Wayfinding in Indoor, Outdoor, and Transitional Spaces Respecting Access Rights:

Exploring Spatial Cognition Through Virtual Reality

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PhD Go/ No Go Report
TU Delft Digital Technologies

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ABBREVIATIONS

3D	3 Dimension
A+BE	Architecture and Build Environment
ANOVA	Analysis of Variance
AR	Augmented Reality
BLE	Bluetooth Low Energy
CAVE	Cave Automatic Virtual Environment
DSLR	Digital Single-Lens Reflex
FAD	Fakultas Arsitektur dan Desain
FAIR	Findability, Accessibility, Interoperability, and Reuse
FOV	Fields of View
GDMC	Geo-Database Management Centre
GIS	Geographic Information Systems
GNSS	Global Navigation Satellite System
GS	Graduate School
HMD	Head-Mounted Device
HREC	Human Research Ethics Committee
KA	Knowledge Gathering & Processing Ability
LADM	Land Administration Domain Model
LiDAR	Light Detection and Ranging
LOJ	Learning on the Job
MANOVA	Multivariate Analysis
NCG	Nederlands Centrum voor Geodesie en Geo-Informatica
OA	Orientation Ability
QGIS	Quantum Geographical Information System
SRQ	Sub-Research Question
TAPs	Thinking Aloud Protocols
UE5	Unreal Engine 5
UPNVJT	Universitas Pembangunan Nasional "Veteran" Jawa Timur
VR	Virtual Reality

GLOSSARY

3 Dimension – a digital model represented in three axes allowing for the perception of volume and spatial relationships

Access Rights - a piece of accessibility information determining the rights of certain groups of users to enter, navigate, or use a particular space

Allocentric Frame - spatial representation which entirely relies on the relationship between the spatial entities (independent to the observer)

Angular Choice - spatial measurement of betweenness centrality aimed to identify key navigation route

Angular Integration - spatial measurement of closeness centrality aimed to identify space accessibility concerning other spaces

ANOVA - a statistical test which is used to compare different groups of data

Augmented reality - is a technology that combines digital content with the real environment by overlaying it with various digital devices.

Axial Lines - the longest straight line representing the maximum extension of a point of space.

Cardinal Direction - Spatial orientation which refers to the main compass direction: North, South, East, and West

Central Point Strategy - wayfinding strategy which focuses on remaining at the core of the space or building

CityGML - geospatial information model and XML-based encoding for the representation, storage and exchange of the virtual 3D city and landscapes.

Cognitive Map - a rich internal model of the world that accounts for the relationships between events and predicts the consequences of actions.

Cognitive Mapping - the process of encoding, storing, and manipulating experienced and sensed geo-referenced information

Cognitive Process - a series of cognitive operations carried out in the creation and manipulation of mental representations of information

Constructivist Learning Mechanism - is a learning mechanism in which learners actively contribute to constructing their knowledge rather than passively receiving information.

Continuous – something that is going without interruption or gaps

Continuous Wayfinding - an act of wayfinding involving movement through different environments uninterruptedly

Declarative memory - holds knowledge that can be clearly described, such as people’s understanding of mathematical formulas and chemical principles

Direction Strategy - wayfinding strategy which utilizes a path that leads directly to the destination effectively

District - part of the city structure which recognize a certain sectional character

Edge - serves as a limit between regions, which can emerge as a wall, shore, railroad cuts, etc

Egocentric Frame - spatial representations which relate to the body axes (dependent to the observer)

Error signals - feedback generated when an expected outcome does not match reality, prompting learning adjustments.

Error-Driven Learning Mechanism - a learning process which focuses on error reduction often found in the process of practice

Eye Tracking - research technique in collecting gaze patterns and visual attention

Fields of View - total visual area observable through the eye of a person

Gaussian Splatting - a 3D point-based rendering technique utilizing anisotropic 3D Gaussians

Global Landmark – a landmark which is seen from many angles and distances

Indoor - the space inside a structure (interior of a house, building, etc.)

IndoorGML - an OGC® standard for representing and exchanging indoor navigation network models

Isovist - a set of all points visible from a given vantage point in space and with respect to an environment. The shape and size of an isovist is liable to change with position

Kinaesthetic sense - our body's ability to perceive movement and positioning

Knowledge Gathering and Processing Ability - attitude and preferences to extend knowledge about the environment, e.g. explore cities and take new routes

Landmarks - external point references that are recognizable from various points of view

Latency - the processing time incurred by the computer system used for the VR application

Localization – is a process following positioning, which generates more descriptive spatial information gathered from the local environment

Local Landmark - landmarks that tend to only be visible from close up

Locomotion – sensory responsive behaviour, responsible for navigation activities such as steering, obstacle avoidance, and approaching visible object

Long-term memory - stored memory as part of a cognitive system over an extended period

Navigation - coordinated and goal-directed movement through the environment by organisms or intelligent machines

Navigational Aptitude - the ability of a person to have an efficient navigation in an environment

Nodes - cross-section point or a concentrated part of a city network

Orientation - the process of identifying your current direction and location using mentally structured reference points

Orientation Absolute - positioning based on fixed reference points such as cardinal directions.

Orientation Relative - positioning based on local reference objects rather than global coordinates.

Outdoor - the space outside the building structure

Path - the routes where people walk right through

Path Tracing - research technique for recording movement patterns in a spatial environment

Pause/ Break Points – areas in which participant takes a break or pause to collect information from the environment

Plan Configuration - structural layout of spaces in a building, which could affect the wayfinding and movement pattern

Point Cloud - a set of digital representation points data in a three-dimensional coordination system

Positioning - the process of one's location establishment relative to a reference point

Procedural Memory - the relationship between the input stimulation and the output, such as sports skills and habits

Regression - a statistical method utilized in determining the relationship between variables

Routing Free Space - a navigation method that does not rely on predefined paths but allows movement in open spaces.

Routing Network - a structured system of interconnected pathways used for navigation.

Screen Curvature - the degree of a curved display surface affects the spatial visualization and depth perception

Seamless Wayfinding - wayfinding which does not encounter interventions when transitioning between different environments

Segment Analysis - analysis of a segment map, including topological, angular and metric analyses used to identify movement patterns and route selection

Self-Organizing Learning Mechanism - learning process that develops a structured representation of the environment which does not require external feedback

Self-Localization - a process of identifying one's current position within a spatial layout, driven by cognitive processing, at any given time during wayfinding and navigating

Self-Monitoring - process and ability to constantly identify the current position relative to the chosen path during wayfinding

Semi-Bounded - a partially enclosed spatial situation

Semi-Indoor - a space covered with canopies that are related to a building and can combine indoor and outdoor climate conditions.

Semi-Outdoor - a space that is not enclosed entirely and has some settings, including human-made structures that moderate the effects of the outdoor conditions

Semi-Structured Interview - a qualitative data collection method that uses a predetermined set of open-ended questions while allowing the interviewer to probe deeper into emerging themes based on participant responses

Sensory Stimuli - environmental inputs from sensory receptors such as visual, auditory, and tactile cues

Short-Term Memory - temporarily stored memory as part of a cognitive system for immediate task

Signage - visual cues of indicators used to guide wayfinding or navigation

Space Syntax - theory of space and a set of analytical, quantitative and descriptive tools for analysing space layout in buildings and cities.

Spatial Cognition - part of the human cognitive ability to acknowledge and process spatial information and use it for various activities

Spatial Orientation – the localization of objects in imagination either with reference to oneself, to one another, or fixed, standard directions

Spatial Visibility - a measurement depicting the visibility range of a space from the given location

Statistical Learning Mechanism - learning mechanism developed from detecting statistical regularities in continuous sensory input

Thinking Aloud Protocols - qualitative data collection method involving vocalisation of thoughts, reasoning, and decision-making of the research participant during task performance

Transitional Space - spaces that can be neither consistently classified as being indoors nor being outdoors and that share properties with either category

Verbatim – transcription word-for-word reproduction of verbal data, where the written words are an exact replication of the audio-recorded words

Virtual Reality - a digital environment which simulates an immersive experience with user interaction feature

Visual Access - the ability to see through or out of a spatial setting

Visual receptors - the visual sensory organ (eyes) which is responsible for processing visuospatial information

Wayfinding - an ability and a process of a person to find a way and get to the intended location, supported by their cognition and action, with information provided by the environment

Working memory - brain system that provides temporary storage and manipulation of the information necessary for such complex cognitive tasks as language comprehension, learning, and reasoning

ABSTRACT

In investigating spatial cognitive development, various studies have explored wayfinding performance exclusively in either indoor or outdoor environments. However, continuous wayfinding across environments is often inevitable in real-life situations involving transitional space between indoor and outdoor spaces. Transitional spaces are significant in wayfinding performance, serving as cognitive processing points where individuals reassess spatial information, adjust their wayfinding strategies, and integrate environmental cues to maintain orientation. Meanwhile, wayfinding studies addressing transitional space are rarely found despite great potential in supporting the cognitive development process. Furthermore, intricate access rights in various environments could affect spatial cognition development due to path restrictions from access classifications, such as different building access groups or traffic regulations. On the other hand, despite the ability to overcome wayfinding challenges, most navigation apps only focus on providing path alternatives, leading to navigation app dependency. With all issues related to the emergence of transitional space and access rights, it is important to explore these topics in a controlled environment that could offer the flexibility of simulation scenarios which possess the details of the real environment. Therefore, this study aimed to explore wayfinding spatial cognitive development in a multi-environment (indoor, outdoor, and transitional space), addressing the role of access rights using 3D photorealistic VR simulation. The study will commence in four stages: 1. Contextual analysis, 2. Simulation tools and system development, 3. Simulation and data analysis, and 4. Demonstration of the optimized wayfinding. The simulation will investigate visual cues during wayfinding and the importance of transitional space in spatial cognitive development. With all the addressed issues, utilizing the VR simulation method, this study will contribute to investigating the transitional space's role in spatial cognitive development and how 3D photorealistic VR simulation could provide participants with close to real wayfinding simulation experience. From the participants' user experience, the study will be able to capture the important visual cues (or relevant visual cues). The gained knowledge of visual cues will be used to develop a wayfinding design guideline that stimulates spatial awareness, which will be tested in an enhanced VR environment and demonstrate optimized wayfinding. By addressing the interplay between indoor, outdoor, and transitional spaces, as well as the influence of access rights, this study aims to bridge existing research gaps in wayfinding performance. Through the use of 3D photorealistic VR simulations, the findings will contribute to the development of more effective wayfinding strategies and guidelines, ultimately enhancing spatial awareness and navigation efficiency in real-world applications.

KEYWORDS:

access rights; indoor; outdoor; spatial cognition; transitional space; virtual reality; wayfinding

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1. INTRODUCTION

1.1. Research Background

One of the biggest challenges whenever arriving in a new location is wayfinding. Wayfinding is the cognitive and behavioural process of navigating in an unfamiliar space to reach the intended destination, guided by environmental information (Farr et al., 2012; Passini, 1984a), which is done both by humans and animals (Hegarty et al., 2023; Melzer & Madison, 2020; Tolman, 1948). To successfully wayfinding from one place to another, a person needs to be able to gather visual information and identify their position in the foreign situation (Downs & Stea, 1973). However, due to differences in space morphology and visual information, wayfinding between indoors and outdoors requires different strategies and cognitive processing (Golledge, 2003; Hillier & Hanson, 1989; Peponis & Wineman, 2002; Sima & Zhang, 2009).

Meanwhile, continuous wayfinding across environments is often unavoidable. It involves transitional space, which acts as a cognitive processing spot where individuals must reorient themselves, adapt to changing environmental cues, and shift between different wayfinding strategies. Transitional space is a space which does not classify as strictly indoor or outdoor but serves as a connecting zone between the two (Kray et al., 2013). Transitional spaces introduce additional wayfinding challenges, as they often lack consistent signage, differ in spatial configuration, and may create temporary disorientation due to abrupt changes in visibility, scale, or accessibility. This situation can increase cognitive load and slow decision-making during wayfinding.

On the other hand, wayfinding in spaces with intricate access rights may disrupt a person's spatial cognitive processing. Access rights in indoor and outdoor environments might related to privacy, permission, and legal constraints. For instance, hospitals and university buildings possess various classifications of access rights, classifying patients/ students, staff, and visitors as different groups, limiting access for each user group. The classification establishes a space permission applied to a specific access group, such as patients, who may not be permitted to access an examination room in a particular condition. Subsequently, a new patient in a hospital might experience disorientation and difficulties in developing a cognitive map due to encounters with restricted areas (Pouyan et al., 2021). The same goes for outdoor wayfinding, where traffic rules and space permits limit pedestrian mobility.

In the meantime, people tackle wayfinding challenges with the help of a navigation app, which provides them with direct navigation to the desired location. However, the navigation map often does not consider the spatial restriction of the environment, especially in indoor situations (A. F. M. Alattas et al., 2021). Whenever someone navigates and finds themselves in a situation where a particular area is restricted, it will be hard to redevelop the potential route due to the lack of environmental knowledge. Furthermore, the ease of navigating maps causes people to have less spatial/environmental awareness (Vaez et al., 2021), which potentially causes them to rely on the navigation app whenever they need to navigate. This reliability is not necessarily positive, especially in emergency situations where wayfinding ability is crucially needed.

In relation to wayfinding studies, numerous studies have employed Virtual Reality (VR) with a 3D digital environment to explore wayfinding performances in different scenarios. VR has become a reliable simulation method due to its ability to accommodate various scenarios that cannot be done in conventional simulation, such as emergency evacuation and fire-induced simulation (Dong et al., 2022; Feng et al., 2022b; Meng & Zhang, 2014; Zhiming et al., 2020). Generally, wayfinding VR simulation adopt 3D digital modelling for the virtual environment. However, the 3D digital model often lacks the details and ambience of a real environment, essential in sensory-induced cognitive processing in wayfinding (Bomfim & Cruz, 2023; Newman et al., 2022). The lack of 3D photorealistic environment representation can reduce the accuracy of wayfinding behaviour, affecting its result validity.

Wayfinding activities operate using spatial cognition, which is built on the person's ability to do cognitive mapping. Spatial cognition is part of the human cognitive ability to acknowledge and process spatial information (figure1). Meanwhile, cognitive mapping is building an environment's mental image by encoding, storing, and manipulating experienced and sensed geo-referenced information (Golledge, 1999; Passini, 1984a). Information collected from cognitive mapping is used to build spatial orientation, which supports the wayfinding process.

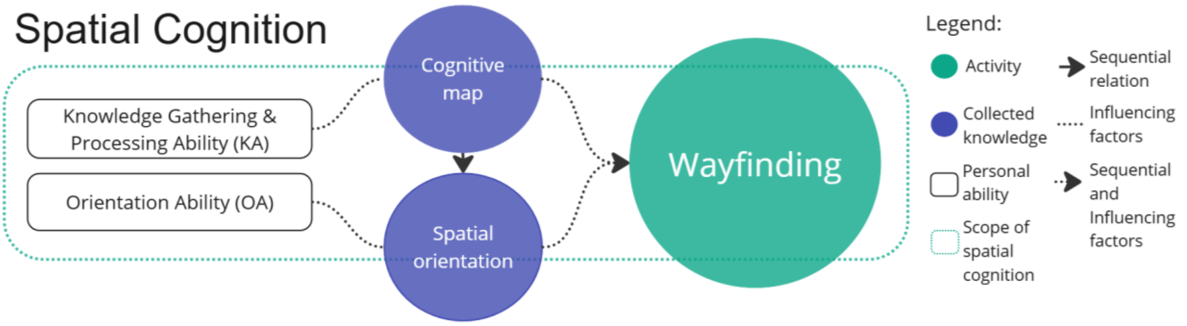


Figure 1. Hierarchical relationship between spatial cognition, cognitive map, spatial orientation, and wayfinding

The wayfinding process comprises cognitive mapping, wayfinding plan development, and physical movement (J. L. Chen & Stanney, 1999a). Several cognitive processes were executed during wayfinding, beginning with recognising local direction or orientation to identify the person's current position relative to the environment (figure 2) (Xia et al., 2008). The local cognitive map is utilised in this process, and it is collected from identifying local environment features such as landmarks, decision points, and paths. With information collected from the cognitive map, the person began to develop a navigation plan and followed up by wayfinding action.

All the cognitive maps collected in the wayfinding process are part of spatial cognition determining the wayfinding performance. In multi-environment wayfinding, cognitive maps will constantly be updated along with the wayfinding process, especially during the transition across the environment where new spatial information is introduced. Exploration of wayfinding across environments will provide initial information on spatial cognition processing during environment transition, which significantly benefits movement behaviour study concerning continuous movement across environments.

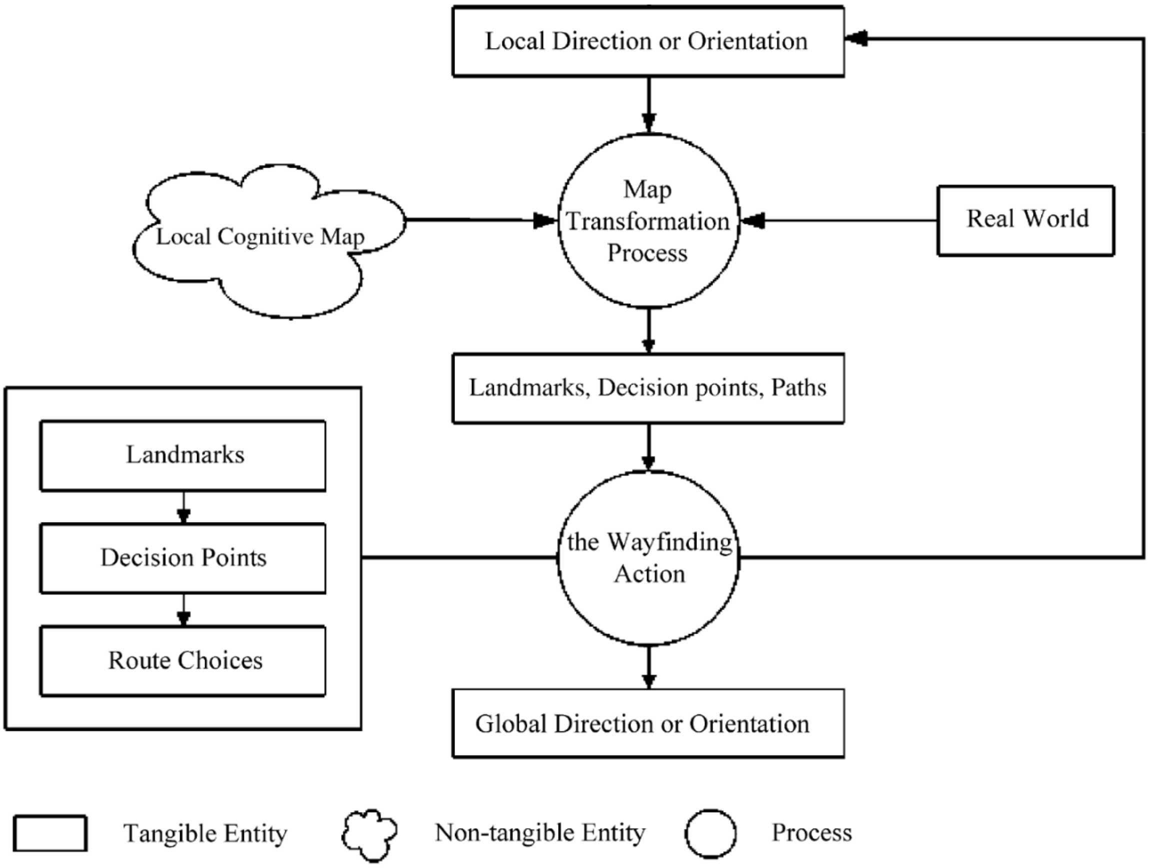


Figure 2. Wayfinding process according to a complete cognitive map
Source: Xia et al., 2008 with author adaptation

However, despite the dynamic nature of cognitive map updates in multi-environment wayfinding, much research has not fully explored how spatial cognition evolves during transitions, particularly in relation to access rights. While studies on continuous wayfinding are gaining recognition, much of the existing research focuses on wayfinding within single environments, overlooking the complexities of wayfinding performance during environmental transitions (Fu et al., 2023; Hölscher & Brösamle, 2007; Khan & Kolay, 2017; Makri et al., 2015; Vaez et al., 2021). At the same time, studies related to transitional space mainly discuss how it is classified and differentiated from indoor and outdoor space (Kray et al., 2013; Zlatanova et al., 2020). Similarly, studies related to access rights mainly discuss how it is classified in various buildings and affects the user movement during evacuation exercise (A. Alattas et al., 2017, 2020). The research gaps call for a study of wayfinding, which concerns continuous movement across environments by considering access rights' role in spatial cognition development.

