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The Emotional and Aesthetic Impact of Vegetation Density in a Virtual Urban Environment

GEO 511 Master's Thesis

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Abstract

Growing population causes a rapid increase in urbanisation leading to denser urban environments at the expense of nature and aesthetics. The loss of natural elements has a negative impact on both the environment as well as the population. The lack of restorative natural environments combined with the pressures associated with urban living can lead to serious health problems. To counteract this development, continuous urban greenery is key. While there have been several studies exploring the positive effect of vegetation on stress, this study aims to find out if different vegetation densities affect stress and perceived aesthetics differently.

For this purpose, 40 participants were recruited and randomly assigned to one of three groups representing *low* (0 – 25%), *medium* (26 – 41%), and *high* (42 – 67%) vegetation density. Using a virtual reality (VR) model, participants were exposed to five different urban environments while their electrodermal activity (EDA) was measured to assess stress levels. In addition, participants provided self-reported arousal, valence, and questionnaire ratings based on landscape aesthetics theories such as Attention Restoration Theory (ART), Preference Matrix (PM), and Prospect-Refuge Theory (PR).

Results indicate that *medium* vegetation density provides the most effective stress relief. *High* vegetation density, while visually appealing, led to increased physiological arousal, suggesting that excessive greenery may introduce visual complexity that counter acts its restorative potential. Questionnaire ratings showed no significant relationship between vegetation density and perceived restoration, preference, or safety. Some environments had a significant influence on valence and questionnaire ratings, suggesting urban design having a stronger impact on these measures than vegetation density.

Future research could further explore the interaction between vegetation and urban design or expand on other urban factors, such as layout, lighting, noise, or social activity to determine what affects emotion and aesthetic perception in urban environments besides vegetation.

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1 Introduction

This chapter provides the motivation behind the thesis as well as the research goal and the specific research questions. Finally, the structure of the thesis is briefly outlined.

1.1 Motivation

Urban environments are increasingly becoming the primary living space for a majority of the global population. Scenarios show that in 2050 over 68% of the world's population will live in urban areas (United Nations, 2018). This shift has led to a concerning trend of natural degradation, where green spaces are sacrificed to accommodate growing populations and infrastructure needs. This loss of nature within urban environments has profound consequences for human well-being and ecological stability. It has been linked to increased stress levels, diminished air quality, and reduced overall well-being (Pätzold, 2023; World Health Organization, 2016). Modern life demands constant adaptation to fast-paced routines, and the pressures associated with urban living can contribute to chronic stress, which is a precursor to serious health conditions such as cardiovascular disease, depression, and anxiety disorders (Dimsdale, 2008; Lederbogen et al., 2011; Wang, 2004). Urban stressors, including noise pollution, overcrowding, and lack of restorative environments, increase these risks, making mental health a growing public concern in urban areas.

In response to these challenges, urban greenery poses a high potential. Exposure to natural environments has been associated with stress reduction and improved psychological well-being in various research. Studies suggest that even brief interactions with green spaces such as viewing trees or walking through parks, can induce physiological relaxation responses, including lower heart rate, reduced blood pressure, and decreased cortisol levels (Hartig et al., 1997; Tyrväinen et al., 2014; Ulrich et al., 1991). Furthermore, theories of landscape aesthetics, such as the Attention Restoration Theory (Kaplan & Kaplan, 1989) or Appleton's (1975) Prospect-Refuge Theory, propose that natural environments help to restore cognitive resources, mitigate the effects of urban stressors, and influence perceived safety when meeting certain conditions.

To measure the positive impact of vegetation on stress reduction and emotion, researchers have used various methods, such as electroencephalography (EEG) to assess brain activity, heart rate variability, and electrodermal activity (EDA) (Fu et al., 2022; Olszewska-Guizzo et al., 2023; C.-P. Yu et al., 2018). While still being a relatively new method, virtual reality (VR) has been used successfully in studies on the emotional impact of environments (Batistatou et al., 2022;

Huang et al., 2020; Lendenmann, 2023) and poses several advantages against traditional methods like reviewing photographs or real-world observations. Photographs and videos lack depth perception and real-world studies introduce uncontrollable variables, making it challenging to isolate the effects of vegetation from other environmental factors (Higuera-Trujillo et al., 2017).

1.2 Research Gap and Goal

While numerous studies have examined the benefits of urban greenery, there is a lack of research that quantitatively analyses the nuanced effects of vegetation density levels within urban settings. How does the dose-response curve between vegetation density and stress relief look like? Is it a linear relationship or is there a detectable maximum? While there has been a study dealing with this question, it was set in a low-density suburb where urban stress is less pronounced (Jiang et al., 2014).

Additionally, there are not a lot of studies that combine the theories of landscape aesthetics with physiological and psychological emotion measurements. Most studies focus only on some of these factors. A combination of these concepts and measures can potentially provide to a more holistic understanding of the effect of vegetation density on people's perception.

This thesis aims to investigate the influence of vegetation density in high-density urban environments on stress reduction and aesthetic perception. By using VR technology and a combination of subjective and objective emotion measurements, this thesis aims to build on previous research an provide insights into how urban landscapes can be designed to optimise both emotional well-being and visual appeal. The findings have the potential to inform future policies that prioritise well-being, sustainability, and aesthetics in urban development.

1.3 Research Questions

Based on the research goal and previous research, the following research questions and hypotheses have been defined:

RQ1: How does the vegetation density in an urban environment affect people's emotion represented by arousal and valence?

> ***H1.1***: *Arousal decreases with increasing vegetation density.*
>
> ***H1.2***: *Medium vegetation density leads to the highest stress relief.*
>
> ***H1.3***: *Valence increases with increasing vegetation density.*
>
> ***H1.4***: *Medium vegetation density leads to the highest valence.*

RQ2: How does the amount of vegetation affect people's preference and aesthetic perception?

> ***H2.1****: Higher vegetation density leads to the highest perceived restoration.*
>
> ***H2.2****: Medium vegetation density leads to the highest preference.*
>
> ***H2.3****: Medium vegetation density enhances perceived safety and shelter.*

RQ3: Is there a correlation between measured stress relief and people's rating based on theories of landscape aesthetics in an urban environment?

> ***H3.1****: Environments with higher stress relief are also perceived more aesthetically pleasing*.

1.4 Structure of the Thesis

Following the **Introduction**, the **State of Research** provides a detailed literature review and presents the theoretical frameworks on which this thesis is based. The **Methods** chapter describes the experimental design and the different emotion measurements. This is followed by the **Results** presenting the findings and exploring patterns in physical and subjective emotion responses. The **Discussion** contextualises the results within existing literature and discusses their limitations. Finally, the **Conclusion** summarises the main findings and outlines directions for future research.

2 State of Research

This chapter provides the theoretical background for this thesis. It starts with the impact of urbanisation on various aspects of life, followed by some key concepts of landscape aesthetics and the importance of urban green space. The chapter is concluded by the introduction of VR as a tool for environmental assessment, as well as different emotion measurements.

2.1 Urbanisation and its Challenges

As populations grow the demand for housing and infrastructure expands and the process of urbanisation rapidly transforms landscapes, posing a pressing challenge for the preservation of rural and natural spaces. Especially in countries with constrained land availability, this issue becomes complex as cities often expand into surrounding rural areas which is referred to as urban sprawl. This leads to the fragmentation of rural spaces and a loss of cultural landscapes, biodiversity and agricultural land. The trend of building upwards instead of outwards is therefore emerging as a strategy to accommodate growing urban populations while preserving cultural landscapes. Besides spatial efficiency, high-density cities require shorter travel distances and encourage public transport, thereby reducing emissions from vehicles (Bureau, 2011). Another important aspect of urban planning is compliance with global sustainability goals. Some see high-density cities as a successful strategy to achieve these goals, however, density alone is not enough. Cities need strategies to minimise the negative environmental, social, and health impacts of densifying (Hamnett, 2011; Pont et al., 2021).

2.1.1 Aesthetics vs. Functionality in Urban Environments

One of the negative impacts of densification is the tendency toward functional, utilitarian design at the expense of aesthetics. Urban areas often prioritise economic efficiency and maximising spatial utilisation over creating environments that are visually appealing or emotionally stimulating (Hendawy et al., 2022). As a result, many cities are designed to meet immediate physiological needs while neglecting deeper human needs, such as a sense of identity, belonging, and well-being (Proshansky, 1978). Noor and Kamar (2022) identify these needs as non-physical design needs, including rest, interconnection, privacy, safety, and clear orientation. This neglect of aesthetics is particularly evident in rapidly growing cities.

High-density living is therefore often perceived as less desirable compared to the traditional single-family house picture (Howley et al., 2009). It is important for urban planners and designers to identify the advantages of low-density single-home communities and explore ways to integrate them into high-density cities. For example, incorporating architectural elements that respect local traditions and providing sufficient private and public green spaces can enhance urban liveability. To be efficient, urban planning must also consider integrating multi-functional spaces, such as rooftop gardens or underground transit systems (Lovell, 2010). The possibility of forming smaller communities within large cities is an important factor that urban designers should consider. There need to be places where people feel safe and undisturbed. Rural environments are characterised by natural surfaces, small homogeneous populations, low-density living, and traditional cultural practices (Arenibafo, 2020). Some ways to incorporate rural elements into urban settings include urban agriculture, urban forests, and rural aesthetics, such as the use of natural materials like wood, stone or earth (Arenibafo, 2020).

2.1.2 Degradation of Natural Elements in Cities

With increasing urban populations, cities expand, and natural elements are often neglected in favour of infrastructure, transportation, and housing. This leads to numerous challenges, such as urban heat islands, increased pollution, and limited access to restorative natural environments like parks. Together, these issues contribute to "urban stress", a term describing stress that arises from environmental factors specific to cities, including air pollution, noise, overcrowding, and visual overstimulation (GEMET - Environmental thesaurus, 2017). Chronic exposure to urban stress has become a significant health concern, as it is linked to issues such as mental fatigue, anxiety, and depression (Lederbogen et al., 2011; Pätzold, 2023; Wang, 2004).

Green spaces are critical for urban environments as the act as carbon sinks, provide natural habitats for wildlife, and help mitigate urban heat island effects and air pollution. However, these essential regulating services are increasingly threatened by urbanisation. To increase urban density, parks, meadows, and forests are often replaced with new buildings and roads, leading to surface sealing. The replacement of natural ground with impermeable materials like asphalt and concrete leads to urban heat island effects as these surfaces absorb and radiate more heat, creating higher temperatures compared to rural areas (Bhargava et al., 2017).

While urbanisation's immediate challenges, such as housing shortage, infrastructure demands, and environmental stress, dominate policy discussions, the role of aesthetics should not be overlooked. Urban design that integrates beauty and functionality enhances liveability, strengthens community identity and supports long-term sustainability. Recognising the importance of aesthetics is not only about improving the visual appeal of cities, but about creating functional, inviting spaces that support the well-being of residents. The next chapter will focus on theories of landscape aesthetics and their impact on people's perception of their environment.

2.2 Landscape Aesthetics

Incorporating aesthetic principles into urban planning is essential for fostering sustainable environments and creating emotional attachment (Taylor, 2009). While landscape aesthetics originally stem from rural and natural settings, their application in urban contexts plays a crucial role in shaping human experiences. This chapter explores how landscapes are perceived and focusses on four key concepts of landscape aesthetics: Preference Matrix (Kaplan & Kaplan, 1989), Attention Restoration Theory (Kaplan & Kaplan, 1989), Prospect-Refuge Theory (Appleton, 1975), and Neuroaesthetics (Chatterjee & Vartanian, 2014, 2016).

2.2.1 Landscape Perception

Landscape perception is shaped by object-related, culture-related, and subject-related factors (Rodewald et al., 2020). Object-related perception assesses beauty independently of a cultural or personal influences. An example would be the Alpine landscape, which is generally perceived as beautiful. It is linked to the field of neuroaesthetics that will be discussed later in this chapter. Culture-related perception frames beauty as a construct shaped by cultural context, where the idea of a landscape is more important than reality. It is influenced by concepts such as place identity (Proshansky, 1978), sense of place (Jorgensen & Stedman, 2001), and place attachment (Gerson et al., 1977). Finally, subject-related perception is driven by individual emotions and experiences, leading to diverse interpretations of the same landscape.

Given the complexity of landscape perception, this thesis focuses on four theories that represent different intersections of these perspectives. Neuroaesthetics is primarily object-related, while Prospect-Refuge-Theory integrates both object- and culture-related elements. Attention restoration Theory and Preference Matrix on the other hand lie on the intersection of object- and subject-related influences (Rodewald et al., 2020). These four theories will now be further explored.

2.2.2 Preference Matrix

Kaplan & Kaplan (Kaplan & Kaplan, 1989) identified four factors that influence landscape preference: coherence, legibility, complexity, and mystery (Table 1). These factors are defined by two overarching domains: understanding vs. exploration and immediate vs. inferred, predicted, which arrange them in a Preference matrix (PM). While the first domain refers to how easily a landscape can be interpreted and understood and whether the landscape sparks curiosity to engage further with the scene, the second domain refers to how quickly the necessary information can be extracted from the scene. For example, a park with clear paths and visible landmarks makes understanding easy, while a dense forest trail invites more exploration. Similarly, a well-maintained garden has an immediate appeal, while mountains covered in mist have more of an inferred intrigue. In studies where the Preference Matrix has been used to assess the aesthetics of landscapes, the factors complexity and mystery seem to predict preference the best (Herzog, 1989; Memari & Pazhouhanfar, 2017; Shayestefar et al., 2022; Van Der Jagt et al., 2014).

Table 1: Preference Matrix by Kaplan & Kaplan (1989)

	Understanding	**Exploration**
Immediate	Coherence	Complexity
Inferred, predicted	Legibility	Mystery

Coherence

Coherence refers to the degree of which a scene provides a sense of order and organisation that helps to understand it immediately. In a coherent landscape, the contained elements harmoniously relate to each other creating a scene that feels structured and predictable. Coherence can be measured by describing the degree of repetition or autocorrelation, for example with Moran's I. Examples are evenly spaced trees or flowerbeds and uniformity in texture like the lines of hedgerows in the English countryside (Figure 1). These structures make it easy to comprehend the scene at one glance, creating a sense of calm and order. On the other hand, a disorganised, overloaded landscape, such as an overgrown garden with no distinguishable paths, might feel overwhelming with its lack of coherence (Zhang et al., 2021).

Figure 1: English pastures with hedgerows (Abell, 2023)

Legibility

Legibility describes how easily an observer can navigate and make sense of a scene. A highly legible environment provides clear orientation through distinctive landmarks, enabling individuals to move confidently through the space and to find their way back to any given point (Stamps, 2004). For example, a well signposted hiking trail with distinct landmarks enhances legibility, whereas an urban alleyway with identical-looking buildings can cause disorientation. Although legibility contributes to a sense of ease, research suggests it has the least impact on preference compared to the other factors in the matrix (Herzog & Leverich, 2003; Stamps, 2004).

Complexity

Other than the previous factors, complexity calls on the curiosity of the observer and is described as the richness of a scene based in the amount of different visual elements (Kaplan & Kaplan, 1989). A complex landscape contains multiple layers of interest, which can hold attention over time. While coherence provides clarity, complexity ensures that the scene is captivating. This suggests that variety in a scene enhances exploration and ultimately preference. However, the relationship between complexity and preference is not linear but rather an inverted U-shape (Figure 2) (Berlyne, 1963). High complexity often creates interest and attention but not necessarily preference. Many studies have explored the effect of complexity in natural environments on preference. The results differ because of the difficulty to display the whole range of complexity (Wohlwill, 1976). Some studies that concluded a linear relationship between complexity and preference, only considered natural scenes with low to medium complexity (Ulrich, 1983). If complexity is too high, it can lead to confusion if the scene lacks coherence as well. An example for a complex landscape might be a dense rainforest with an abundance of sensory stimuli like sounds, visuals, and smells. In an urban area, it would be a large square in the city centre with bustling activity.

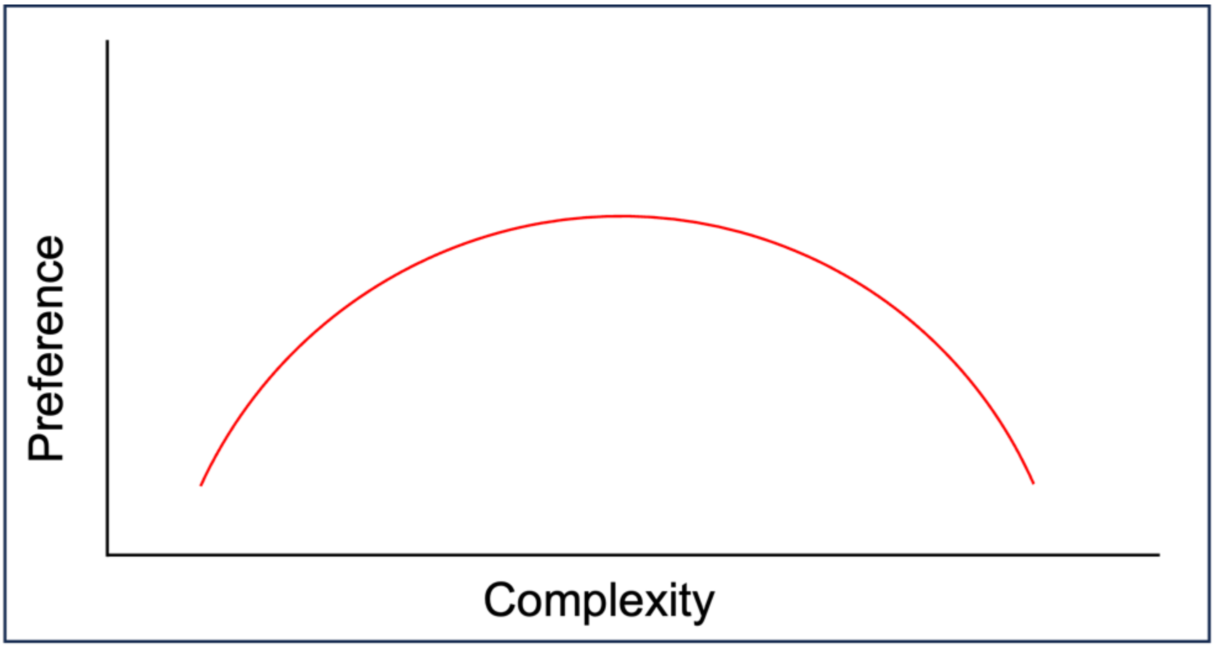

Figure 2: Dose Response Curve between preference and complexity based on Berlyne's (1963) theory

Mystery

Landscapes that provide a sense of mystery are not immediately understandable and have multiple dimensions to them. Mystery sparks invite to further exploration and the unknown draws the viewer into the scene. It suggests that there is more to discover which encourages the observer to engage with their environment (Kaplan & Kaplan, 1989). The dimension of inferred or predicted information is particularly important in this case, as it inspires the imagination. One example would be a misty scene where only the nearest features are recognisable or a bended path that disappears behind vegetation or buildings. Ultimately, it is a scene that promises to find more information through exploration and therefore sparks curiosity. While mystery is a strong indicator for preference, it also predicts perceived danger (Herzog & Miller, 1998). This paradox shows that the combination of all four factors is crucial for an ideal environment as they balance each other perfectly.

2.2.3 Attention Restoration Theory

In The Experience of Nature, Kaplan & Kaplan (Kaplan & Kaplan, 1989) introduced the Attention Restoration Theory (ART) alongside the Preference Matrix. While the Preference Matrix explains why certain landscapes are visually preferred, ART explores how environments restore cognitive function after mental fatigue. It claims that directed attention is a limited cognitive resource that needs restoring after a certain time. In today's high-demand world it becomes an increasingly relevant concept. Like the Preference Matrix, ART was initially designed to describe natural settings and is defined by four key factors: being away, extent, fascination, and compatibility.

Being Away

Being away refers to the sense of escape from daily stress and routine that drain cognitive resources. This occurs when individuals experience an environment distinctly different from their everyday surroundings. Physical distance is not necessarily required but rather the feeling of detachment from routine stress is crucial. Natural settings such as forests, waterfronts, or remote mountains would be examples for being away. Even urban parks can create a sense of being away if they contrast sufficiently with the surrounding environment. This desire of being away can be observed in the choice of vacation destinations. The dream of a quiet beach with palm trees and clear blue water is the prime example of being away.

Extent

Similar to factors in the Preference Matrix, extent refers to the immersive quality of an environment, providing enough depth and coherence to fully engage the mind. A space with high extent offers a sense of vastness and connectedness, inviting deeper exploration. This is achieved through landscapes with layered elements, such as expansive parks or rolling hills. In urban settings, large green spaces like Central Park provide extent by offering diverse features and pathways that extend beyond the immediate view. In rural settings, extent is often easier to achieve due to the naturally expansive qualities of the landscape. Examples include a mountain range, or vast, open terrains covered with meadows and fields, creating a sense of boundless space.

Fascination

Fascination captures the ability of an environment to hold attention effortlessly. Kaplan & Kaplan (1989) differentiate between “soft fascination”, which involves subtle, undramatic stimuli such as the movement of leaves or waves, and more intense forms of engagement. Soft fascination is particularly beneficial for restoration, as it allows the mind to relax while still being engaged. An environment that sparks fascination should have the capability to hold the attention of the viewer for a longer time. One of the best examples according to Kaplan & Kaplan (1989) is a garden that combines aesthetics and interest while allowing the mind to take a break from daily stress. Soft fascination is therefore unexciting but captivating enough to get lost in thought while viewing a scene. This way the scene helps to process potentially stressing experiences that happened before.

Compatibility

Compatibility describes how well an environment aligns with individual’s needs and preferences. A compatible setting allows effortless interaction, reducing cognitive strain while engaging in preferred activities. Studies suggest that environments fostering a “sense of oneness” enhance restoration by seamlessly accommodating users’ activities and preferences (Talbot & Kaplan, 1986). An example for a highly compatible environment would be a park with spaces that are designed for diverse activities like well-maintained paths for jogging, playgrounds for children to play, or comfortable seating areas for picnicking or quiet reading. In more natural areas, compatibility is achieved when the environment offers intuitive access to its features like paths that naturally lead to viewpoints or recreation areas like a lake or the beach.

2.2.4 Prospect-Refuge Theory

Appleton’s Prospect-Refuge Theory (PR) builds on Habitat Theory, suggesting that landscapes are aesthetically pleasing when they fulfil fundamental biological needs (Appleton, 1975). In the Prospect-Refuge Theory he develops the idea further by suggesting that aesthetics in a landscape is met when it provides the possibility “to see without being seen” (Rodewald et al., 2020). This theory is based on more primal needs and looks at aesthetics from a different standpoint that the previous two.

Prospect

Prospect refers to the opportunity to survey a landscape, which originally aided in detecting potential threats. Today, this translates to an appreciation for expansive views, such as panoramic overlooks or open fields. For example, landscapes with clear vantage points and outlooks like mountain tops are popular tourist attractions.

Refuge

Refuge, on the other hand, describes the presence of shelter, offering protection from external elements. Appleton differentiates between hiding from animate hazards and seeking shelter from inanimate hazards (Appleton, 1975) playing into the hunter role of humans, which sparked some critic. Hudson (Hudson, 1992) added to the theory by stressing the desire for shelter over the need to hide, mentioning the popularity of balconies and gazebos. Both provide shelter from weather influences while being a place of relaxation and restoration close to a more open space.

2.2.5 Neuroaesthetics

Neuroaesthetics explores the brain's role in aesthetic judgment, moving beyond subjective preferences to uncover underlying neural mechanisms. It identifies three key systems, known as the "aesthetic triad": sensory-motor, emotion-valuation, and knowledge-meaning (Vartanian & Chatterjee, 2022). The sensory-motor system processes visual features like colour, luminance, and shape and seems to not be affected by expertise. The emotion-valuation system links aesthetic pleasure to the brain's reward system, while the knowledge-meaning system emphasizes how context and personal interpretation shape aesthetic judgment. People often value authentic art more than forgeries, suggesting that knowledge and perceived authenticity affect behavioural responses more than sensory qualities (Vartanian & Chatterjee, 2022).

Neural responses also vary between natural and urban environments. A study found that rural scenes activated brain regions linked to spatial awareness, sensory processing, and reward pathways, suggesting they are perceived as open, less structured places that can be explored. In contrast, urban scenes stimulated areas associated with detailed visual processing, memory, and emotional evaluation, reflecting their complexity and density (Kim et al., 2010). Understanding these neural responses helps laying the groundwork for further research on the effects of environments on well-being. Especially in urban areas where green spaces serve as a counterbalance to the dense, stimulating environments.

These theories of landscape aesthetics highlight the role of beauty and natural elements in restoration, well-being, and neurological responses. Understanding these connections can inform better urban design, enhancing residents' well-being. Given the complexity of the topic, this thesis focuses on the impact of natural elements, explored in the next chapter.

2.3 Urban Green Space

The integration of green spaces into urban environments enhances both aesthetic appeal and overall liveability. Parks, gardens, and street greenery provide a visual and sensory counterbalance to the hard materials dominating cityscapes, such as concrete, asphalt, and steel. Beyond their visual benefits, urban green spaces offer essential ecosystem services, such as air purification, climate regulation, and biodiversity support (Romanazzi et al., 2023). Additionally, the concept of biophilic design, which integrates natural elements into built environments, has gained attention for its role in reducing stress and improving cognitive function (Kellert & Calabrese, 2015). Green spaces, therefore, serve not only an ecological function but also contribute significantly to human well-being.

Perceived beauty is closely related to natural environments, often triggering positive neural responses. In urban areas, where natural elements are scarce, this effect becomes particularly important. This chapter explores the benefits of urban green spaces on people’s health and overall well-being by identifying different types of urban greenery and examining the impact of vegetation density on human experience.

2.3.1 Types of Urban Greenery

Urban greenery takes various forms, each contributing differently to ecological sustainability and human health. These include parks, gardens, urban forests, green walls, street greenery, and green rooftops. As urban expansion limits available space for large-scale green infrastructure, alternative solutions such as vertical and rooftop greenery become increasingly important.

Parks and Gardens

Parks and gardens provide essential recreational spaces, supporting physical activity, relaxation, and social gatherings. Public parks are often the primary local recreating areas for urban residents who lack private green spaces. Gardens, both public (e.g. botanical gardens) and private, provide similar benefits as parks on a smaller scale. They enhance biodiversity, are associated with aesthetic beauty, and offer a peaceful retreat from the urban hustle. Community gardens in cities are increasingly in demand, especially in dense urban centres. They serve as recreation space, provide vegetables and flowers, and serve as a place of environmental education (Zheng & Chou, 2023).

Green Walls

As urban areas become denser, green walls, also known as vertical gardens, offer a space-efficient way to incorporate vegetation. These installations not only enhance aesthetics but also mitigate urban heat islands, improve air quality, and provide insulation, A notable example is the Vertical Garden at the Caixa Forum in Madrid, designed by Patrick Blanc, which demonstrates the potential of vertical greenery to transform urban facades (Figure 3).

Figure 3: Vertical Garden at the Caixa Forum, Madrid (Blanc, 2021)

Street Greenery

Street greenery, including trees, shrubs, grass strips, and flower beds along sidewalks and streets, improve the pedestrian experience by offering shade, reducing air pollution, and enhancing safety. Trees create a buffer between road traffic and sidewalks, making streets more comfortable and walkable (Ausserer & Risser, 2018), which in turn enhances perceived safety and comfort which promotes active travel like walking and cycling (J. Yu et al., 2024). Additionally, they contribute to urban cooling, particularly in warm climates where excessive heat can impact public health.

Green Rooftops

Green rooftops serve as both ecological and social spaces, particularly in dense urban areas where traditional parks are limited. They help manage stormwater runoff (Bliss et al., 2009), reduce energy consumption in buildings (Ragab & Abdelrady, 2020), and provide tranquil settings for relaxation. Their elevation offers a sense of retreat from the bustling ground level, creating unique vantage points for urban nature experiences.

2.3.2 Effects of Urban Green Space on Health and Well-Being

Urban green spaces play a critical role in promoting both physical and mental health. Research has linked access to greenery with reduced stress, improved mood, and enhanced cognitive function (Rieves et al., 2024; Ulrich et al., 1991).

In this section, the effects of urban green space on health and overall well-being are discussed. In the previous chapter (2.2) the positive impact of perceived beauty on restoration and well-being was explored. This discussion expands on that foundation by examining the specific ways in which urban green spaces contribute to physical and mental health outcomes. Over the years, urban green space has been the focus of numerous studies exploring its role in stress recovery and overall well-being (Rieves et al., 2024; Ulrich et al., 1991).

One of the foundational theories explaining these benefits is Ulrich's Stress Recovery Theory (Ulrich et al., 1991), which states that exposure to natural environments facilitates stress reduction and psychological restoration, similar to the concepts from ART by Kaplan & Kaplan (Kaplan & Kaplan, 1989). Empirical studies support these claims, showing that interacting with green spaces lowers physiological stress markers such as heart rate and blood pressure (Fu et al., 2022; C.-P. Yu et al., 2018). They have a calming effect on the observer by holding their attention and diverting from previous stressful feelings which in turn enables mental restoration (Ulrich, 1979).

While the physical benefits of urban vegetation, such as improved air quality and temperature regulation, can be measured through satellite data, its psychological benefits are more nuanced. For example, Rieves et al. (Rieves et al., 2024) compared perceived green space with satellite-measured vegetation density and found that mental health benefits were more strongly correlated with subjective perceptions rather than objective measures. It showed that factors such as accessibility, safety, maintenance, quality, and thoughtful design significantly influence how positively green spaces are perceived and, consequently, their restorative potential.

Beyond individual health, urban greenery also addresses broader societal issues such as social cohesion and loneliness. Schulten (Schulten, 2023) found that tree-lined streets and well-maintained vegetation contribute to a greater sense of safety and belonging, reducing feelings of isolation. This is particularly relevant in densely populated urban environments where social interactions can feel impersonal. The correlation between perceived beauty and stress reduction observed in earlier chapters aligns closely with these findings, further illustrating the importance of designing green spaces that are not only functional but also aesthetically pleasing.

Recognising these benefits, urban planners must prioritise not only the quantity but also the quality and accessibility of green spaces. The following section will explore strategies for optimising green space distribution to ensure equitable access and maximise its positive impact on urban populations.

2.3.3 Optimal Green Space Distribution

Determining the optimal distribution of green spaces in urban areas is a complex yet critical issue for enhancing public well-being. While vegetation generally supports mental and physical health, an excessive or poorly managed abundance of greenery may not provide additional benefits. Striking a balance between quantity, quality, and accessibility is essential. As various studies have explored (Beute et al., 2023; Jiang et al., 2014; Konijnendijk, 2021; M. Liu & Gou, 2024; Rieves et al., 2024; Wolch et al., 2014).

The perception of green space does not always align with its actual presence. Studies indicate that areas with high vegetation density, as measured by NDVI, are not necessarily perceived as greener by residents (Rieves et al., 2024). Perceived quality, influenced by factors such as safety, maintenance, and accessibility, often outweighs sheer quantity in determining the restorative effects of green spaces.

