016). Light conditions in nursing homes: visual comfort and visual functioning of residents.

Sinoo, M. M., Van Hoof, J., & Kort, H. S. (2011). Light conditions for older adults in the nursing home: Assessment of environmental illuminances and colour temperature. Building and Environment, 46(10), 1917-1927.

Stampfer, M. J., Buring, J. E., Willett, W., Rosner, B., Eberlein, K., & Hennekens, C. H. (1985). The 2× 2 factorial design: Its application to a randomized trial of aspirin and US physicians. Statistics in Medicine, 4(2), 111-116.

Stockman, A., & Sharpe, L. T. (2000). The spectral sensitivities of the middle- and long-wavelength-sensitive cones derived from measurements in observers of known genotype. Vision Research, 40(13), 1711-1737.

Taylor, L. H., LH, T., EW, S., & DH, S. (1975). Office lighting and performance.

Viola, A. U., James, L. M., Schlangen, L. J., & Dijk, D. J. (2008). Blue-enriched white light in the workplace improves self-reported alertness, performance and sleep quality. Scandinavian Journal of Work, Environment & Health, 34(4), 297-306.

Visser, E. K., Beersma, D. G., & Daan, S. (1999). Melatonin suppression by light in humans is maximal when the nasal part of the retina is illuminated. Journal of Biological Rhythms, 14(2), 116-121.

van Hoof, J., Schoutens, A., & Aarts, M. (2009). High colour temperature lighting for institutionalised older people with dementia. Building and Environment, 44(9), 1959-1969.

Vandewalle, G., Gais, S., Schabus, M., Balteau, E., Carrier, J., Darsaud, A., ... & Maquet, P. (2007). Wavelength-dependent modulation of brain responses to a working memory task by daytime light exposure. Cerebral Cortex, 17(12), 2788-2795.

Vandewalle, G., Maquet, P., & Dijk, D. J. (2009). Light as a modulator of cognitive brain function. Trends in Cognitive Sciences, 13(10), 429-438.

Vazzana, R., Bandinelli, S., Lauretani, F., Volpato, S., Lauretani, F., Di Iorio, A., ... & Ferrucci, L. (2010). Trail Making Test predicts physical impairment and mortality in older persons. Journal of the American Geriatrics Society, 58(4), 719-723.

Veitch, J. A. (2001). Psychological processes influencing lighting quality. Journal of the Illuminating Engineering Society, 30(1), 124-140.

Veitch, J. A., & Newsham, G. R. (2000). Exercised control, lighting choices, and energy use: An office simulation experiment. Journal of Environmental Psychology, 20(3), 219-237.

Veitch, J. A., Newsham, G. R., Boyce, P. R., & Jones, C. C. (2008). Lighting appraisal, well-being and performance in open-plan offices: A linked mechanisms approach. Lighting Research & Technology, 40(2), 133-151.

Veitch, J. A., Newsham, G. R., Mancini, S., & Arsenault, C. D. (2010). Lighting and office renovation effects on employee and organizational well-being. Journal of Environmental Psychology, 30(4), 533-541.

Viola, A. U., James, L. M., Schlangen, L. J., & Dijk, D. J. (2008). Blue-enriched white light in the workplace improves self-reported alertness, performance, and sleep quality. Scandinavian journal of work, environment & health, 297-306.

Wong, M. O., Du, J., Zhang, Z. Q., Liu, Y. Q., Chen, S. M., & Lee, S. H. (2019, February). An experience-based interactive lighting design approach using BIM and VR: A case study. In IOP Conference Series: Earth and Environmental Science (Vol. 238, No. 1, p. 012006). IOP Publishing.

Woodford, H. J., & George, J. (2007). Cognitive assessment in the elderly: A review of clinical methods. QJM: An International Journal of Medicine, 100(8), 469-484.

Wright Jr, K. P., McHill, A. W., Birks, B. R., Griffin, B. R., Rusterholz, T., & Chinoy, E. D. (2013). Entrainment of the human circadian clock to the natural light-dark cycle. Current Biology, 23(16), 1554-1558.

Wu, A., Zhang, W., & Zhang, X. (2009). Evaluation of wayfinding aids in virtual environment. International Journal of Human-Computer Interaction, 25(1), 1-21.

Yamadera, H., Ito, T., Suzuki, H., Asayama, K., Ito, R., & Endo, S. (2000). Effects of bright light on cognitive and sleep-wake (circadian) rhythm disturbances in Alzheimer-type dementia. Psychiatry and Clinical Neurosciences, 54(3), 352-353.

Yang, W., & Jeon, J. Y. (2020). Effects of correlated colour temperature of LED light on visual sensation, perception, and cognitive performance in a classroom lighting environment. Sustainability, 12(10), 4051

Yearout, R., & Konz, S. (1989). Visual display unit workstation lighting. International Journal of Industrial Ergonomics, 3, 265-273.

Zhu, S., Sui, Y., Shen, Y., Zhu, Y., Ali, N., Guo, C., & Wang, T. (2021). Effects of virtual reality intervention on cognition and motor function in older adults with mild cognitive impairment or dementia: A systematic review and meta-analysis. Frontiers in Aging Neuroscience, 13, 586999.