Therefore, this study aims to explore wayfinding performance in wayfinding across environments by taking into account the role of access rights as part of the learning mechanism of spatial cognition development. This study will employ a 3D photorealistic VR environment to capture a more accurate cognitive response from immersive sensory stimulation.

1.2. Problem Statement

1. Intricate wayfinding situations in indoor, outdoor, and transitional space

Each environment (indoor, outdoor, and transitional space) has intricate situations which will affect the wayfinding performance. For example, indoor wayfinding and navigation will rely mainly on the presence of signages instead of visual connectivity. Meanwhile, visual connectivity in outdoor environments, particularly in urban areas, will arguably be more significant than signage during wayfinding performance. Moreover, transitional spaces introduce additional wayfinding challenges due to their hybrid nature. These spaces often exhibit inconsistent environmental cues, requiring individuals to adjust their wayfinding strategies dynamically while processing varying levels of visibility, scale, and spatial configurations. Therefore, exploring the level of visual cues in each environment is crucial in providing a more detailed understanding of how wayfinding is performed in different settings.

2. Spatial cognition challenge due to access rights

Changes in access rights during wayfinding may challenge the process of spatial cognition development. Usually, when people do wayfinding, they rely on spatial information such as landmarks, signages, visual connectivity, and accessibility (environmental layout). The cognitive map retrieval process requires a stable spatial layout so that people can record that spatial information effectively. However, access rights may differ in some areas depending on the time or occasion (e.g. road closure). Therefore, in an uncertain accessibility situation, a person’s cognition map towards the space may be disrupted due to the spatial access restriction. On the other hand, encounters with intricate access rights could help people understand the spatial layout better, especially when building the cognitive map. Therefore, it is essential to examine how access rights affect our decision on wayfinding.

3. Navigation application dependency

Various technologies, such as navigation apps, have emerged to provide aids in tackling wayfinding and navigating challenges. However, the use of navigation apps has caused dependency, reducing the awareness of the spatial layout, which is significant in developing spatial cognition. Spatial awareness is crucial, especially in responding to unprecedented scenarios in space, such as emergency evacuation due to earthquakes or fires. Therefore, exploring methods for building spatial awareness is crucial in reducing the navigation app's dependency.

4. Lack of 3D photorealistic environment in VR wayfinding simulations

Many VR simulations use digital modelling to simulate wayfinding studies, which do not necessarily provide details and ambience similar to the real environment. Meanwhile, VR wayfinding performance significantly depends on the environment's visual quality due to wayfinding processes that involve response to sensory stimulation. Therefore, it is crucial to test the wayfinding performance using a 3D photorealistic environment derived from the real environment scan to capture the wayfinding variable.

1.3. Research Questions

Main Research Questions

"What factors contribute to spatial cognition development and wayfinding performance across indoor, outdoor, and transitional spaces, respecting access rights?"

Sub Research Questions

1. "What are spatial cognition and wayfinding visual cues in indoor, outdoor, and transitional spaces and addressing access rights?"
    a. Which wayfinding variables are related to the visuospatial interpretation of indoor, outdoor, and transitional space?
    b. What is the role of intricate access rights in advancing spatial cognition development?
    c. In what way is the access right interpreted in wayfinding indoor, outdoor, and transitional space?
2. "Which VR simulation approach effectively captures the visual cues for wayfinding?"
    a. What digital environment (e.g. meshes, coloured point clouds or Gaussian splats) effectively captures details of spatial visual cues for wayfinding simulation?
    b. What VR simulation systems must be implemented to capture visual cues of wayfinding?
3. "To what extent does the significance of each wayfinding visual cue differ between indoor, transitional, and outdoor spaces with respect to access rights?"
    a. How do the visual cues affect wayfinding performance in each space?
    b. What are continuous simulation's implications for developing spatial cognition across integrated environments?
    c. How do access rights affect decision-making regarding wayfinding?
4. "How can we demonstrate optimized wayfinding, developed through the encouragement of spatial awareness, by exploiting gained knowledge on visual cues in a multi-environment setting?"
    a. What design guidelines should be established to develop spaces that integrate the gained knowledge to optimise wayfinding?
    b. What evaluation parameter can be implemented to validate the optimized wayfinding and spatial awareness demonstration?

1.4. Research Objectives

1. To interpret wayfinding visual cues in indoor, outdoor, and transitional spaces and the role of access rights in spatial cognition.
2. To develop VR simulation methods that effectively capture the visual cues of wayfinding.

3. To explore the significance of wayfinding visual cues of indoor, transitional, and outdoor spaces with respect to access rights.
4. To develop a virtual reality environment that demonstrates optimized wayfinding by enhancing spatial awareness through improved visual cues.

2. RELATED WORK AND BACKGROUND THEORIES

This section explores related work and background theories revolving around spatial cognition, wayfinding development in various environments, access rights in wayfinding, VR as a wayfinding simulation method, and wayfinding design guidelines. It begins by describing the cognitive map processing and how it employs spatial memory representation. This is followed up by describing allocentric and egocentric, responsible for framing spatial cognition and interpretation. Background theories related to cognitive maps and spatial cognition laid the foundation for the discussion afterwards, corresponding to multiple works of wayfinding in various environments. This part states the definition of indoor, outdoor, and transitional space, along with wayfinding variables and related works in these environments. The following part is a discussion related to wayfinding stages, which establish the core methodology of this research. This study's methods developed following the wayfinding processing stages generated from human spatial cognitive processing. The proceeding part discusses related works and the interpretation of building access rights. Background theories and related works surrounding wayfinding design guidelines are discussed at the end of this section. Various parameters of appropriate wayfinding design covering analysis, design, and detail execution process were explored to indicate a potential gap for the additional parameters which will be investigated in this study. All discussions in this section are designed to establish the research scope concerning the formulated research questions.

2.1. Human Cognition, Spatial Memory Representation, and Cognitive Map

Spatial cognition is one of the human capabilities in processing spatial information. This skill is associated with the general human ability to process information, which is called cognition. The cognitive process itself is defined as “a series of cognitive operations carried out in the creation and manipulation of mental representations of information”, which is done straightforwardly or consciously (Bayne et al., 2019; Krch, 2011). Learning a particular concept is one example of cognitive process conscious execution. Meanwhile, unconsciously, a person develops his cognitive ability by learning a particular skill. Cognitive ability is also interpreted as general mental ability/ intelligence, which is either measured as a single construct or multiple distinct intellectual abilities (Berrocal & Checa, 2016; Pardeller et al., 2017). Furthermore, a cognitive process can be generated internally by memory recall or triggered by external sensory input through problem-solving (Krch, 2011). All the cognitive operations carried out through reasoning, emoting, manipulation of stored information, attention, rearrangement, perception, memory storage, synthesizing, retrieval, learning, and metacognition (Baker et al., 2004; Krch, 2011).

Learning mechanism and the memory representation in wayfinding

Cognitive processes are generally executed through various learning mechanisms such as error-driven, self-organizing, statistical, and constructivist (Johnson & Munakata, 2005). The learning processes trigger cognitive development, affecting representational changes such as increased specialization, focal activation, and causal maps.

The self-organizing learning mechanism sourced from Hebbian learning aims to construct the setting reasonably. Self-organizing is obtaining and building essential symbols of the environment's structure. This learning mechanism does not require external feedback, hence the name, self-organizing (O’Reilly & Munakata, 2000). Furthermore, self-organizing learning is constructed by forming simultaneous processing units (Johnson & Munakata, 2005). Meanwhile, Error-driven is a learning process that focuses on error reduction, often found in practice, helping humans learn quickly (Johnson & Munakata, 2005; Zhou et al., 2020). Both self-organizing and error-driven learning only differ in the motivation to achieve the goal. Nonetheless, both are believed to be placed in the cortex, potentially affecting one another in cognitive performance (O’Reilly & Munakata, 2000). Meanwhile, the constructivist learning mechanism focuses on active knowledge reconstruction rather than passively receiving information. The statistical learning mechanism is a response to continuous sensory input, which induces a learning method through the detection of statistical regularities (Polyanskaya, 2022).

Human information processing systems involve many aspects employing long and short-term memory. Beginning from the external trigger, which is coming in a physical signal, the stimulation brought to the memory structure to undergo thought process, pulling various cognitive stimulants such as memory processes, awareness, motivations, emotions and attention (Norman, 1980). The memory structure allows the development of pattern recognition and motor programs before finally being processed as physical activity responding to the placed information. This information processing is relevant to the recent study in brain cognitive mechanisms, demonstrating long- and short-term memory use in processing information and knowledge.

Our brain's cognitive mechanism during the learning process involves several aspects, including long-term memory, short-term memory, working memory, long-term knowledge, embryonic knowledge, stable knowledge, and error signals (Zhou et al., 2020). The first is storing information in working memory, gathered from interaction with the environment, and using long-term memory as the guide (figure 3). The error signal is produced from the transformation of working memory processing by long-term knowledge. The error signal turned into embryonic knowledge kept in the short-term memory. Along with the progress from learning, stable knowledge is slowly developed from short-term memory. Stable knowledge will become fundamental in the human interaction process and learning. This process makes it possible for humans to learn quickly, which comes from the long and short-term learning that enables the quick transformation of information into knowledge.

Meanwhile, in navigating and wayfinding, there are two tasks that people need to acquire to successfully navigate themselves to the desired location: self-orientation and route planning (Kelly & McNamara, 2008; Lawton, 1996). Both tasks utilize three (3) different memory representations, which trigger spatial cognition by utilizing spatial memory and orientation in the navigating process. Firstly, the navigator would utilize long-term representation, essential in route planning collected from past navigating experience. Second is the utilization of working memory representation formed as part of a sensorimotor representation, which is temporarily represented. This memory emerges due to the body-defined performing actions, such as movement between spatial entities, which is egocentrically organized. Movement between spatial entities in this matter is related to wayfinding spatial determinants such as moving toward landmarks or along spatial obstacles. Finally, to keep the navigator oriented, the navigation process must utilise long-term spatial memory by matching the surrounding features to the ones kept in the memory.

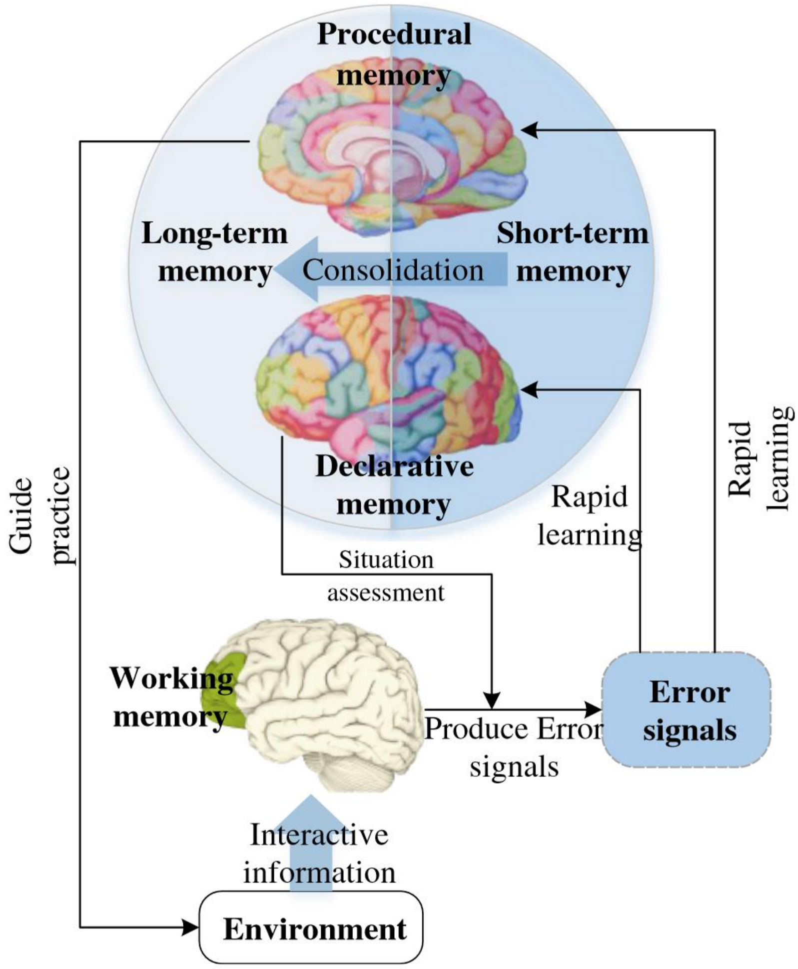


Figure 3. The brain's cognitive mechanism in the learning process
Source: (Zhou et al., 2020)

This memory representation process is aligned with studies in neuroscience which mentioned that spatial representations are of use of behaviour control (Burgess, 2008). The hippocampus, specializing in locational processing concerning environmental boundaries, supports this activity. Furthermore, it was mentioned that the system utilizing the entorhinal cortex and the hippocampus was developed from the processing of spatial landmarks and body movement (Buzsáki & Moser, 2013).

Cognitive mapping in Wayfinding

On the other hand, preserved memory of the mental representation of an environment is essential information in the wayfinding and navigating process. This spatial mental representation is a cognitive map (Darken & Peterson, 2002). The earliest study of cognitive maps dates back to a study by Tolman (1948), who taught a rodent following a path to a specific end goal (figure 4 (left)). The trained path shows an apparatus with circular space, leading to a straight line and an end goal. The simulation then continued with a tested apparatus with a blocked straight path, forcing the rodent to explore 12 alternative paths and deciding a single path to go out (figure 4 (right)). They showed that most rodents choose the correct paths, indicating traces of path training, which directs them to the right side of the apparatus. This indicated the role of the representation of location, labelled as a cognitive map, in providing information for self-orientation and navigation.

Cognitive mapping is "the process of encoding, storing, and manipulating experienced and sensed geo-referenced information." (Golledge, 1999). It is part of the wayfinding stages alongside plan development and physical movement (Arthur & Passini, 1992; J. L. Chen & Stanney, 1999b; Passini, 1984b). The storing process involves spatial information coding, which is stored as memory in specific place cells. This coding allows a person to understand his current location and the position of objects related to his position.

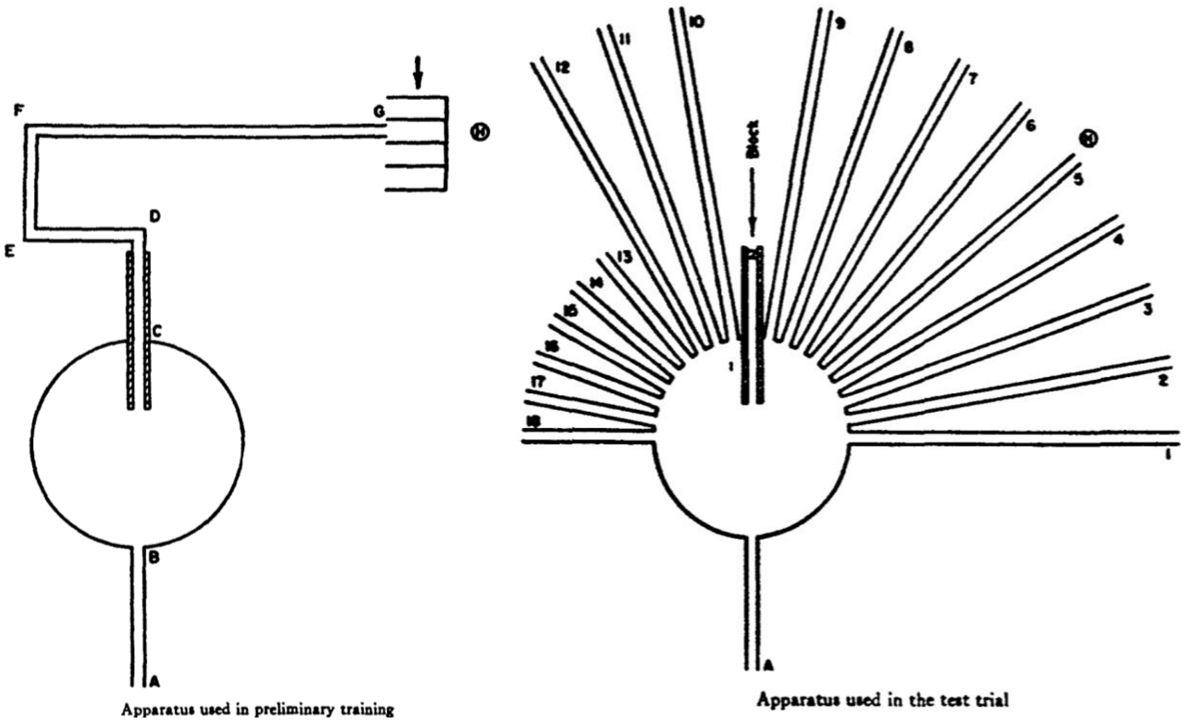


Figure 4. Preliminary training apparatus (left) and test trial apparatus (right)
Source: (Tolman et al., 1946)

2.2. Allocentric and Egocentric in Spatial Cognition

Spatial cognition is a part of the human cognitive ability to acknowledge and process spatial information and use it for various activities (Vasilyeva, 2005). Many spatial information can be explored as part of spatial cognition processing. Several processed spatial information covering the size, shapes, and locations can be interpreted differently according to the use and retrieval method. The primary retrieval information method is through sensory stimuli, especially the visual receptor (Burgess, 2008). The eyes provide direct information about the external information required in building our spatial knowledge. Nevertheless, information acquisition relies not only on visual stimuli. Body coordination also possesses a significant role in providing accurate spatial information to reach the visual target. With eye and body coordination combined as sensorimotor integration, the spatial cognitive is being developed with each intricate individual character. Another spatial information retrieval method that has become more advanced in the last decade is the use of maps. Map provided us with spatial information about our targeted location and its surroundings. Helping us build spatial knowledge through direct experience of the spatial situation and understanding how each network is connected systematically (Uttal, 2000).