Accessibility plays a pivotal role in determining how frequently people utilise green spaces. While proximity encourages regular visits, barriers such as physical distance, safety concerns, and mobility constraints can hinder access. Gender disparities in mobility patterns and socioeconomic factors also influence travel behaviour, often limiting access to high-quality green spaces (Bornioli et al., 2024; Rieves et al., 2024). Addressing these disparities is crucial for ensuring that all urban populations benefit from green spaces, particularly in low-income neighbourhoods, where both the quantity and quality of green spaces tend to be lower.

A useful guideline for green space planning is the 3-30-300 rule (Konijnendijk, 2021). According to this framework, every resident should have access to at least three trees visible from their home, fostering mental restoration and a sense of connection with nature. Additionally, there should be a tree canopy cover of 30% within each neighbourhood, enhancing microclimates, improving air quality, and mitigating urban heat. The rule also emphasises the importance of proximity, advocating for access to a green space of at least 0.5 hectares within 300 meters of every residence, which encourages frequent use, promotes physical activity, and reduces stress. Together, these principles underscore the importance of a well-distributed network of green spaces to ensure both visual presence and physical accessibility.

The density of vegetation within green spaces also affects their usability and restorative qualities. While a certain level of vegetation is necessary for stress relief and mental restoration, excessively dense greenery may create feelings of confinement or reduce perceived safety (Beute et al., 2023). Jiang et al. (Jiang et al., 2014) identified an optimal vegetation density range of 24% to 34%, which supports the fastest recovery from stress. Densities outside this range were associated with diminished benefits. This finding aligns with Berlyne's inverted U-shaped theory from Chapter 2.2.2, which suggests that environments must balance variety and simplicity to be both engaging and restorative (Berlyne, 1963). Overly uniform spaces may fail to captivate users, while chaotic or overcrowded environments may overwhelm and detract from their calming effects.

Understanding the importance of green space distribution sets the foundation for evaluating its effects on human well-being. However, to determine how urban greenery influences emotions, researcher must employ appropriate assessment tools. The next chapter delves into different methodologies used to measure the relationship between green spaces and emotional responses, ranging from traditional observational studies to advanced technologies such as virtual reality and physiological monitoring. These tools provide a more comprehensive understanding of how vegetation impacts emotional well-being, ultimately guiding urban planning strategies toward creating more restorative environments.

2.4 Tools for Assessing Urban Green Space and Emotion

Traditional approaches to evaluating urban greenery and its emotional impact often rely on indirect or static representations of the environment. For instance, studies have used street- level images or photographs of landscapes to assess the greenness of cities (Sánchez & Labib, 2024; Wu et al., 2020). While these methods offer valuable insights, they lack the capacity to capture the immersive quality of real-world experiences.

Some studies have sought to address this by allowing participants to directly interact with urban nature before completing questionnaires to evaluate their emotional experiences and stress levels (Tyrväinen et al., 2014). However, while real-world interactions offer immersion, they make it more difficult to create controlled experimental settings (Martin, 2008). The complexity of the environment makes it difficult to isolate individual stimuli and reliably link emotional responses to specific elements, such as vegetation or layout. As a solution, virtual reality (VR) provides an ideal balance between immersion and experimental control.

2.4.1 Advantages of VR in controlled Experiments

Virtual reality (VR) technology has emerged as a powerful tool for investigating the impact of environmental factors on physiological responses in urban environments (Batistatou et al., 2022; Jiang et al., 2014; Tabrizian et al., 2018; C.-P. Yu et al., 2018). VR enables the creation of fully immersive, controlled simulations, allowing researchers to manipulate specific environmental variables, such as vegetation density, layout, and ambient conditions with high precision (Wilson & Soranzo, 2015). Immersive VR experiences of nature environments, such as those using VR headsets, are also more effective in restoring participants' well-being than non-immersive tools like a TV screen (Kari et al., 2024). Studies have shown that VR environments engage the same neurological and physiological responses as actual physical spaces, making VR an effective proxy for reality in experimental research (Llinares et al., 2023).

Compared to other digital tools, such as panoramic 360° images or photographs, VR offers distinct advantages. The use of head-mounted displays (HMDs) isolates participants from external distractions, providing a fully immersive experience. Moreover, VR can deliver interactive and adaptable environments, incorporating auditory inputs and other sensory feedback to enhance the realism of the simulation (Higuera-Trujillo et al., 2017; Naef et al., 2022). These features make VR particularly effective for studying emotional responses in environments, as it can simulate an environment in a controlled yet immersive manner.

2.4.2 Emotion Measurement Techniques

Emotion plays a central role in human behaviour, decision-making, and well-being, and it is crucial for understanding how people interact with their surroundings. In the context of urban greenery, measuring emotional responses can help urban planners and environmental psychologists understand how different urban vegetation affects human experiences. This section explores techniques for measuring emotions, with a focus on tools that pair well with VR environments, including self-reported feedback and physiological metrics (Kari et al., 2024).

Emotions can be understood as reactions to stimuli, whether real, simulated, or imagined. These reactions are often measured in two key dimensions: valence and arousal (Apicella et al., 2021). Valence refers to the positivity or negativity of an emotion (e.g., happiness vs. sadness), while arousal measures the intensity or excitement of the emotional response (e.g., calm vs. excited) (Bradley & Lang, 1994; Russell, 1980). While emotions are complex and multifaceted, the focus of this thesis will be on these two dimensions, valence and arousal, because they are widely recognised in psychological models of emotion (Bradley et al., 1992; Russell, 1980).

Subjective measures

Subjective emotional responses are often assessed through self-reported tools, such as questionnaires, interviews, and pictorial scales. One of the most widely used instruments for emotion measurement is the Self-Assessment Manikin (SAM) (Bradley & Lang, 1994; Lendenmann, 2023; Mazumder et al., 2022; J. Yu et al., 2024). The SAM uses graphical representations to measure the dimensions of pleasure, arousal, and dominance (Figure 4), making it an effective an accessible tool for cross-cultural studies and diverse populations. Pleasure can be equated with valence and describes the positive or negative feeling towards an object. It is therefore a good indicator for aesthetic preference while arousal can be used for stress measurement.

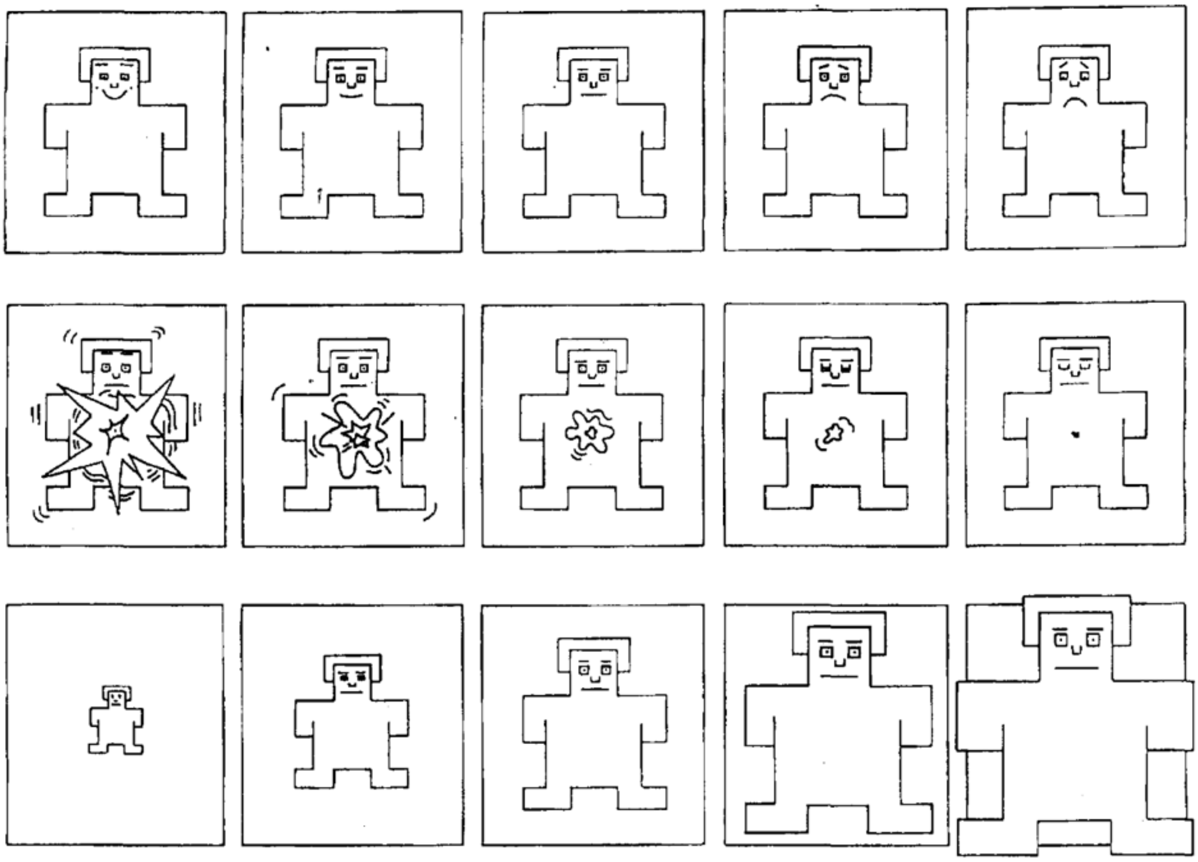

Figure 4: The Self-Assessment Manikin (SAM) as designed by Bradley & Lang (1994) with the three dimension of valence (top), arousal (middle), and dominance (bottom).

Bradley and Lang (Bradley & Lang, 1994) emphasise the importance of measuring both valence and arousal, as emotional valence significantly influences arousal levels. For example, participants who report a very positive or negative feeling are also likely to experience a corresponding increase in arousal, making it crucial to measure both dimensions for accurate emotional assessment.

Questionnaires have been widely used to assess emotional and aesthetic responses to landscapes (Chen et al., 2016). Online surveys, often based on photographs, enable large sample sizes and broad geographical reach (Zhang et al., 2021). In VR-based studies, questionnaires can be administered before, during or after exposure to measure changes in emotional states. Common tools include the Perceived Restorativeness Scale (PRS) (Hartig et al., 1997) for environmental impact and the Positive and Negative Affect Schedule (PANAS) for mood assessment. While no standardised questionnaire exists for this study's theoretical background, previous studies have adapted items based on the ART, the PM, and the PR (Subiza-Pérez et al., 2019; Zhang et al., 2021).

Physiological measures

In addition to subjective reports, physiological measures can offer objective data on emotional responses. One widely used metric is Electrodermal activity (EDA), which reflects changes in the skin's electrical conductance in response to emotional arousal. EDA is a valuable tool for measuring stress and excitement, as it provides real-time data on emotional fluctuations. It has been used in studies on landscape assessment (Spielhofer et al., 2021) and proven to be one of the most effective methods to detect stress reactions (Y. Liu & Du, 2018).

There are two primary forms of EDA measurement: tonic skin conductance level (SCL), which indicates the general state of arousal, and phasic skin conductance response (SCR), which captures momentary reactions to specific stimuli (e.g., viewing a particular landscape feature) (Figner & Murphy, 2011). EDA is non-invasive and provides reliable data on emotional responses in real-time, making it a very useful physiological measure. Other physiological measures, such as heart rate (Batistatou et al., 2022), salivary cortisol concentration (Tyrväinen et al., 2014) and brain activity (Chatterjee et al., 2021; Olszewska-Guizzo et al., 2022), can complement EDA to provide a more comprehensive understanding of emotional responses.

3 Methods

This chapter outlines the study's design, procedure, and analytical approach. First, the participant selection process is described, followed by details on the study design and procedure. The used materials are presented, concluding with an explanation of data collection and analysis.

3.1 Participants

A total of 40 participants (19 male, 21 female) took part in the study. The required sample size was determined using G*Power software (Figure 5). Participants ranged in age from 19 and 58 years. Due to a technical error during data storage, the EDA data from one participant was unusable, resulting in 39 valid EDA samples for analysis.

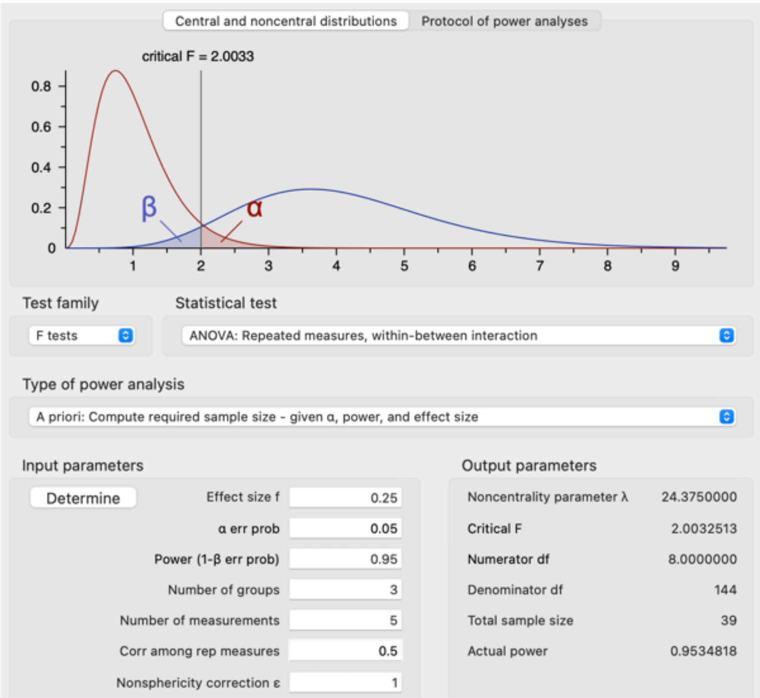

*Figure 5: Determining the sample size with G*Power resulted in 39.*

Participants were recruited via email from the Geography Department of the University of Zurich and through word-of-mouth within the researcher's personal network. Eligibility criteria included: age between 18 and 65 years, no regular use of psychopharmaceuticals, no visual impairments such as achromasia, and no phobia of virtual rollercoasters. During registration, participants completed a brief demographic questionnaire covering age, gender, and living situation. The results can be found in Appendix E. Following registration, participants were randomly assigned to one of three groups by age and gender. Each group experienced a different vegetation level (*low*, *medium*, *high*).

3.2 Study Design

The study was conducted as a within-between-subject design with repeated measures. Each participant was exposed to only one vegetation density level but in five distinct urban environments. The between-subjects component involved comparing responses across the three groups, while the within-subjects component assessed responses across the five urban environments within each group. The between-subjects approach was chosen to prevent contamination of participants' responses, while the within-subjects design minimised bias and disruptive factors. Additionally, within-subject designs require fewer participants (Martin, 2008). A purely between-subject design with three groups would have required a sample size of 153. Integrating the within-subjects element reduced the sample size to 39. The within-subjects design also helped control for individual preferences in urban design. The five urban environments differed in orientation, street layout, and building arrangement, which influenced lighting as well. The primary goal was to isolate vegetation density as the independent variable. The dependent variables measured included EDA, valence and arousal (SAM), and aesthetic preferences (questionnaire).

Based on previous research (Jiang et al., 2014) the three vegetation density levels (Levels) were defined as follows:

- *Low* Density (0 – 25%): Minimal greenery, isolated trees
- *Medium* Density (26 – 41%): Multiple layers of vegetation (ground cover, understory, canopy)
- *High* Density (42 – 67%): Dense, multi-layered vegetation with opaque coverage

Screenshots of the urban environments used in the study are available in Appendix A. Each participant experienced the same five urban environments, differing only in vegetation density. They were designed in Twinmotion (2023.2.2), which allows for the creation of sequenced VR Room presentations. To mitigate order effects, the sequence of environments was randomised using an online random number generator (Maple Tech International LLC, 2024) and three versions of each Twinmotion presentation were created (see Appendix A). To establish their emotional baseline, participants watched a video prior to the urban environments. Throughout the experiment, participants wore a BITalino device to measure their EDA.

3.3 Procedure

The experiment consisted of three phases: an introduction, the VR experience, and a post-experience questionnaire. The entire experiment lasted approximately 30 minutes, with 8.5 minutes spent in the VR space. The full study protocol can be found in Appendix B.

3.3.1 Pre-experiment

Before the experiment, all necessary measures and materials were prepared in the CAVE lab at the University of Zurich. Participants were welcomed by the experimenter and asked to read and sign the informed consent form (see Appendix C). They were then seated in a stationary chair to prevent movement, which could cause motion sickness and affect data accuracy. The pilot study indicated that rapid head movements led to increased EDA and a lag between actual and perceived movement, contributing to motion sickness. To reduce this factor, participants were instructed to move their heads slowly and only within a shoulder-to-shoulder range. Although the virtual urban model was designed as a 360° environment, only the frontal 180° field of view was considered for measurement, as the rear portion was excluded following pilot testing.

Once seated, the BITalino device's EDA sensors were placed on the index and middle fingers of the participant's right hand (Figure 9). Participants then received final instructions and put on the HTC VIVE headset. At this point, EDA recording in Open Signals and the experiment timer were started.

3.3.2 VR Experience and Questionnaire

Before being exposed to the virtual urban environments (Rooms), participants were asked to close their eyes and relax for one minute and then watched a 1:10-minute rollercoaster video on a 2D screen within the VR space using the Media Player in SteamVR Beta. This aimed to establish a physiological and emotional baseline, ensuring that the following measurements captured the relaxation effect of vegetation. In prior research, stress was induced with the Markus and Peters arithmetic (MPA) test (Huang et al., 2020) or the Trier Social Stress Test (TSST) (Jiang et al., 2014).

Following the video, the Twinmotion presentation began. A detailed timeline of the VR experiment, including all tasks of the experimenter, can be found in Table 2. Each transition between urban environments and SAM assessments required pressing the space bar twice, once to start the scene and again to stop it. Otherwise, the presentation would have continued automatically, with each Room visible for only five seconds. To differentiate between EDA signals of each environment, a pushbutton was triggered upon entry into each new scene.

Additionally, transition times were logged using an online timer (online-timers, 2024), which generated a downloadable text file. To ensure smooth transitions and prevent motion sickness, instructions were given between environments. Pressing the space bar returned the scene to the starting position, which could cause discomfort. The instructions also ensured that the new scene was correctly oriented.

Table 2: Detailed documentation of the experimenter's tasks during the VR part of the study.

Time	Display	Action	Stopwatch + Pushbutton	Instruction to Participant	Notes
00:00	Baseline Video in media player		Start stopwatch	"Close your eyes for 1 min"	EDA start
01:00	Baseline Video in media player			"Open your eyes"	
01:30	Baseline Video in media player	Start video	Tap	"Only look at the screen"	
02:40		Close player, open Twinmotion			
03:00	SAM Baseline		Tap		SAM Baseline
03:25		Space Bar (start)		"Don't move"	
03:30	Room 1	Space Bar (pause)	Tap	"You can look around"	
03:55		Space Bar (start)		"Don't move"	
04:00	SAM 1	Space Bar (pause)	Tap	"You can look around"	SAM 1
04:25		Space Bar (start)		"Don't move"	
04:30	Room 2	Space Bar (pause)	Tap	"You can look around"	
04:55		Space Bar (start)		Don't move"	
05:00	SAM 2	Space Bar (pause)	Tap	"You can look around"	SAM 2
05:25		Space Bar (start)		"Don't move"	
05:30	Room 3	Space Bar (pause)	Tap	"You can look around"	
05:55		Space Bar (start)		"Don't move"	
06:00	SAM 3	Space Bar (pause)	Tap	"You can look around"	SAM 3
06:25		Space Bar (start)		"Don't move"	
06:30	Room 4	Space Bar (pause)	Tap	"You can look around"	
06:55		Space Bar (start)		"Don't move"	
07:00	SAM 4	Space Bar (pause)	Tap	"You can look around"	SAM 4
07:25		Space Bar (start)		"Don't move"	
07:30	Room 5	Space Bar (pause)	Tap	"You can look around"	
07:55		Space Bar (start)		"Don't move"	
08:00	SAM 5	Space Bar (pause)	Tap	"You can look around"	SAM 5

		Exit VR	Stop stopwatch		EDA stop

The first Room in the VR presentation contained the first SAM assessment, where participants rated their baseline valence and arousal. These baseline values served as a reference for the subjective measurements. Following this, participants were immersed in the main VR experience, where they explored five urban environments corresponding to their assigned vegetation density. Each environment was displayed for 30 seconds, allowing participants to freely observe their surroundings. This duration was chosen to provide enough time for participants to engage with the scene while maintaining a controlled experimental setting. Throughout the experience, physiological stress responses (EDA) were continuously recorded. After each urban environment, participants completed the SAM assessment, rating their valence and arousal on a scale from 1 to 5 (Figure 11). These ratings were recorded manually by the experimenter.

Upon completing the VR experience, participants filled out an online questionnaire (see Appendix D). Details of the questionnaire design can be found in Chapter 3.4.3. The questionnaire took approximately seven minutes to complete. Participants were thanked and given a small token of appreciation for their time. The entire experiment lasted around 30 minutes.

3.4 Materials

This section focuses on the design of the virtual urban environments, the VR equipment and software, as well as on the physiological and subjective measurement tools used in the study.

3.4.1 Virtual Urban Environments

First, the design process is described, followed by the choice of stimuli and the used equipment.

Design of Virtual Urban Environments

Five virtual urban environments (A-E) were designed to minimise the influence of external factors such as building features, people, lighting conditions, and viewing angles. The base model, including the ground structure without vegetation, was adapted from Lendenmann (2023) and further customised for this study. The given layout determined the arrangement of streets and buildings, restricting modifications such as widening pavements to accommodate additional vegetation while maintaining pedestrian space. Consequently, the environments represent a highly simplified version of urban settings, omitting elements such as shops, restaurants, and dense pedestrian activity to reduce irrelevant influences on the study results. The decision to limit human presence was also based on the “uncanny valley” effect, where near-realistic humanoid characters evoke discomfort, that is even heightened in VR (Stein, 2018). For this reason, all human figures were either placed in the background or in a position that they were not directly facing the observer.

All environments shared the same foundational framework, including buildings, benches, street signs, parked cars, and a minimal number of pedestrians. The primary variable was vegetation density, which differed across the environments. It was decided to focus on ground vegetation, as this is the most common type of urban greenery. Building façades were presented in neutral tones (grey, cream, terra cotta) with materials such as brick, concrete, and plaster.

To ensure consistency across environments, the highest vegetation density level was designed first. Lower density levels were then created by systematically removing plants while maintaining coherence in the overall scene. The emphasis was on ground vegetation, while façade greenery was introduced only when necessary to reach the required density level. The vegetation elements used were all taken from the Twinmotion material library. To enhance realism, only plants native to temperate oceanic climates, or those visually familiar to participants, were included. Deciduous trees with dense foliage, such as oak, linden, maple, ash, and poplar, were selected to achieve varying density levels. Exotic species, large conifers, and colourful or fruit-bearing plants were excluded to ensure the study focused solely on greenery's impact. Additional shrubs and grasses were included to create a denser, park-like vegetation structure.

Figure 6 shows an urban environment from Twinmotion with *low* vegetation density, followed by the same environment with *medium* (Figure 7) and *high* vegetation density (Figure 8). All designed urban environments can be found in Appendix A.

Figure 6: Example of a virtual urban environment designed in Twinmotion with low vegetation density.

Figure 7: Example of an urban environment with medium vegetation density.

Figure 8: Example of an urban environment with high vegetation density.

Stimuli

Vegetation density was approximated using the pixel count in Photoshop. First, a screenshot of the primary viewing angle of the environment was taken in Twinmotion, then a sample of representative shades of green was taken with the colour sampler tool to make a selection of greens that should encompass all pixels that depict vegetation. Using the RGB channel in the histogram, the number of pixels in the selection could be derived. The density resulted from the ratio of the selected pixels to the total number of pixels of the image, converting this ratio into a percentage. To ensure consistency across the 180° field of view, additional screenshots were taken from the left and right perspectives and analysed similarly.

VR Equipment and Software

VR was chosen to provide a controlled study environment (Martin, 2008), allowing for systematic manipulation of visual stimuli (Batistatou et al., 2022). All equipment was provided by the University of Zurich at the GIVA CAVE lab.

Twinmotion, a 3D visualisation tool integrated with Unreal Engine, was chosen due to its compatibility with the base model adopted from Lendenmann's (2023) thesis and its suitability for VR applications. To experience the VR environments, participants wore the HTC VIVE headset.

A baseline rollercoaster video was presented via the SteamVR Beta Media Player, which displayed the 2D video on a virtual screen. The screen was adjusted to 1.2x its standard size to maximise immersion while maintaining a comfortable viewing distance. The video included audio to further enhance realism. The software SteamVR was then used to present the Twinmotion project in virtual reality. This provided the participants with a 360° environment. However, as mentioned previously; to minimise VR-induced motion sickness, participants were instructed to limit their movement to a 180° field of view.

3.4.2 Physiological Recording: EDA

To assess participants' physiological stress response, EDA was measured, specifically through SCL and SCR, both of which are well-established indicators of arousal, as discussed in Chapter 2.4.2.

As outlined in Chapter 3.2, EDA was recorded using the BITalino (r)evolution device. It was chosen for its affordability, ease of use, and demonstrated reliability compared to more established EDA recording devices (Batista et al., 2019). The toolkit included the Assembled BITalino Core BT, Assembled EDA Sensors, gelled self-adhesive disposable Ag/AgCI-electrodes, and a Bluetooth dongle (PLUX, 2020a).

Data acquisition was conducted using OpenSignals (r)evolution (2.2.5), a free software recommended by PLUX for physiological signal recording. The BITalino device was wirelessly connected to OpenSignals via a Bluetooth, enabling continuous data collection throughout the experiment. Recorded signals were saved as individual files for each participant to ensure organised data management.

Data Collection

The electrodes were placed on the lower part of the participants' right index and middle fingers (Figure 9). They were selected due to their stability and reliability in electrodermal recordings (Boucsein et al., 2012).To minimise movement artifacts that could introduce noise, the electrodes were secured with Velcro straps on both fingers and the wrist.

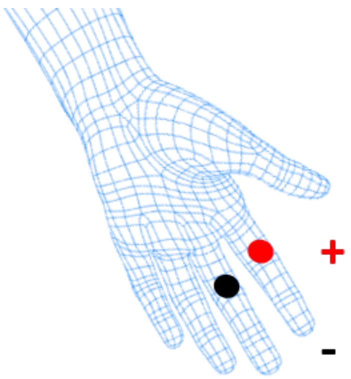

Figure 9: Placement of electrodes on index and middle finger (PLUX, 2020a).

As mentioned before, data were recorded using the BITalino device connected to OpenSignals (r)evolution software PLUX. The sampling rate was set to 100 Hz, and continuous mode was selected to ensure uninterrupted data acquisition. Data were stored in three formats: European Data Format (EDF), which is suitable for storing multichannel biological signals, Text (TXT) format, which contains raw digital signal values, and Hierarchical Data Format (H5), which is used for further data processing in analysis software (PLUX, 2019). Since the TXT file contains only raw digital values, an additional file with converted physical unit values (microSiemens) was generated using the transfer function:

$$EDA(\mu S) = (ADC / 2n) \times VCC / 0.132$$

where ADC is the sampled channel value, VCC is the operating voltage (3.3V), and n is the number of bits of the channel (10) (PLUX, 2020b).

Data Processing and Analysis

Raw EDA data were processed and analysed using AcqKnowledge (5.0.8), following the methodology outlined by Sara Lanini-Maggi (Lanini-Maggi, 2023; Maggi, 2017). The detailed processing steps are provided in Appendix F, and an extract of the data is shown in Figure 10.

The raw EDA data were imported in volts by default, and a mean value smoothing filter (factor 5) was applied twice to remove noise and artifacts, such as sudden spikes. The smoothed signal was named SCL (Channel 10), representing the tonic EDA signal. A 0.05 high-pass filter and a SCR threshold of 0.03µS were applied (BIOPAC Systems, Inc., 2022). The baseline window was set to 5 seconds, and SCRs below 10% of the maximum amplitude were excluded. The phasic EDA signal was derived from the tonic signal, named SCR (Channel 11), and normalised using the formula:

$$COND(SCR * 100 / (Max - Min))$$

where Max and Min refer to the maximum and minimum values of the SCR. The normalised signal was named PHI (Channel 12) and further transformed by extracting only the positive values:

$$COND(PHI, 0, 0, PHI)$$

resulting in the signal PHI_pos (Channel 13) and serving as a proxy for arousal. Based on this signal, the SCRs were located on the smooth SCL channel (blue water drops). Focus areas were defined to mark the signal during stimulus exposure. Each focus area starts one second after stimulus onset and ends four seconds after the next stimulus to account for latency of the reaction (Figner & Murphy, 2011). The stimulus onsets are recorded in Channel 1. Each vertical line represents the change from one Room to another. The grey highlighted sections (focus areas) represent exposure to virtual environments, while white sections indicate the phase during self-assessment. Only the signal during the baseline video and the urban environments were evaluated. Within these focus areas, the following EDA metrics were extracted: Number of SCR peaks and averaged Area Under the Curve (AUC). Mean AUC values were normalised against baseline using the following formula (Spielhofer et al., 2021):

$$AUC\ Room - AUC\ Baseline\ = Standardised\ SCL$$

Similarly, the number of SCRs per Room was normalised as:

$$nSCR\ Room - nSCR\ Baseline\ = Standardised\ nSCR$$

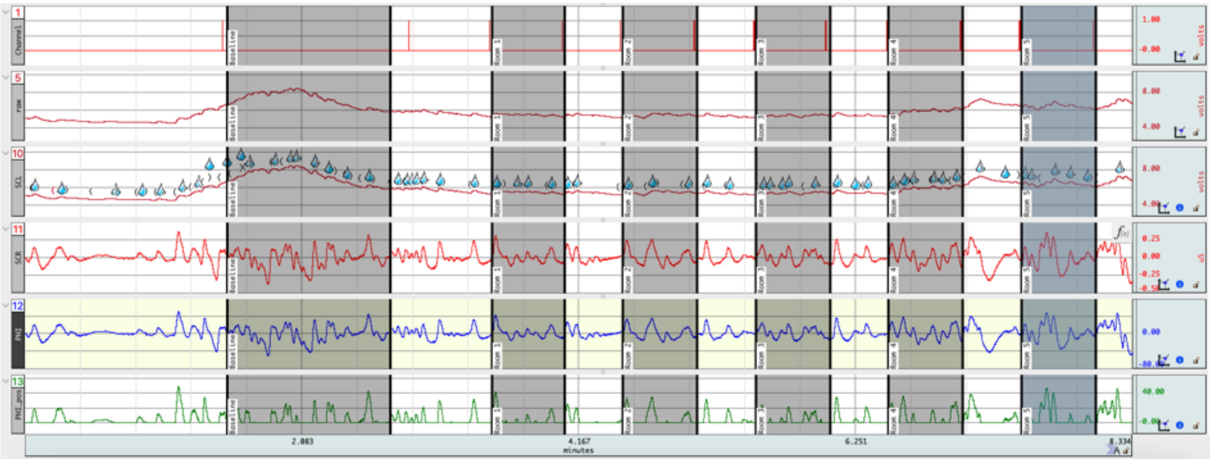

Figure 10: EDA signal recorded in AcqKnowledge. The graph consists of multiple channels, including raw EDA signals, SCL, SCR, and derived features such as PHI and PHI_pos. The signals are segmented into the different conditions (Baseline and Rooms), marked by the grey shaded areas. Blue water-drop symbols indicate detected SCR peaks.

All statistical analyses and visualisations of EDA data were performed in RStudio (2024.09.0).

3.4.3 Subjective Measurement: SAM and Questionnaire

Participants completed a self-assessment after experiencing each environment using the SAM. Additionally, their subjective perceptions of aesthetics were assessed through a questionnaire administered after the VR experience. This provided insights into aesthetic preferences and provided some additional interpretation of objective physiological measurements.

Data collection SAM

After each urban environment exposure, the SAM was displayed within the VR space to capture participants' immediate responses regarding valence and arousal. Dominance was deemed less relevant for this study and was therefore excluded.

To minimise misinterpretation (Montefinese et al., 2014), extreme values were labelled with descriptive adjectives alongside a numeric Likert scale (1 – 5) (Figure 11). The SAM was labelled bilingually, as the experiment was conducted in both English and German. As discussed in Chapter 2.4.2, valence describes the positivity or negativity of an emotional experience, with the upper row of pictograms aligned with happiness, ranging from "happy" to "unhappy". The lower row corresponds to arousal, labeled from “excited” to “calm”. Participants rated their self-assessments using the Likert scale, where 1 indicated high valence/arousal and 5 indicated low valence/arousal. To ensure real-time emotional responses comparable to the physiological measurements, participants provided their ratings immediately after each exposure. Because Twinmotion does not support direct answer selection within the VR space, responses were given verbally. To display the Sam in Twinmotion, the image was saved as material and applied to a vertical plane placed within the urban environments.

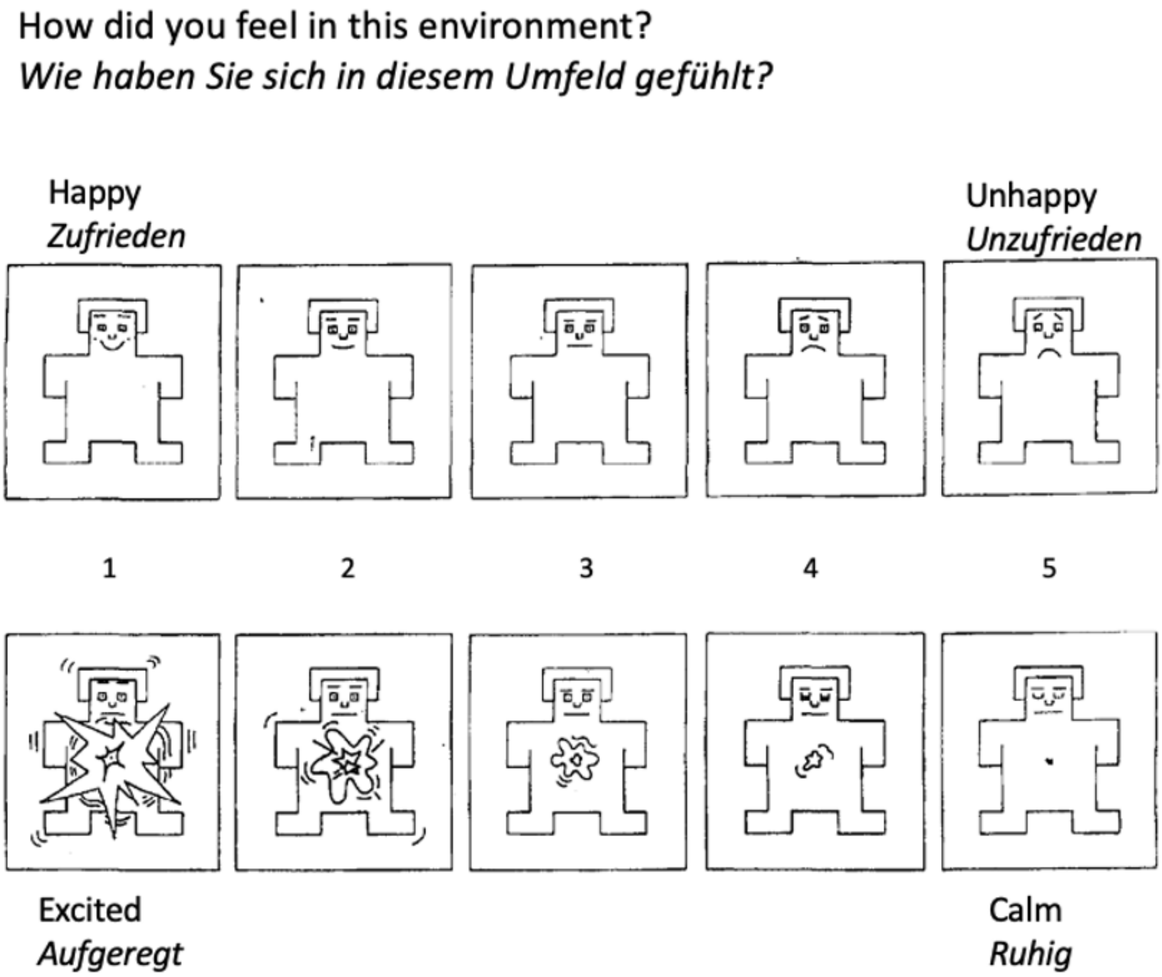

Figure 11: The Self-Assessment Manikin (SAM) was shown after each urban environment to assess valence (happy - unhappy) and arousal (excited - calm).

Data Collection Questionnaire

After the VR experience, participants completed an online questionnaire consisting of ten statements assessing their subjective impression of each environment based on the theories of landscape aesthetics. It was written with PsyToolkit (3.4.6), a software package designed to conduct psychological surveys (Stoet, 2010, 2017). Each factor of the theories was represented by a statement (Table 3). Like the SAM, the questionnaire was bilingual. The detailed questionnaire can be found in Appendix F.

Responses were recorded on a five-point Likert scale (1 = strongly disagree to 5 = strongly agree) and could therefore be used to calculate mean values to represent each of the theories (ART, PM, and PR). This resulted in three scores for each participant: ART score, PM score, and PR score.

In total, there were three different questionnaires, one for each vegetation density level. The Questionnaire only differed between vegetation density levels while the sequence stayed the same. Therefore, the only effect that was explored was the difference between Levels (*low*, *medium*, *high*) and Rooms (A, B, C, D, E).

Data processing and analysis of the SAM and Questionnaire answers took place in Excel and RStudio.

Table 3: Questionnaire Statements based on Theories of Landscape Aesthetics (ART, PM, PR).

Attention Restoration Theory	
Being away	This environment makes me feel like I am getting away from the stress of everyday life.
Extent	This environment gives me the feeling of being in a larger connected environment.
Compatibility	The environment in this picture corresponds to my personal preferences and interests.
Fascination	This environment attracts my attention in a gentle way.
Preference Matrix	
Coherence	The elements in this environment fit together well to create a coherent, understandable picture.
Mystery	This place makes me curious about the surroundings beyond the picture.
Complexity	This environment is rich in detail.
Legibility	This place has striking elements that help me orientate myself.
Prospect Refuge Theory	
Prospect	This scene gives me an overview of the area in front of me.
Refuge	This place makes me feel safe or protected.

4 Results

This chapter presents the findings of the study. It is structured into three main sections corresponding to the measurement approaches: objective physical response (EDA), subjective emotional responses captured using the SAM, and evaluations based on the questionnaire.

During the VR experiment, the five virtual urban environments were presented in a random order to minimize positional or room-based effects. Therefore, the influence of three factors was examined: the vegetation density level (Level), the design of the individual urban areas (Room), and the order in which they were experienced by participants (Position). The Levels are named *low*, *medium*, and *high*, the Rooms are named with letters (A, B, C, D, E) while Positions are numbered (1, 2, 3, 4, 5). The primary focus is on the three Levels, however, potential interaction effects of Room and Position are also considered, as their influence cannot be ruled out.

The statistical analysis was performed in RStudio using the aligned rank transform (ART) ANOVA with the ARTool package for R (Elkin et al., 2021; Wobbrock et al., 2011) with a significance level of 0.05. ART ANOVA enables a factorial design while accommodating data that do not meet the assumptions of normality or homogeneity of variance. It aligns and ranks the data before performing a traditional ANOVA (Wobbrock et al., 2011). For each test, the F-value, p-value, and partial eta-squared (η_P^2) by Cohen (1988) are reported to indicate significance and effect size. η_P^2 is used to measure effect size in studies with multiple independent variables, as in this study, which includes Level, Position, and Room (Richardson, 2011). Table 4 provides the interpretation of η_P^2.

In addition, descriptive statistics such as the median (Mdn), mean (M), and standard deviation (SD), are also provided where relevant. The detailed results of all statistical tests, including normality tests, are documented in Appendix E.

Table 4: Effect size by Cohen (1988)

Effect size	η_P^2
small	0.01 – 0.059
medium	0.06 – 0.139
large	≥ 0.14

4.1 Electrodermal Acitivity

This section presents findings for EDA, structured in two parts. First, the mean skin conductance level (SCL), which reflects the average tonic EDA signal over time, is analysed. Next, the number of skin conductance responses (nSCR), representing the phasic EDA signal, is examined. The SCL values were calculated by determining the normalised mean AUC over the time each urban environment was displayed (μ/s). nSCR values were derived by calculating the mean nSCR for each Room (1/s).
The normality of SCL and nSCR data for each factor (Level, Room, Position) was assessed using the Shapiro-Wilk test. In most cases it was not normally distributed and therefore required a non-parametric test like ART ANOVA. Changes in SCL and nSCR were assessed by subtracting baseline values from the recorded data for each Room. Positive values indicate heightened arousal relative to the baseline, whereas negative values indicate reduced arousal.

ART ANOVA revealed a significant effect of the interaction Room:Position for both SCL ($F(14, 135) = 1.96$, $p = 0.03$, $\eta_P^2 = 0.17$) and nSCR ($F(14, 135) = 1.90$, $p = 0.03$, $\eta_P^2 = 0.16$). However, post-hoc analysis showed no significant differences. As a results, this interaction effect will not be explored further in a separate section.

4.1.1 Skin Conductance Level

This section presents the results of the average skin conductance level over time for each virtual urban environment. The analysis starts with the impact of Level (between-subject factor), followed by the within-subject factors Position and Room. For Position and Room, the mean SCL is discussed first without considering the Levels to highlight the overall influence of the factors. This is followed by an analysis incorporating the Levels to provide more detailed information.

Level

Figure 12 shows the (baseline corrected) mean SCL for each Level. There is a small trend observable, with the mean and median of the *medium* Level (Mdn = -3.15, M = -2.93, SD = 2.30) being lower than those of *low* (Mdn = -1.88, M = -1.57, SD = 2.72) and *high* (Mdn = -2.28, M = -2.08, SD = 3.78). All medians lie below the red dotted line, showing a general decrease in SCL compared to the baseline. There is a large variability in the data and a few outliers, especially for *low* and *high* Level.

ART ANOVA reveal a significant effect of Level on SCL ($F(2, 192) = 3.76$, $p = .025$, $\eta_P^2 = .038$). The partial eta-squared (η_P^2) indicates a small effect size. To further explore the effect, a post-hoc test was conducted using the ART-C test (Elkin et al., 2021). It shows a significant difference between *low* and *medium* (p = .02) but not between the other Levels.

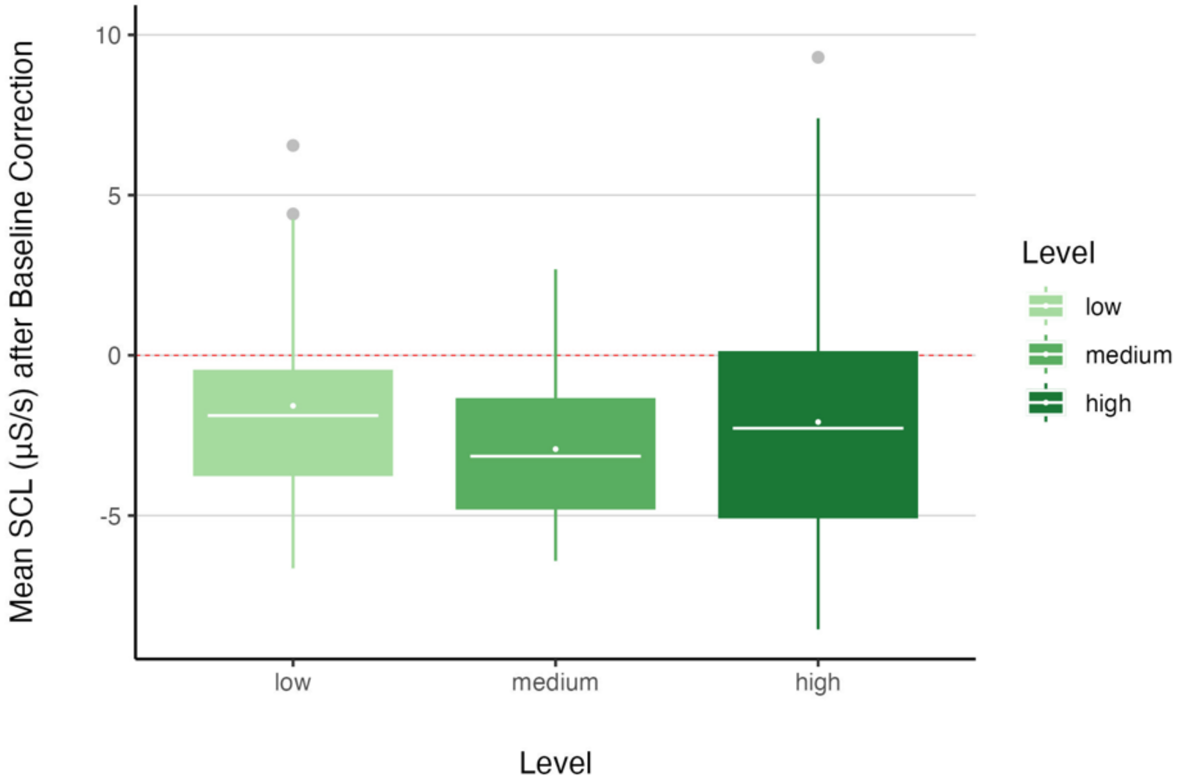

Figure 12: Mean SCL after the baseline correction shows a significant difference between low and medium Level. The red dotted line shows the baseline. [dots = mean, bars = median, whiskers = +/- 1.5 interquartile range (IQR)]

Position

Figure 13 presents a boxplot illustrating the mean SCL after baseline correction for each of the five Positions. The median SCL values appear consistent across Positions, with all medians falling below the baseline (red dotted line), indicating a general decrease in arousal. The interquartile ranges (IQRs) are similar across Positions, suggesting stable variability in responses. A few outliers are present in higher SCL values, particularly in Position 1 and 3, but they do not indicate a strong deviation from the overall trend.

Statistical analysis did not reveal a significant effect of the within-subject factor Position on SCL ($F(4, 144) = 0.48$, $p = .75$, $\eta_P^2 = .01$), confirming that the order in which participants experienced the virtual environments did not meaningfully influence SCL responses.

However, median SCL values vary slightly between Levels at most Positions (2, 3, 4, and 5) (Figure 14), showing a similar trend to that in Figure 12, with *medium* Level generally having a lower median per Position compared to *low* and *high*. Despite this trend, the data are widely spread, limiting statistical significance.

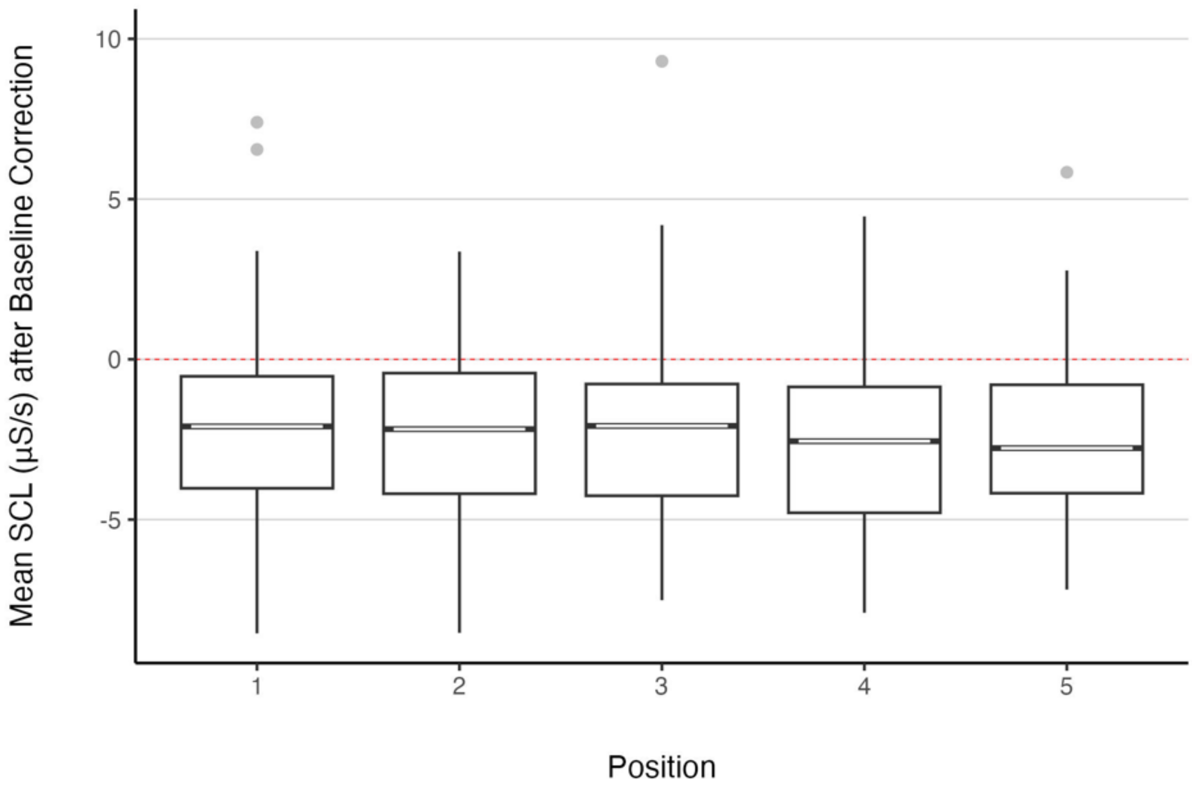

Figure 13: Mean SCL after the baseline correction shows no significant effect of Position.

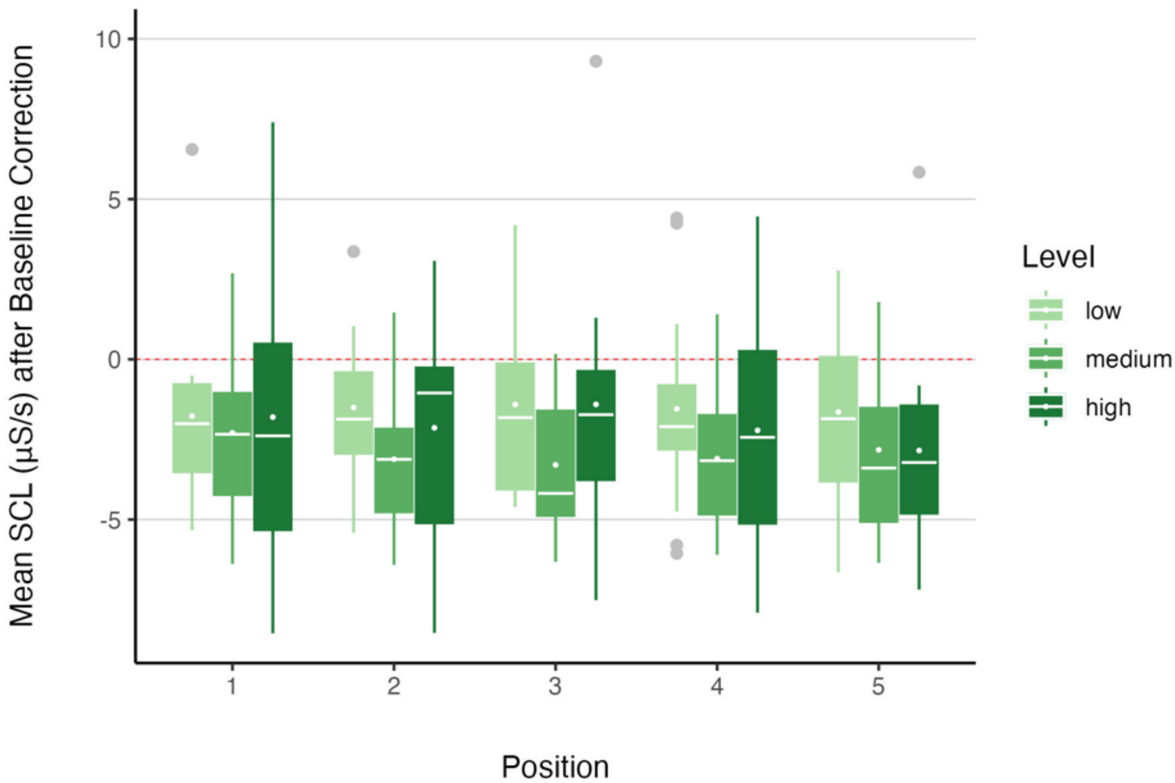

Figure 14: Mean SCL after the baseline correction shows slight variations between Levels within Positions.

Room

Figure 15 presents a boxplot of mean SCL values across the five different urban environments (Rooms) after baseline correction. The median SCL values appear comparable across all

Rooms, with slight variations in central tendency. The spread of values remains consistent, although a few Rooms have a slightly larger IQR. All medians lie below the baseline, indicating a general decrease in SCL regardless of vegetation density.

Statistical analysis for the second within-subject factor Room shows no significant effect on SCL ($F(4, 144) = 0.91$, $p = .52$, $\eta_P^2 = .02$).

Figure 16 extends the analysis by depicting mean SCL across Rooms, categorised by vegetation density Levels. Although median SCL values appear to vary more between Levels in each Room (except for Room C), especially between *low* and *medium*, the high variability within limits the statistical significance of these differences.

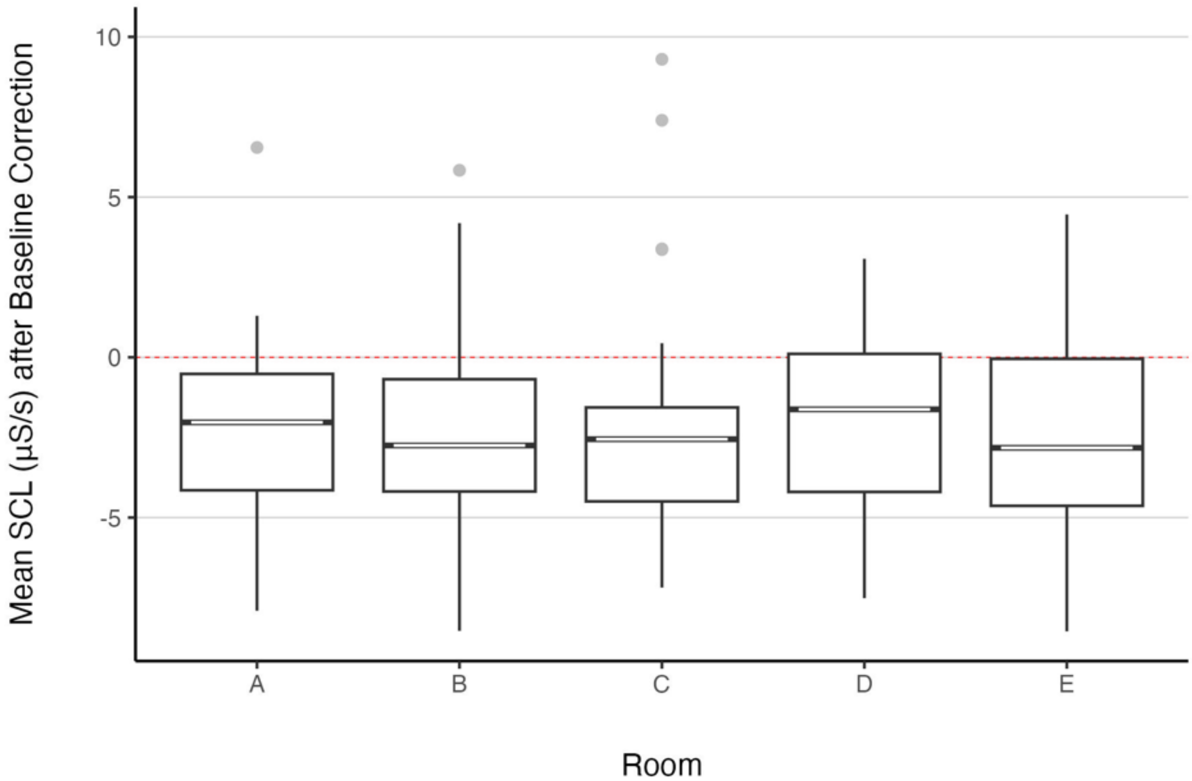

Figure 15: Mean SCL after the baseline correction shows no significant changes between Rooms.

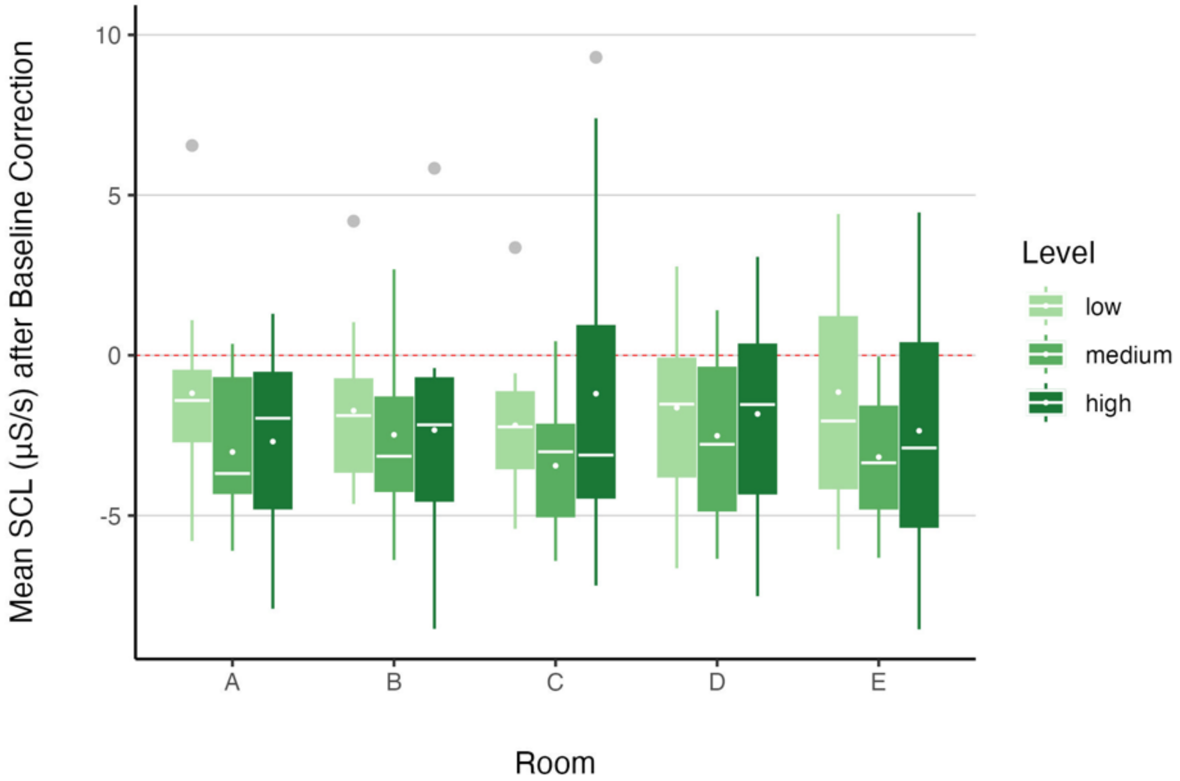

Figure 16: Mean SCL after the baseline correction shows some differences between Levels within Rooms, especially between low and medium.

4.1.2 Number of Skin Conductance Responses

This chapter discusses the average number of skin conductance responses over the time span of each virtual urban environment. The analysis follows the structure of the section before.

Level

As illustrated in Figure 17, the mean and median nSCR values for the *low* (Mdn = -0.18, M = -0.18, SD = 0.13) and *medium* (Mdn = -0.18, M = -0.20, SD = 0.10) Levels are similar while differing significantly from the *high* Level (Mdn = -0.09, M = -0.12, SD = 0.09). The data are not widely distributed as indicated by the small IQR across Levels. As with SCL before, the mean and median of all Levels lie below the baseline value.

ART ANOVA shows a highly significant effect for the between-subject factor Level on nSCRs ($F(2, 192) = 10.79$, $p < .001$, $\eta_p^2 = .10$). The partial eta-squared indicates a medium effect size. The post-hoc test shows a significant difference between *low* and *high* ($p < .001$) and *medium* and *high* ($p < .001$).

This indicates that participants exposed to *high* Level vegetation density experienced significantly more skin conductance responses than participants experiencing *low* or *medium* Level vegetation density.

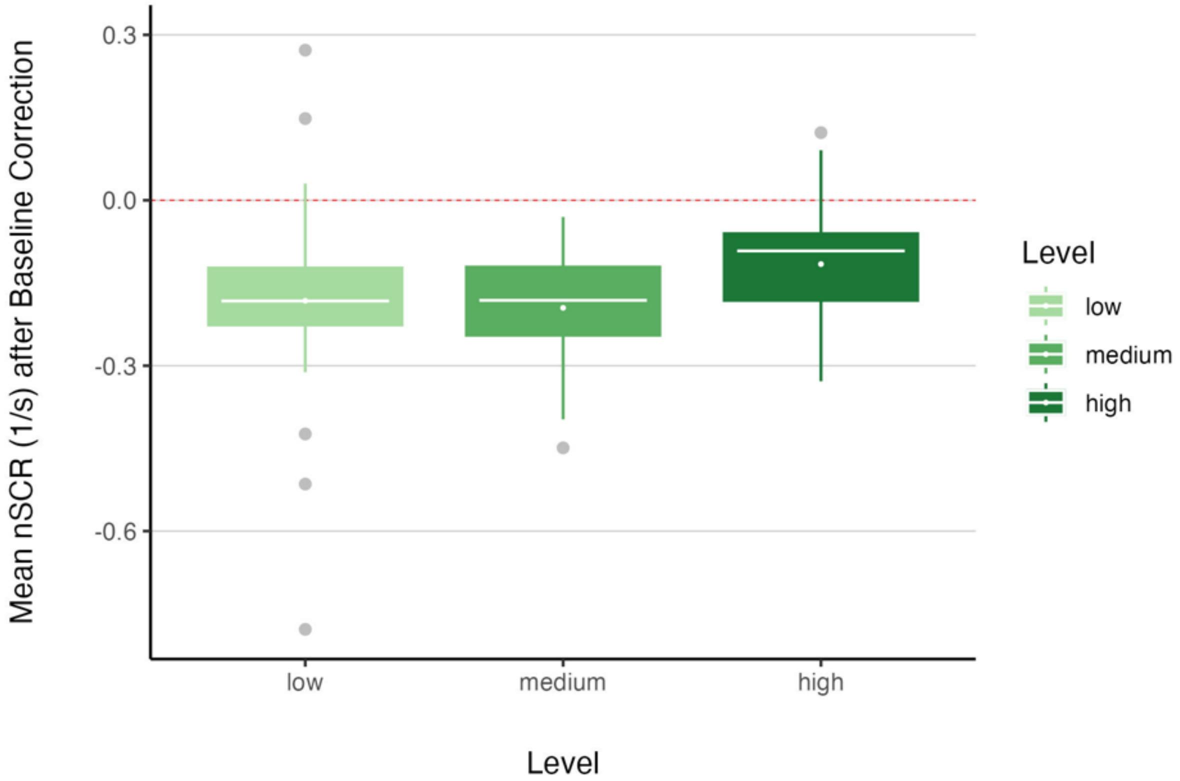

Figure 17: Mean nSCR after the baseline correction shows significantly higher values for high Level than for low and medium.