Spatial information is generated through the mental representation of a location, supported by two spatial reference frames, egocentric and allocentric (Burgess, 2008; Proulx et al., 2016). Egocentric is spatial information that is dependent on the observer. This means that the spatial interpretation would rely on the observer, which is affected by the sensorimotor representation, mental state, prior spatial information, and how all the existing information relates to each other. Meanwhile, allocentric is the spatial representation which entirely relies on the relationship between the spatial situation itself, without the observer's interpretation (Weniger et al., 2011). Each code has a significant role in determining how spatial cognition is being used. For instance, many studies have shown that allocentric plays the most significant role in its performance in wayfinding and navigating.

Some challenges encountered during navigation are influenced by wayfinding ability, which is shaped by spatial cognition and governed by allocentric and egocentric frameworks (Allen, 1999; Verghote et al., 2019). Allocentric (or viewer-independent) coding is coding related to elements of the environment other than oneself. Egocentric (or viewer-dependent) coding, which is coding relevant to oneself. Both egocentric and allocentric are thought to be the two primary ways that location can be stored (figure 5) (Vasilyeva & Lourenco, 2012). The effectiveness of these spatial coding strategies directly influences an individual's ability to navigate, as successful wayfinding requires the integration of multiple cognitive and behavioural processes. Several individual performances executed during wayfinding are decision making, decision execution, information processing, use of maps, subjects' navigational aptitude, familiarity with the environment, and the layout of the environment (Chebat et al., 2005; Gerber & Kwan, 1994; Hölscher et al., 2006; Kato & Takeuchi, 2003; Passini, 1984a). Understanding how these cognitive and behavioural elements interact is crucial for improving wayfinding strategies, particularly in complex environments where spatial information must be constantly updated and processed.

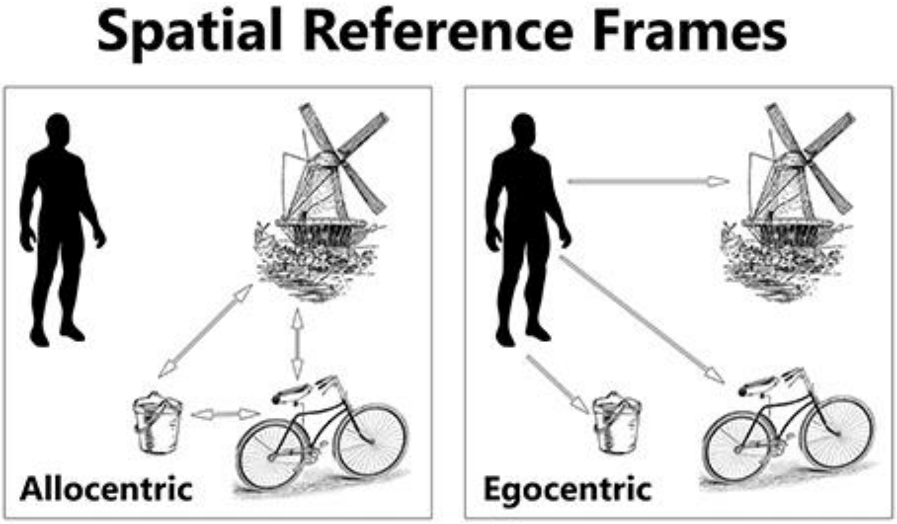


Figure 5. Visualisation of Egocentric (viewer-dependent) and Allocentric (viewer-independent)
Source: Proulx et al., 2016

2.3. Wayfinding in Multi Environment

Wayfinding is an ability and a process of a person to find a way and get to the intended location, supported by their cognition and action, with information provided by the environment (Farr et al., 2012; Passini, 1984a). It is a form of human interaction with the environment that pushes our cognitive response from external stimuli. Wayfinding has been discussed for quite a while, beginning with its previously known term spatial orientation, often referred to as orientation, which is the process of identifying one's current direction and location by mentally structuring references relative to oneself, other objects, or fixed standard directions (Freeman, 1916; Li et al., 2014). Spatial orientation studies laid the foundation of wayfinding researchers from various findings in the ability of the body positioning to the spatial layout in children and animals (Freeman, 1916; Lord, 1941; Tolman, 1948).

The term changed into wayfinding when Lynch discussed way-finding as a form of cognitive processing and actions, which occurred by structuring the environment from various memory and sensory cues of the external environment (1960). In his book, The Image of the City, he explains how a city could build a mental image of an environment, which helps the observer understand and provide a sense of security through their relationship and mind processing with the external settings. The environmental image was built in accordance with the past memory in combination with the direct sensation of exploration, creating a process of data interpretation and navigating (Arthur & Passini, 1992; Lynch, 1960). This idea provides the fundamental ground for wayfinding and spatial cognition studies, which now have been implemented in various essential products and critical elements for human well-being.

Distinguishing Wayfinding from Navigation

However, wayfinding is often interpreted similarly to navigating, which generally has a different focus. Wayfinding and navigating have three main differences: environment familiarity, self-monitoring, and settings (Golledge, 1999). Unlike navigation, wayfinding runs in an unfamiliar environment, creating a unique wayfinding system for each individual. Furthermore, navigating involves self-monitoring, often utilising navigation tools such as maps and navigation apps, which is considered a separate process in wayfinding (Barker, 2019; Hofmann-Wellenhof et al., 2003).

Wiener (2009) discussed the navigation taxonomy, which possesses two components: locomotion and wayfinding (figure 6). In this sense, wayfinding was seen as part of the navigation process. He further explained the classification of wayfinding as aided and unaided, indicating the role of assisting tools in the process. Nonetheless, it was mentioned that wayfinding includes cognitive processing as the source of movement activity, while navigation generally focuses on the movement process. (Farr et al., 2012; Passini, 1984a; Wiener et al., 2009). Due to the nature of the navigation term, subsequently, it is often used in discussions about navigation aid systems, specifically in navigation apps. (Prandi et al., 2023).

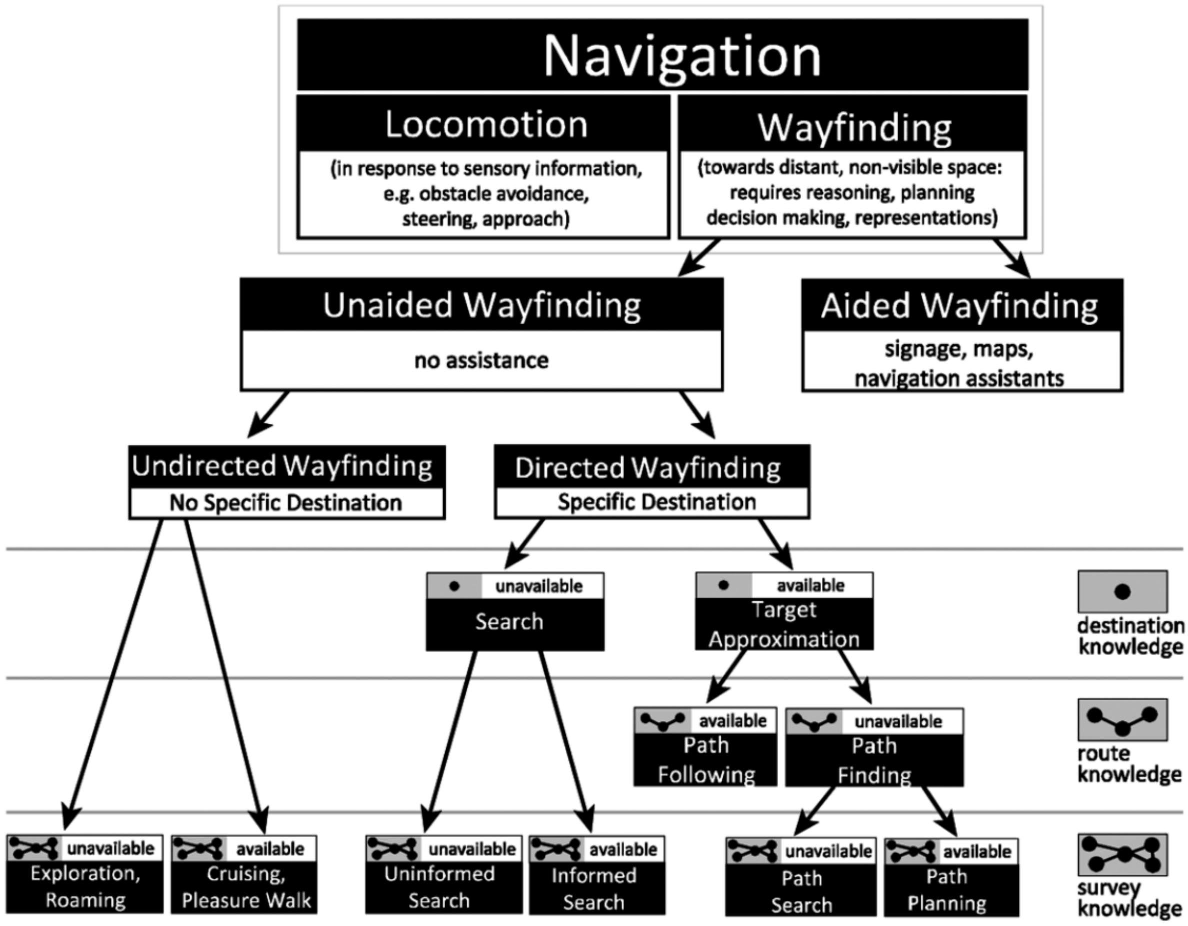


Figure 6. Taxonomy of wayfinding task
Source: (Wiener et al., 2009)

Orientation, Positioning, and Localization

One of the early stages of wayfinding and navigating is understanding your current position and direction relative to the reference point. This process is interpreted in terms such as orientation, positioning, and localization. Orientation is the process of identifying your current direction and location using mentally structured reference points (Freeman, 1916; Li et al., 2014). The stated orientation definition is related to the wayfinding cognitive process aimed at developing a cognitive map to understand the environment. In order to be able to orient themselves, a person must be able to have a general knowledge of the area through building the environment mental imaging (Paratore & Leporini, 2024). Additionally, the orientation reference recognizes two main points, which are absolute and relative orientation. Absolute orientation is location referencing based on fixed reference points such as cardinal directions. In contrast, relative orientation is location referencing based on local reference objects rather than global coordinates. Absolute and relative orientation terms adopted from aerial triangulation and photogrammetry in establishing the spatial relationship between multiple images (Heipke, 1997).

Similarly, positioning is defined as "the process of pertaining a position." (Hofmann-Wellenhof et al., 2003). Positioning would answer the question of "Where am I?" by collecting information gained from the environment. However, positioning is generally used in navigation systems, particularly navigation aid applications. A positioning system must be integrated when developing a navigation application, utilizing GPS, GNSS, Wi-Fi, or BLE (Bluetooth Low Energy) to determine location accurately. Positioning allows a person to generate more descriptive/ meaningful value to the location, or what is called as localization. Figure 7 depicts the difference between positioning, localization, and navigation, highlighting a sequential process of environment processing before navigating. Additionally, in an indoor mobile device, localization would act as a data-matching process between an indoor environment and a reference model, indicating the role of local information in the localization process (Bot et al., 2019).

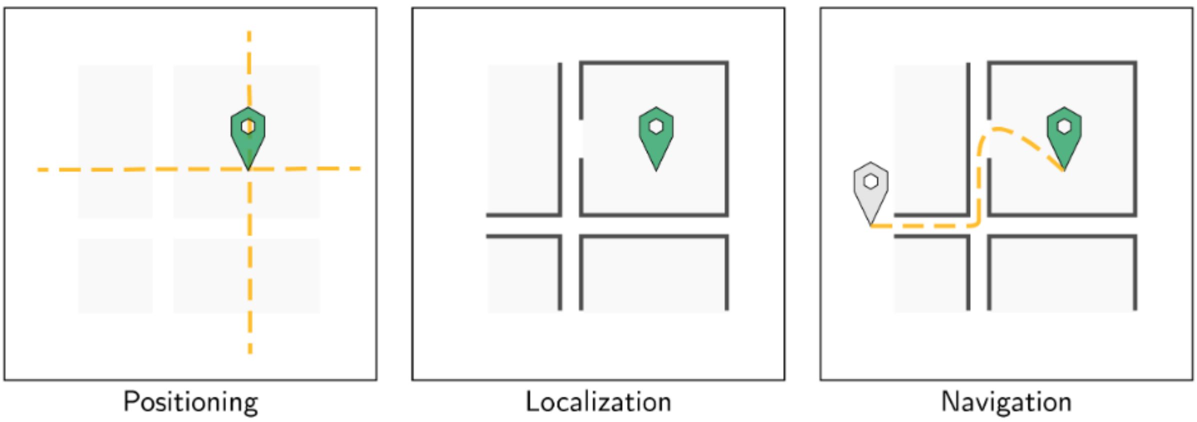


Figure 7. The difference between positioning, localization and navigation
Source: (Bot et al., 2019)

Although orientation, positioning, and localisation share certain commonalities, each has a unique function in various domains that aid in comprehending one's spatial circumstances. The primary functions of orientation are directional awareness and cognitive processing, which establish which way an object or person is facing. Meanwhile, positioning aims to pinpoint a precise or approximate placement within a spatial arrangement. At the same time, localization integrates both orientation and positioning by providing information about one's position relative to the surrounding environment or local setting.

Urban Wayfinding

Wayfinding can happen in various settings. Starting from urban environments, rural areas, or even natural environments close to natural vegetation like forests and mountains. Nonetheless, several earlier studies of wayfinding were explored and found in outdoor settings, specifically in urban areas. Lynch (1960) first, introduce the context of a city's mental image, which becomes the fundamental cue for wayfinding. The image of the city itself is predetermined by the city's physical form, which can be identified by five different elements: paths, edges, nodes, districts, and landmarks (figure 8). Paths are the routes that people walk right through. It can be a street, pathways, or roads. Through this path, people can observe their environments and acknowledge the elements of the city they are in. The edge acts as a boundary. It is not a path; instead, it serves as a limit between regions, which can emerge as a wall, shore, railroad cuts, etc. Districts are fragments of the city. People may consider it part of the city structure, which recognises a particular sectional character. Nodes are considered a cross-section point or a concentrated part of a city network. It can be presented as junctions, crossings, or merging paths. Landmarks are external point-references that are recognizable from various points of view (Lynch, 1960). It can occur in the form of buildings, signages, towers, etc. All elements contribute to the mental map individuals create of a city related to one another. This study is becoming one of the fundamentals of cognitive map study, which is the foundation of wayfinding performance in urban settings.

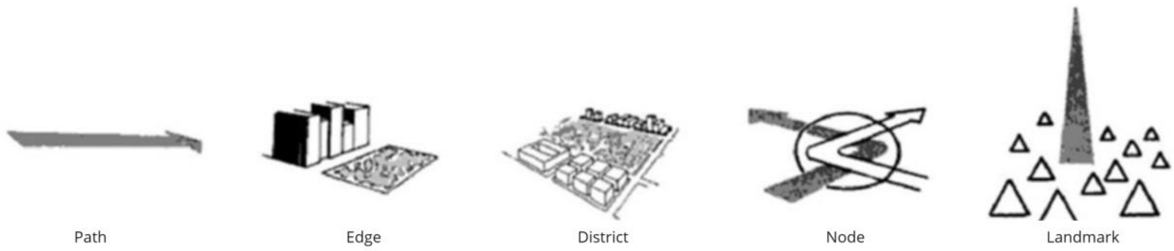


Figure 8. Kevin Lynch Wayfinding theoretical model
Source: (Lynch, 1960)

Furthermore, urban wayfinding process was affected by four general aspects, which are 1. socio-demographic and motility, 2. urban environment, 3. navigational preferences, and 4. daily travel behaviour (Zomer et al., 2019). Other than the urban environment as an environment determinant in path choice, the other 3 aspects are more on personal preferences, which are also derived from personal background (figure 9). Social demographic aspects range from individual traits to household and motility. The daily travel behaviours range from activity type, mobility portfolio (preferred transportation mode), and mobility pattern (preferred combination of transportation mode).

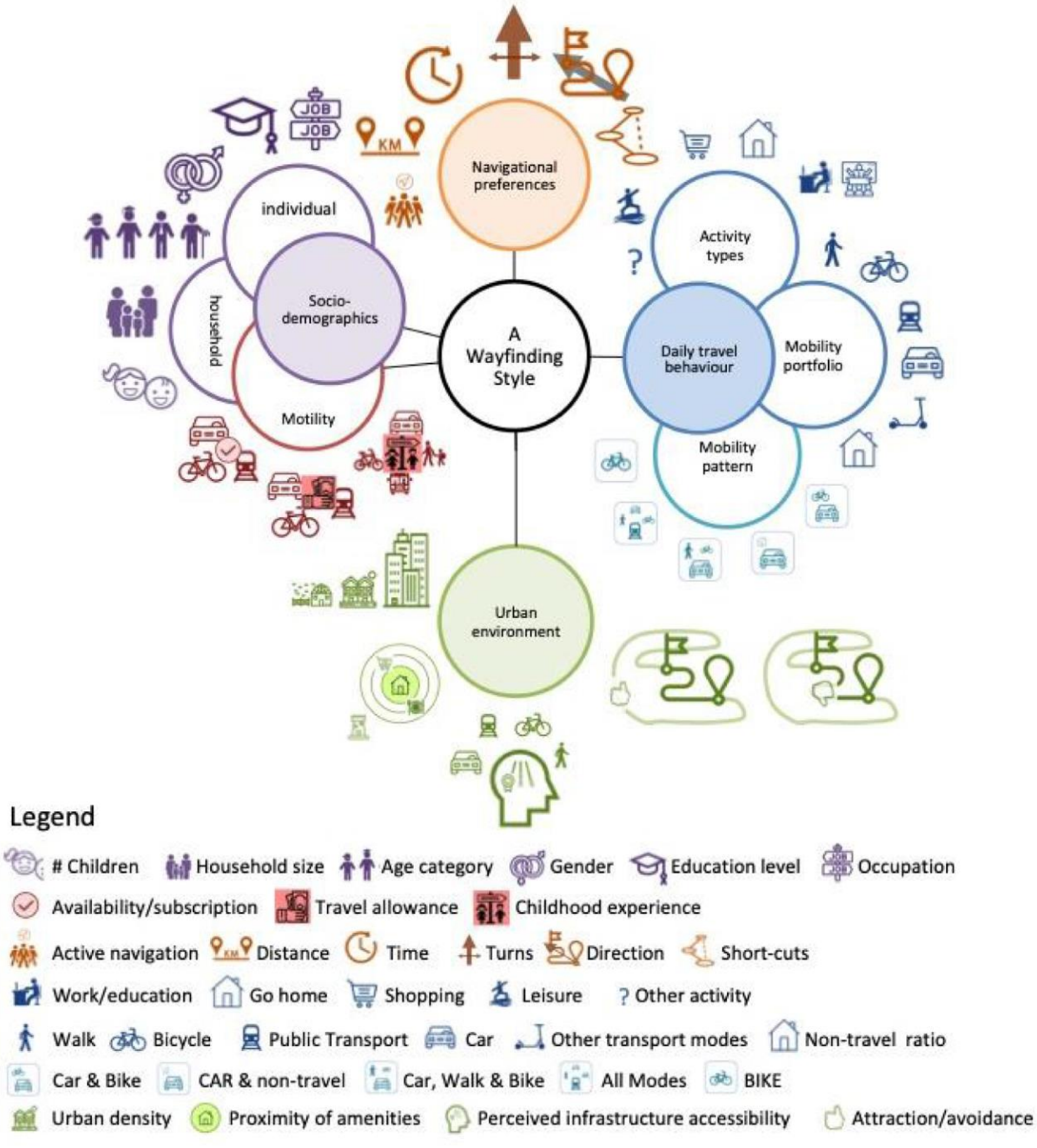


Figure 9. Conceptual model of wayfinding variables with urban wayfinding lifestyle
Source: (Zomer et al., 2019)

Meanwhile, navigational preferences are related to the navigator's various responses to the wayfinding options. In this study, it was described that there are two wayfinding styles implemented in urban wayfinding, which are Orientation Ability (OA) and Knowledge Gathering and Processing Ability (KA). Orientation Ability refers to the "attitude and basic skills to orient and navigate effectively in an urban environment". In contrast, Knowledge Gathering and processing Ability refers to "attitude and preferences to extend knowledge about the environment, e.g. explore cities and take new routes" (Zomer et al., 2019). People with lower OA tend to make up for complex urban paths with longer routes that possess more familiar situations despite the general wayfinding performance of choosing a more efficient path to reach the targeted destination.

Furthermore, wayfinding descriptions in urban environments are more precise and related to the landmarks (Brosset et al., 2008). References to landmarks are becoming more frequent toward the end of the wayfinding simulation, highlighting the importance of landmarks in urban wayfinding. On the other hand, despite the importance of landmarks in wayfinding performance, in some countries, it was mentioned that the utilization of cardinal direction is creating faster and more efficient wayfinding (Hund & Minarik, 2006). Nonetheless, the wayfinding ability does not necessarily depend on the responsive behaviour (searching for spatial clues, route planning, and walking through the selected). However, it is also affected by the cognitive ability to gather the information presented in the environment and restructure it as a mental image (Bomfim & Cruz, 2023).

Indoor Wayfinding

Following the outdoor simulation, indoor wayfinding studies highlighted different spatial classifications responding to indoor spatial traits, indicating similar wayfinding complex processes required for self-orientation and path-finding (Makri et al., 2015). There are four environmental variable classes in indoor wayfinding: architectural differentiation, plan configuration, signage and room numbers, and visual access (Weisman, 1981). Each variable is significant in supporting the wayfinding performance. Additionally, Jamshidi (2020) discusses various wayfinding variables and their relationship to one another (figure 10). It was mentioned that environmental and user factors determine the wayfinding performance.

In indoor wayfinding performance, environmental factors are classified into environmental elements and environmental cues. Like outdoors, environmental elements include edges, paths, nodes, regions, and landmarks. In addition, indoor environment elements include the floor plan configuration, a more detailed spatial layout typically possessed by the indoor environment. Furthermore, environmental cues in the indoor environment emerge as signs, maps, and other environmental factors. Other environmental factors in this context are indoor elements or attributes provided by designers, which emerge and are used in various ways in indoor settings. Elements or attributes of the physical environment procured or designed by interior designers are used differently by subjects (Pati et al., 2015).

All the indoor wayfinding variables contribute to the wayfinding performance. It was mentioned that visual access restrictions and complex floor plans could decrease wayfinding performance (Makri et al., 2015). However, the presence of signage could alleviate the wayfinding performance (Holscher et al., 2007; O'Neill, 1991). This is due to the effect of wayfinding signage in reducing confusion, anger, crowding, and discomfort (Wener & Kaminoff, 1983). Nonetheless, too much signage could cause confusion, affecting the wayfinding performance (Montello & Sas, 2006). However, despite the significant influence of signage, the plan configuration has the greatest impact on inducing effective wayfinding (O'Neill, 1991).

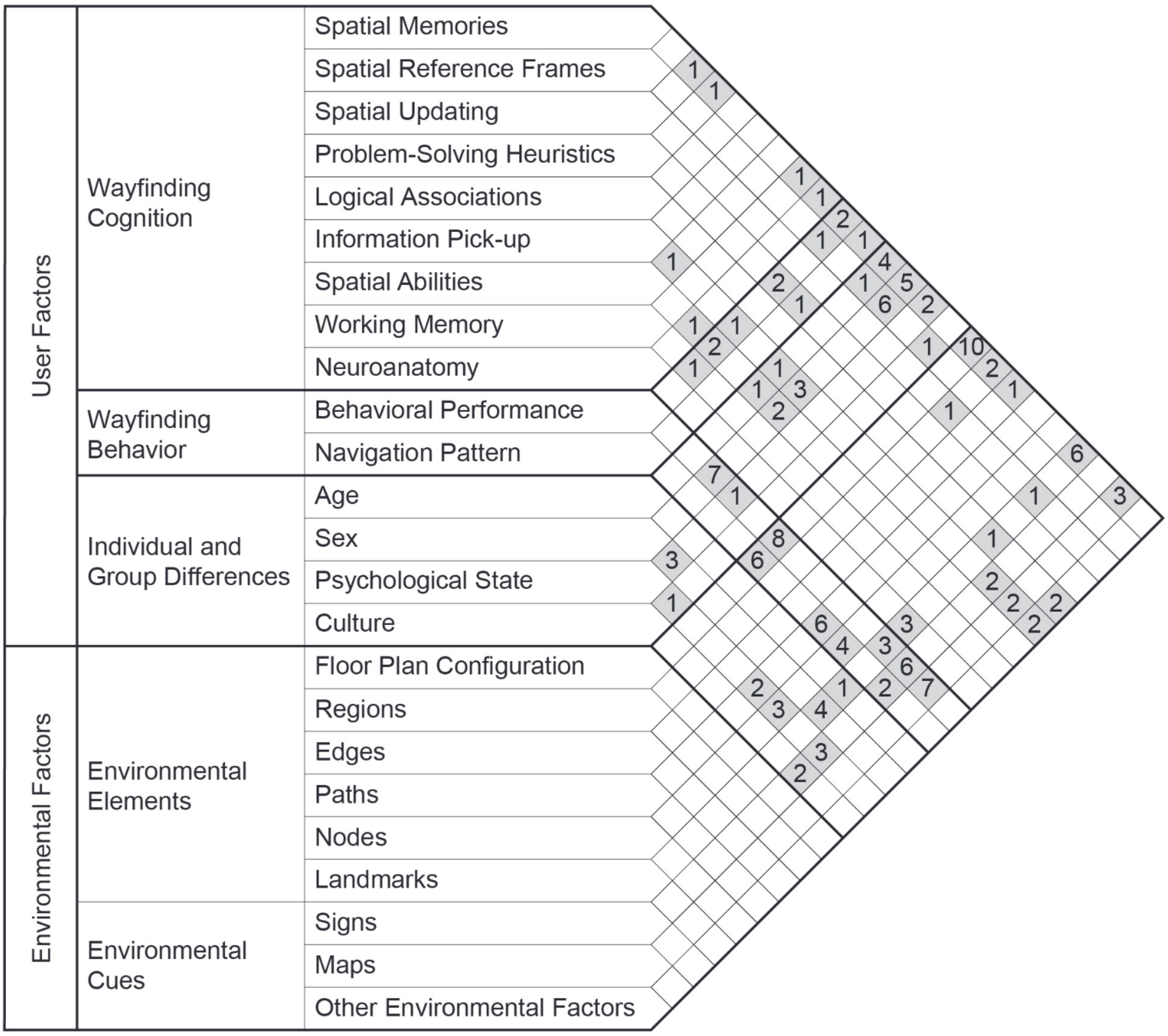


Figure 10. Indoor wayfinding variables matrix
Source: (Zomer et al., 2019)

On the other hand, as spatial familiarity increases, wayfinding performance could also improve (Baskaya et al., 2004; O'Neill, 1991). Therefore, the complexity of the floor plan would not necessarily affect the wayfinding anymore, unlike the first encounter with an unfamiliar environment, where wayfinding would significantly rely on the building layout (Baskaya et al., 2004). This situation indicated the connection of the study, mentioning that inexperienced users would prefer to rely on the building's central point as a wayfinding orientation aid due to the nature of the reliability of proper building layout, despite intricate accessibility (Hölscher et al., 2006). Meanwhile, an experienced user would use a straightforward direction to navigate to their targeted destination (Holscher et al., 2007).

Transitional Space

Apart from indoor and outdoor spaces, the concept of transitional space began to emerge, facilitating activities in areas identified as either indoor or outdoor. Kray et al (2013) explain transitional definition as “spaces that can be neither consistently classified as being indoors nor being outdoors and that share properties with either category”. This space is generally used as a space in utilized during movement between indoor and outdoor (A. Alattas, 2022). A study mentioned transitional space as a semi-bounded area that is located attached to a building but not necessarily enclosed (figure 11) (Zlatanova et al., 2020). The semi-bounded areas also classify transitional spaces as semi-indoor and semi-outdoor. Additionally, semi-bounded space is categorized differently, following the bounding style. I-space is an indoor space which is entirely bounded (figure 12) (Yan et al., 2019). Meanwhile, sI-space is a semi-indoor space bounded by the roof but liberated on the walls. Furthermore, there is sO-space, a semi-outdoor space, possessing almost no bound due to the remaining partial wall on the space. On the other hand, o-space (outdoor space) is an open area without any boundaries. For example, an area with a canopy in an Indonesian building is not necessarily indoor but is also not classified as outdoor due to the presence of a roof. Understanding transitional space is crucial, following the challenges of identifying unclassified spaces that are more common nowadays (Mainelli, 2022). Furthermore, confusion or loss of orientation is prone to happen during urban navigation, continuously passing through indoor and outdoor spaces (Kray et al., 2013). Unfortunately, wayfinding studies related to transitional space were not necessarily found, projecting the need for further exploration in transitional space.

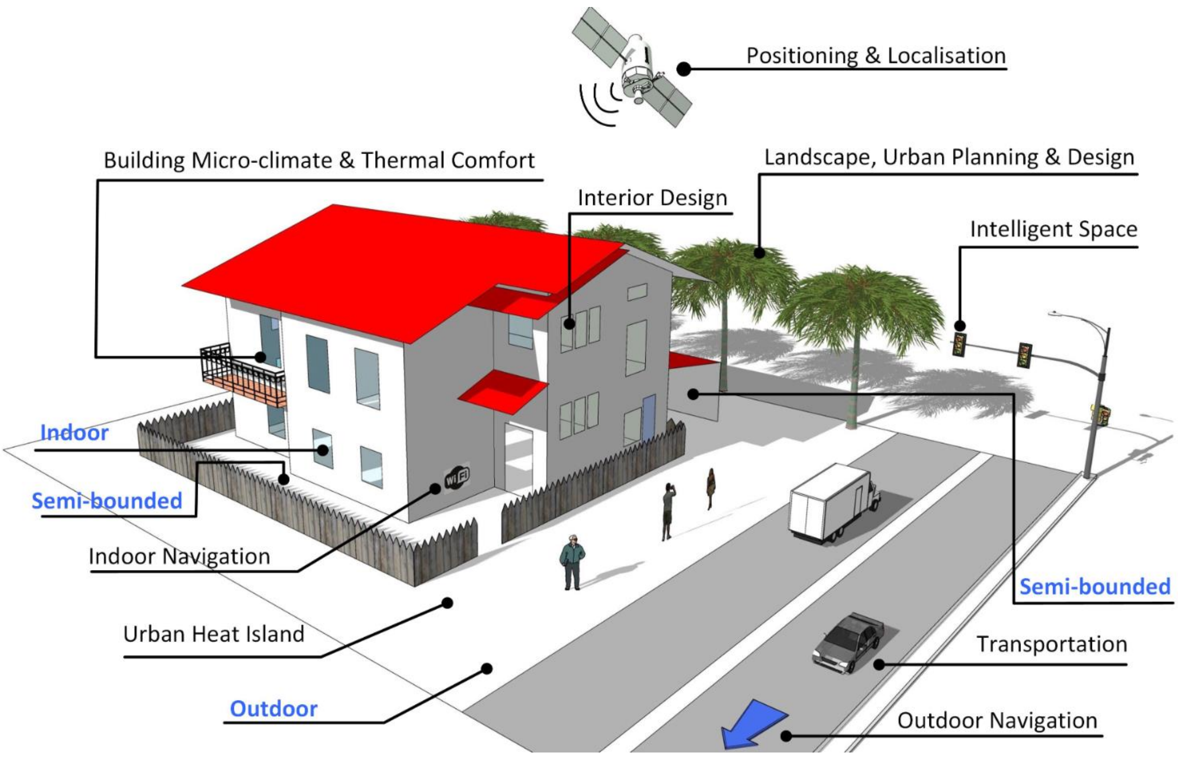


Figure 11. Transitional spaces in the building and its relation to the surrounding
Source: (Zlatanova et al., 2020)

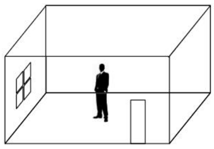
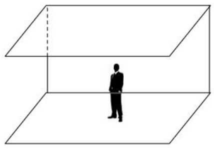
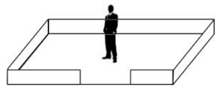
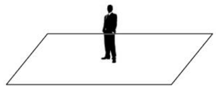
Environment	I-space	sI-space	sO-space	O-space
Definition	$C^T \geq \beta$ & $C^S \geq \delta$	$C^T \geq \eta$ & $C^S \in [0,1]$ *except* $C^T \geq \beta$ & $C^S \geq \delta$	$C^T < \eta$ & $C^S \in [0,1]$ *except* $C^T < \alpha$ & $C^S < \gamma$	$C^T < \alpha$ & $C^S < \gamma$
Example				
Scene				
Thresholds	$0 \leq \alpha \leq \eta \leq \beta \leq 1$ & $0 \leq \gamma \leq \delta \leq 1$			

Figure 12. Classification of transitional space concerning bounded area
Source: (Yan et al., 2019)

2.4. Stages of Wayfinding

The process of wayfinding utilizes the cognitive ability to go to the intended destination, which comprises three stages which are cognitive mapping, wayfinding plan development, and physical movement (J. L. Chen & Stanney, 1999a) (figure 13). Cognitive mapping is a process in which the environment's mental map is collected and structured in the brain. The collected cognitive map was followed up with a wayfinding plan in an action plan and structure. Finally, the wayfinding process is finalized with the execution of path navigation until arriving at the intended location. Similarly, Downs and Stea (2017) introduce four wayfinding stages: orientation, route selection, route control, and destination recognition. Orientation is the identification of oneself to the respected landmark and targeted destinations (Farr et al., 2012). Route selection is constructing a mental path to the desired destination. Route control is the action that involves self-confirmation when following the planned route. Recognition of destination is the ability to identify the environment in which the desired destination is located.

In performing these wayfinding stages, the information development through the cognitive process needs to be developed. The information development of wayfinding is generally a process of spatial exploration that gathers various knowledge, such as landmark knowledge, route knowledge, survey knowledge, and graph knowledge (Kim & Bock, 2021; Siegel & White, 1975). Landmark knowledge is knowledge acquired by memorizing the look of recognizable objects during the course. Often, the memorized recognizable objects were landmarks of the area, which helped with self-localisation. Route knowledge is knowledge in building a sequence of a path. Often, it is represented in understanding a path arrangement with or without identifying the landmarks (e.g. left then right at the first intersection) (Kuipers, 1978; Tlauka & Wilson, 1994). Meanwhile, survey knowledge is the general comprehension of spatial layout and its connection with various entities in the area (Münzer et al., 2006). In other words, it is a mental representative of the recorded spatial layout. On the other hand, graph knowledge is a type of knowledge in which the survey knowledge is first identified before the route knowledge (Hegarty et al., 2023; Kim & Bock, 2021).

Many studies explain that the knowledge acquisition process generally starts with landmark knowledge, followed by route knowledge, and then ends with survey knowledge (Hermer & Spelke, 1994; Jansen-Osmann & Wiedenbauer, 2004; Tonucci & Risotto. The notion was inferred from studies of spatial cognition, which indicated landmark knowledge as the first knowledge acquisition in children's early years for spatial awareness (Nys et al., 2015). However, a recent study indicated the breakdown of the knowledge, suggesting that the knowledge should be acquired in parallel or a more detailed type of stages. On the other hand, stages of wayfinding are also determined by the strategy implemented following the person's preferences. Several wayfinding strategies that have been discussed are survey strategy and place strategy.