Position

Figure 18 presents the mean nSCR values across Positions after baseline correction. The median nSCR values appear consistent throughout Positions and the variability is low as indicated by the small IQR. All median values are well below the baseline.

Statistical analysis showed no significant effect of the within-subject factor Position on nSCRs ($F(4, 144) = 0.13$, $p = .97$, $\eta_P^2 < .01$).

Figure 19 confirms the same effect between Levels for each Position seen in Figure 17, with *medium* and *low* Level having a lower median per Position than the *high* Level, indicating this effect is independent from Positions.

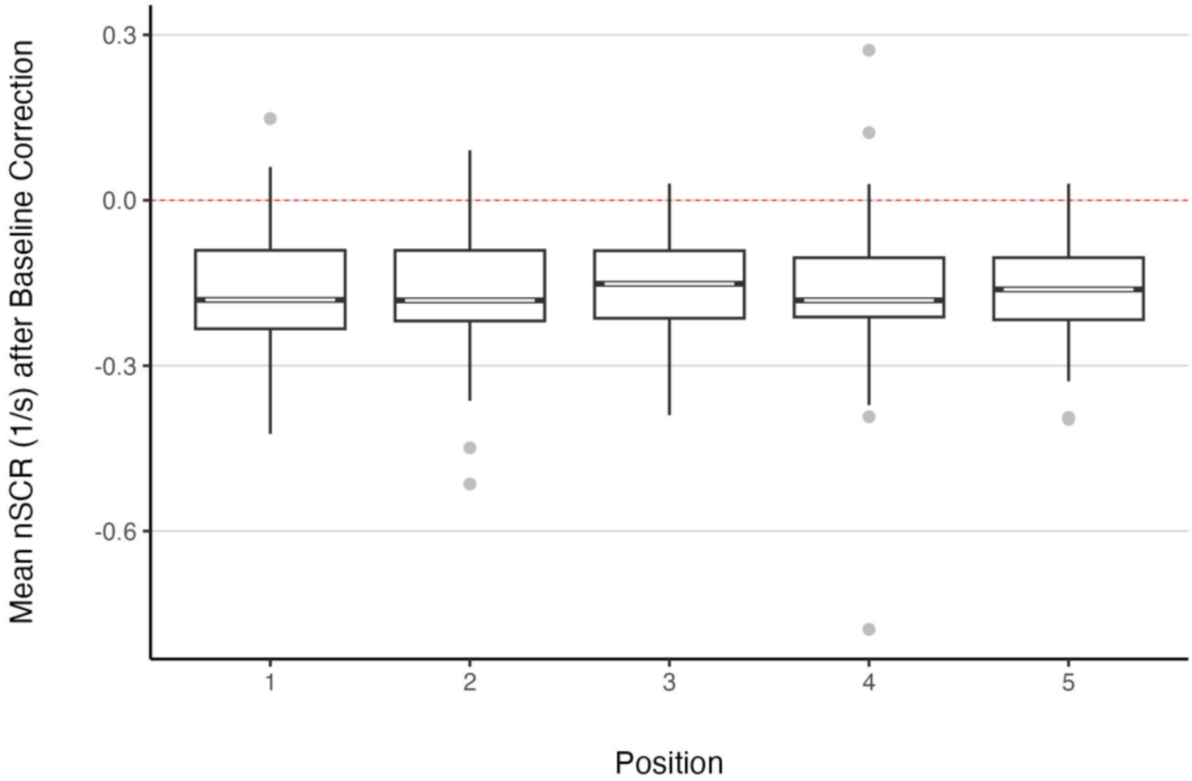

Figure 18: Mean nSCR after the baseline correction shows no significant differences between Positions.

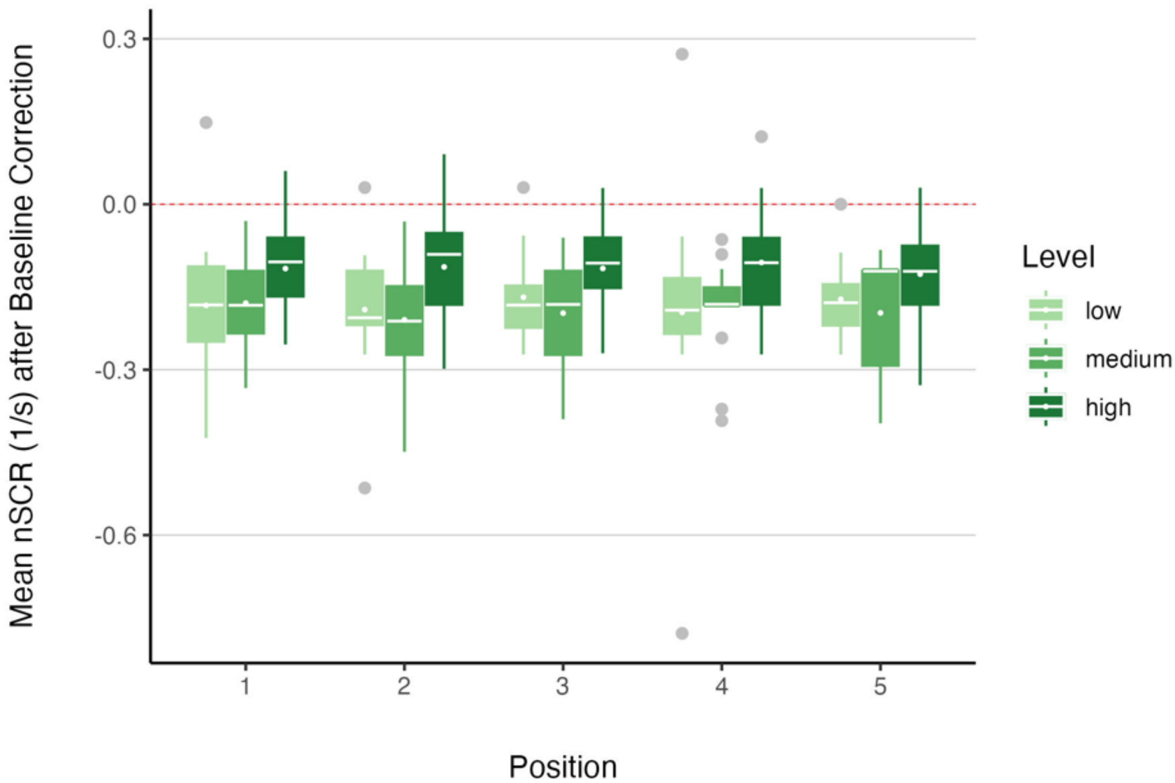

Figure 19: Mean nSCR across Positions categorised by Levels after the baseline correction Mean nSCR after the baseline correction shows considerably higher values for high Level throughout Positions.

Room

Similar to SCL, Figure 20 shows no significant change in median nSCR values between Rooms. Again, all medians lie below the baseline, indicating an overall decrease in nSCR regardless of vegetation density. While the IQR is low, indicating low variability in responses, there are several outliers for most Rooms.

ART ANOVA supports this finding by revealing no significant effect of the within-subject factor Room on nSCRs ($F(4, 144) = 1.30$, $p = .27$, $\eta_P^2 = .03$).

Like for the Positions, the influence of Levels on nSCRs can be seen for each Room, with medium and low having a lower median per Room than the high Level (Figure 21).

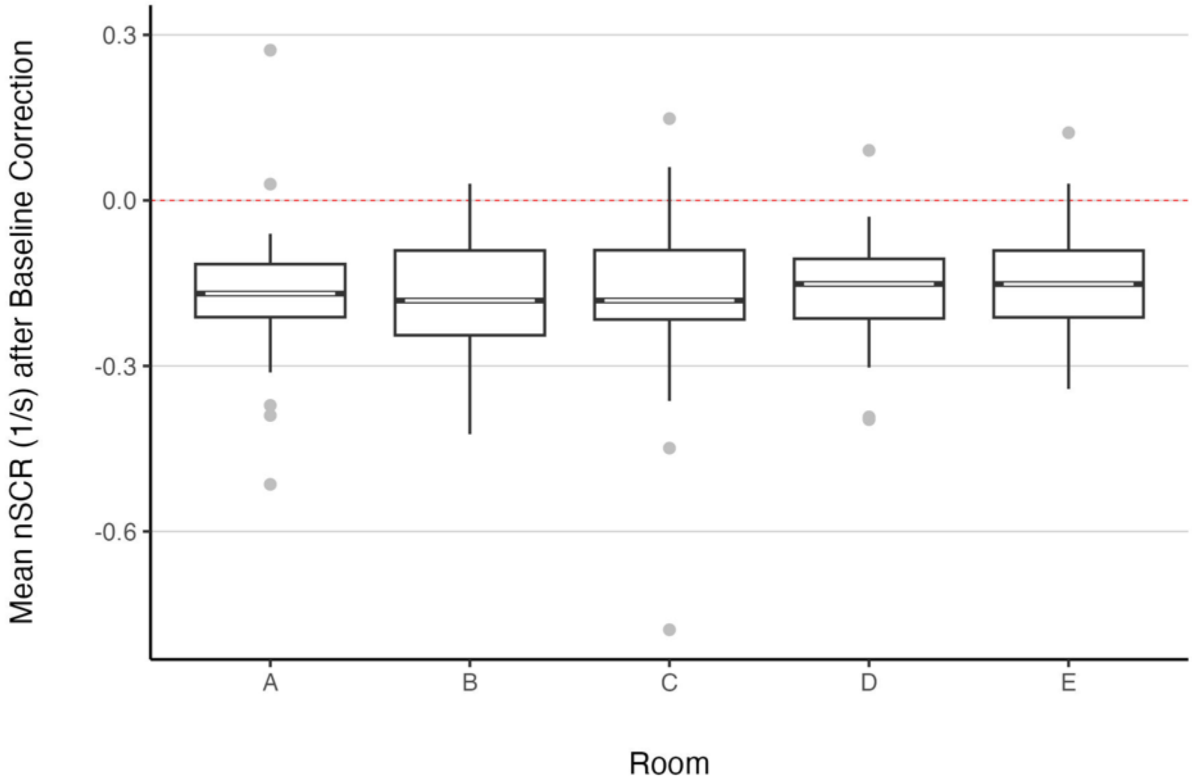

Figure 20: Mean nSCR after the baseline correction shows no significant difference between Rooms.

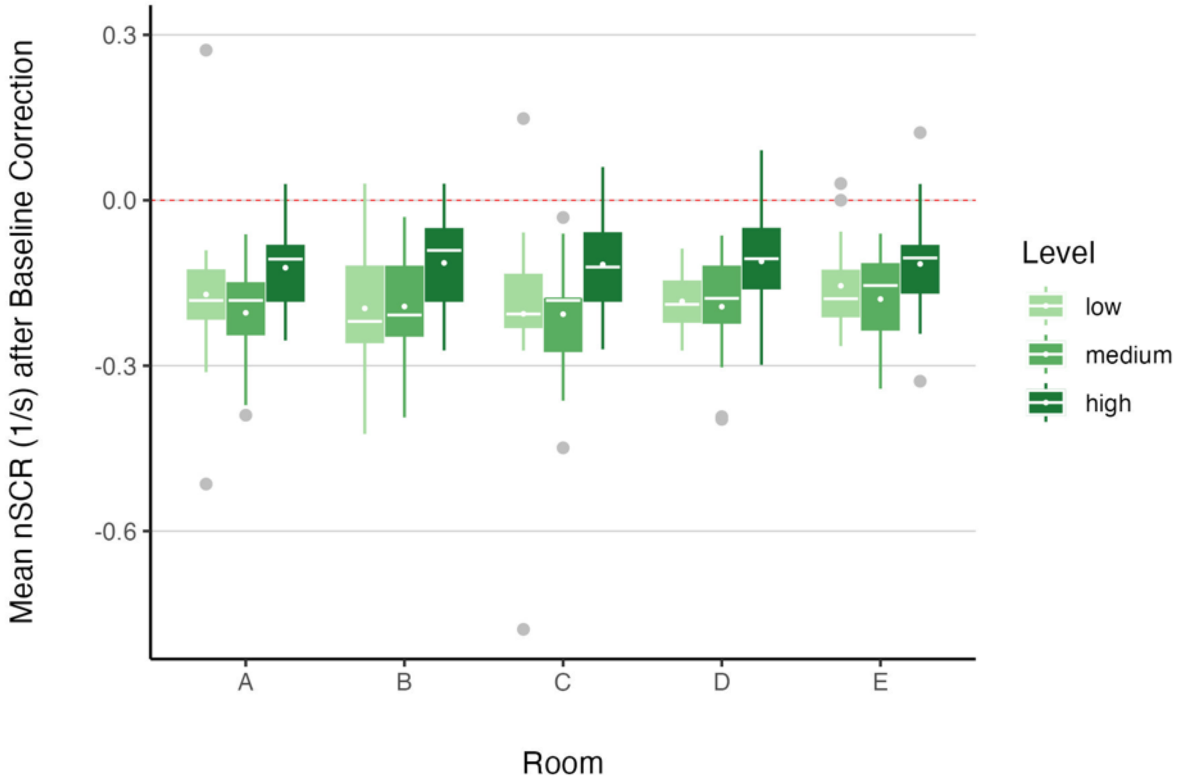

Figure 21: Mean nSCR after the baseline correction shows the highest values for high Level in each Room.

4.2 Self-Assessment Manikin

This chapter presents participants' responses to the SAM for each virtual urban environment. First, the effects of the vegetation density levels on arousal are discussed, followed by the effect on valence. As the SAM answers for both variables are not normally distributed, they are analysed using ART ANOVA.

Consistent with the approach for EDA, the data were baseline corrected (Value – Baseline) to assess changes relative to the baseline video. For arousal, negative values indicate an increase in arousal while positive values describe a decrease. Higher values, therefore, correspond to a more relaxing influence of the city environment. For valence, the scale is inverted: higher values indicate a reduction in valence and, therefore, a decline in perceived happiness, while lower values are indicative of an increase in perceived happiness. The analysis of both variables follows the structure of the chapter before.

4.2.1 Arousal

This section presents how the mean arousal for each virtual urban environment is affected by Level, Position, and Room and how it changes relative to the baseline. ART ANOVA shows no significant interaction effects between any of the three factors.

Level

Figure 22 presents the mean self-reported arousal ratings across the three vegetation density levels after baseline correction. The median values lie above the baseline across all three Levels *low* (Mdn = 1, M = 1.20, SD = 1.36), *medium* (Mdn = 1, M = 1.23, SD = 1.14), and *high* (Mdn = 1, M = 1.34, SD = 1.53), with no substantial differences observed, indicating a general decrease in arousal ratings across all Levels. The IQRs indicate a moderate spread of data, with a few outliers present.

Statistical analysis using ART ANOVA did not reveal a significant effect of between-subject factor Level on arousal ($F(2, 197) = 2.09$, $p = .13$, $\eta_P^2 = .02$), suggesting that vegetation density did not systematically influence self-reported arousal levels.

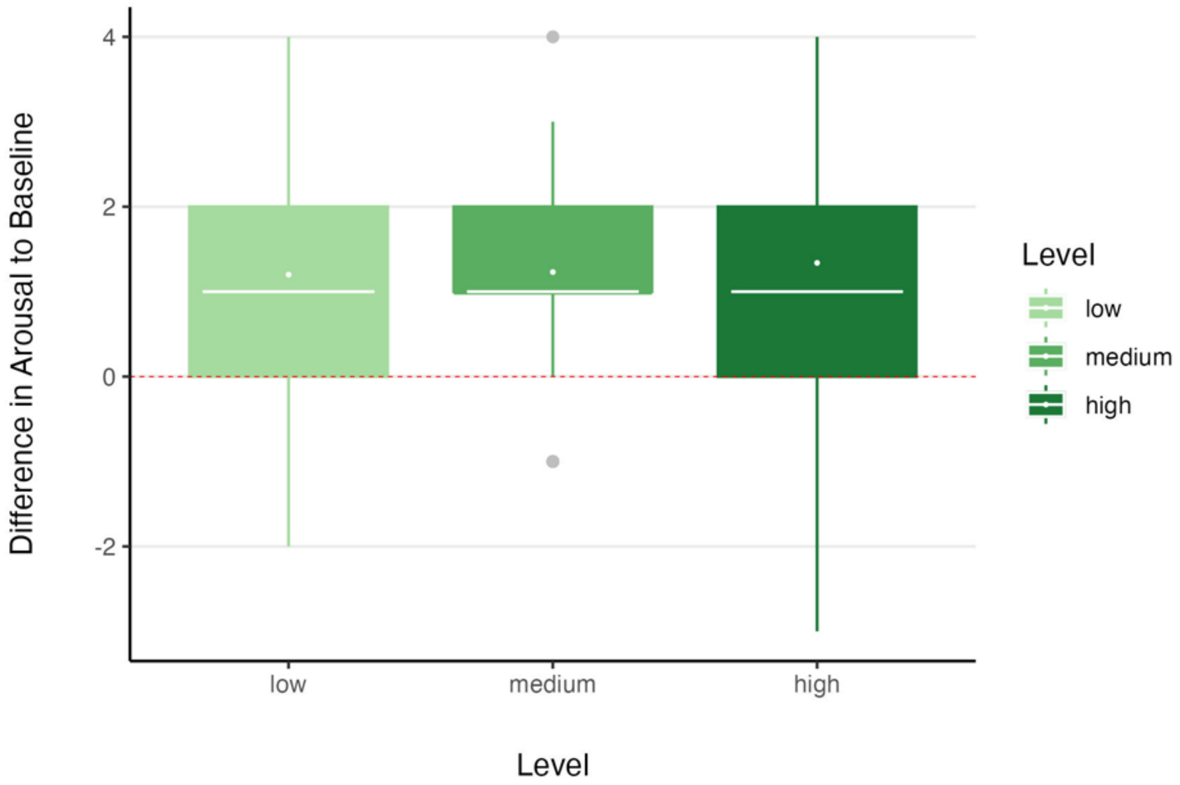

Figure 22: The difference in arousal ratings to the baseline (Value – Baseline) does not change significantly between Levels. The red dotted line represents the baseline answer. A positive value represents stronger relaxation.

Position

The median arousal ratings across Positions remain relatively stable (Figure 23). However, there are slight fluctuations observed, particularly in Position 1, which shows a marginally higher median arousal level compared to the other Positions. The IQRs are consistent across all Positions, indicating uniform data variability.

ART ANOVA showed no significant effect of the within-subject factor Position on arousal ($F(4, 148) = 2.00$, $p = .10$, $\eta_P^2 = .05$), confirming that the order of exposure did not have a substantial impact on self-reported arousal.

Even if the Levels are taken into account, there is no real trend in the mean values of arousal across Positions (Figure 24). Large variability is observed in some Positions, but no systematic pattern emerges between Levels. Although certain Positions exhibit slight differences in arousal ratings, these fluctuations do not indicate a clear trend.

Statistical analysis confirmed no significant of Level on self-reported arousal within Positions (F(2, 37) = 0.10, p = .90, $\eta_P^2 < .01$), indicating that the impact of Position on arousal ratings was not dependent on vegetation density.

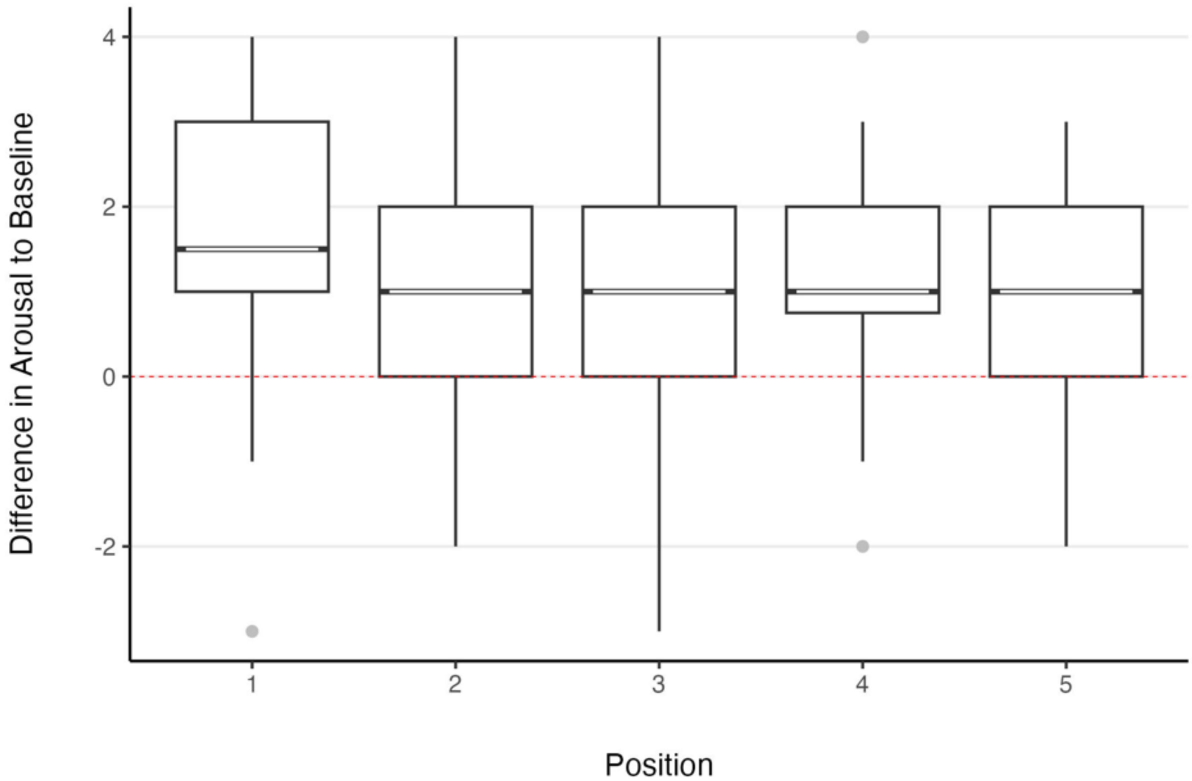

Figure 23: The difference in arousal ratings to the baseline does not change significantly between Positions.

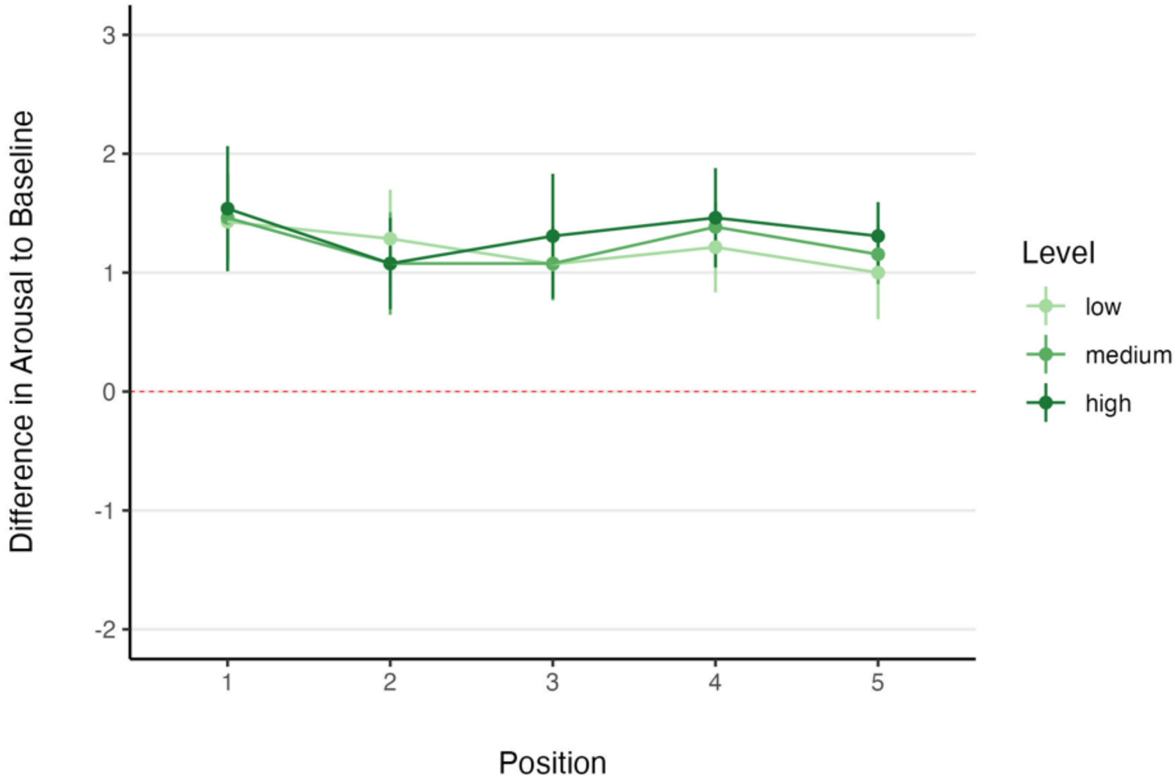

Figure 24: The difference in arousal ratings to the baseline for each Position is not affected by Level.

Room

This is further supported by Figure 25, where the median values of arousal are the same across Rooms regardless of Level (Mdn = 1). Room C and E have a slightly smaller IQR suggesting less variability in arousal for those Positions.

ART ANOVA did not detect a significant main effect of the within-subject factor Room on arousal ($F(4, 148) = 1.22$, $p = .30$, $\eta_P^2 = .03$), indicating that the specific urban environment did not systematically alter self-reported arousal levels.

The further break down of arousal ratings by vegetation density levels shows only minor differences between some Room-Level combinations with no consistent trend evident (Figure 26). The median values remain relatively uniform, with no strong interaction effect apparent.

Statistical analysis confirmed that the effect of Level on arousal within Rooms was not significant ($F(2, 37) = 0.09$, $p = .92$, $\eta_P^2 < .01$), indicating that arousal ratings were not meaningfully influenced by the combination of vegetation density and urban environment.

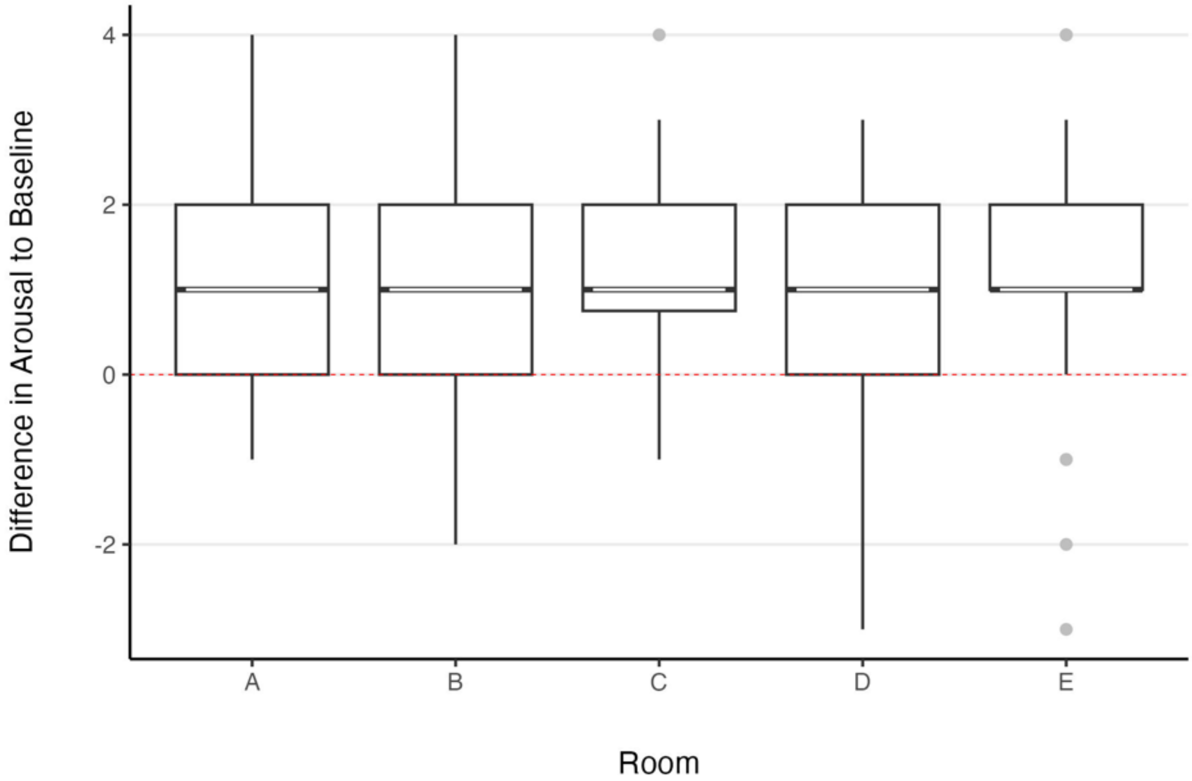

Figure 25: The difference in arousal ratings to the baseline shows no significant effect of Room.

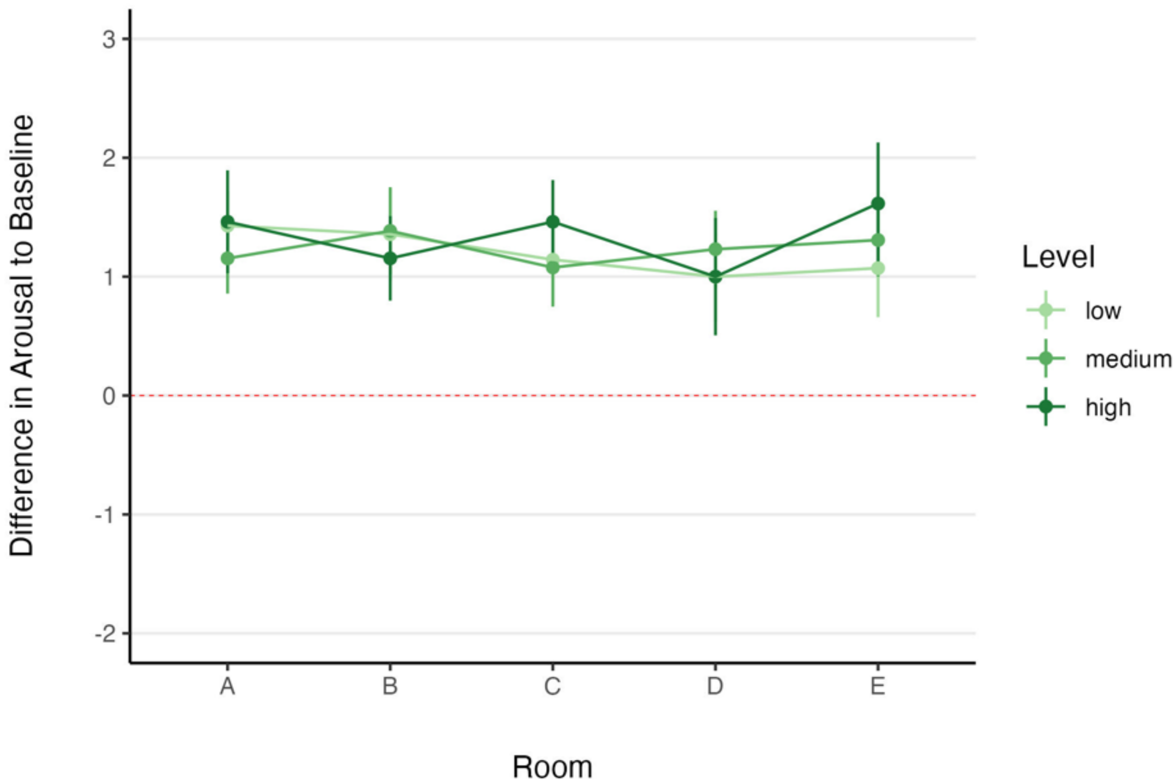

Figure 26: The difference in arousal to the baseline for each Room shows no significant effect of Level.