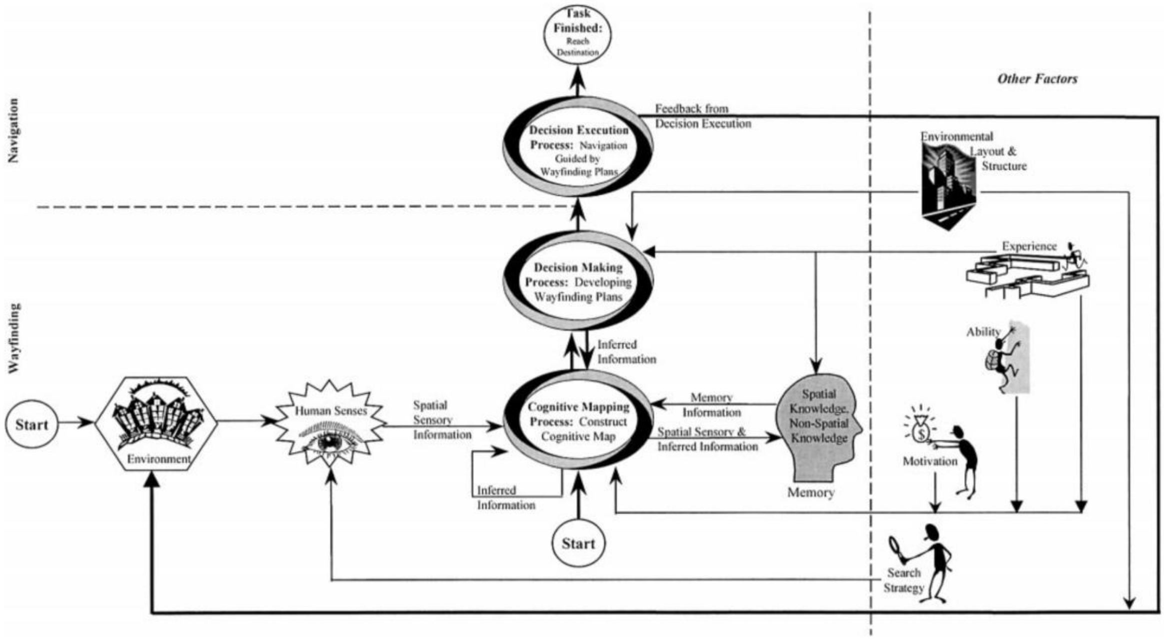


Figure 13. Wayfinding process involving sensory stimuli and memory acquisition
Source: (J. L. Chen & Stanney, 1999a)

2.5. User Access Rights in Navigation

Indoor or outdoor navigation should consider the accessibility provided by the spatial feature. User accesses are implemented following spatial regulation, limiting navigation accessibility depending on the spatial category. For instance, many hospital building areas are restricted from allowing patients to secure confidential data or health facility devices. In outdoor settings, access rights are implemented in the division of roads, limiting paths for cars, cyclists, and pedestrians. Access rights are accessibility information often embedded in various computational systems, just like in the Land Administration Domain Model (LADM). In a study by Alattas et al. (2017), he utilises access rights in providing building information systems regarding various access rights in the university. He classifies different access rights for students and employees (figure 14). It was described that students, employees, and visitors have different access rights to different rooms in the Faculty of Architecture and Built Environment building, TU Delft. The access rights are classified into student groups/cohorts, departments/ staff groups, lecture schedules, individual room assignments, meeting room reservations, and access hours. Alattas (2020) also mentioned that access rights should be considered in various scenarios, such as fire emergency evacuation. In this case, additional access for firefighters could also affect the dynamic of access rights in the building. These different access rights efficiently affect navigation routes and human behaviour in the building. Therefore, it is crucial to carefully identify appropriate building access rights in studying human wayfinding and navigation.

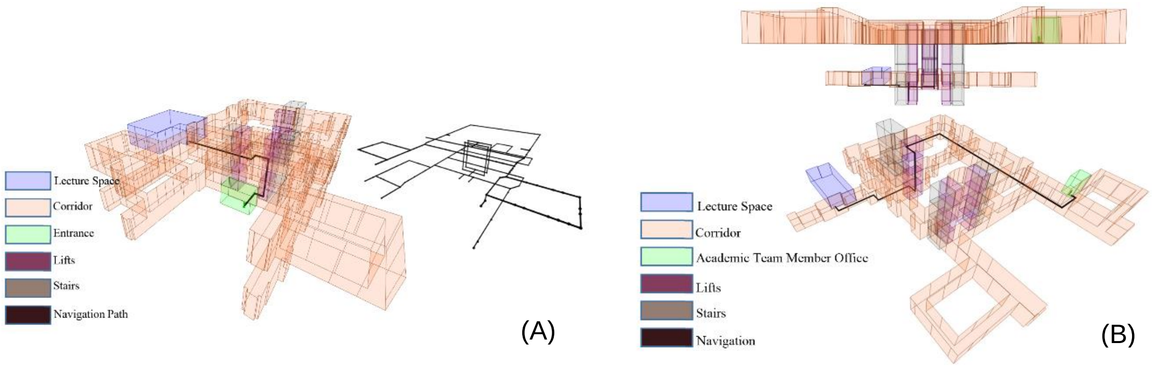


Figure 14. Primal space and navigation path for students (A) and academic members (B) Sub Research Questions Source: (A. Alattas et al., 2017)

2.6. VR Wayfinding Simulation

Wayfinding simulation utilizing virtual reality (VR) simulation has recently become more popular due to its ability to overcome challenges in conventional wayfinding study (Dong et al., 2022; Feng et al., 2022b). Many human subject researchers with sensitive study cases, such as emergency evacuation and fire simulation, often encounter ethical problems when commencing the study simulation. The emergence of VR wayfinding simulation allows researchers to manipulate and control the environment and simulation scenarios easily (Zhiming et al., 2020). There are many attempts to utilise VR to understand wayfinding behaviour in various scenarios such as evacuation, lighting modification, and health facility mobility (Bansal et al., 2022; Cao et al., 2019; Y. Chen et al., 2019; Feng et al., 2019; Kinateder et al., 2018).

The application of VR in wayfinding simulation allows researchers to retrieve detailed behavioural data in an advanced method, such as movement data, personal characteristics, head rotation, and gaze points (Meng & Zhang, 2014; Zhang et al., 2021). Nonetheless, despite the tremendous potential VR simulation can provide, VR must also undergo a validity process following several studies indicating disadvantages of VR simulation such as motion sickness, lack of the realistic representation of the real world, and under-representation of real-life detail (Meng & Zhang, 2014; Newman et al., 2022; Somrak et al., 2019). Furthermore, it was also indicated that the success of VR does not necessarily ensure the legitimacy of the resulting outcome (Schneider & Bengler, 2020). Several researchers have indicated effort in the validity verification of their research results (Feng et al., 2019; Kinateder et al., 2018; Kobes et al., 2010). Several aspects can be tested to verify the validity of the VR simulation: face, ecological, construct, and content validity (Deb et al., 2017).

VR Technologies in Wayfinding Simulation

Various VR technologies have been implemented in wayfinding simulations. There is desktop VR, which is done by undergoing simulation tasks through visualisation on a computer desktop (Feng et al., 2022b) (figure 15). Cave Automatic Virtual Environment (CAVE) is also a method to provide an immersive reality by projecting a digital environment on a confined wall covering all eye fields of view (FOV) (figure 15) (Combe et al., 2023). The most advanced VR technology utilizes a Head Mounted Device (HMD) (Feng et al., 2022b) (figure 15). HDM technology emerges in various forms; some use smartphones embedded in a head strap. The high-end HMD installs a complete device system containing RAM, storage, and an updated operating system to contain and run immersive information such as Oculus Rift and HTC Vive (Kelly et al., 2022). Several significances between the three visualization methods lie in computer rendering capabilities, visual resolution, latency, eye distance to the screen, FOV, screen curvature, and any user perception and immersion-related (Combe et al., 2023). Thus, the utilization of selected VR should consider the required wayfinding simulation and expected outcome.

Figure 15. Utilization of Desktop VR for wayfinding simulation (left), Cave system by BlueLemon (middle), HMD for wayfinding simulation (right)
Source: (Combe et al., 2023; Feng et al., 2022b)

The spatial data structure implemented in the wayfinding system must cater to the selected environment. Open Geospatial Consortium (OGC) standards such as IndoorGML and CityGML provide standardized spatial data models for indoor and outdoor environments. These standards provide the spatial data structure needed for the simulation system. IndoorGML is "an OGC® standard for representing and exchanging indoor navigation network models" (OGC, 2019). CityGML "is a geospatial information model and XML-based encoding for the representation, storage and exchange of the virtual 3D city and landscapes" (Kang & Li, 2017; OGC, 2023). IndoorGML provides hierarchical relationships of rooms, corridors, and other spatial elements supporting spatial analysis and connectivity-based routing. On the other hand, CityGML provides multiscale representation extended across urban environments. Both are significant in building structured environment elements embedded in VR simulation.

2.7. Design Guideline for Wayfinding

To help with wayfinding, buildings have implemented various wayfinding aids in the form of signages across building locations. All the implemented wayfinding aids follow design guidelines that environmental graphic design experts have discussed (Gibson, 2009). Various design guidelines have been published, highlighting the importance of an inclusive approach, design clarity, aid in self-orientation, and proper analysis of existing spaces (Apelt et al., 2007; Connell et al., 1997; Gibson, 2009).

Good wayfinding system must be able to give the user the ability to confirm their start and finish point, identify their location, ensure they proceed in the right path and direction, orient themselves, have a general comprehension of the spatial situation and possible risk within the path, recognize the targeted location, get away during the occurrence of emergency (Apelt et al., 2007). All these parameters would be achieved with appropriate user-centred planning and design processes.

Gibson (2009) mentioned several stages of wayfinding planning, including planning, site analysis, design, and implementation:

1. Planning: This stage involves unravelling and responding to the current space condition in an initial strategy and development program. The process began with research and analysis to explore existing wayfinding problems. The next is strategy, which aims to develop strategies to address the problem statement, producing a wayfinding strategy, design goals and outline of sign design. The last is programming, which aims to provide early design draft documents by developing important aspects such as arrival, departure, decision points, circulation pathways, and signing opportunities.
2. Design: This stage comprises design development, which will be executed at the implementation stage. The process comprises 3 phases: schematic design, design development, and construction documentation. Schematic design is the design development process that overviews key design types and design alternatives that cater to the selected wayfinding strategy. After finalizing the schematic design, the process is followed up with design development, which processes the design details. After that, construction documentation is created detailing a design-intent drawing of the agreed sign type.
3. Implementation: This stage aims to put the design plan into reality by planning the bidding process and being involved in the preconstruction discussions (Gibson, 2009).

A structured approach must be established in designing the wayfinding elements, integrating strategic, elemental, and graphic components to assist navigation (figure 16). The wayfinding system strategy possesses three key principles, which are the concept of districts, street connectors, and landmarks (Gibson, 2009). These strategies make spatial structures recognizable, which makes navigation more intuitive. These strategies are the foundation of the wayfinding system, which developed in accordance with the primary wayfinding elements: architectural, graphic, audible, and tactile components (Gibson, 2009). In association with the wayfinding elements, graphic communication plays a role in driving navigation through visual cues. This leads to the graphic elements, which are categorized into four main functions: identification, reinforcement, orientation, and destination (Apelt et al., 2007). These elements work together to provide users with clear and intuitive guidance, ensuring a practical and accessible wayfinding system.

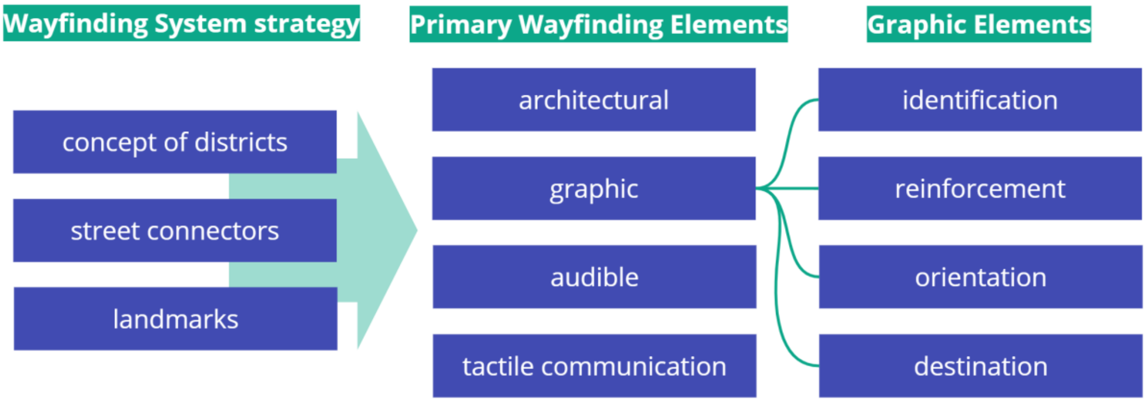


Figure 16. Wayfinding system strategies, elements, and graphic components

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3. METHODOLOGY

This study aims to investigate wayfinding in multiple environments, respecting access rights through exploring spatial cognitive processing in wayfinding. To achieve the research objectives, this study adopts the Design Science Research (DSR) methodology because it will not only identify factors contributing to spatial cognitive development in a multi-environment but also develop and validate a design solution that integrates these factors. DSR method allows this study to provide a comprehensive approach to develop artefacts such as wayfinding principles, VR simulation systems, and wayfinding design guidelines to address wayfinding challenges with respect to access rights. Furthermore, this method allows system development and evaluation implementation that could establish a theoretical foundation and practical solution, which is significant in wayfinding study.

DSR consists of 6 processes: (1) Problem identification and motivation, (2) Define the objectives for a solution, (3) Design and development, (4) Demonstration, (5) Evaluation, and (6) Communication (Peffers et al., 2007). Figure 17 provides an overview of the implementation of the DSR principle in this study. All six processes are applied in the overall research procedure, from developing a PhD research design as problem identification and motivation, simulation tools and system development as the design and development stage, simulation and data analysis as the demonstration stage, demonstration of optimized wayfinding as evaluation stage, and finally publication of research result as the communication stage.

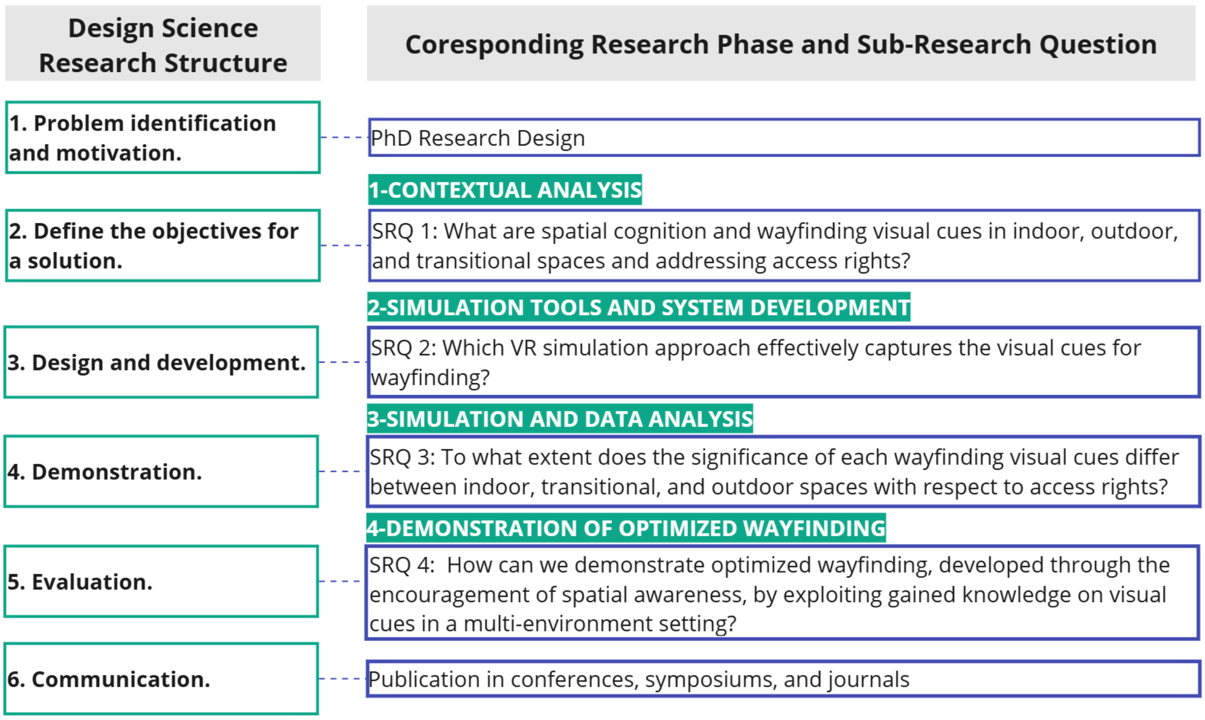

Figure 17. The connection between DSR structure with research phases and corresponding sub-research questions

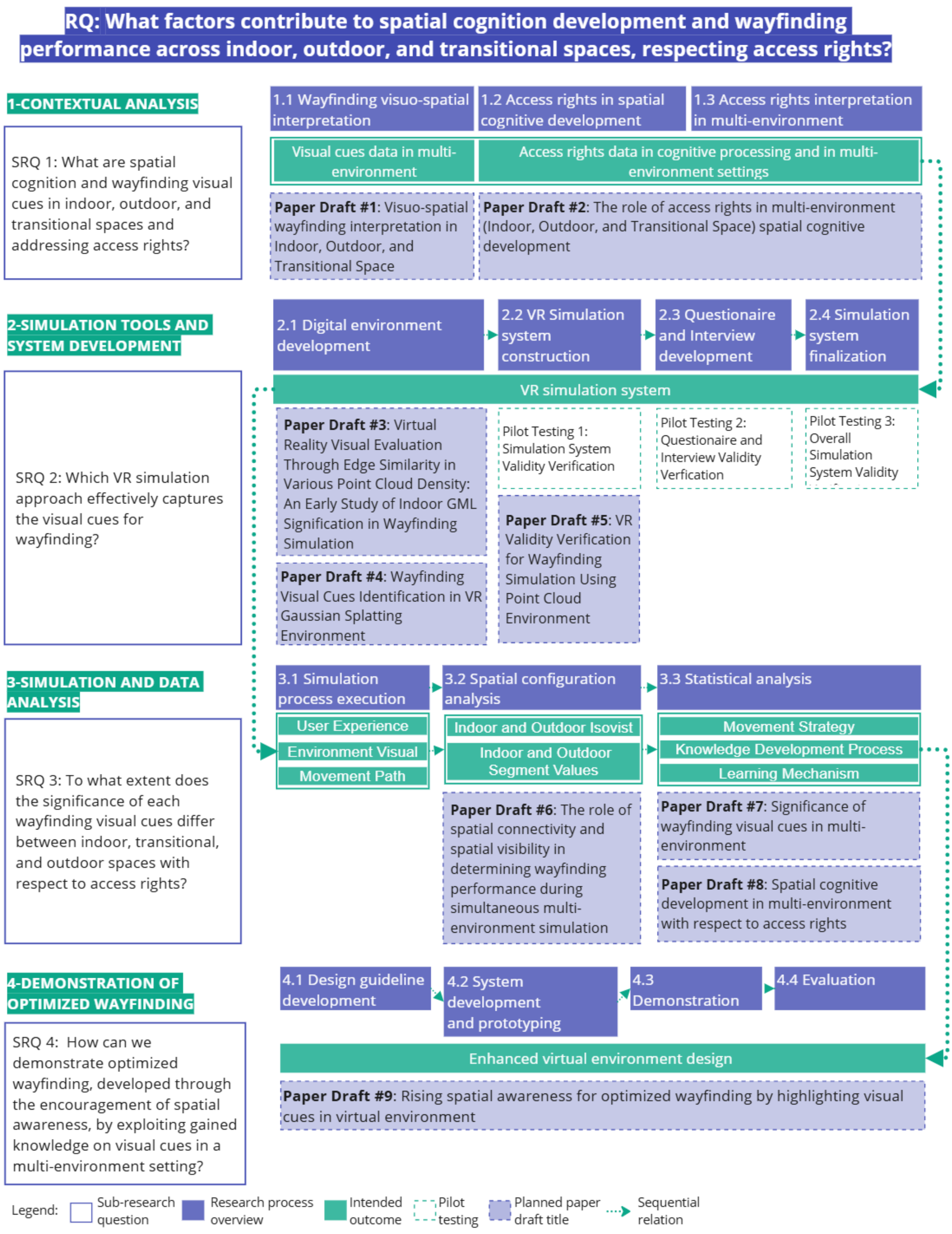

Figure 18. Research Question, Process, and Intended Outcomes for Spatial Cognition and Wayfinding Across Multi-Environment Settings

Beginning from the second DSR stage, the following stage is executed by answering four research questions, which produce various data supporting the subsequent research stage and research publications. Figure 18 depicts the relationship between the research question, process, and intended outcomes for spatial cognition and wayfinding across multi-environment settings. Four research stages are developed to answer four sub-research questions, beginning from (1) contextual analysis, (2) simulation tools and system development, (3) simulation and data analysis, and (4) demonstration of optimized wayfinding. Contextual stages will produce data that lay the theoretical foundation, becoming the ground for solution objectives, research methods, and simulation analysis. Following that stage, simulation tools and system development will provide tools that will be used in the following stage: simulation and data analysis. In the simulation and data analysis stage, the simulation will produce various data such as user experience, environment visuals, movement path, and spatial configuration, all of which will be analysed statistically. Subsequently, the simulation data will be used to develop a design guideline and demonstrate wayfinding optimization at the demonstration optimized wayfinding stage.