4.2.2 Valence

This section analyses SAM responses for valence across each urban environment. As with arousal, valence, here, refers to the difference between baseline and each Room.

Level

Analogous to the chapters before, Figure 27 shows the mean valence values across the three vegetation density levels after baseline correction. The medians of *medium* (Mdn = 0, M = -0.17, SD = 1.26) and *high* (Mdn = 0, M = 0.26, SD = 1.05) lie on the baseline while the one for *low* Level (Mdn = 1, M = 0.56, SD = 1.18) lies above, indicating a possible trend toward more positive affective responses for higher vegetation densities. However, the data are widely distributed (especially in *medium* Level) as indicated by the large IQR and long whiskers across Levels.

Statistical analysis did reveal a significant effect of the between-subject factor Level on valence ($F(2, 197) = 5.87$, $p < .01$, $\eta_P^2 = .05$), with the partial eta-squared indicating a moderate effect size. The post-hoc test shows a significant difference between *low* and *medium* Level ($p < .01$).

This indicates that participants exposed to *medium* Level vegetation density rated their valence significantly higher than participants experiencing *low* Level vegetation density.

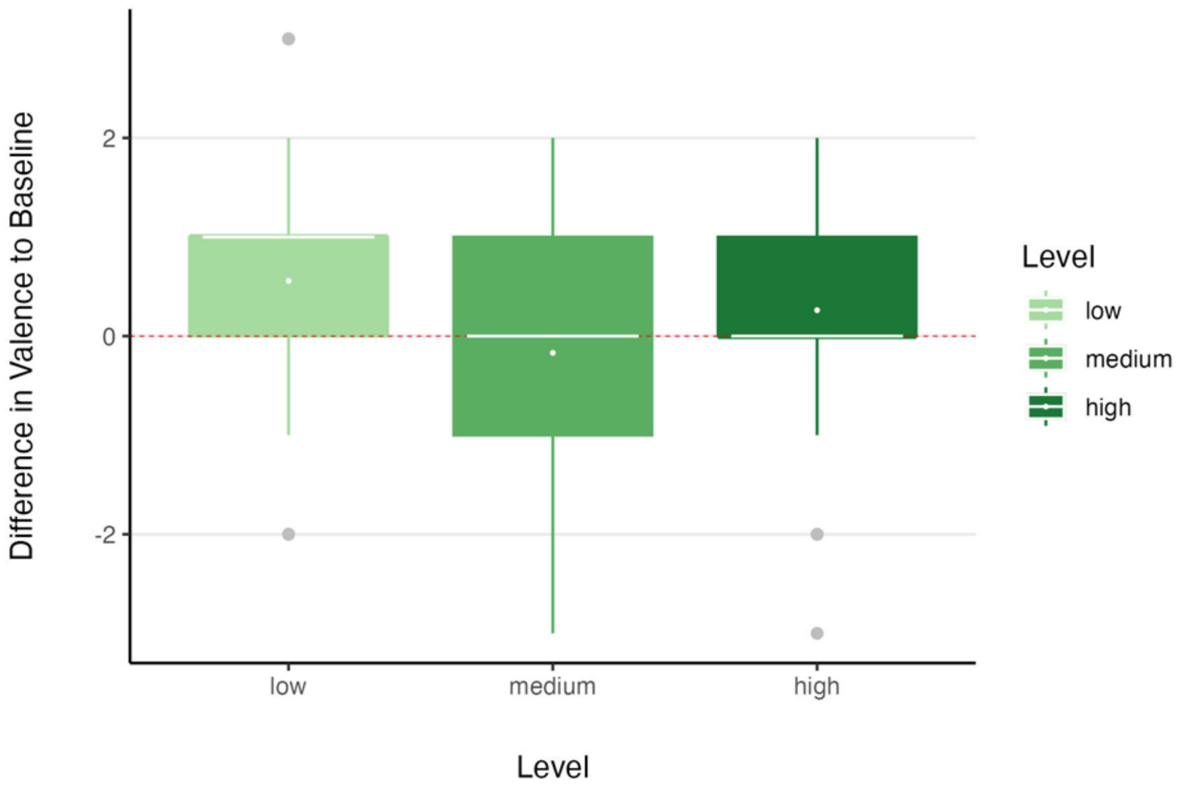

Figure 27: The difference in valence to the baseline shows a significant effect between low and medium Level. The red dotted line represents the baseline. Higher values indicate a decline in perceived happiness (Value – Baseline).

Position

Figure 28 shows that the median values remain stable across Positions (Mdn = 0), with no clear trend. The IQRs are high again but decrease at the fourth and fifth Position, where a few outliers are present.

The ART ANOVA showed no significant effect of the within-subject factor Position on valence ($F(4, 148) = 1.02$, $p = .40$, $\eta_P^2 = .03$), indicating that the order of exposure did not substantially affect participants' self-reported valence.

When considering the different Levels across Positions, there is a small trend visible where *low* has the highest values followed by *high* and *medium* (Figure 29). However, the values are too close together to be significant ($F(2, 37) = 1.71$, $p = .19$, $\eta_P^2 = .08$). Of note is the sudden decline in the difference of valence from the fourth to the fifth Position in *medium* Level. This indicates a strong increase in valence during the urban environment at the fifth and therefore last position. Overall is *medium* the only Level where the difference occasionally is negative, indicating a more positive rating of the urban environments than of the baseline.

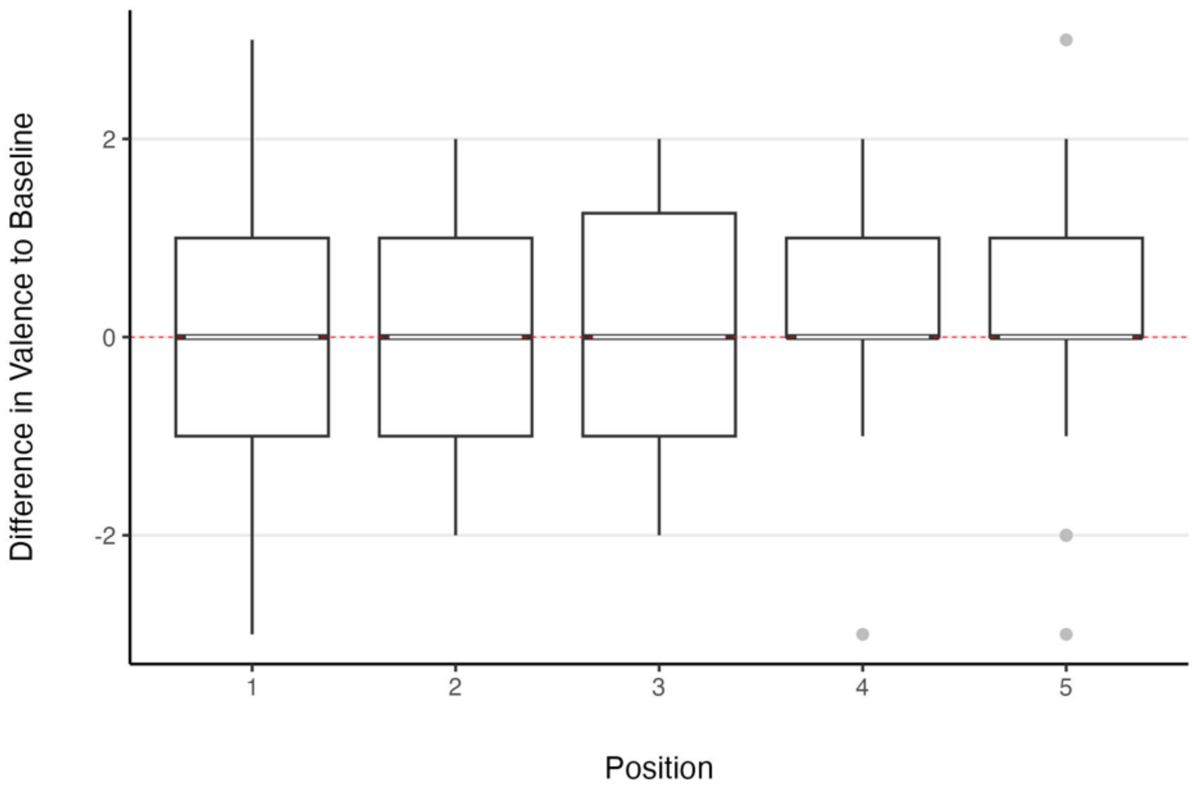

Figure 28: The difference in valence to the baseline is not significantly affected by Position.

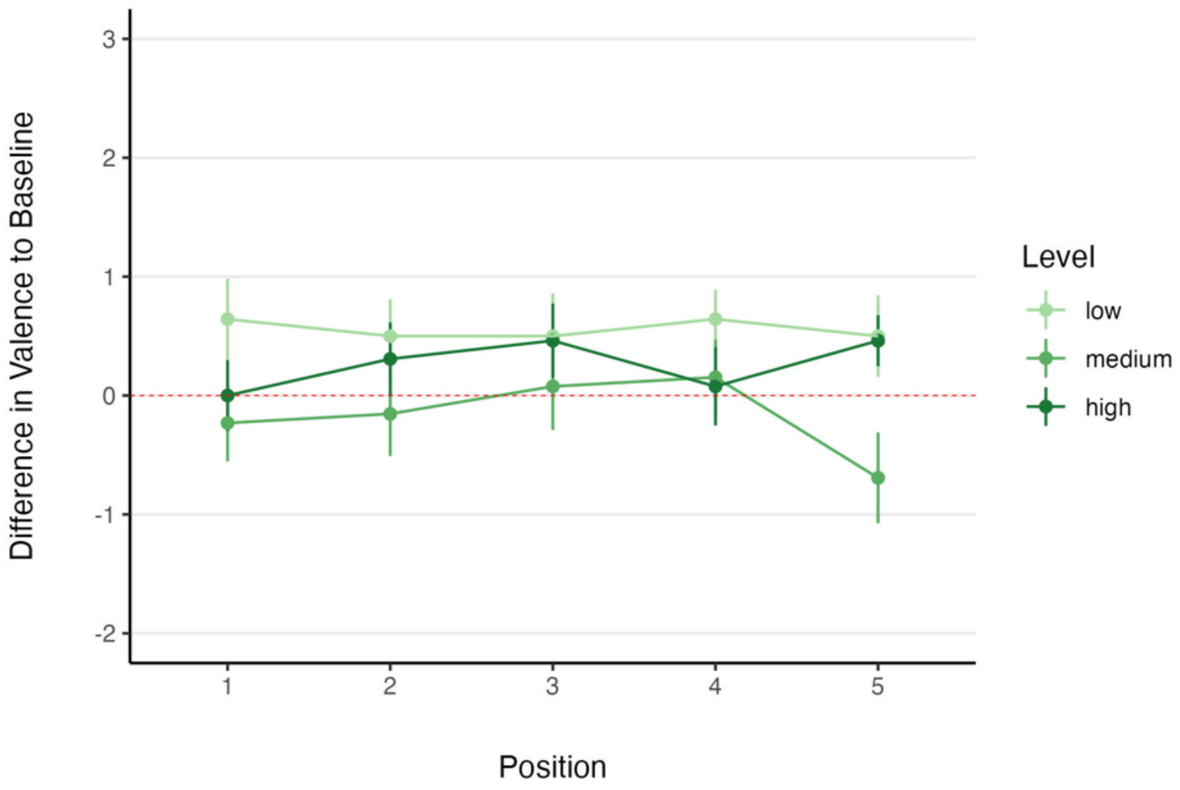

Figure 29: The difference in valence to the baseline for each Position shows a clear distinction between low and medium Level, while the values for high lie in the middle.

Room

Other than for the factors of the previous chapters, Room seems to have an effect on valence. Figure 30 shows distinct changes in median values across Rooms. Especially Rooms C and D seem to differ from the others with higher medians. IQRs are highly differentiating across Rooms as well, indicating inconsistent data variability.

ART ANOVA shows a highly significant effect of the within-subject factor Room on valence ($F(4, 148) = 5.39$, $p < .001$, $\eta_P^2 = .13$). The post-hoc test shows significant differences between Rooms B and C ($p = .01$), B and D ($p < .01$), as well as between D and E ($p = .01$).

When looking at Figure 31, the difference between Levels across Rooms is evident, with *low* having the highest values followed by *high* and *medium.* This supports the findings that Level has a significant effect on valence. Especially the Rooms C and D show distinct differences of mean values between Levels. The differences between Rooms seem to appear mostly in *low* and *high* Level, indicating that Room has a stronger influence on valence in these Levels. Interestingly, only *medium* Level has values below the baseline, indicating that is the only Level where mean valence ratings were higher than the baseline.

However, despite the visually detected differences between Levels, the ART ANOVA results show no significant effect of Level on valence across Rooms ($F(2, 37) = 1.67$, $p = .20$, $\eta_P^2 =$

.08), indicating that the impact of Room on valence ratings was independent of vegetation density.

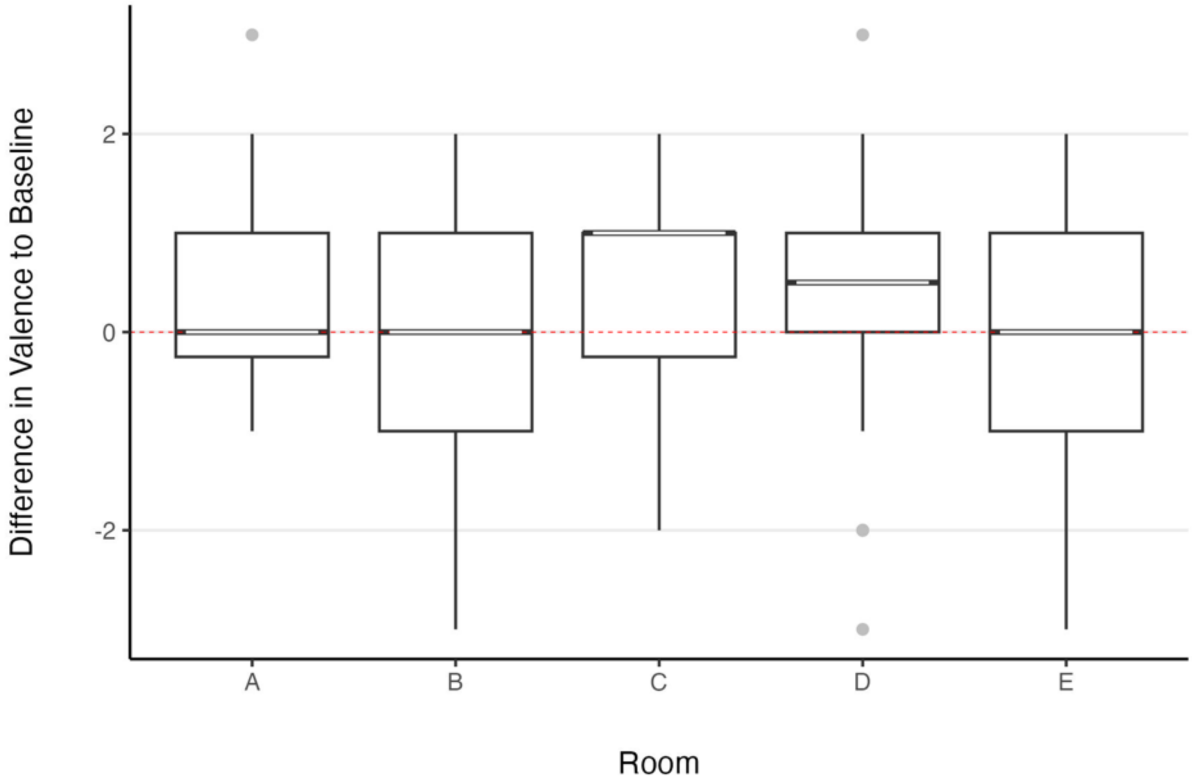

Figure 30: The difference in valence to the baseline changes significantly between Rooms.

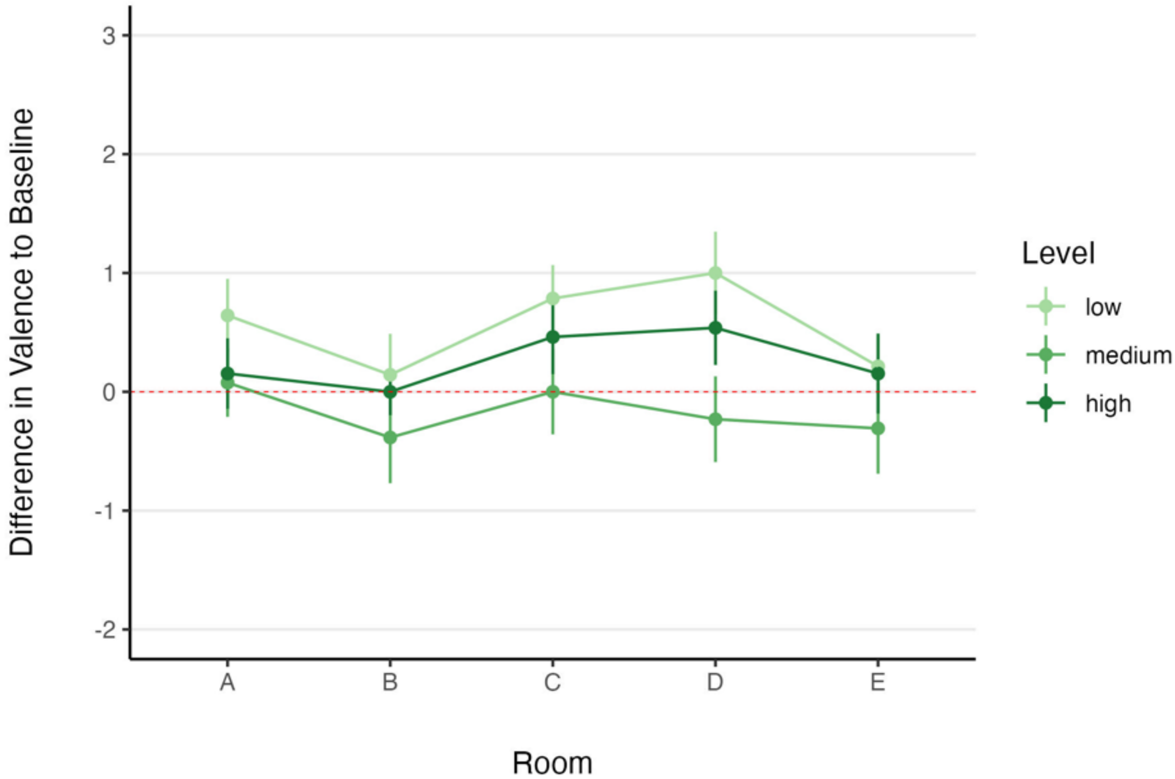

Figure 31: The difference in valence to the baseline shows a clear distinction between Levels within Rooms, especially between low and medium.

4.3 Questionnaire

This chapter presents the analysis of the answers to the questionnaire based on the three theoretical frameworks (ART, PM, PR) as described in the Methods section (Chapter 3.4.3).

A total of 40 participants, aged between 19 and 58, finished the questionnaire (f = 21, m = 19). Participants' demographic information regarding age, gender, and the living situation (city, agglomeration, or rural) can be found in Appendix E. As the distribution is very even for gender and living situation, the influence of these factors was not analysed separately, due to time constraints.

Analogous to the EDA and SAM data, the questionnaire scores were tested for normality. Since none of the scores were normally distributed, the ART ANOVA was conducted like with the variables before. Unlike EDA and SAM, the questionnaire did not include baseline values, so difference values were not calculated. There is also no Position factor, as the questionnaire was identical for all participants except for the variations between Levels.

The questionnaire utilised a 5-point Likert scale, where the value 3 represents a neutral response. Therefore, answers above 3 indicate a positive rating, while answers below 3 reflect a negative rating. For clarity, a red dotted line at the value of 3 in each graph shows the neutral midpoint.

For each theory, the influence of vegetation density and Room on the score will be analysed. Because of time constraints, the individual statements will only be statistically tested by Levels. The Room's influence will be discussed descriptively. All detailed statistic results can be found in Appendix E.

4.3.1 Attention Restoration Theory Score

This section analyses the Attention Restoration Theory (ART) score that consists of the mean ratings of the four statements on being away, compatibility, extent, and fascination. The full statements can be found in Chapter 3.4.3.

Level

Figure 32 shows a slight trend of an increasing median from *low* (Mdn = 3.13, M = 3.05, SD = 0.78) to *high* (Mdn = 3.5, M = 3.37 , SD = 0.79) indicating higher perceived attention restoration in environments with higher vegetation density. All median values lie above the neutral rating, suggesting generally positive ratings. However, high data variability is observed in all Levels, as indicated by the large IQRs.

The ART ANOVA did not reveal a significant effect of the between-subject factor Level on ART scores ($F(2, 197) = 2.09$, $p = .13$, $\eta_P^2 = .02$), indicating that vegetation density did not substantially influence perceived attention restoration. However, when analysing individual statements, “being away” showed a significant difference between Levels ($F(2, 197) = 4.32$, $p = .01$, $\eta_P^2 = .04$) with the post-hoc test showing a significant difference between *low* and *high* Level ($p = .01$), supporting the trend in Figure 32.

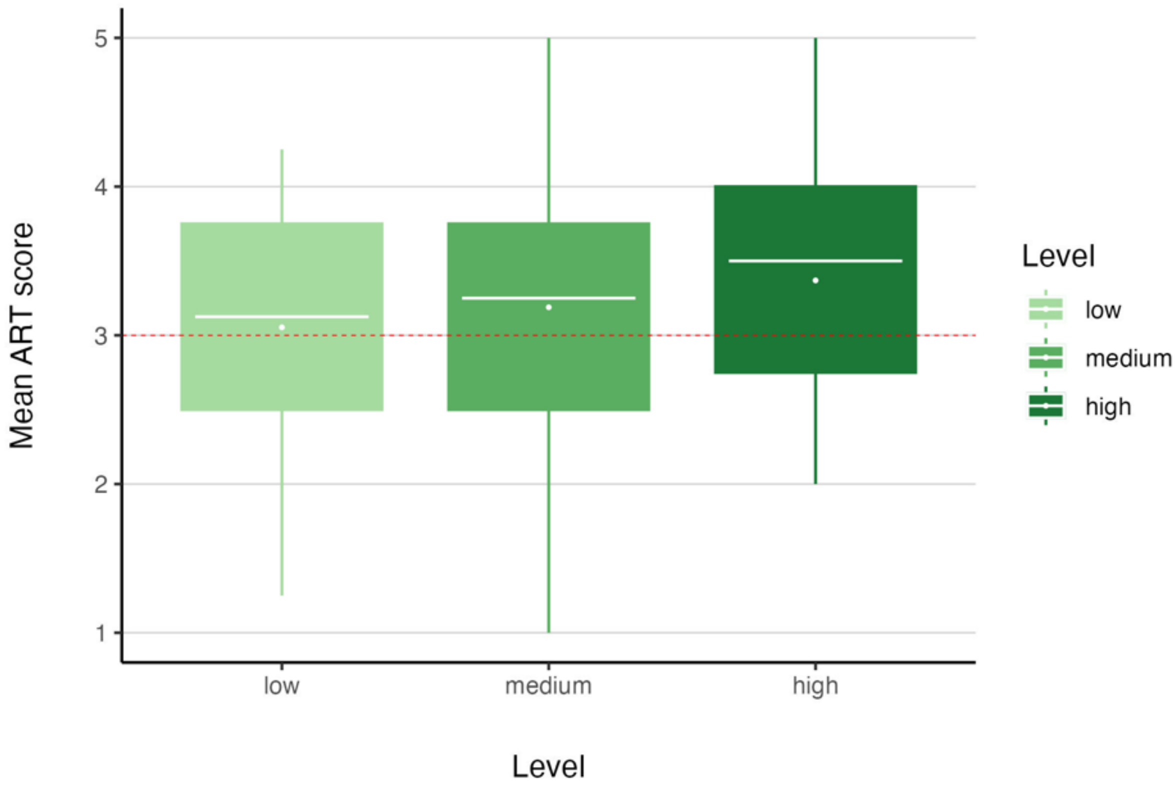

Figure 32: Mean ART scores rise with each Level but show no significant differences. The y-axis represents the 5-point Likert scale. The red dotted line shows the neutral answer. A higher score indicates higher perceived restoration. [dots = mean, bars = median, whiskers = +/- 1.5 IQR]

Room

While the impact of vegetation density is not significant, there are noticeable differences in ART scores between Rooms, with some environments receiving consistently higher ratings (Figure 33).

Statistical analysis showed a significant effect of the within-subject factor Room on ART scores ($F(4, 148) = 30.06$, $p < .001$), $\eta_P^2 = .45$), indicating that the specific urban environment had a strong influence on perceived attention restoration. The post-hoc test shows a significant difference between most Rooms except between A and C, and D and E. However, there was no significant effect of Level on ART scores across Rooms ($F(2, 37) = 1.36$, $p = .27$, $\eta_P^2 = .07$), indicating that the impact of Room on ART scores was independent of vegetation density. The results of the individual statements also show no significant difference between Levels while Rooms significantly impact the ART score (Figure 34).

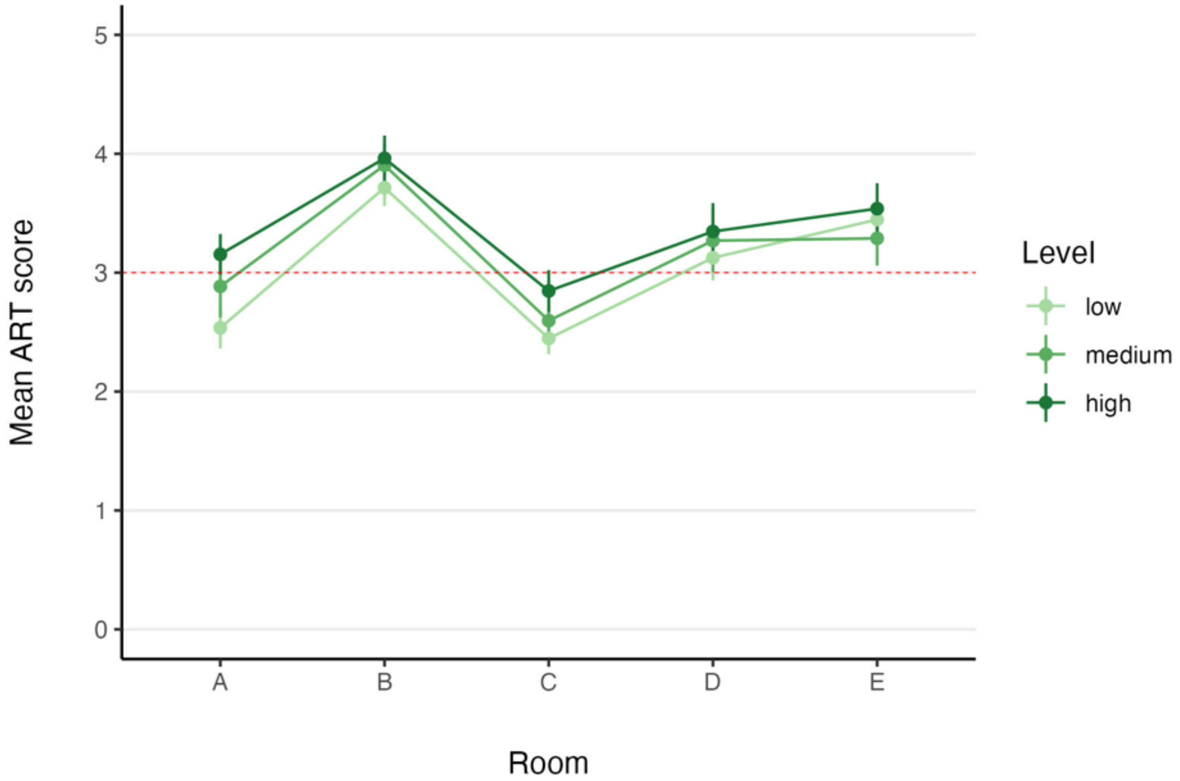

Figure 33: Mean ART scores show significant changes between Rooms but no significant distinction between Levels within each Room. [dots = mean, +/- SE]

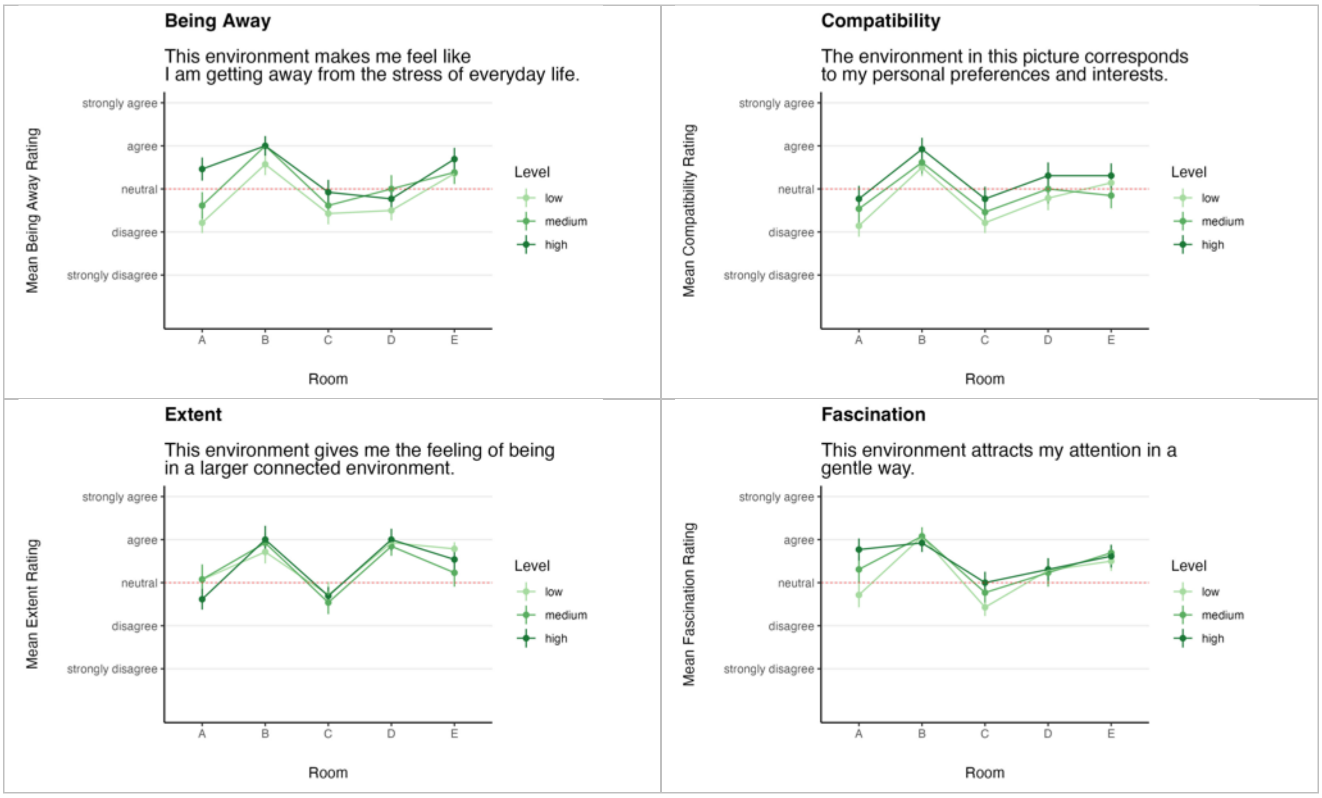

Figure 34: Mean ratings of the individual statements for the ART score regarding the aspects of Being Away, Compatibility, Extent, and Fascination per Room and Level. They show significant differences between Rooms but not between Levels.

4.3.2 Preference Matrix Score

This part analyses the Preference Matrix (PM) score that consists of the mean ratings of the four statements on coherence, mystery, complexity, and legibility.

Level

Figure 35 shows the mean PM score across the three vegetation density levels. Median values are similar across Levels, with slightly lower values for the *medium* Level (Mdn = 3.25, M = 3.24, SD = 0.78) than for *low* (Mdn = 3.5, M = 3.38, SD = 0.72) and *high* (Mdn = 3.5, M = 3.46, SD = 0.63), indicating a lower preference for the *medium* Level. All median values lie above the neutral answer, indicating generally positive ratings across all Levels. However, the variability of the data is very high for all Levels, as indicated by the large IQRs and long whiskers.

There is no significant difference between Levels regarding the PM score ($F(2, 197) = 1.28$, $p = .28$, $\eta_P^2 = .01$).

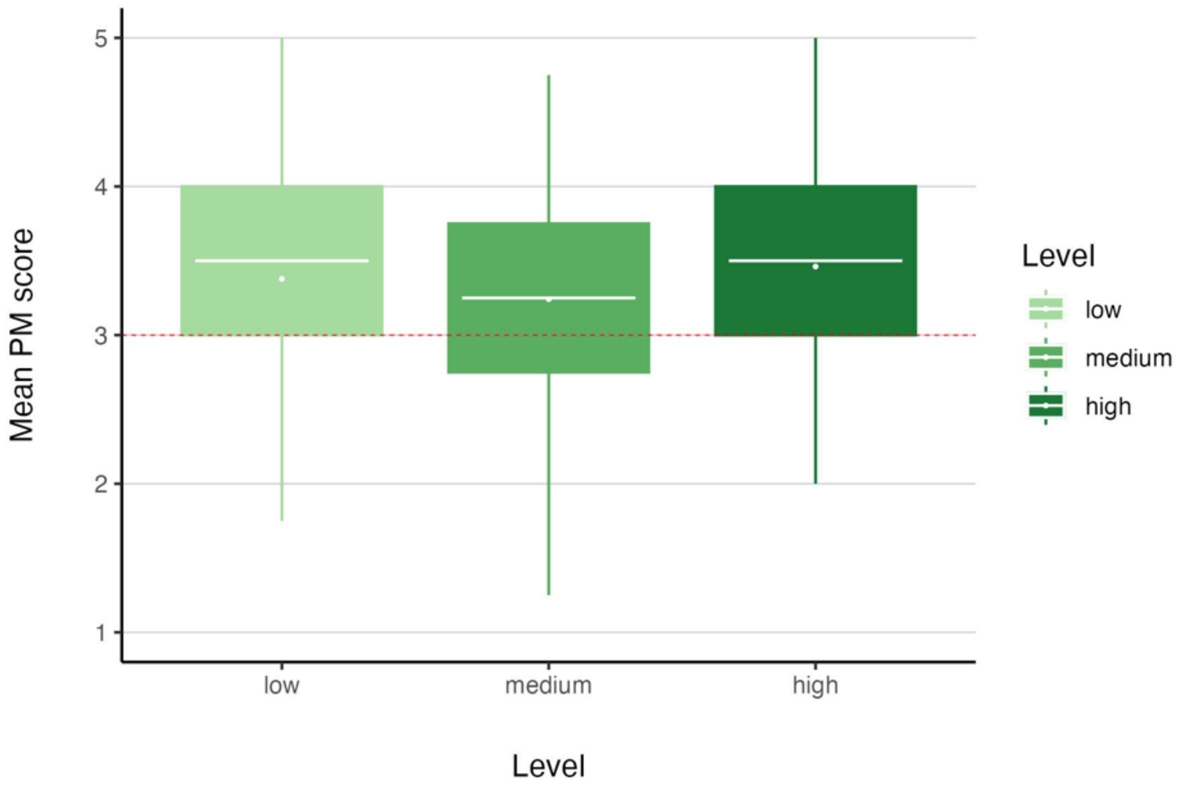

Figure 35: Mean PM scores across Levels show a trend to lower preference ratings for medium Level but no statistical significance.

Room

Figure 36 illustrates the mean PM scores across all Rooms, further divided by vegetation density levels. Differences between Rooms are visible, with some environments (notably B and D) rated more favourably than others.

Like with the ART score before, statistical analysis shows significant effects of the within-subject factor Room on the PM score ($F(4, 148) = 39.44$, $p < 0.01$, $\eta_p^2 = 0.52$), indicating that the specific urban environment significantly influenced preference ratings. The post-hoc test shows a highly significant difference between all Rooms except between A and C, and B and D. However, no significant effect on PM scores between Levels was found across Rooms ($F(2, 37) = 0.80$, $p = .46$, $\eta_p^2 = .04$), indicating that vegetation density had no significant influence on the different ratings for each Room.

The mean ratings of the individual statements across Rooms and Levels (Figure 36) support these findings, with ART ANOVA showing no significant difference between Levels. However, some Rooms received consistently higher ratings across all statements, indicating that these have a significant effect on preference ratings.

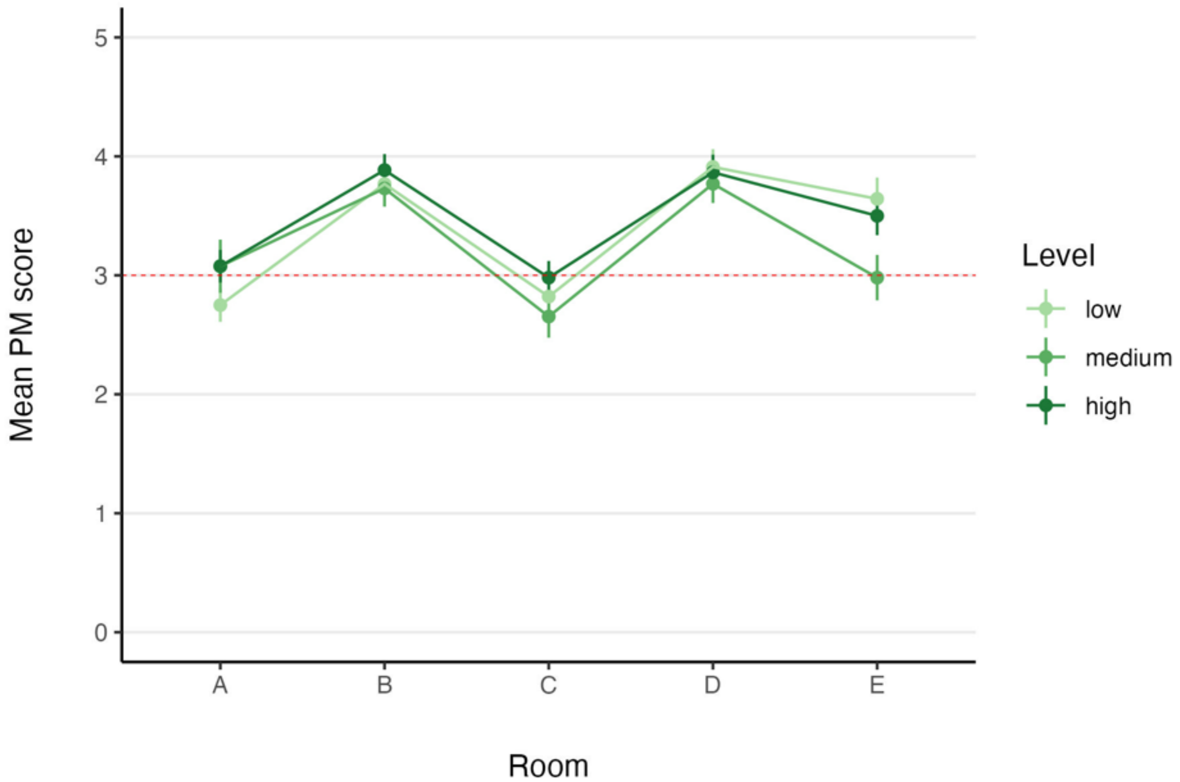

Figure 36: Mean PM scores per Room and Level show significant differences between some Rooms, while Level has no influence.

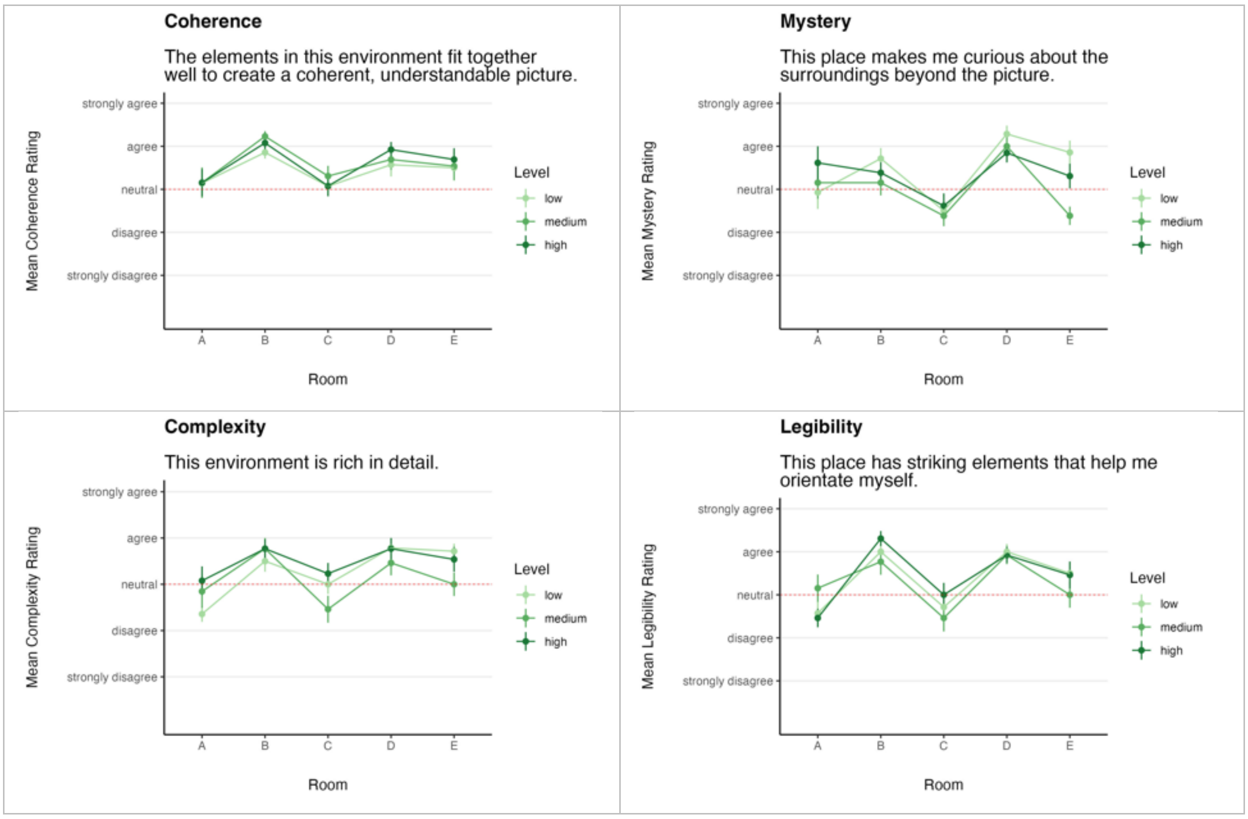

Figure 37: Mean ratings of the individual statements regarding the aspects of Coherence, Mystery, Complexity, and Legibility per Room and Level. Room has a significant influence on each rating while Level has not.

4.3.3 Prospect-Refuge Theory Score

This part analyses the Prospect-Refuge Theory (PR) score that consists of the mean ratings of the two statements on prospect and refuge.

Level

Figure 38 shows that median values are the same across Levels (Mdn = 3), and no clear trend is observed. The large IQRs indicate high variability in the responses, especially for *medium* and *high* Level.

As with the previous scores, there is no significant effect of Level on the PR score ($F(2, 197) = 0.50$, $p = .28$, $\eta_p^2 = .01$), indicating that vegetation density did not significantly influence perceptions of prospect and refuge.

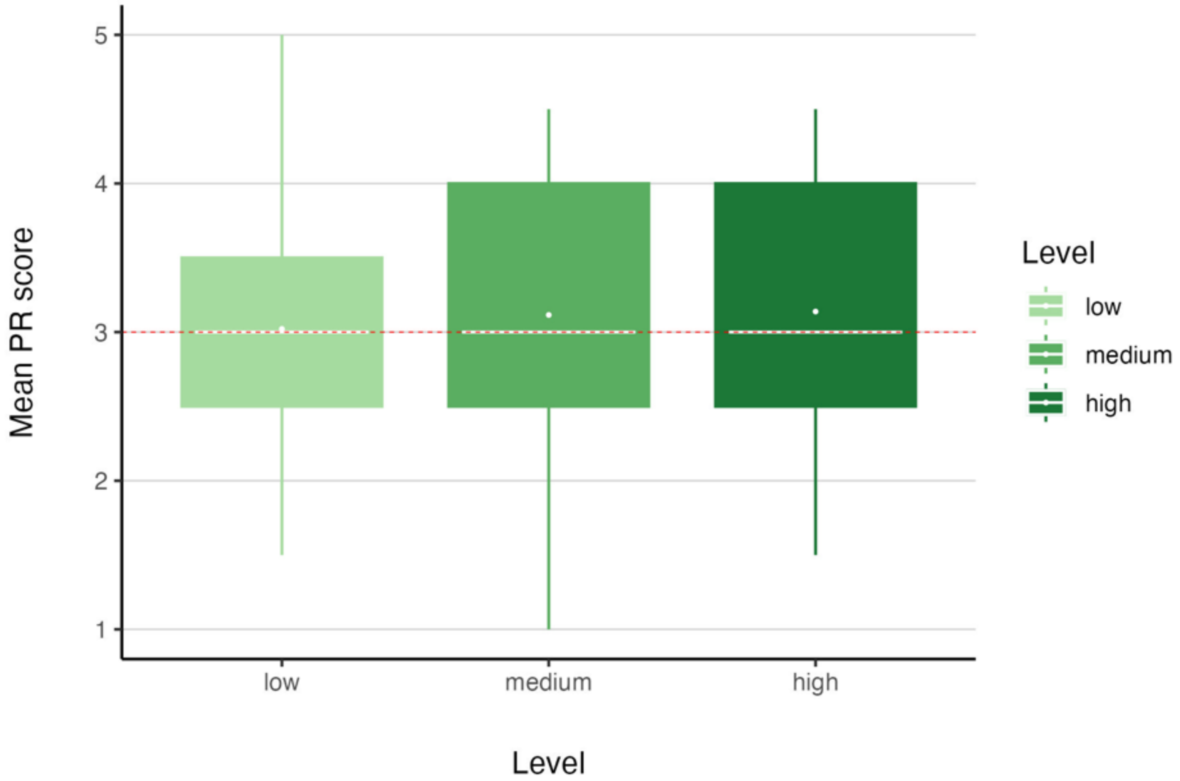

Figure 38: Mean PR scores show no significant effect of Level and a high variability in the data.

Room

Again, as with previous scores, there are clear differences visible between Rooms, with some environments (B and D) rated higher than others (Figure 39).

ART ANOVA showed a significant effect of the factor Room on PR scores ($F(4, 148) = 15.83$, $p < .01$, $\eta_P^2 = .30$), indicating that the specific urban environments significantly influenced perceptions of prospect and refuge. The post-hoc test shows significant differences between six of the Rooms (Appendix E). However, no significant effect of Level within Rooms was found ($F(2, 37) = 0.46$, $p = .63$, $\eta_P^2 = .02$).

The ratings for the individual statements align with these findings, similar to the two preceding scores, by revealing no significant effects of Level on PR scores. The only visible difference between Levels can be found in Room D for the refuge rating, indicating that vegetation density influenced perceived safety in this specific urban environment. However, the ratings between Rooms change significantly (Figure 40).

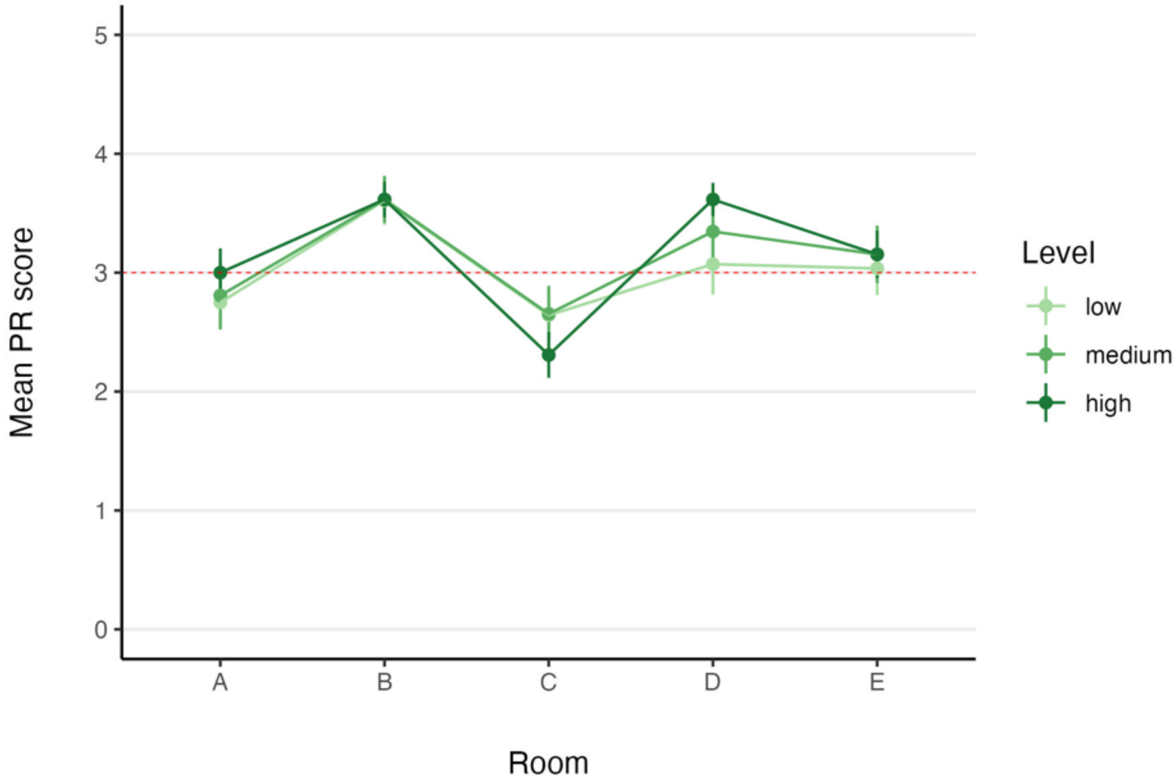

Figure 39: Mean PR scores show a significant effect of Room but no significant changes between Levels within each Room.

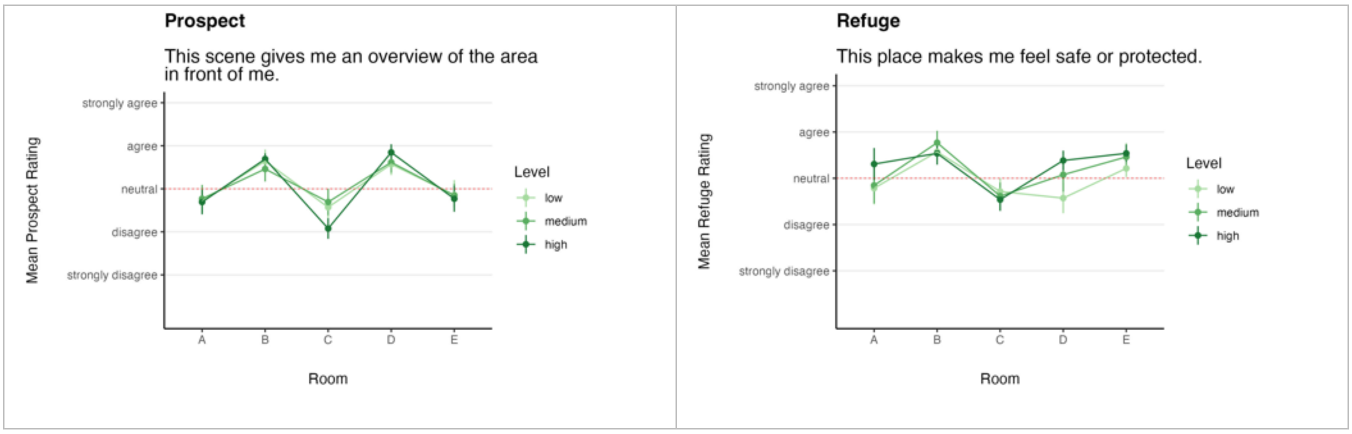

Figure 40: Mean ratings of the statements regarding the aspects Prospect and Refuge per Room and Level. They are significantly different between Rooms but show no significant effect of Level within Rooms.

5 Discussion

This chapter discusses the findings from the study, integrating results across the objective physical response (SCL and nSCR), subjective emotional responses (SAM), and questionnaire evaluations. The focus lies on interpreting the influence of vegetation density levels (*low*, *medium*, *high*) on physiological and psychological responses while considering potential effects of Room and Position. While physiological data suggests that *medium* vegetation density has the most pronounced stress relieving effect, subjective measures paint a more nuanced picture, highlighting the role of individual differences and the influence of urban spatial design. The discussion contextualises the results within existing literature and relevant theories of landscape aesthetics presented in Chapter 2.2. It is closed by a section on limitations and future research directions.

5.1 Objective Measures (EDA)

This section discusses the results of the skin conductance level and the number of skin conductance responses during the VR experience.

The results of the EDA measures indicate that *medium* vegetation density (26 – 41%) had the most pronounced calming effect on participants, as evidenced by the largest reduction in SCL compared to the baseline condition. This supports the hypothesis (**H1.2**) that *medium* vegetation density is optimal for stress relief, as well as previous research (Jiang et al., 2014; Kaplan & Kaplan, 1989). In contrast, environments with *high* vegetation density induced more nSCR responses than both *low* and *medium* Levels, indicating heightened arousal. This suggests that *high* vegetation density might add to perceptual complexity that leads to increased stimulation rather than relaxation. And, in turn, *low* vegetation density might allow for a better focus on singular details with less complexity in objects and textures, leading to a lower phasic EDA signal. These findings are consistent with previous literature suggesting that environments with dense greenery provide less prospect, resulting in overstimulation rather than stress reduction (Gatersleben & Andrews, 2013). The SAM and questionnaire results discussed in the following chapter give more insights into possible reasons behind the physical responses.

Both SCL and nSCR values were consistently lower in the virtual urban environments compared to the baseline, indicating a general decrease in stress regardless of vegetation density level. This could be attributed to the transition from the highly dynamic and exciting rollercoaster video to the more static and calm environments, aligning with Lendenmann's (2023) results. The differences between SCL (tonic) and nSCR (phasic) responses highlights the complexity of physiological reactions. While SCL primarily reflects sustained emotional states, SCR is more sensitive to short-term events or stimuli. This difference might help explain the heightened responses in nSCR in *high* Level, where the increased visual complexity captures more attention and leads to temporary arousal. This is supported by Kilpatrick's (1972) claim that SCR is more closely tied to psychological stress, and thus more likely to be influenced by immediate attentional demands or sensory overload.

The variability in *high* Level, particularly the large standard deviation in SCL values, points to individual differences in emotional responses to these environments. This suggests that individual preferences and backgrounds might play a role in the experience. Participants who are more accustomed to urban settings or who prefer less-stimulating spaces might experience heightened stress in dense vegetation, whereas others might find these environments restorative. This is reflected in the different mean preference ratings (PM score) based on participants' living situation. Participants from rural areas rated environments with *high* vegetation density higher than participants from agglomerations followed by those living in cities (see Appendix E).

There were no significant effects for Room or Position in relation to SCL or nSCR. This suggests that vegetation density was the primary factor influencing physiological responses, independent of the spatial design or order of exposure.

Overall, it can be stated that *medium* vegetation density seems to be optimal for promoting stress relief, which supports **H1.2**. This means that in turn, **H1.1**, stating stress relief increases with vegetation density, is only partially supported by the data. Although SCL decreased from *low* to *medium* Level, it rose again for *high* Level. And nSCR values only differed in *high* Level where they even showed heightened arousal compared to the other Levels. This indicates that stress relief is not directly proportional to vegetation density but follows a non-linear trend.

The arousal measured with EDA cannot differentiate between positive and negative arousal. Therefore, to get more insight into the subjective perception of participants, the self-reported measures SAM and a questionnaire added to the subjective measures and are discussed in the following chapter, helping to put the physical measures into perspective.

5.2 Subjective Measures (SAM, Questionnaire)

This section focuses on the self-reported arousal and valence ratings during the VR experience, as well as the answers to the post-experiment questionnaire based on theories of landscape aesthetics.

SAM

The SAM results for arousal showed no significant effects of vegetation density level, Position, or Room suggesting that self-reported arousal is less sensitive to changes in vegetation density than physiological measures like SCL or SCR. Unlike EDA, which captures immediate physiological reactions, the SAM requires participants to reflect on their emotional state which can be subject of recall bias (Hassan, 2005). The lack of significance in arousal ratings could also stem from the variability in subjective perceptions. Notably, *medium* vegetation density showed the least variability in arousal ratings, while being lower than the baseline. This suggests that even though participants did not report major differences in arousal across vegetation levels, they reported low arousal values most consistently in *medium* Level, which aligns with the EDA findings where *medium* Level had the most pronounced calming effect.

A minor shift was observed in relation to Position, where the first Position had slightly higher arousal ratings than the subsequent ones. This might reflect a residual effect from the rollercoaster video in which participants experienced heightened arousal before adjusting to the more static virtual urban environments. However, the effect is not as distinctive as in other studies where participants got continuously calmer over the course of the experiment (Lendenmann, 2023).

In contrast to arousal, valence ratings showed a significant effect of vegetation density. *Medium* vegetation density elicited the most positive responses, partially supporting the hypothesis that valence increases with vegetation density (**H1.3**). However, the relationship was not linear, as valence increased significantly from *low* to *medium* density but did not continue to rise for *high* Level. *Medium* Level is the only one where the difference in valence to the baseline is negative for some Rooms, indicating a more positive feeling and therefore confirming **H1.4**. This suggests that while moderate greenery in cities enhances emotional well-being, there might be an upper threshold regarding positive perception. *Low* vegetation density, on the other hand, lies on the opposite spectrum and while it provides openness, which people generally prefer (Brown & Corry, 2011), it provides not enough greenery for people to rate favourably. Previous research has indicated that individuals tend to prefer environments that balance natural features with openness and navigability, which aligns with these findings (Franěk, 2023; Tabrizian et al., 2018).

The significant differences in valence ratings between Rooms highlight the role of urban design in shaping emotional responses. Some environments were perceived more positively than others, with Room B and E receiving higher valence ratings, while Rooms C and D were rated significantly lower. Several factors may explain these differences. In Room C, there is a man sitting on a bench near the observer. His face is turned towards the viewer and could therefore have triggered an uncanny valley effect. In Room D, participants were positioned in a shaded, enclosed space between tall buildings, which may have created a sense of confinement or insecurity (Mazumder et al., 2022). In contrast, Rooms B and E are more open and brighter, providing more overview and therefore a sense of safety and spaciousness (Appleton, 1975; Gatersleben & Andrews, 2013). When considering the interaction between vegetation density and Room, *medium* Level was the only condition in which valence ratings either exceeded or matched those of the baseline. In contrast, *low* and *high* vegetation densities were associated with lower valence scores, particularly in environments that can be perceived as enclosed or visually complex. Additionally, the difference between Rooms seems to be more pronounced in *low* and *high* Level. This suggests that moderate greenery can reduce certain negative aspects of an urban environment.

The findings support the hypothesis (**H1.4**) that *medium* vegetation density leads to the highest valence. While *high* vegetation density provides complexity and even shelter, it reduces clarity and therefore its restorative potential, highlighting the importance of balance in urban greenery design (Jansson et al., 2013). Hypotheses **1.1** and **1.2** cannot be statistically confirmed with arousal not changing significantly between Levels but having slightly lower ratings in *medium* Level. **H1.3** can only be partially supported by the data with valence only increasing from *low* to *medium* Level.

Questionnaire

The results of the questionnaire showed no significant effects of vegetation density on the overall ratings. The ART score, intended to reflect perceived restoration, only shows a small trend suggesting slightly greater restoration at higher vegetation density. While this aligns with the Attention Restoration Theory where exposure to nature helps with restoration of mental capacity (Kaplan & Kaplan, 1989), the effect was weak, and the variability in response was high. The only statement that received significantly higher ratings for *high* compared to *low* was the one representing “being away”, indicating that denser vegetation leads to a greater perceived escape from daily stress. The hypothesis (**H2.1**) claiming higher vegetation density leads to higher perceived restoration can therefore not be confirmed. This contradicts prior studies that have found significant restorative effects in green environments (Berman et al., 2008; Franěk, 2023; Lindal & Hartig, 2015), raising questions about why vegetation density did not have a stronger influence on ART scores in this study. One possible explanation is that ART has primarily been studied the contrast of nature and urban settings (Berman et al., 2008), whereas the present study examined greenery within urban environments where architectural features and spatial design may have had a stronger impact on participants' perceptions. This interpretation is supported by the significant effect of Room, which had a greater influence on ART scores than vegetation density itself.