3.1. Problem Identification and Motivation

The first research phase is problem identification and motivation, which has been conducted along with the development of the research plan. Various sources have been explored to highlight the novelty of this research, discussing from the theoretical ground to the methodological approaches overviewing relevant topics such as cognitive mapping, spatial cognitive development, wayfinding in indoor, outdoor, and transitional spaces, spatial analyses approaches, 3D photorealistic environments, access rights, and virtual reality simulation technologies. Through this stage, various problems are identified, beginning with the intricate wayfinding situation in each environment, spatial cognition challenge due to access rights, navigation application dependency, and lack of 3D photorealistic environment in VR wayfinding simulations. All the mentioned problems indicate gaps in wayfinding studies, comprising the cognitive, environmental, application, and methodological aspects, which become the foundation of this study's motivation and objectives.

3.2. Define the Objectives for a Solution (Contextual Analysis)

After identifying research problems that revolve around wayfinding in a multi-environment that respects access rights, the objectives for a solution to this research will be developed. The study objectives in this research were built during the development of the research plan, which mentioned (1) the interpretation of wayfinding visual cues in indoor, outdoor, and transitional spaces and the role of access rights in spatial cognition, (2) developing VR simulation methods that effectively capture the visual cues of wayfinding, (3) exploring the significance of wayfinding visual cues of indoor, transitional, and outdoor spaces with respect to access rights, and (4) developing a virtual reality environment that demonstrates optimized wayfinding by enhancing spatial awareness through improved visual cues. Nonetheless, they will be further defined through contextual analysis, providing a detailed foundation for building the solution to the research problems.

In this stage, this study will interpret aspects of spatial cognition, wayfinding visual cues in multi-environment, and access rights specific to the case studies by answering SRQ 1, **“What are spatial cognition and wayfinding visual cues in indoor, outdoor, and transitional spaces**

and addressing access rights?" (figure 18). From this SRQ, 3 theoretical contexts were expected to unravel: (1) wayfinding visuospatial interpretation, (2) access rights in spatial cognitive development, and (3) access rights interpretation in multi-environment. Discussion on wayfinding visuospatial interpretation will explore indoor, outdoor, and transitional space environments, providing initial information on visual cues that need to be observed during the simulation. Several aspects will be explored, including identifying global and local landmarks in indoor spaces. Global landmarks are seen from many angles and distances, while local landmarks are only visible from close-ups (Steck & Mallot, 2000). This stage will also produce a paper draft explaining the result of visuospatial interpretation across the environment. The second theoretical context will explore access rights in spatial cognitive development which will discuss the role of access rights in spatial cognitive development. This information is significant for determining the simulation task that would test the difference of learning mechanisms in wayfinding performance. The third theoretical context that will be explored is the interpretation of access rights in a multi-environment. This stage will produce a paper draft describing the investigation result, exploring spatial situations that represent the context of access rights and their spatial cognitive development. Visual cues and access rights data will be produced from the contextual analysis stage in cognitive processing and multi-environment settings. This will be the foundation for simulation tool development and data analysis.

3.3. Design and Development (Simulation Tools and System Development)

The second stage of this research is design and development, which involves developing simulation tools and systems. This stage is established to answer the second sub-research question, **"How to build a VR simulation method that effectively captures visual cues of wayfinding?"**. This SRQ aimed to build a VR simulation environment and system that effectively accommodates wayfinding simulation.

To effectively address the sub-research question, this research design is developed following the spatial cognitive processing of wayfinding, consisting of three stages: cognitive mapping, wayfinding development, and physical movement (figure 19). The cognitive mapping process involves storing spatial layout maps through spatial exploration. A cognitive map is developed through several learning mechanisms. In this study, error-driven and self-organizing learning mechanisms will be adopted as wayfinding tasks, and the movement result will be observed to investigate the wayfinding performance quality. The error-driven mechanism will represent the user access challenge, while self-organizing will represent the normal situation.

Furthermore, the knowledge collected during wayfinding will be identified to provide information on relevant variables used in spatial cognition development. Three pieces of knowledge collected in cognitive mapping are landmark knowledge, route knowledge, and survey knowledge. The knowledge would be retrieved from exploring space in indoor, outdoor, and transitional spaces, capturing each environment's spatial wayfinding feature. The second wayfinding stage is wayfinding plan development. In this stage, people will create a movement strategy using the route and survey knowledge, which is developed from landmark knowledge. Two movement strategies used in wayfinding are the central point and direction strategy. These strategies are used in physical movement, which is the last wayfinding stage. Physical movement is when the person walks through the planned route to reach the target.

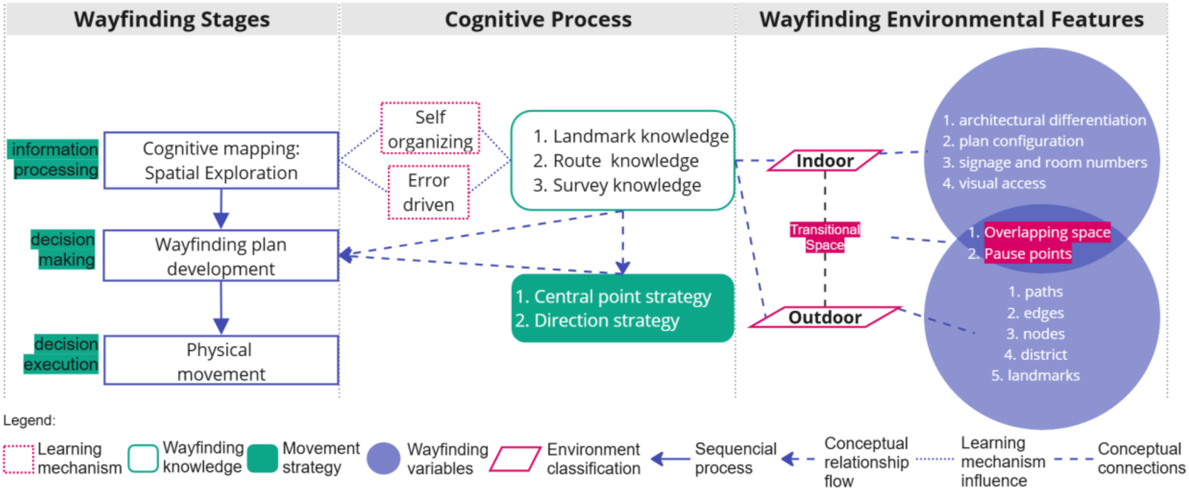

Figure 19. Spatial cognitive process analysis structure

Concerning the spatial cognitive process mentioned before, this study will observe three cognitive-related analysis processes to analyse the spatial cognitive process of wayfinding. The three cognitive-related analysis processes include knowledge development identification, learning mechanism analysis, and movement strategy identification. The analysis will commence using data from three groups: simulation, user experience, and spatial configuration (figure 20). Simulation data will be collected from the VR simulation process, collecting spatial classification, eye tracking, path tracing, and pause/breakpoints. User experience data will be collected through a thinking-aloud process, interview, and questionnaire. Meanwhile, spatial configuration data will be collected through spatial mapping and space syntax analysis, producing isovist, spatial integration, and spatial choice data.

To support cognitive-oriented analysis, the VR simulation system employing digital environments must be developed to ensure effective capture of wayfinding behaviour and visual cues, a crucial element in the wayfinding study. The first process of building the VR simulation system is digital environment development, which is aimed at exploring and developing an effective VR environment for wayfinding simulation. To accurately represent wayfinding visual cues, the VR simulation will use a 3D photorealistic environment that could capture the geometric and spatial visual features indoors or outdoors. With that in mind, this section aimed to utilize point cloud as the VR environment, which opted for two different kinds of point: LiDAR point cloud and Gaussian splatting (figure 21). Both point environment types will undergo a visual quality assessment to determine which point type effectively represents the actual environment for VR simulation.

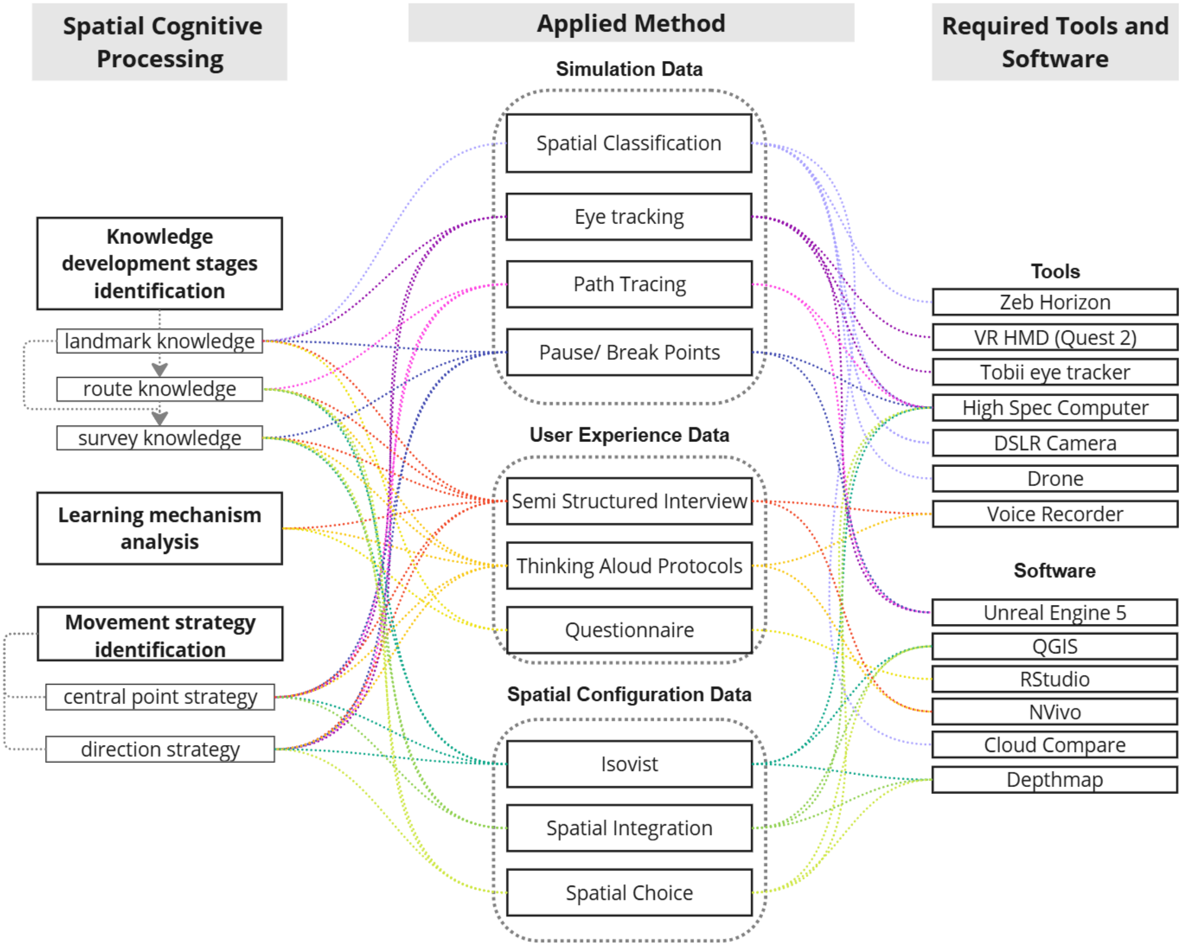

Figure 20. Analysed spatial cognitive process with the data required for the analysis

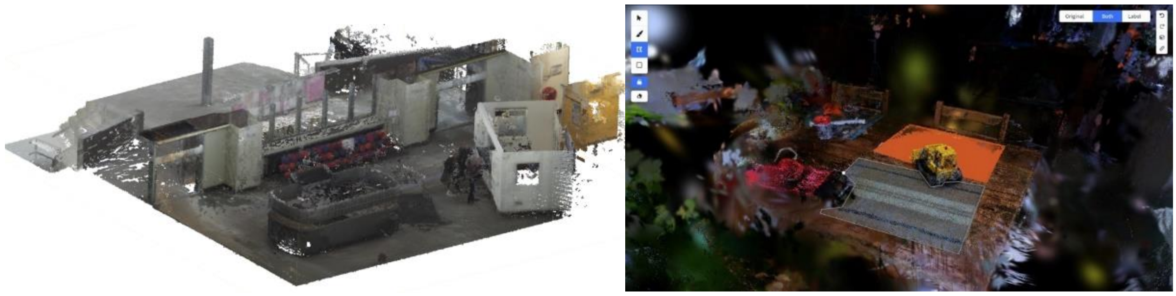

Figure 21. LiDAR point cloud scan (left) and Gaussian Splatting scan (right)
Source: segments.ai

Once the point type is decided, the environment data acquirement is commenced by scanning it using a LiDAR scanner or photogrammetry. Several tools are required for this process in Zeb Horizon, drone, and camera DSLR, as shown in figure 22, contains a diagram of the analysed spatial cognitive process with the data required for the analysis. After that, the process will continue with environment pre-processing. In this step, the collected environment scan will be processed using Faro connect software or open-source Gaussian Splatting processing method by the Graph Deco team (Kerbl et al., 2023), turning the data into point cloud data (las/ laz/ ply/ spz). Once the point data is ready, the point data must undergo noise reduction, cleaning unnecessary points using cloud compare software. The process will continue with point fragment integration if the environment data is scanned in multiple sessions. Once the point environment is ready, the process continues with visual cues identification/segmentation for the VR simulation system.

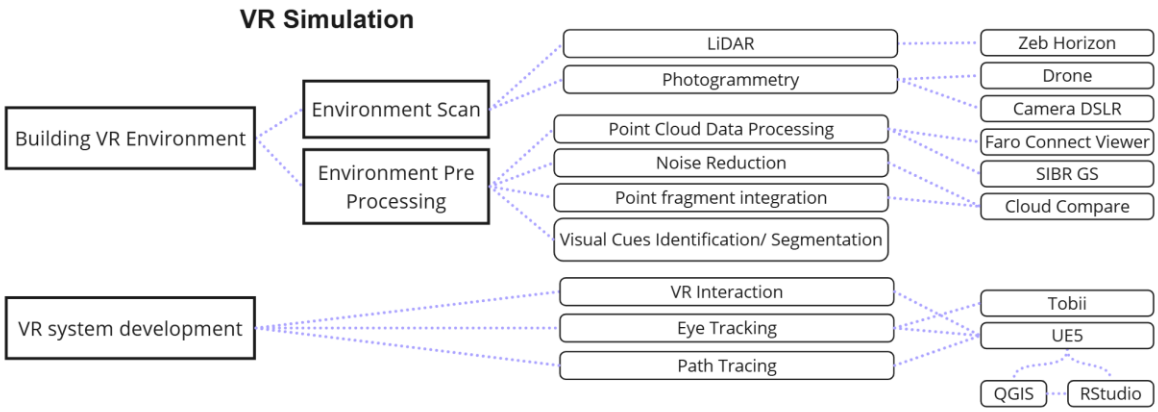

Figure 22. Data and tools required for the analysis during VR simulation system development

After the environment data is ready, the next step is to develop the VR system using VR simulation software (Unreal Engine 5). In this stage, the point cloud data is inserted in the software and continued by developing the VR interaction; therefore, the respondent can walk around in the built environment. The spatial system will adopt access rights using the Land Administration Domain Model (LADM), which would define the relationship between the user and the environment spaces (indoor and outdoor) based on the rights and restrictions of the spaces to indicate the accessible spaces. This system ensures that the space classification considers access rights to indicate accessible spaces. LADM will be combined with IndoorGML to provide the indoor classification model, which will be extended to outdoor spaces with CityGML for seamless wayfinding.

The next stage is developing/embedding the eye tracking device and software with the head-mounted device (Quest 2) so that it will be able to record the eye movement of the participant, capturing the studied visual cues (figure 23). Finally, the path tracing would also be set up in the VR simulation software (UE5) to capture the path movement of the participant (Boyd & Barbosa, 2017) (figure 24). After the VR system is set up, the simulation process must be tested in pilot testing. In the pilot simulation, several aspects are tested, such as face, ecological, construct, and content validity (Deb et al., 2017). Furthermore, this process will evaluate the orientation ability in identifying cardinal direction, comparing behaviour in real life with virtual reality. The pilot testing result shows the validity verification result written as paper draft 5.