Another factor that may have contributed to the weak effect of vegetation density is the nature of the questionnaire itself, the Likert-scale format may have introduced response tendencies such as central tendency bias, where participants avoid extreme ratings (Douven, 2018). It might also be that the statements chosen to represent each factor could be improved to fit the concepts better. Additionally, the retrospective nature of self-report measures means that immediate physiological effects, which were observed in the EDA data, may not have been fully captured in the questionnaire responses.

Similar to the ART score, the preference matrix (PM) score did not show a significant effect of vegetation density. This contradicts the hypothesis (**H2.2**) that *medium* Level should be the most preferred and challenges previous findings that suggest people favour moderate greenery in urban settings (Bjerke et al., 2006; Lis et al., 2022). However, these studies mostly examined urban green spaces like parks and not consistent greenery across streets. Surprisingly, *medium* vegetation density was rated slightly lower than both *low* and *high* Levels. One possible explanation is that urban design elements such as street width, building height, and spatial openness played a stronger role in shaping preferences than vegetation density itself. Given that the effect of Room was highly significant, this suggests that participants' preferences were more influenced by structural aspects of the environment than by the amount of greenery.

For the Prospect-Refuge (PR) score, no significant differences were found between vegetation levels, disproving the hypothesis that *medium* vegetation density enhances perceived safety and shelter (**H2.3**). However, Room had a strong effect, with Room C receiving the lowest and Rooms B and D receiving the highest PR ratings overall. A more detailed analysis of the individual components suggests that different aspects of spatial perception influenced responses. In Room C, the lowest prospect ratings were observed, likely due to limited visibility (dead end) and the presence of an ambiguous human figure (uncanny valley), causing feelings of unsafety and confinement (Gatersleben & Andrews, 2013; Stein, 2018). In Room D, refuge ratings varied widely between Levels, suggesting that vegetation density can transform enclosed spaces by making them feel safer. These findings highlight the complexity of environmental perception and suggest that vegetation alone does not determine preference or perceived safety; instead, spatial configuration, visibility, and elements such as human presence play crucial roles.

Overall, the results suggest that while *medium* vegetation density generally enhances emotional well-being, its effect on perceived restoration, preference, and safety are highly dependent on the broader urban design. Previous research has emphasised the benefits of greenery in urban environments, yet the findings from this study indicate that vegetation density interacts with spatial structure and individual perception in complex ways. The hypotheses regarding preference (**H2.2**) and perceived safety (**H2.3**) were not confirmed. **H2.1**, stating higher vegetation density leads to higher perceived restoration, could also not be statistically proven but there is a slight trend supporting the statement. These results underscore the importance of considering not only the quantity of vegetation in urban planning but also how it is integrated within the built environment.

5.3 Correlation between Stress Relief and Aesthetic Perception

The relationship between stress relief and perceived aesthetics is a key factor in understanding participants' emotional responses to urban greenery. Prior research suggests that environments perceived as aesthetically pleasing often contribute to greater psychological restoration, as beauty itself can induce positive emotions and reduce stress levels (Chatterjee & Vartanian, 2016; Ulrich, 1983; Van Den Berg et al., 2014). In this study, stress relief as measured by EDA and self-reported arousal, was generally high in *medium* vegetation density, which also received the highest valence ratings, suggesting a general alignment between the different emotion measures. However, there is not a complete overlap between the measures as *high* density received also high valence ratings and *low* vegetation density received lower nSCR values. The ART, PM, and PR scores, meant to provide additional insight into aesthetic perception based on restoration, preference, and perceived safety, showed only weak effects of vegetation density, not aligning with EDA results. At the same time, the specific urban environments had a strong impact on the scores, independent of vegetation density. This suggests that while participants may feel happiest and generally calm in environments with *medium* greenery, it does not strongly influence their self-reported sense of restoration, preference, or safety. The hypothesis **(H3.1),** that stress relief and perceived aesthetics correlate, can therefore not be supported. This highlights the complexity of environmental perception, where aesthetic preference, physiological stress reduction, and subjective restoration do not always align perfectly.

These differences between measures can be caused by various reasons. Some might be explained by the limitations of this study that will be discussed in the following chapter.

5.4 Limitations

Although the repeated-measures design allowed for robust comparisons with a smaller sample, the sample size of only 40 participants limits the generalisability of findings. The high variability and lack of significance in some results could be related to this small sample size. Additionally, participants were primarily recruited at the University of Zurich, introducing potential biases related to age, background, or familiarity with urban green spaces. Future research could take personal background more into account by incorporating a more diverse sample.

The difference between vegetation density levels might have been too small to get more significant results. However, as this study only focused on ground vegetation, space constraints limited the extent of possible variations. Future studies could consider designing an urban environment with wider pavements to allow for a more natural integration of trees and shrubs. It is also possible to add more façade greenery to increase density for the *high* Level and create a wider range. Although, prior research has shown a saturation effect of vegetation density at 60% (Jiang et al., 2014), this effect might be less pronounced in virtual urban environments due to limitations in visual fidelity, including flickering and lower resolution.

While vegetation density was isolated as the primary independent variable, urban perception is influenced by multiple interacting factors, including lighting, architecture, and human presence. The significant impact of Room on self-reported valence and the questionnaire ratings emphasises the role of urban design in shaping perceptions of preference, restoration and safety. Also, the virtual environments lacked real-world complexities such as traffic, social interactions, and environmental sounds, which were excluded to minimise confounding variables. However, this absence might have unintentionally increased the influence of individual Rooms on subjective perception by making city environments appear abandoned, potentially influencing participants' perception more than vegetation.

Previous research on the emotional influence of vegetation has primarily focused on natural environments, where variations in greenery do not drastically alter the overall realism. In contrast, this study's virtual urban environments appeared noticeably artificial, which might have affected how participants perceived vegetation density. Future research should carefully design urban environments to avoid overshadowing the influence of vegetation.

This study exclusively examined the emotional impact of vegetation density in urban environments. Future research could expand on these findings by exploring similar experiments in agglomerations or industrial areas, where a greater variety of built structures interact with greenery. These underrepresented environments could provide valuable insights into the advantages of urban vegetation.

Some statements in the questionnaire had not previously been used in an experiment like this and might need refinement to get more nuanced responses. Future implementations could benefit from revising these statements for clarity. Additionally, adopting a 4-point Likert scale could help mitigate central tendency bias by compelling participants to choose between positive and negative ratings.

Despite these limitations, this study provides valuable insights into the emotional impact of vegetation density in virtual urban environments. While challenges such as sample size, artificiality, and design constraints should be considered, the study contributes to the broader understanding of urban greenery's effect on well-being.

Conclusion

This thesis examined the influence of vegetation density in virtual urban environments on emotions and personal perception. It aims to emphasise the importance of urban greenery, in addition to its ecological benefits, for the quality of life and provide a recommendation for the optimal amount of greenery.

To answer the research questions, a VR experiment was conducted where participants were divided into three groups (*low*: 0 – 25%, *medium*: 26 – 41%, and *high*: 42 – 67%) and exposed to urban environments with one of three vegetation densities. To measure emotion, both objective and subjective measures were combined. The objective method consisted of measuring skin conductance level and the number of skin conductance responses. For the subjective methods, participants rated the urban environments using the SAM based on the dimensions of arousal and valence, and completed a questionnaire based on landscape aesthetics theories.

The results show that *medium* vegetation density consistently reduced stress across all emotion measurements. However, the results for stress reduction were not entirely straightforward. While the objective measurements found a significant difference between *medium* and *high* vegetation density, the results for *low* vegetation density were not as distinct. The SCL values showed reduced stress reduction for both *low* and *high* densities compared to a significantly stronger reduction in *medium* density, while the number of SCRs for *low* and *medium* densities were very similar. It can therefore be stated that *medium* vegetation density is preferred for stress reduction over *high* density, while *low* vegetation density yields somewhat less consistent results. Self-reported arousal, however, showed no significant differences between Levels.

The valence ratings showed a significant increase from *low* to *medium* and generally the most positive ratings for *medium* Level, highlighting the positive perception of *medium* vegetation density. The results of the questionnaire showed no direct relationship between vegetation density and perceived restoration (ART), preference (PM), or safety (PR). However, the Room itself had a significant influence on valence and questionnaire ratings, suggesting that vegetation density alone does not determine preference or perceived restoration, rather, it interacts with spatial configuration, visibility, and perceived safety. The variability in subjective ratings across different environments suggests that urban planning must consider not only the amount of greenery but also how it is integrated within the built environment. By considering factors such as spatial layout, navigability, and visibility, cities can create restorative environments that promote mental health and aesthetic appeal.

Conclusion

In summary, it can be said that vegetation density between 26% and 41% offers stress relief most reliably, as evidenced by both physiological and self-reported measures, aligning with key concepts of landscape aesthetic theories. However, not all hypotheses could be statistically confirmed, highlighting the complexity of emotion measures. The thesis highlights the importance of a balanced approach in urban greenery design, challenging simplistic assumptions that more vegetation is always beneficial. Additionally, it shows the importance of urban design and layout. Strategic placement of vegetation, ensuring clear sightlines and open spaces while maintaining a certain density, can optimise urban spaces for both well-being and functionality. By integrating insights from environmental psychology, urban planning, and human physiology, this study provides findings for future interdisciplinary efforts to design cities that are not only functional but also promote human well-being and restoration.

Future research should further explore the interaction between greenery and urban design, particularly by incorporating larger sample sizes to reduce data variability and improve the generalisability. Additionally, studies that compare different urban contexts could help determine whether these findings are specific to the environments examined here or if they apply more broadly. Future work could also explore how greenery interacts with other urban factors, such as lighting, noise, and social activity, to provide a more holistic understanding of environmental perception.

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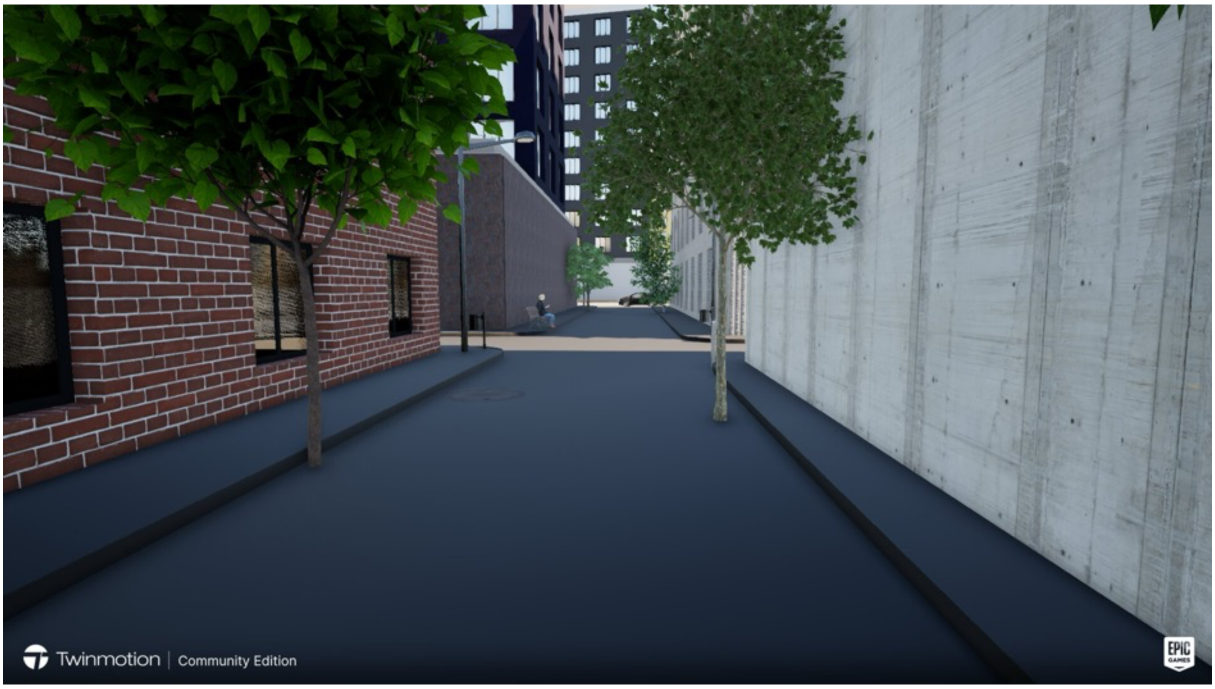
Appendix

A – Images of Virtual Urban Environments

Below, the screenshots of the individual urban areas (Rooms) are shown in the respective vegetation density levels (*low*: 0 – 25%, *medium*: 26 – 41%, *high*: 42 – 67%).

Room A



Room B

Appendix

Room C


Twinmotion | Community Edition
EPIC GAMES


Twinmotion | Community Edition
EPIC GAMES

Room D

Appendix

Room E


Twinmotion | Community Edition
EPIC GAMES


Twinmotion | Community Edition
EPIC GAMES

Random Series of Virtual Urban Environments

This shows the three versions of each presentation in Twinmotion and the order in which the Rooms were shown.

Series	Low	Medium	High
1	B, A, E, C, D	E, C, A, D, B	C, D, A, E, B
2	C, B, D, A, E	B, C, E, A, D	A, D, C, B, E
3	A, C, B, E, D	D, B, A, C, E	E, B, D, A, C

B – Experiment Procedure

Study Protocol

Materials

- Desktop computer
- Laptop
- Twinmotion software: Presentation of virtual urban spaces
- VR headset: HTC VIVE
- BITalino device for measuring EDA
- Printed experiment procedure
- Pen to write down SAM answers

Preparation

- Check BITalino device battery: recharge between participants
- Open online-timer with split times on the laptop
- Place chair on the marked spot
- Prepare BITalino device:
  - Connect Bluetooth dongle to the PC
  - Connect EDA cable to input A4
  - Connect push button to I1
  - Attach electrodes
- Open OpenSignal and connect it to BITalino:
  - Sampling rate: 100Hz
  - Digital: select the first dot
  - Settings: all formats, continuous modes, converted values
  - Save locations: auto-save (store in a pre-prepared folder on the desktop for each participant separately)
- Start SteamVR and connect it to the headset
- Open the presentation in Twinmotion:
  - Check if VR is running
- Open the roller coaster video in Media Player:
  - Format: screen
  - Screen size: 1.2x
  - Repeat off
- Have the printed experiment procedure and pen ready

Experiment

- Welcome the participant and provide the consent form for reading and signing
- The participant takes a seat in front of the desktop computer
- Attach BITalino sensors to the fingers of the right hand:
  - Index finger: red
  - Middle finger: black
  - Secure with Velcro on each finger and the wrist
  - Turn on the device and attach the box to a belt or pocket
- Give final instructions to the participant

- Adjust the headset to fit the participant's head
- Start BITalino measurement and online-timer
- Conduct the experiment as described in the detailed procedure
- End the presentation, stop BITalino measurement, remove the headset
- The participant completes the online questionnaire
- Thank participant with a small token of appreciation

Post-Experiment

- Recharge BITalino
- Rename EDA files for each participant (participantcode_yyyy-mm-dd) and store them in a separate folder, save a copy on an external disk
- Transfer SAM responses to an Excel spreadsheet
- Download questionnaire data and save it in an Excel spreadsheet with the participant code

Participant Instructions

Participants were instructed not to touch the sensor to avoid interference with data acquisition. They were informed that the visual quality of the environment was low, with possible flickering, but the focus was on their overall experience rather than realism. They were advised to move their heads slowly, only up to their shoulders, to reduce motion sickness. During transitions between rooms, they were asked to remain still to allow the image to load properly. After the instructions, they had time to ask final questions.

Detailed Procedure of VR Experiment

Time	Display	Action	Stopwatch + Pushbutton	Instruction to Participant	Notes
00:00	Baseline Video in media player		Start stopwatch	"Close your eyes for 1 min"	EDA start
01:00	Baseline Video in media player			"Open your eyes"	
01:30	Baseline Video in media player	Start video	Tap	"Only look at the screen"	
02:40		Close player, open Twinmotion			
03:00	SAM Baseline		Tap		SAM Baseline
03:25		Space Bar (start)		"Don't move"	
03:30	Image 1	Space Bar (pause)	Tap	"You can look around"	
03:55		Space Bar (start)		"Don't move"	
04:00	SAM 1	Space Bar (pause)	Tap	"You can look around"	SAM 1
04:25		Space Bar (start)		"Don't move"	
04:30	Image 2	Space Bar (pause)	Tap	"You can look around"	
04:55		Space Bar (start)		Don't move"	
05:00	SAM 2	Space Bar (pause)	Tap	"You can look around"	SAM 2
05:25		Space Bar (start)		"Don't move"	

05:30	Image 3	Space Bar (pause)	Tap	“You can look around”	
05:55		Space Bar (start)		“Don’t move”	
06:00	SAM 3	Space Bar (pause)	Tap	“You can look around”	SAM 3
06:25		Space Bar (start)		“Don’t move”	
06:30	Image 4	Space Bar (pause)	Tap	“You can look around”	
06:55		Space Bar (start)		“Don’t move”	
07:00	SAM 4	Space Bar (pause)	Tap	“You can look around”	SAM 4
07:25		Space Bar (start)		“Don’t move”	
07:30	Image 5	Space Bar (pause)	Tap	“You can look around”	
07:55		Space Bar (start)		“Don’t move”	
08:00	SAM 5	Space Bar (pause)	Tap	“You can look around”	SAM 5
		Exit VR	Stop stopwatch		EDA stop

C – Informed Consent Form

Purpose of the Study

Thank you for your interest and participation in my urban virtual reality (VR) study. The goal of this study is to investigate people's felt experiences in virtual urban environments. This study is part of my master's thesis at the Department of Geography at the University of Zurich and is being supervised by Prof. Dr. Sara Irina Fabrikant and Dr. Arman Kapaj.

The experiment takes place at the **GIVA CAVE lab (room Y25-J-87)** at the University of Zurich, Irchel Campus (Winterthurerstrasse 190, Zurich).

Inclusion and Exclusion Criteria

To participate in this study, you must meet the following criteria:

Inclusion Criteria:

- Age 18 – 65

Exclusion Criteria:

- Current use of any medication that affects the nervous system
- Achromasia (color vision deficiency)
- Fear of (virtual) roller coaster rides

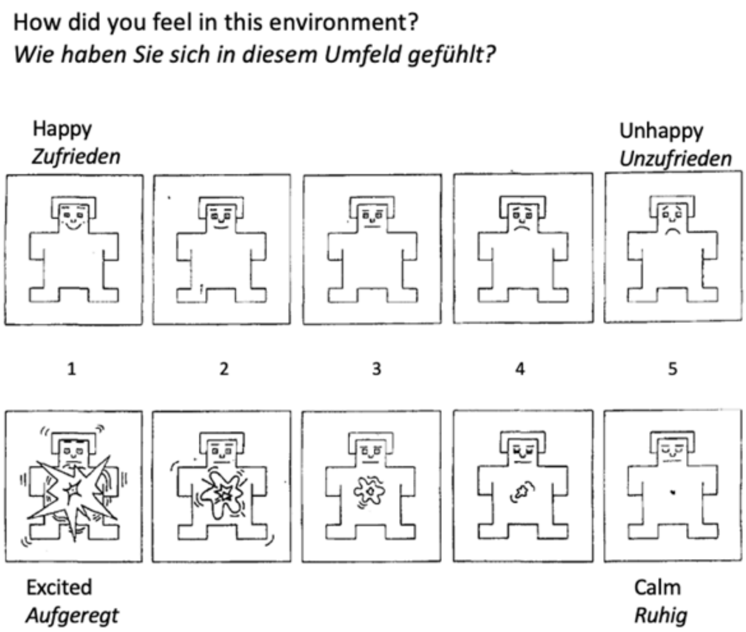
Procedure

The study will take about **30 minutes** and will be carried out from 09.09.2024 to 04.10.2024. The procedure will be as follows:

1. Receive instructions (about 10 minutes)
2. Virtual Reality Experience (9 minutes)
3. Fill out a questionnaire (about 10 minutes)

VR Experiment

First you will watch a short video and then explore five urban environments in virtual reality. You will be seated, asked to wear the VR headset and the wrist sensor. These cannot be taken off during the VR part of the study. Each urban environment will be shown for half a minute. After each environment you will be asked to evaluate your felt experience using pictograms. They look like this and will appear after each environment in virtual reality:



The upper row shows five symbols ranging from happy (left) to unhappy (right). The lower row shows five symbols ranging from excited (left) to calm (right).

You will evaluate each urban environment using these symbols to assess your felt experience. For this, we will prompt you to tell us which number (1-5) best corresponds to your chosen answer. Example: "upper row 3, lower row 2".

Online Questionnaire

After the VR experiment, you will be asked to complete an online questionnaire. You will be asked to rate the same environments based on different statements. You will see screenshots of the environments to help you.

Risks and Discomforts

Participating in this study may involve some minor risks and discomforts, including:

- Mild VR-induced motion sickness or dizziness.
- Minor discomfort from wearing the physiological wrist sensor.

If you experience significant discomfort, you can stop participating at any time. To reduce motion sickness, you will stay comfortably seated for the entire study.

Confidentiality

We will keep your responses and data confidential. We will not connect your identity with your data, and we will anonymize all collected information. Your name will be replaced with a code and will not appear in any publications. The data will be stored securely and only be accessible to the research team.

The following personal data will be recorded during the study:

- demographic information
- electrodermal responses (EDA)

- assessments of the urban environments

Voluntary Participation

Your participation in this study is entirely voluntary. You may withdraw at any time without giving a reason. If you decide to withdraw from this study, the data collected up to that point will not be used.

Contact Information

If you have any questions or concerns about this study, please contact:

The experimenter: Carola Moos (carola.moos@uzh.ch)

The supervisors: Sara Irina Fabrikant (sara.fabrikant@geo.uzh.ch), Armand Kapaj (armand.kapaj@geo.uzh.ch)

Consent

By signing below, I confirm that I have read and understood all the information above, and I agree to participate in this study.

- I meet the conditions for participation mentioned above.
- I am participating in the study voluntarily and know that I can stop at any time without any negative consequences
- I have been informed in writing about the study and have had enough time to decide whether to participate.
- I have read the data protection rules and agree to them.

Participant's Signature: ____

Date: ____________________

D – Questionnaire

The online questionnaire was created using PsyToolkit. Because of its repetitional nature, only one image is shown here. The others can be found in Appendix B. Each participant rated five urban environments in the assigned vegetation density level.

Please rate this urban environment according to the following statements.
Bitte bewerten Sie dieses städtische Umfeld anhand der folgenden Aussagen.

Item	strongly disagree	disagree	neither agree or disagree	agree	strongly agree
This environment makes me feel like I am getting away from the stress of everyday life. Diese Umgebung gibt mir das Gefühl, dem Stress des Alltags zu entkommen.	○	○	○	○	○
This environment gives me the feeling of being in a larger connected environment. Diese Umgebung gibt mir das Gefühl, in einer größeren, vernetzten Umgebung zu sein.	○	○	○	○	○
The environment in this picture corresponds to my personal preferences and interests. Die Umgebung auf diesem Bild entspricht meinen persönlichen Vorlieben und Interessen.	○	○	○	○	○
This environment attracts my attention in a gentle way. Diese Umgebung zieht meine Aufmerksamkeit auf sanfte Weise an.	○	○	○	○	○
The elements in this environment fit together well to create a coherent, understandable picture. Die Elemente in dieser Umgebung passen gut zusammen und ergeben ein kohärentes, verständliches Bild.	○	○	○	○	○
This place makes me curious about the surroundings beyond the picture. Dieser Ort macht mich neugierig auf die Umgebung jenseits des Bildes.	○	○	○	○	○
This environment is rich in detail. Diese Umgebung ist reich an Details.	○	○	○	○	○
This place has striking elements that help me orientate myself. Dieser Ort hat markante Elemente, die mir helfen mich zu orientieren.	○	○	○	○	○

This scene gives me an overview of the area in front of me. Diese Szene gibt mir einen Überblick über das vor mir liegende Gebiet.	○	○	○	○	○
This place makes me feel safe or protected. An diesem Ort fühle ich mich geborgen oder beschützt.	○	○	○	○	○

E – Statistical Analysis

All statistical analysis was performed in R. Fields marked red show where the data was not normally distributed.

EDA & nSCR

Shapiro-Wilk-Test: Test on Normal Distribution for EDA and nSCR by Room

Room	EDA p-value	nSCR p-value
A	0.168	0.002
B	0.369	0.591
C	0.002e-01	0.002e-01
D	0.602	0.316
E	0.115	0.636

Shapiro-Wilk-Test: Test on Normal Distribution for EDA and nSCR by Position

Position	EDA p-value	nSCR p-value
1	0.048	6.392e-01
2	0.844	3.421e-01
3	0.004	7.783e-01
4	0.149	5.469e-05
5	0.377	4.029e-01

Shapiro-Wilk-Test: Test on Normal Distribution for EDA and nSCR by Level

Level	EDA p-value	nSCR p-value
low	0.023	2.660e-07
medium	0.052	1.348e-02
high	0.098	5.436e-01

ART ANOVA for EDA by Level (between)

```
Analysis of Variance of Aligned Rank Transformed Data

Table Type: Anova Table (Type III tests)
Model: No Repeated Measures (lm)
Response: art(EDA_diff)

        Df Df.res F value   Pr(>F) part.eta.sq
1 Level  2    192  3.7559 0.025116    0.037651 *
---
Signif. codes:   0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

Post-hoc test for EDA by Level (between)

contrast	estimate	SE	df	t ratio	p-value	sig.
low - medium	26.273	9.586	192	2.741	0.020	*
low - high	12.674	9.791	192	1.294	0.348	
medium - high	-13.599	9.963	192	-1.365	0.348	

ART ANOVA for EDA by Position and Level (within)

```
Analysis of Variance of Aligned Rank Transformed Data
```

```
Table Type: Analysis of Deviance Table (Type III Wald F tests with Kenward-Roger
df)
Model: Mixed Effects (lmer)
Response: art(EDA_diff)

                       F Df Df.res  Pr(>F) part.eta.sq
1 Level          0.82747  2     36 0.44530    0.043950
2 Position       0.48225  4    144 0.74873    0.013219
3 Level:Position 1.39940  8    144 0.20151    0.072136
---
Signif. codes:   0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

ART ANOVA for EDA by Room and Level (within)

```
Analysis of Variance of Aligned Rank Transformed Data

Table Type: Analysis of Deviance Table (Type III Wald F tests with Kenward-Roger
df)
Model: Mixed Effects (lmer)
Response: art(EDA_diff)

                   F Df Df.res  Pr(>F) part.eta.sq
1 Level      0.84869  2     36 0.43636    0.045027
2 Room       0.81206  4    144 0.51940    0.022060
3 Level:Room 0.55378  8    144 0.81405    0.029847
---
Signif. codes:   0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

ART ANOVA for EDA by Room, Position and Level (within)

```
Analysis of Variance of Aligned Rank Transformed Data

Table Type: Analysis of Deviance Table (Type III Wald F tests with Kenward-Roger
df)
Model: Mixed Effects (lmer)
Response: art(EDA_diff)

                            F Df  Df.res  Pr(>F) part.eta.sq
1 Level               0.15503  2  39.361 0.85691   0.0078158
2 Room                0.38276  4 107.001 0.82055   0.0141067
3 Position            0.16568  4 104.099 0.95534   0.0063260
4 Level:Room          0.84598  8 129.034 0.56404   0.0498359
5 Level:Position      0.97621  8 129.235 0.45758   0.0569862
6 Room:Position       1.95568 14 135.495 0.02578   0.1681013 *
7 Level:Room:Position      NA  0   0.000      NA          NA
---
Signif. codes:   0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

Post-hoc test for EDA by Room, Position, and Level (within)

contrast	estimate	SE	df	t ratio	p-value	sig.
A,4 - B,2	-1.467	13.222	145.82	-0.111	1	
A,4 - E,5	-7.664	17.826	108.285	-0.430	1	
B,2 - E,5	-6.198	16.335	105.759	-0.380	1	

Appendix

ART ANOVA for nSCR by Level (between)

```
Analysis of Variance of Aligned Rank Transformed Data

Table Type: Anova Table (Type III tests)
Model: No Repeated Measures (lm)
Response: art(SCR_diff_mean)

        Df Df.res F value     Pr(>F) part.eta.sq
1 Level  2    192  10.794 3.6094e-05     0.10108 ***
---
Signif. codes:   0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

Post-hoc test for nSCR by Level (between)

contrast	estimate	SE	df	t ratio	p-value	sig.
low - medium	0.314	9.264	192	0.034	0.973	
low - high	-38.62	9.462	192	-4.082	0.001e-01	***
medium - high	-38.934	9.628	192	-4.044	0.001e-01	***

ART ANOVA for nSCR by Position and Level

```
Analysis of Variance of Aligned Rank Transformed Data

Table Type: Analysis of Deviance Table (Type III Wald F tests with Kenward-Roger
df)
Model: Mixed Effects (lmer)
Response: art(SCR_diff_mean)

                        F Df Df.res   Pr(>F) part.eta.sq
1 Level           2.59161  2     36 0.088813   0.1258577 .
2 Position        0.12646  4    144 0.972673   0.0035005
3 Level:Position 0.58063  8    144 0.792589   0.0312493
---
Signif. codes:   0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

ART ANOVA for nSCR by Room and Level (within)

```
Analysis of Variance of Aligned Rank Transformed Data

Table Type: Analysis of Deviance Table (Type III Wald F tests with Kenward-Roger
df)
Model: Mixed Effects (lmer)
Response: art(SCR_diff_mean)

                    F Df Df.res   Pr(>F) part.eta.sq
1 Level       2.51798  2     36 0.094729    0.122721 .
2 Room        1.29804  4    144 0.273630    0.034802
3 Level:Room 0.58345  8    144 0.790294    0.031396
---
Signif. codes:   0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

ART ANOVA for nSCR by Room, Position, and Level (within)

```
Analysis of Variance of Aligned Rank Transformed Data

Table Type: Analysis of Deviance Table (Type III Wald F tests with Kenward-Roger
df)
Model: Mixed Effects (lmer)
```

```
Response: art(SCR_diff_mean)

                              F Df  Df.res  Pr(>F) part.eta.sq
1 Level                 1.88819  2  39.656 0.16470    0.086949
2 Room                  0.37531  4 110.455 0.82583    0.013409
3 Position              0.65100  4 107.238 0.62741    0.023707
4 Level:Room            0.87223  8 130.120 0.54180    0.050897
5 Level:Position        0.88812  8 130.247 0.52850    0.051728
6 Room:Position         1.90077 14 135.522 0.03130    0.164130 *
7 Level:Room:Position        NA  0   0.000      NA          NA
---
Signif. codes:   0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

Post-hoc test for nSCR by Room, Position, and Level (within)

contrast	estimate	SE	df	t ratio	p-value	sig.
A,4 - B,2	-1.740	13.292	147.187	-0.131	0.896	
A,4 - E,5	-24.666	17.437	113.490	-1.415	0.462	
B,2 - E,5	-22.926	15.97	114.368	-1.436	0.462	

SAM

Shapiro-Wilk-Test: Test on Normal Distribution for Arousal and Valence by Level

Level	Arousal p-value	Valence p-value
low	0.002	0.006e-01
medium	0.009e-01	0.002
high	0.002	0.001e-01

ART ANOVA for Arousal by Level (between)

```
Analysis of Variance of Aligned Rank Transformed Data

Table Type: Anova Table (Type III tests)
Model: No Repeated Measures (lm)
Response: art(Arousal)

        Df Df.res F value  Pr(>F) part.eta.sq
1 Level  2    197 0.37518 0.68766   0.0037945
---
Signif. codes:   0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

ART ANOVA for Arousal by Room and Level (within)

```
Analysis of Variance of Aligned Rank Transformed Data

Table Type: Analysis of Deviance Table (Type III Wald F tests with Kenward-Roger
df)
Model: Mixed Effects (lmer)
Response: art(Arousal)

                    F Df Df.res  Pr(>F) part.eta.sq
1 Level      0.086319  2     37 0.91749   0.0046442
2 Room       1.215467  4    148 0.30672   0.0318056
3 Level:Room 1.457114  8    148 0.17772   0.0730123
---
Signif. codes:   0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

ART ANOVA for Arousal by Position and Level (within)

```
Analysis of Variance of Aligned Rank Transformed Data

Table Type: Analysis of Deviance Table (Type III Wald F tests with Kenward-Roger
df)
Model: Mixed Effects (lmer)
Response: art(Arousal)

                      F Df Df.res    Pr(>F) part.eta.sq
1 Level          0.10304  2     37 0.902349   0.0055389
2 Position       1.99808  4    148 0.097766   0.0512355 .
3 Level:Position 0.88567  8    148 0.530175   0.0456870
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

ART ANOVA for Arousal by Room, Position, and Level (within)

```
Analysis of Variance of Aligned Rank Transformed Data

Table Type: Analysis of Deviance Table (Type III Wald F tests with Kenward-Roger
df)
Model: Mixed Effects (lmer)
Response: art(Arousal)

                            F Df  Df.res  Pr(>F) part.eta.sq
1 Level              0.074473  2  40.439 0.92836   0.0036698
2 Room               0.125980  4 108.363 0.97278   0.0046288
3 Position           0.245099  4 106.474 0.91206   0.0091238
4 Level:Room         0.548347  8 133.715 0.81814   0.0317649
5 Level:Position     0.264339  8 133.173 0.97624   0.0156312
6 Room:Position      0.451772 14 140.118 0.95392   0.0431896
7 Level:Room:Position      NA  0   0.000      NA          NA
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

ART ANOVA for Valence by Level (between)

```
Analysis of Variance of Aligned Rank Transformed Data

Table Type: Anova Table (Type III tests)
Model: No Repeated Measures (lm)
Response: art(Valence)

        Df Df.res F value    Pr(>F) part.eta.sq
1 Level  2    197  5.8692 0.0033427    0.056235 **
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

Post-hoc test for Valence by Level (between)

contrast	estimate	SE	df	t ratio	p-value	sig.
low - medium	32.087	9.430	197	3.403	0.002	**
low - high	12.133	9.430	197	1.287	0.2	
medium - high	-19.954	9.603	197	-2.078	0.078	.

ART ANOVA for Valence by Room and Level (within)

```
Analysis of Variance of Aligned Rank Transformed Data

Table Type: Analysis of Deviance Table (Type III Wald F tests with Kenward-Roger
df)
Model: Mixed Effects (lmer)
Response: art(Valence)

                   F Df Df.res     Pr(>F) part.eta.sq
1 Level      1.66976  2     37 0.20216803    0.082785
2 Room       5.39185  4    148 0.00044215    0.127191 ***
3 Level:Room 0.94351  8    148 0.48276417    0.048526
---
Signif. codes:   0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

Post-hoc test for Valence by Room and Level (within)

contrast	estimate	SE	df	t ratio	p-value	sig.
A - B	13.297	7.396	148	1.798	0.371	
A - C	-10.242	7.396	148	-1.385	0.673	
A - D	-14.947	7.396	148	-2.021	0.271	
A - E	9.284	7.396	148	1.255	0.673	
B - C	-23.538	7.396	148	-3.182	0.014	*
B - D	-28.244	7.396	148	-3.819	0.002	**
B - E	-4.013	7.396	148	-0.543	1	
C - D	-4.705	7.396	148	-0.636	1	
C - E	19.526	7.396	148	2.64	0.064	.
D - E	24.231	7.396	148	3.276	0.012	*

ART ANOVA for Valence by Position and Level (within)

```
Analysis of Variance of Aligned Rank Transformed Data

Table Type: Analysis of Deviance Table (Type III Wald F tests with Kenward-Roger
df)
Model: Mixed Effects (lmer)
Response: art(Valence)

                      F Df Df.res  Pr(>F) part.eta.sq
1 Level          1.7095  2     37 0.19493    0.084590
2 Position       1.0151  4    148 0.40159    0.026703
3 Level:Position 1.2890  8    148 0.25341    0.065137
---
Signif. codes:   0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

ART ANOVA for Valence by Room, Position, and Level (within)

```
Analysis of Variance of Aligned Rank Transformed Data

Table Type: Analysis of Deviance Table (Type III Wald F tests with Kenward-Roger
df)
Model: Mixed Effects (lmer)
Response: art(Valence)

                            F Df   Df.res  Pr(>F) part.eta.sq
```

```
1 Level              0.61339  2  41.124 0.54639   0.0289671
2 Room               0.97365  4 112.415 0.42494   0.0334847
3 Position           0.24509  4 109.690 0.91208   0.0088585
4 Level:Room         0.53930  8 135.011 0.82517   0.0309665
5 Level:Position     0.47596  8 134.406 0.87145   0.0275493
6 Room:Position      0.54252 14 139.928 0.90392   0.0514850
7 Level:Room:Position     NA  0   0.000      NA          NA
---
Signif. codes:   0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

Questionnaire

Shapiro-Wilk-Test: Test on Normal Distribution for all Scores by Rooms

Room	ART p-value	PM p-value	PR p-value
A	0.294	0.386	0.046
B	0.013	0.082	0.047
C	0.461	0.031	0.028
D	0.094	0.082	0.007
E	0.007e-01	0.048	0.032

Shapiro-Wilk-Test: Test on Normal Distribution for all Scores by Level

Level	ART p-value	PM p-value	PR p-value
low	0.007	0.117	0.012
medium	0.124	0.035	0.003
high	0.028	0.152	0.006

ART ANOVA for all Scores by Level (between)

ART Score

```
Analysis of Variance of Aligned Rank Transformed Data

Table Type: Anova Table (Type III tests)
Model: No Repeated Measures (lm)
Response: art(ART)

        Df Df.res F value  Pr(>F) part.eta.sq
1 Level  2    197  2.0854 0.12699    0.020733
---
Signif. codes:   0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

PM Score

```
Analysis of Variance of Aligned Rank Transformed Data

Table Type: Anova Table (Type III tests)
Model: No Repeated Measures (lm)
Response: art(PM)

        Df Df.res F value  Pr(>F) part.eta.sq
1 Level  2    197  1.2824 0.27968    0.012852
---
Signif. codes:   0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

PR Score

```
Analysis of Variance of Aligned Rank Transformed Data

Table Type: Anova Table (Type III tests)
Model: No Repeated Measures (lm)
Response: art(PR)

        Df Df.res F value  Pr(>F) part.eta.sq
1 Level  2    197 0.50458 0.60454   0.0050966
---
Signif. codes:   0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

ART ANOVA for ART Score by Room and Level (within)

ART Score

```
Analysis of Variance of Aligned Rank Transformed Data

Table Type: Analysis of Deviance Table (Type III Wald F tests with Kenward-Roger
df)
Model: Mixed Effects (lmer)
Response: art(ART)

                   F Df Df.res  Pr(>F) part.eta.sq
1 Room       30.0639  4    148 < 2e-16    0.448288 ***
2 Level       1.3646  2     37 0.26804    0.068696
3 Room:Level  0.4808  8    148 0.86834    0.025331
---
Signif. codes:   0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

Post-hoc test for ART Score by Room and Level (within)

contrast	estimate	SE	df	t ratio	p-value	sig.
A - B	-74.048	9.15	148	-8.092	1.769e-12	***
A - C	16.13	9.15	148	1.763	1.6e-01	
A - D	-26.858	9.15	148	-2.935	1.161e-02	*
A - E	-42.615	9.15	148	-4.657	3.576e-05	***
B - C	90.178	9.15	148	9.855	6.296e-17	***
B - D	47.19	9.15	148	5.16	5.547e-06	***
B - E	31.432	9.15	148	3.435	3.077e-03	**
C - D	-42.987	9.15	148	-4.698	3.576e-05	***
C - E	-58.745	9.15	148	-6.42	1.398e-08	***
D - E	-15.758	9.15	148	-1.722	1.6e-01	

ART ANOVA for PM Score by Room and Level (within)

PM Score

```
Analysis of Variance of Aligned Rank Transformed Data

Table Type: Analysis of Deviance Table (Type III Wald F tests with Kenward-Roger
df)
Model: Mixed Effects (lmer)
Response: art(PM)

                    F Df Df.res  Pr(>F) part.eta.sq
```

```
1 Room       39.43743  4    148 < 2e-16    0.515944 ***
2 Level       0.80163  2     37 0.45624    0.041532
3 Room:Level  1.72053  8    148 0.09805    0.085088   .
---
Signif. codes:   0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

Post-hoc test for PM Score by Room and Level (within)

contrast	estimate	SE	df	t ratio	p-value	sig.
A - B	-73.514	9.037	148	-8.135	1.078e-12	***
A - C	10.637	9.037	148	1.177	4.821e-01	
A - D	-75.454	9.037	148	-8.349	3.603e-13	***
A - E	-38.87	9.037	148	-4.301	1.535e-04	***
B - C	84.152	9.037	148	9.312	1.452e-15	***
B - D	-1.94	9.037	148	-0.215	8.3e-01	
B - E	34.645	9.037	148	3.834	5.588e-04	***
C - D	-86.092	9.037	148	-9.526	4.495e-16	***
C - E	-49.507	9.037	148	-5.478	1.081e-06	***
D - E	36.584	9.037	148	4.048	3.317e-04	***

ART ANOVA for PR Score by Room and Level (within)

PR Score

```
Analysis of Variance of Aligned Rank Transformed Data

Table Type: Analysis of Deviance Table (Type III Wald F tests with Kenward-Roger
df)
Model: Mixed Effects (lmer)
Response: art(PR)

                    F Df Df.res      Pr(>F) part.eta.sq
1 Room       15.83020  4    148 8.2915e-11    0.299643 ***
2 Level       0.46013  2     37    0.63476    0.024268
3 Room:Level  0.92414  8    148    0.49842    0.047577
---
Signif. codes:   0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

Post-hoc test for PM Score by Room and Level (within)

contrast	estimate	SE	df	t ratio	p-value	sig.
A - B	-54.828	10.58	148	-5.183	5.893e-06	***
A - C	23.057	10.58	148	2.179	1.237e-01	
A - D	-31.956	10.58	148	-3.020	1.489e-02	*
A - E	-17.159	10.58	148	-1.622	2.140e-01	
B - C	77.885	10.58	148	7.361	1.173e-10	***
B - D	22.872	10.58	148	2.162	1.237e-01	
B - E	37.669	10.58	148	3.56	2.995e-03	**
C - D	-55.013	10.58	148	-5.199	5.893e-06	***
C - E	-40.216	10.58	148	-3.801	1.472e-03	**
D - E	14.797	10.58	148	1.398	2.14e-01	

ART ANOVA of all Questions by Level (between)

```
Analysis of Variance of Aligned Rank Transformed Data

Table Type: Anova Table (Type III tests)
Model: No Repeated Measures (lm)
Response: art(Q1)

        Df Df.res F value   Pr(>F) part.eta.sq
1 Level  2    197  4.3155 0.014646    0.041973 *
---
Signif. codes:   0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Analysis of Variance of Aligned Rank Transformed Data

Table Type: Anova Table (Type III tests)
Model: No Repeated Measures (lm)
Response: art(Q2)

        Df Df.res F value  Pr(>F) part.eta.sq
1 Level  2    197 0.20173 0.81748   0.0020438
---
Signif. codes:   0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Analysis of Variance of Aligned Rank Transformed Data

Table Type: Anova Table (Type III tests)
Model: No Repeated Measures (lm)
Response: art(Q3)

        Df Df.res F value   Pr(>F) part.eta.sq
1 Level  2    197  2.6969 0.069905     0.02665 .
---
Signif. codes:   0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Analysis of Variance of Aligned Rank Transformed Data

Table Type: Anova Table (Type III tests)
Model: No Repeated Measures (lm)
Response: art(Q4)

        Df Df.res F value  Pr(>F) part.eta.sq
1 Level  2    197  1.5164 0.22204    0.015162
---
Signif. codes:   0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Analysis of Variance of Aligned Rank Transformed Data

Table Type: Anova Table (Type III tests)
Model: No Repeated Measures (lm)
Response: art(Q5)

        Df Df.res F value  Pr(>F) part.eta.sq
1 Level  2    197 0.95442 0.38681   0.0095966
---
Signif. codes:   0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Analysis of Variance of Aligned Rank Transformed Data

Table Type: Anova Table (Type III tests)
```

```
Model: No Repeated Measures (lm)
Response: art(Q6)

        Df Df.res F value  Pr(>F) part.eta.sq
1 Level  2    197  2.6285 0.07472    0.025991 .
---
Signif. codes:   0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Analysis of Variance of Aligned Rank Transformed Data

Table Type: Anova Table (Type III tests)
Model: No Repeated Measures (lm)
Response: art(Q7)

        Df Df.res F value  Pr(>F) part.eta.sq
1 Level  2    197  2.2664 0.10638    0.022492
---
Signif. codes:   0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Analysis of Variance of Aligned Rank Transformed Data

Table Type: Anova Table (Type III tests)
Model: No Repeated Measures (lm)
Response: art(Q8)

        Df Df.res F value  Pr(>F) part.eta.sq
1 Level  2    197 0.26414 0.76814   0.0026745
---
Signif. codes:   0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Analysis of Variance of Aligned Rank Transformed Data

Table Type: Anova Table (Type III tests)
Model: No Repeated Measures (lm)
Response: art(Q9)

        Df Df.res  F value  Pr(>F) part.eta.sq
1 Level  2    197 0.070857 0.93162  0.00071885
---
Signif. codes:   0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Analysis of Variance of Aligned Rank Transformed Data

Table Type: Anova Table (Type III tests)
Model: No Repeated Measures (lm)
Response: art(Q10)

        Df Df.res F value  Pr(>F) part.eta.sq
1 Level  2    197  1.4032 0.24826    0.014046
---
Signif. codes:   0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

Post-hoc test for Being Away by Level (between))

contrast	estimate	SE	df	t ratio	p-value	sig.
low - medium	-15.987	9.361	197	-1.708	0.178	
low - high	-27.31	9.361	197	-2.917	0.012	*

medium - high	-11.323	9.533	197	-1.188	0.236	

ART ANOVA of all Questions by Room and Level

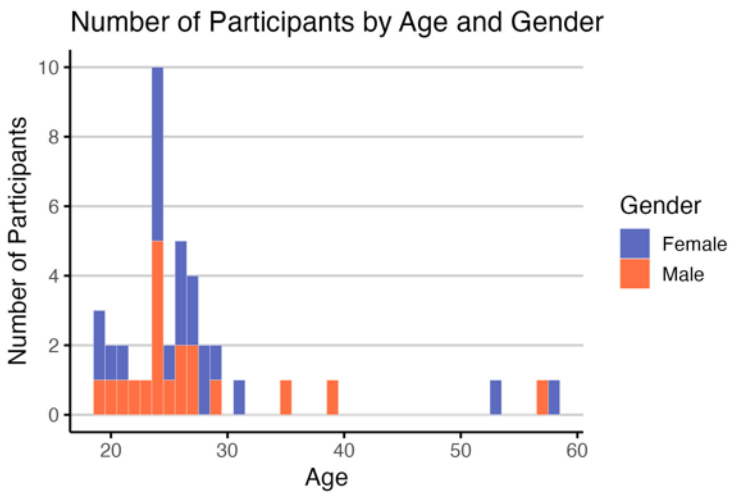
```
Analysis of Variance of Aligned Rank Transformed Data

Table Type: Analysis of Deviance Table (Type III Wald F tests with Kenward-Roger
df)
Model: Mixed Effects (lmer)
Response: art(Q1)

                   F Df Df.res     Pr(>F) part.eta.sq
1 Level       3.1453  2     37   0.054758    0.145311   .
2 Room       18.0507  4    148 4.2953e-12    0.327892 ***
3 Level:Room  1.2629  8    148   0.267179    0.063904
---
Signif. codes:   0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
Analysis of Variance of Aligned Rank Transformed Data

Table Type: Analysis of Deviance Table (Type III Wald F tests with Kenward-Roger
df)
Model: Mixed Effects (lmer)
Response: art(Q2)

                    F Df Df.res     Pr(>F) part.eta.sq
1 Level       0.10952  2     37    0.89655   0.0058851
2 Room       19.56467  4    148 6.0727e-13   0.3458815 ***
3 Level:Room  1.23342  8    148    0.28347   0.0625039
---
Signif. codes:   0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
Analysis of Variance of Aligned Rank Transformed Data

Table Type: Analysis of Deviance Table (Type III Wald F tests with Kenward-Roger
df)
Model: Mixed Effects (lmer)
Response: art(Q3)

                    F Df Df.res     Pr(>F) part.eta.sq
1 Level       1.17634  2     37    0.31967    0.059785
2 Room       17.08769  4    148 1.5298e-11    0.315926 ***
3 Level:Room  0.36051  8    148    0.93965    0.019115
---
Signif. codes:   0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
Analysis of Variance of Aligned Rank Transformed Data

Table Type: Analysis of Deviance Table (Type III Wald F tests with Kenward-Roger
df)
Model: Mixed Effects (lmer)
Response: art(Q4)

                   F Df Df.res     Pr(>F) part.eta.sq
1 Level       1.4578  2     37    0.24580    0.073046
2 Room       14.3423  4    148 6.4216e-10    0.279347 ***
3 Level:Room  1.1836  8    148    0.31264    0.060133
---
Signif. codes:   0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
Analysis of Variance of Aligned Rank Transformed Data
```

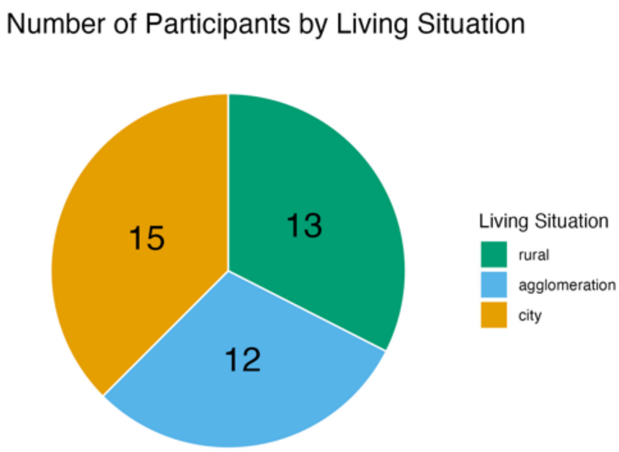
```
Table Type: Analysis of Deviance Table (Type III Wald F tests with Kenward-Roger
df)
Model: Mixed Effects (lmer)
Response: art(Q5)

                   F Df Df.res     Pr(>F) part.eta.sq
1 Level      0.49865  2     37    0.61137    0.026247
2 Room       8.24307  4    148 4.9764e-06    0.182195 ***
3 Level:Room 0.22317  8    148    0.98628    0.011920
---
Signif. codes:   0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
Analysis of Variance of Aligned Rank Transformed Data

Table Type: Analysis of Deviance Table (Type III Wald F tests with Kenward-Roger
df)
Model: Mixed Effects (lmer)
Response: art(Q6)

                   F Df Df.res     Pr(>F) part.eta.sq
1 Level       1.4713  2     37   0.242743    0.073672
2 Room       14.3671  4    148 6.2036e-10    0.279695 ***
3 Level:Room  1.8663  8    148   0.069437    0.091635   .
---
Signif. codes:   0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
Analysis of Variance of Aligned Rank Transformed Data

Table Type: Analysis of Deviance Table (Type III Wald F tests with Kenward-Roger
df)
Model: Mixed Effects (lmer)
Response: art(Q7)

                   F Df Df.res     Pr(>F) part.eta.sq
1 Level       1.4052  2     37   0.258095    0.070596
2 Room       19.1703  4    148 1.0061e-12    0.341289 ***
3 Level:Room  2.5556  8    148   0.012259    0.121372   *
---
Signif. codes:   0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
Analysis of Variance of Aligned Rank Transformed Data

Table Type: Analysis of Deviance Table (Type III Wald F tests with Kenward-Roger
df)
Model: Mixed Effects (lmer)
Response: art(Q8)

                    F Df Df.res     Pr(>F) part.eta.sq
1 Level       0.36491  2     37    0.69673    0.019343
2 Room       19.71340  4    148 5.0241e-13    0.347597 ***
3 Level:Room  1.47663  8    148    0.17031    0.073918
---
Signif. codes:   0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
Analysis of Variance of Aligned Rank Transformed Data

Table Type: Analysis of Deviance Table (Type III Wald F tests with Kenward-Roger
df)
Model: Mixed Effects (lmer)
Response: art(Q9)

                    F Df Df.res     Pr(>F) part.eta.sq
1 Level       0.73038  2     37    0.48854    0.037980
```

```
2 Room       21.58459  4    148 4.8105e-14    0.368435 ***
3 Level:Room  0.66022  8    148    0.72574    0.034458
---
Signif. codes:   0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
Analysis of Variance of Aligned Rank Transformed Data

Table Type: Analysis of Deviance Table (Type III Wald F tests with Kenward-Roger
df)
Model: Mixed Effects (lmer)
Response: art(Q10)

                   F Df Df.res     Pr(>F) part.eta.sq
1 Level      0.99532  2     37    0.37928    0.051054
2 Room       7.57328  4    148 1.4063e-05    0.169906 ***
3 Level:Room 1.13107  8    148    0.34577    0.057616
---
Signif. codes:   0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

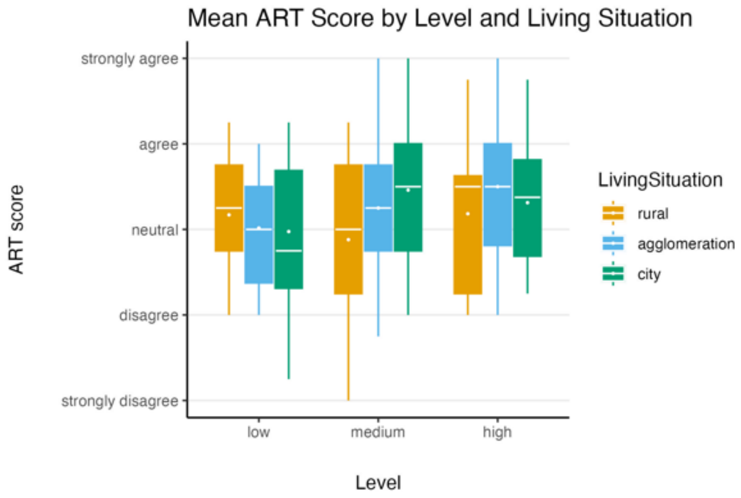
Demographic Information of Participants (Gender, Age, Living Situation)

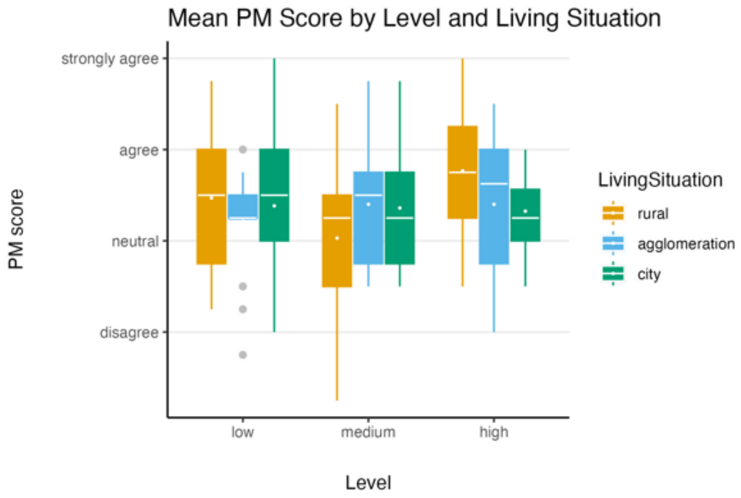
The definitions for the living situations were not strictly specified (e.g. by size or population), thus, the reliability of this factor is limited and reflects participants' subjective categorisation of their environment.

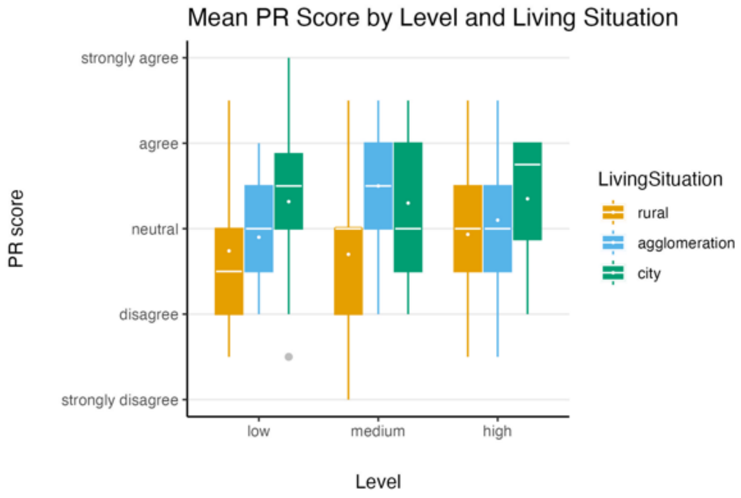




Appendix


Mean ART Score by Level and Living Situation
strongly agree
agree
neutral
disagree
strongly disagree
ART score
low
medium
high
Level
LivingSituation
rural
agglomeration
city


Mean PM Score by Level and Living Situation
strongly agree
agree
neutral
disagree
PM score
low
medium
high
Level
LivingSituation
rural
agglomeration
city


Mean PR Score by Level and Living Situation
strongly agree
agree
neutral
disagree
strongly disagree
PR score
low
medium
high
Level
LivingSituation
rural
agglomeration
city

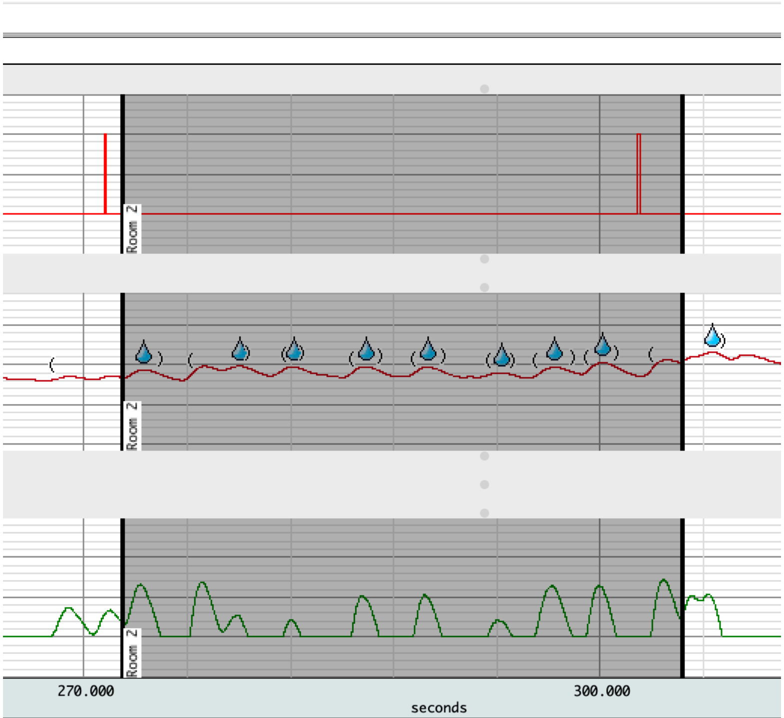
F – EDA Analysis in AcqKnowledge

This procedure was adapted from Sara Lanini-Maggi (2021)

1. Open AcqKnowledge with Dongle
    a. Select «Analyze only»
    b. Open a graph file > Graph file on disk
    c. Load EDA converted as text file
2. Read text file options
    a. Data starts on line 4
    b. Sample rate: 0.01 s/sample
    c. Delimiter: tab
3. Click on -/+ and select: Journal, Display, Mode Toolbar, Scaling Toolbar, Measurements, Focus Areas Bar, Focus Areas, Event Bar, Events, Annotations, Channel buttons
4. Display > Autoscale Horizontal
5. Right click on y-axis > Use adaptive scaling
6. Hide Channels with no information: option + click on Channel button
7. Select channel with raw data by double-clicking on the name (rename: raw)
8. Transform > Smoothing (5, mean)
    a. Repeat 5 times → rename channel Smoothed1, Smoothed2, etc.
    b. Name final channel SCL
9. Transform > Digital Filters > FIR > Low-Pass > Fixed at 1Hz
10. Set EDA preferences: Analysis > Electrodermal Activity > Preferences
    a. Text and Graph Channels
    b. 0.05 Hz High Pass Filter
    c. Threshold Level: 0.03 (see BIOPAC Systems, Inc. (2022) & Lanini-Maggi, S. (2023))
    d. Reject SCRs under 10% of max
11. Analysis > Electrodermal Activity > Derive Phasic EDA from Tonic → name channel SCR
12. Select I-Tool > select SCR signal
    a. Use measurements to find max/min
    b. Save in Journal (Edit > Journal > Paste Measurements)
13. Transform > Expression: (SCR*100/(Max-Min))) → name channel PHI
14. Transform > Expression: COND(PHI,0,0,PHI) → name PHI_pos
15. Select SCL channel
16. Analysis > Electrodermal Activity > Locate SCRs
    a. Tonic channel: SCL
    b. Phasic EDA: use channel PHI (normalized SCR)
17. Select signal sections of interest with I-Tool: Display > Create Focus Area
    a. Name areas: Baseline, Room1, Room2,…
    b. Use Channel 1 (trigger) as guideline
    c. Start 1s after stimulus and end after 73s (Baseline) and 33s (Rooms)
        i. 1s after stimulus onset and 4s after end (the stimulus is defined as the whole response window, see Spielhofer (2021))

ii. If the peak starts before the onset and develops into a "double" peak, the second peak is included in the focus area.

iii. The same is applied to peaks that end after the window. There, the first part is included.

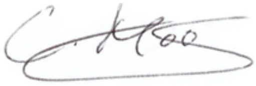


iv. If a single large peak start before the stimulus and at least half of it is in the response window, the whole peak is included to avoid overestimating the area. The same applies to a single peak at the end of the window.

18. Calculate Area, Delta T, and Evt_counts (number of SCR events) for PHI_pos for each Focus Area
    a. Save values in Journal
    b. Save Journal as .xlsx
19. Calculate AUC for each focus area in excel (Area/Delta T)
20. Baseline correction (AUCt – AUCb)

Personal Declaration

I hereby declare that the submitted thesis is the result of my own, independent work. All external sources are explicitly acknowledged in the thesis.



Carola Moos 30.01.2025