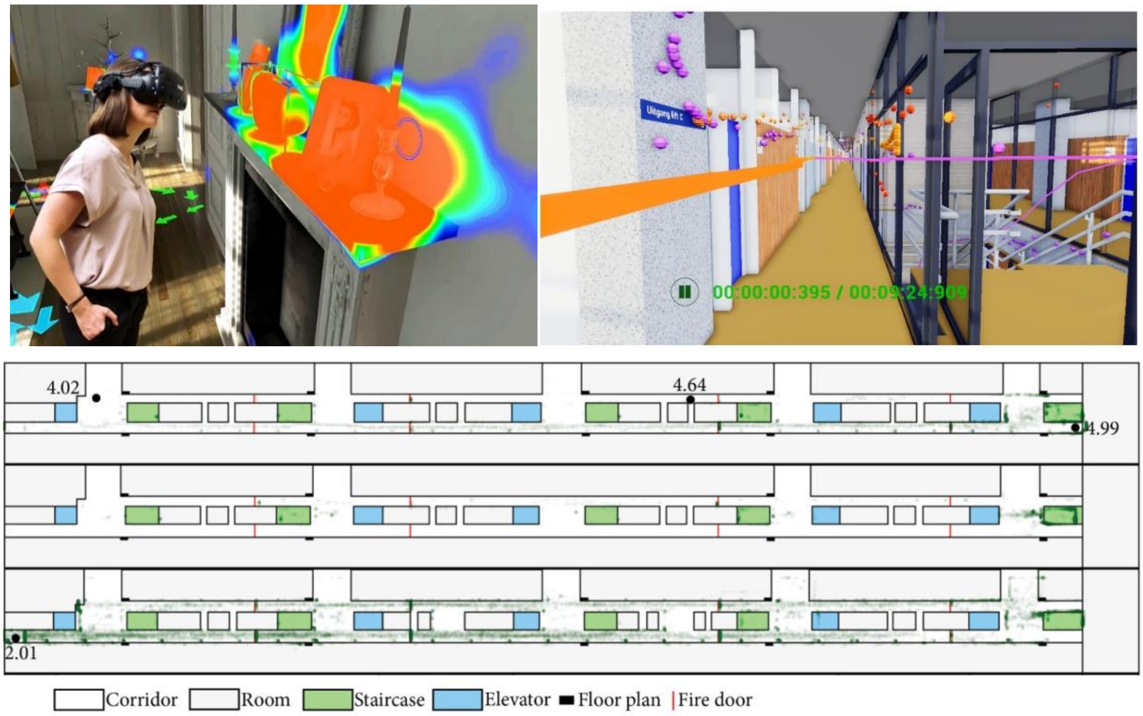

Figure 23. Example of eye-tracking data outcome: eye-tracking heatmap data (left), gaze points in the virtual building (right), spatial distribution of gaze points (bottom)
Source: (Feng et al., 2022a) and Tobii

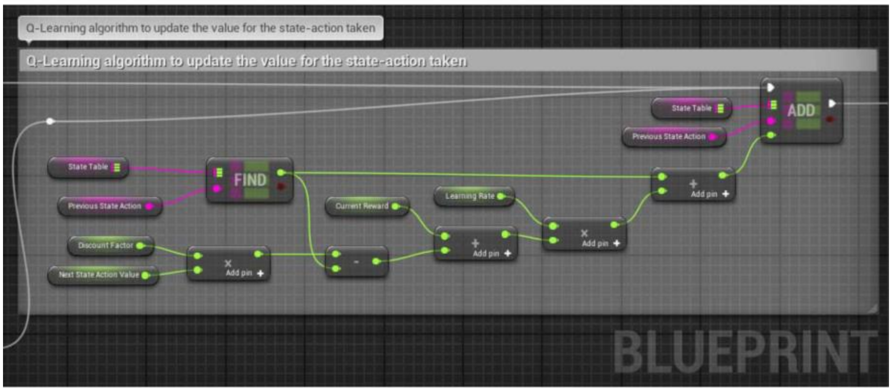

Figure 24. Example of Unreal Engine blueprint setup
Source: (Boyd & Barbosa, 2017)

After the environment system is well developed, the following process is preparing the questionnaire and interview system to collect the user experience data. Some documents that need to be prepared are the interview protocol, questionnaire questions, and Thinking Aloud Protocols. The user experience evaluation system must be tested to verify its validation for VR wayfinding simulation to ensure no misinterpretation and produce the expected outcome. Finally, the process ends with the simulation system finalization, running all the VR simulation systems, including the user experience test. The finalization includes pilot testing to evaluate the overall system and produce the expected result for the study. Further details about the experiment design criteria can be found in Appendix E.

3.4. Demonstration (Simulation and Data Analysis)

Simulation and data analysis commences at the demonstration stage, focusing on retrieving simulation data. There are three sub-stages: (1) simulation execution, (2) spatial configuration analysis, and (3) statistical analysis (figure 25). In simulation process execution, there are two data retrieval processes: VR simulation and user experience. In the VR simulation process, all data simulation data will be collected, such as the identification of visual cues through eye fixation, breakpoints, and movement behaviour with and without access rights. Using the link cable, The simulation will commence using a Quest 2 Head Mounted Device (HMD) connected to a high-performing computer. The simulation will run in Unreal Engine 5, which can visualise the point cloud environment in VR and record the simulation data.

Various user experiences will be recorded during the simulation using several methods: thinking aloud protocol (TAPs), semi-structured interviews and questionnaires. TAPs are a qualitative data collection method involving vocalising the research participant's thoughts, reasoning, and decision-making during task performance (Vaez et al., 2021). TAPs aim to capture the real-time thinking process without relying on memory (Ericsson & Simon, 1980). While semi-structured interviews aimed to overview the thinking process during the simulation. TAPs will commence during the simulation, during which the participants will be asked to express their thinking process aloud. The expected thinking process includes the searched visual cues, path planning, route decision, and task completion. After the simulation, semi-structured interviews will investigate the thinking process in crucial decision-making related to specific observed points. Finally, the participants will also asked to fill in the questionnaire to identify their prior spatial knowledge.

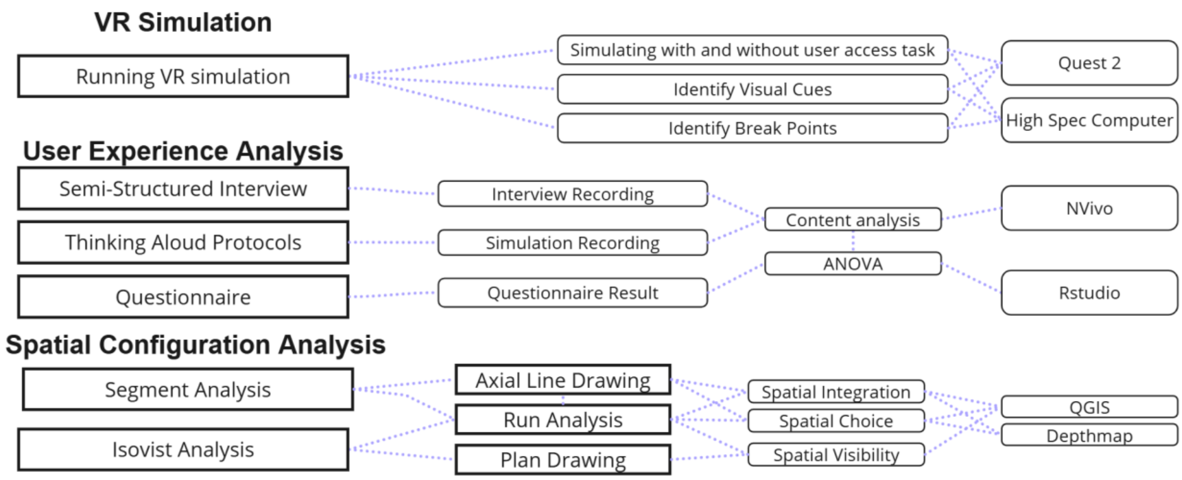

Figure 25. Data and tools required for the analysis during VR simulation, user experience analysis, and spatial configuration analysis

In simulation and data analysis, the spatial configuration will also analysed to identify the spatial character using segment analysis and isovist. Isovist will provide visual connectivity across spaces, indicating potential path directories for the participant and spatial efficiency.

Combined with the importance of visual cues in spatial cognition study, the 3D isovist method will be adopted to identify the correlation between route decisions with the combination of visual connectivity and visual cues (figure 26). Meanwhile, segment analysis will be used to analyse the spatial characteristics concerning overall spatial layout, measuring angular choice and integration. Segment analysis can be measured by applying several metrics, such as angular integration and angular choice, as seen in Figure 27. The angular choice is a spatial measurement of betweenness centrality to identify key navigation routes (Van Nes & Yamu, 2021). Meanwhile, angular integration is a spatial measurement of closeness centrality to identify space accessibility concerning other spaces, influencing pedestrian movement and attraction. Segment analysis data is gathered through axial line drawing, which proceeds to be segmented according to spatial nodes and cross-sections. The identification uses a space syntax toolkit plugin, which can be installed in the QGIS.

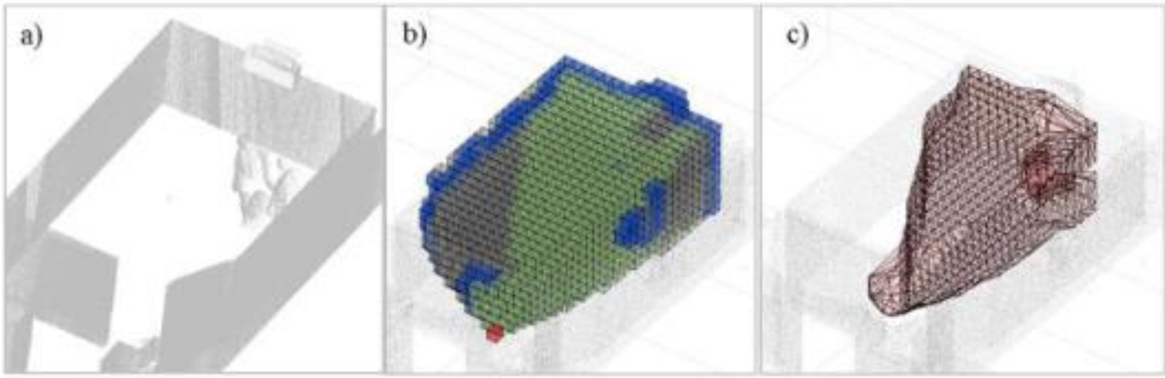

Figure 26. 3D Isovist to measure visual connectivity within VoF periphery
Source: Díaz-Vilariño et al., 2018

All the collected data will undergo statistical analysis to interpret findings following the research problems. Two types of statistical analyses will be commenced: qualitative and quantitative analysis, which will be commenced with various statistical analysis methods, which are regression, multivariate analysis (MANOVA), analysis of variance (ANOVA), and content analysis. Quantitative analysis will analyse spatial configuration and VR simulation data using regression analysis and MANOVA. Regression analysis will explain how wayfinding visual cues impact navigating performance by measuring the correlation between wayfinding duration, spatial integration, spatial choice, and path data. ANOVA will compare mean differences in wayfinding performance across different conditions. At the same time, MANOVA will assess the impact of multiple wayfinding variables on cognitive and navigational outcomes across different sample groups and study cases. Meanwhile, qualitative analysis will employ content analysis and ANOVA in processing data collected from the interview, think-aloud, and questionnaire. Data from interviews and think-aloud will be transcribed and examined with content analysis to capture the verbalized wayfinding cues. The questionnaire data will be analysed using ANOVA to compare the mean difference in wayfinding across sample groups.

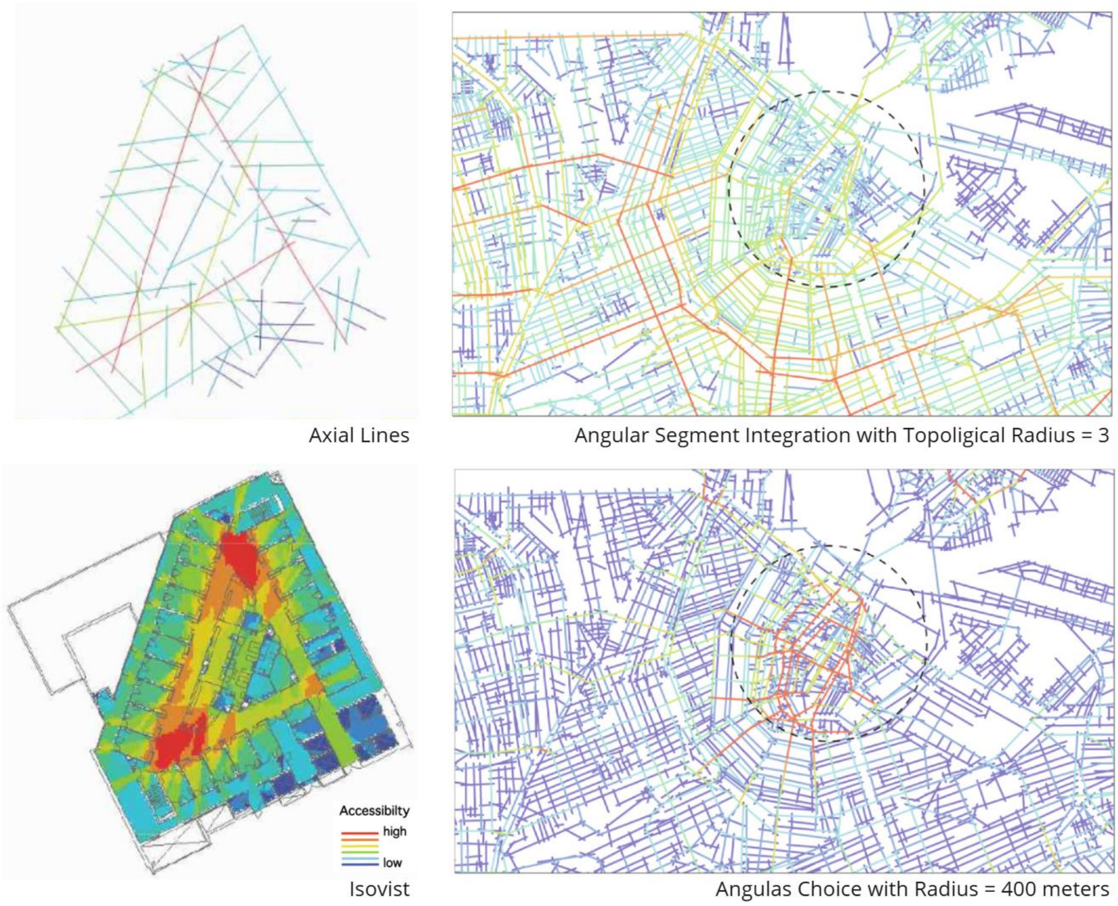

Figure 27. Illustration of indoor isovist, axial lines, angular segment integration analysis, and angular choice analysis
Source: (Cai & Zimring, 2013; Van Nes & Yamu, 2021).

3.5. Evaluation (Demonstration of Optimized Wayfinding)

The final stage is a demonstration of optimized wayfinding, which aims to answer the last SRQ, "How can we demonstrate optimized wayfinding, developed through the encouragement of spatial awareness, by exploiting gained knowledge on visual cues in a multi-environment setting?". This SRQ aimed to demonstrate optimized wayfinding through an enhanced VR environment that elevates spatial awareness by exploiting gained knowledge on visual cues in a multi-environment setting.

The gained knowledge will provide significant information related to important visual cues for efficient wayfinding specifically in the case study. The visual cues will be utilized in building a design guideline which suggests the importance of transitional space as a cognitive processing area of wayfinding. In accordance with the design guideline, an enhanced virtual environment will be developed to demonstrate a well-structured environment that could raise spatial awareness. The virtual environment will be simulated, and respondents will be involved in evaluating the impact of spatial awareness on wayfinding performance. Furthermore, the wayfinding performance result will be analysed with the previous simulation to produce comparative data that could emphasize the impact of spatial awareness on wayfinding performance.

This stage possesses 4 different sub-stages, beginning with concept development, system development and prototyping, demonstration, and evaluation. Concept definition would be the stage where design guidelines are being developed. System development and prototyping would be the stage where the virtual environment is developed following the design guidelines. Finally, the demonstration and evaluation stage would commence the simulation, analyse the result, and compare it with the earlier result.

This stage is expected to contribute to the study of wayfinding in multi-environment settings by publishing a paper titled 'Rising Spatial Awareness for Optimized Wayfinding by Highlighting Visual Cues in the Virtual Environment.' Additionally, the information collected from this stage will be used to optimize the IndoorGML study by incorporating additional space classification for transitional spaces.

3.6. Communication

In this stage, all the data and processes addressing its novelty will be communicated in various academic platforms, including conferences, workshops, and journals. Some of the targeted audience covered study experts of GIS, spatial cognition, wayfinding, 3D geoinformation, extended reality, 3D modelling, IndoorGML, and access rights. This study aims to publish nine drafts of papers covering various topics gathered through multiple research stages. Some papers will be developed in relation to the prior publications, which will evolve through multiple refinements. Figure 28 illustrates the evolving publication relation, where initial studies presented at conferences and symposiums will be further refined for journal publication. This progression allows for deeper analysis and validation from engagement with the academic society.

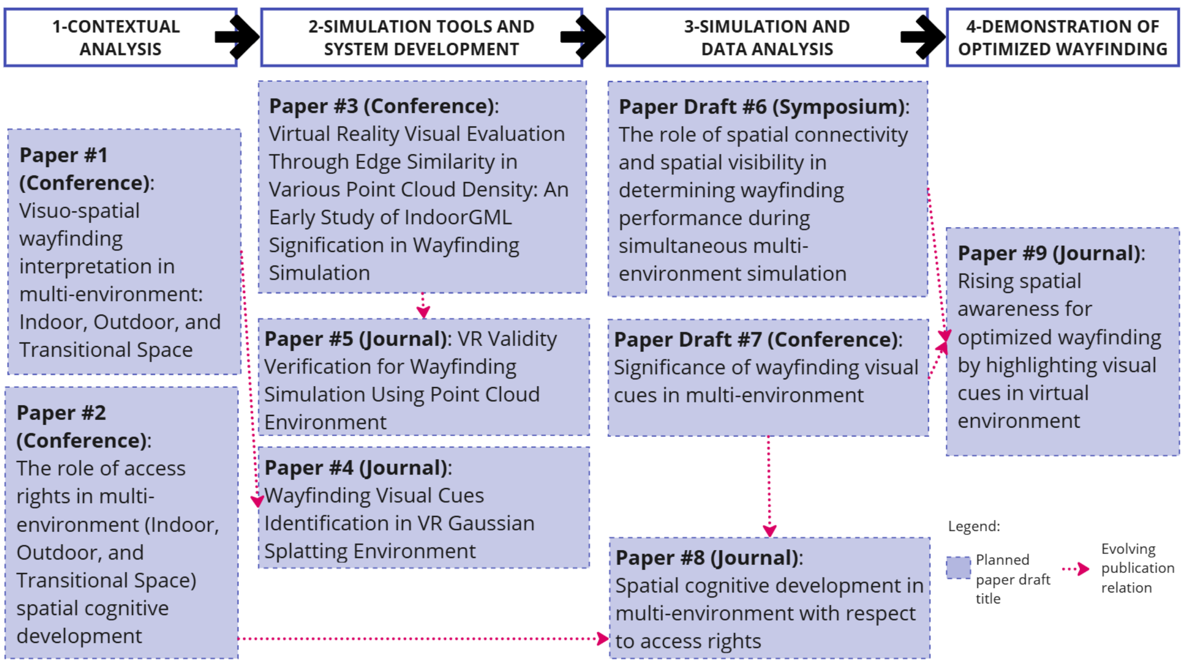

Figure 28. Sequential Development of Research publications

3.7. Tools and Software

Table 1. Tools and software list required for the research

Method and Stages	Sub Stages	Data	Tools and Software
VR Simulation			
		LiDAR point cloud SLAM	Zeb Horizon
		Gaussian Splatting video recording	Camera DSLR
	Environment Scan		Drone
		SLAM Point Cloud	FARO Connect Viewer
		Gaussian Splatting Point Cloud	SIBR Gaussian Splat
		Integrated Point Fragment	Cloud Compare
Building VR Environment	Environment Pre Processing	Visual Cues Identity/ Segment	
		Eye Track	Tobii
		VR interaction	
VR system development		Path trace	Unreal Engine 5
		Simulation task with and without user access	
		Visual Cues/ Eye gaze/ fixation	
Running VR simulation		Break Points	Quest 2 and High performing computer
Spatial Configuration			
	Axial Line Drawing	Axial Line	
Segment Analysis	Run Analysis	Spatial Integration and Choice	
Isovist Analysis	Building Plan Drawing	Spatial Visibility	QGIS and Depthmap
User Experience Analysis			
Semi-structured Interview		Interview Recording	
Thinking Aloud Protocol		Simulation recording	NVivo
Questionnaire		Questionnaire result	RStudio

3.8. Case Studies

In wayfinding performance, several externalized aspects of knowledge, such as cultural and spatial-social, may play a part in building the knowledge structure (figure 9). Each country has its own intricate spatial and building typology, which developed under the origin people's culture, allowing a typical movement behaviour among similar residences. Meanwhile, to test the wayfinding performance, participants must not have prior information about the environment. Therefore, this study will involve participants from Indonesia and The Netherlands, in which both groups will be given spatial information as opposed to their original country. This method will efficiently test the process of cognitive mapping. The cross-country participant method would also diminish the cultural variable affecting the wayfinding performance. Therefore, cross-environment would require the participants to reset their initial spatial knowledge and introduce a new cognitive map into their spatial cognition.

To make sure that the wayfinding variable is well captured and identified appropriately, the case study must be chosen appropriately using several criteria:

1. Similar building context

In order to capture wayfinding visual cues, the study must involve building with well-structured signage and information features across space and allowing the possibility of visual cues capturing and spatial information processing gathered from the wayfinding simulation. Furthermore, possessing a similar building layout typology is an ideal approach, allowing the visual cues to be captured efficiently. The building must have similar functions and spatial interpretations from signages, building districts, and access rights.

2. Similar spatial context

In continuous wayfinding, the case study must pertain to similar spatial typology connecting indoor and outdoor spaces. This would allow the visual cues to be captured efficiently without additional variables involving unnecessary spatial complexity.

Two university buildings in Indonesia and the Netherlands were chosen in response to those criteria, as shown in Figure 29. The Netherlands study case would be using the building of the Faculty of Architecture and Build Environment, Delft University of Technology. The Indonesian study case would use the Faculty of Architecture and Design building, Universitas Pembangunan Nasional "Veteran" Jawa Timur. Both university buildings possess similar building functions and access rights, resulting in similar signage structures for students and staff to navigate indoors. Furthermore, the outdoor navigation will utilize the outdoor navigation covering from the building's front door extending to the surrounding area within a 3 km radius. The radius limits the movement space, keeping the simulation process under 20 minutes.

THE NETHERLANDS

INDONESIA

Figure 29. Research location, TU Delft A+BE Building (top left), Delft City (top middle), TU Delft A+BE Building top view (top right), UPNVJT FAD Building (bottom left), Surabaya City (bottom middle), UPNVJT FAD Building top view (bottom right)
Source: TU Delft (2025), UPNVJT (2025), Google Maps (2025)

3.9. Research Timeline

Table 2. Preliminary PhD Research Timeline

OBJECTIVES	2024											2025												2026												2027												2028
	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12	1
BACKGROUND STUDY																																																
PROPOSAL WRITING																																																
GO/ NO GO MEETING																																																
RESEARCH ETHIC APPLICATION																																																
- Building research ethics application form (research design, DMP, and informed consent form)																																																
- Application and revision process																																																
1-CONTEXTUAL ANALYSIS																																																
1.1 Wayfinding visuospatial interpretation																																																
- Writing research paper 1																																																
1.2 Access rights in spatial cognitive development																																																
1.3 Access rights interpretation in multi-environment																																																
- Writing research paper 2																																																
2-SIMULATION TOOLS AND SYSTEM DEVELOPMENT																																																
2.1 Digital Environment Development																																																
- Testing various digital environment scanning systems and visual quality																																																
- Writing research paper 3																																																
- Writing research paper 4																																																

- Environment scanning using LiDAR / Photogrammetry (Indonesia and The Netherlands)
- Environment preprocessing (noise reduction, gaussian splat conversion, visual optimisation, point segmentation)
2.2 VR simulation system construction
- Environment visualisation into VR software
- In software VR simulation development (user interaction, path tracking system, and movement identification system)
- Eye-tracking development
- PILOT TESTING 1 (testing the VR simulation feasibility)
- System redevelopment post-pilot testing 1
- Writing research paper 5
2.3 Questionnaire and Interview Development
- Developing questionnaire, interview questions, and interview protocol
- PILOT TESTING 2 (identifying issues in the questionnaire and interview)
- Questionnaire and interview protocol redevelopment post-pilot testing 2
2.4 Simulation system finalization
- PILOT TESTING 3 (identifying issues in the overall simulation system, including questionnaire and interview process)

- Overall simulation system redevelopment post-pilot testing 3
3-SIMULATION AND DATA ANALYSIS
3.1 Simulation process execution
- Simulation in Indonesia
- Simulation in The Netherlands
3.2 Spatial Configuration Analysis
- Axial maps drawing of case study buildings
- Segment analysis
- 3D isovist point cloud analysis
- Writing research paper 6
3.3 Statistical analysis
- Comprehensive Data Analysis and Interpretation
- Writing research paper 7 & 8
4-DEMONSTRATION OF OPTIMIZED WAYFINDING
- Concept development
- System development and prototyping
- Demonstration
- Evaluation
- Writing research paper 9
5-DISSERTATION WRITING
FINAL DEFENCE

3.10. Research Significance

Theoretical contribution

This study will contribute to various theoretical significance, beginning from the redefinition of transitional space, access rights in spatial cognitive development, and identification of access rights in multiple environments. The redefinition of transitional space emphasize the role of transitional space in spatial cognition. The current study of transitional space mainly explored space classification, whereas transitional space also plays a role in spatial cognitive development. This study will try to redefine transitional in spatial cognition perspective, which pays great attention to breakpoints as spaces where spatial cognition is being developed. The exploration of transitional space will also be integrated into the IndoorGML framework by introducing additional space classifications that reflect its role in spatial cognition and wayfinding. Furthermore, this study will explore the role of access rights in spatial cognitive development and show how access rights are utilized following the cognitive learning process. This information will contribute to the LADM framework by refining space classification considering movement behaviour due to access rights. At the same time, results from VR simulation will show the degree of visual cues of wayfinding in each of the environments, which is crucial information for the development of wayfinding studies.

Methodological contribution

To be able to execute and capture accurate spatial cognitive representation in wayfinding, this study will develop several methodological contributions beginning from the utilization of a 3D photorealistic VR environment, point cloud data sets, axial lines of Delft and Surabaya City, and isovist analysis of ABE building. In creating a 3D photorealistic VR environment, this study will employ point cloud data to represent a real-life scanned 3D environment. Photorealistic representation in VR wayfinding simulation will be able to provide more accurate human behaviour due to similar sensory stimuli created from the environment. Furthermore, this study will produce various data sets, such as point cloud datasets of the study cases, axial lines, and isovist analysis, which will benefit future research. The combination of capturing wayfinding behaviour from eye movement, identification of breakpoint, and spatial data representation from segment analysis and isovist will also provide an advanced approach to wayfinding study that explores the correlations of movement behaviour and spatial situations.

Practical contribution

The research result of identifying visual cues in a multi-environment will benefit architecture and urban design in optimizing user experience, especially for improving efficient mobility. Buildings or spaces requiring efficient mobility across the environment, such as public transport hubs, universities and hospitals, could utilize visual cues research outcomes to optimize their spatial design. Furthermore, visual cues collected in this research will be used to develop a design guideline highlighting the development of spatial awareness and the role of transitional space in multi-environment wayfinding. After that, the design guideline will be implemented as an enhanced virtual environment, which would demonstrate optimized wayfinding. The enhanced virtual environment will be applied in both case studies (Indonesia and The Netherlands) and can be archived as a design proposal for future building development.

3.11. Research Scope

Environment Scope

The study will examine wayfinding in multi-environment, indoor and outdoor, emphasising transitional space within structured urban space surrounding the study case area. To limit the spatial and cultural aspects, the research will be conducted in two study cases: the FAD building at UPNVJT, Indonesia, and the A+BE building at TU Delft, The Netherlands. Furthermore, the explored environment will only be limited to the ground floor, focusing on the transition between indoor and outdoor spaces.

Cognitive and Wayfinding Framework Scope

This study will only accommodate pedestrian movement and focus on allocentric spatial cognition. Allocentric is an understanding of space as an independent structure rather than from a personal point of view. Within this scope, the implemented key wayfinding variable is the visual cues of spatial elements. In the indoor environment, these variables are interpreted as architectural differences, layout configuration, signage, room numbers, and visual access. Meanwhile, in the outdoor environment, the explored variables are paths, edges, nodes, districts, and landmarks. Additionally, the main aspect to be observed in transitional spaces is the overlapping spaces and pause points where wayfinding decisions often occur.

Methodological Scope

The methodology implemented in this study adopts Virtual Reality with a Gaussian splatting digital environment to create a photorealistic environment. This approach provides a controlled environment to cater to the tested wayfinding variables, which focuses on visual cues interpretation in wayfinding performance. Compared to real-world simulation, VR offers a more flexible and repeatable testing environment, which minimizes external distractions and provides consistency in experimental conditions. Furthermore, it allows for the controlled manipulation of spatial elements, which would be difficult to achieve in real-world settings.

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4. PRACTICAL ASPECTS

4.1. Deliverables

The main deliverables that are expected to be produced during the PhD research period are as follows:

1. PhD Research Proposal,
2. Three (3) publications in various journals,
3. Six (6) presentations and paper publications in various conferences, workshops, and symposiums,
4. Datasets,
5. PhD Dissertation.

In fulfilling PhD agreement publications, this research aims to publish at least 9 publications, which will be published in various journals and conferences. Of the 9 publications, 3 were expected to be published in journals, while the other 6 were expected to be published in conferences. In the future, more publications are expected to be published in journals and conferences listed in Table 3. Nonetheless, the list may be updated following the adjustments of the paper topics and other circumstances.

Paper 1: Visuospatial wayfinding interpretation in multi-environment: Indoor, Outdoor, and Transitional Space

Paper 2: The role of access rights in multi-environment (Indoor, Outdoor, and Transitional Space) spatial cognitive development

Paper3: Virtual Reality Visual Evaluation Through Edge Similarity in Various Point Cloud Density: An Early Study of Indoor GML Signification in Wayfinding Simulation

Paper 4: Wayfinding Visual Cues Identification in VR Gaussian Splatting Environment

Paper 5: VR Validity Verification for Wayfinding Simulation Using Point Cloud Environment

Paper 6: The role of spatial connectivity and spatial visibility in determining wayfinding performance during continuous multi-environment simulation

Paper 7: Significance of wayfinding visual cues in multi-environment

Paper 8: Spatial cognitive development in multi-environment with respect to access rights

Paper 9: Rising spatial awareness for optimized wayfinding by highlighting visual cues in virtual environment

Table 3. List of the targeted Journal and Conferences

Journal	Conference
International Journal of Applied Earth Observation and Geoinformation spatial awareness	Workshops of the AGILE Conference on Geographic Information Science

ISPRS International Journal of Geo-Information (IJGI)	International Workshop on Geoinformation Advances
International Journal of 3-D Information Modelling (IJ3DIM)	Geo-informatie Nederland
Journal of Spatial Science (TJSS)	AGILE Conference on Geographic Information Science
International Journal of Spatial Data Infrastructures Research (IJSDIR)	Workshops of the ICA Commission on Generalization and Multiple Representation
International Journal of Geographical Information Science (IJGIS)	3DGeoInfo conference
Journal on Data Semantics	International Conference on 3D Web Technology
Journal of Geographical Systems	Conference on Location-Based Service
Advanced Engineering Informatics	The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences (ISPRS)
Journal of Navigation	LADM workshop
Trends in Cognitive Sciences	Space Syntax Symposium 15 2026
Journal of Building Engineering	
Frontiers in Human Neuroscience	
Journal of Environmental Psychology	
Environment and Planning B: Urban Analytics and City Science	
Scientific Reports	
International Journal of Architectural Computing	

4.2. Supervision

This research will be conducted under the Geo Database Management Center (GDMC) with the supervision of Prof. Dr. Ir. P.J.M. van Oosterom as the promotor and Ir. Edward Verbree as the daily supervisor. The PhD supervisory comprises bi-weekly meetings with the promotor and co-promotor. A monthly progress report will be presented with the additional material discussed during the meeting.

4.3. Collaborations

This research comprises many subjects that could involve various support from other parties. To achieve its most optimum result, this research would collaborate with Professor Sisi Zlatanova from The University of New South Wales (UNSW) as an expert in 3D indoor navigation (indoorGML), Prof. Nico Van de Weghe from Ghent University, Ir. Hans Hoogenboom from A+BE TU Delft VR lab, and Dr Florent Poux as an expert in the smart point cloud. In developing wayfinding contextual understanding, this research also hopes to collaborate with wayfinding and spatial cognitive experts such as Professor Ruth Conroy Dalton from Northumbria University and/or Professor Christoph Hölscher from ETH Zurich. In supporting data processing and collection in Indonesia, this research will collaborate with researchers from Universitas Pembangunan Nasional “Veteran” Jawa Timur involving Dominikus Aditya Fitriyanto as the head of Architectural Design Laboratory and Tri Lathif Mardi Suryanto as the Head of Information System Management Laboratory. Furthermore, Synthesis Project master students have participated as collaborators in this research and will continue to be involved in supporting the research outcome for the upcoming years.

4.4. Doctoral Education Programme

As part of the skill development during the PhD research process, PhD researcher must complete a minimum of 45 Graduate School (GS) credits throughout the PhD research period.

The GS credit can be obtained by completing courses covering 3 primary skills (discipline-related skills, transferable skills, and research skills) and Learning on the Job activities (LOJ). Among the provided courses, there are 4 mandatory university GS courses and 1 mandatory faculty GD course, which needs to be completed during the first year of PhD research. The mandatory courses are Module A-I - Introduction to the Graduate School, Module A-II – Navigating the PhD Life, Module A-III – Conquering Challenges, PhD Start-up Module B – Scientific Integrity, and ABE009 - Research Proposal for Architecture & the Built Environment. Thus, in fulfilling the GS credit criteria, various taken and planned courses have been prepared to be completed throughout the PhD research period. In the first year, 20,5 GS credits were collected, leaving 24.5 GS credits to be collected (Table 4).

Table 4. Planned and Taken Graduate School Credits

COMPETENCES	NAME OF MODULE/ ACTIVITY	DONE GS Credit	PLANNED GS Credit
Discipline related skills			
	GEO1007 - Geoweb Technology	5	
	Geospatial Data Carpentry for Urbanism	1,5	
	GEO1003 - Positioning and Location Awareness		5
	GEO1000 - Python Programming for Geomatics		5
Research skills			
R.1 Research Management Designing, Project management, Problem solving, Valorization	R1.A1 Research Design	3	
	R1.A2 The Informed Researcher – Information and Data Skills		1,5
	R1.B1 Managing the Academic Publication Review Process		1
	R1.C2 How to Select / Make a Questionnaire and Conduct an Interview	2	
	ABE009 - Research Proposal for Architecture & the Built Environment	4	
R.2 Academic Thinking Conceptual thinking, Analytical thinking, Synthetic skills, Critical thinking, Creativity & Innovation	R2.B2 Statistics for PhD Research		1
	R2.B3 Data Visualisation as a Tool for Scientific Research (using R / using Python)		1
	R2.C1 Analysis of Interviews and Other Unstructured Data		2
	R2.D1 How to Formulate Successful Propositions for your PhD Defence		2
	ABE 007 - Discovering Statistics Using SPSS"		4
	R4.A1 | Research Data Management 101	2	

R4.A1 Research Data Management 101	R4.B1 Personal Data and Human Subjects in Research	1	
Transferabel skills			
T.4 Self-management Autonomy, Time management, Flexibility, Perseverance, Dealing with risk and uncertainty, Entrepreneurship, Personal development	T4.G1 - AI Module A-I - Introduction to the Graduate School	0,5	
	T4.G1 - AII Module A-II – Navigating the PhD Life	0,5	
	T4.G1 - AIII Module A-III – Conquering Challenges	0,5	
	T4.G1 - B PhD Start-up Module B – Scientific Integrity	0,5	
T.1 Effective communication Presenting, Writing skills, Storytelling, Language skills	T1.A9 Scientific Text Processing with LaTeX		1
	T1.A10 Designing Scientific Posters		1
	T1.B3 Writing a Scientific Article in English		5
	T1.D9 Dutch for Non-Native Speakers (NT2)		4
T.2 Working with others Networking, Collaboration, Negotiation, Leadership	T2.A2 The PhD Network Hub		1
T.4 Self-management Autonomy, Time management, Flexibility, Perseverance, Dealing with risk and uncertainty, Entrepreneurship, Personal development	T4.B5 Project Management for PhD Candidates		2
	T4.G14 Career Development – From Scientist to Entrepreneur		3
Learning on the Job (LOJ)			
	Addressing a large audience (examples: speaker at major international conference / workshop incl. conf. paper		
	Poster presentation conference / workshop incl. conf. abstract / paper		
	Scientific Presenting & Interacting Participation in work consultation with research partners		
	Writing an international, peer-reviewed journal article		
	Teaching assistance: assisting in laboratory course/tutorial (Synthesis Project)		
	Teaching assistance: assisting in laboratory course/tutorial (Positioning and Location Awareness – GEO1003)		

	TOTAL	**20,5**	**39,5**
	TOTAL	**60**	

4.5. Risk and Ethics

One of the risks of this study is the emergence of motion sickness during the VR simulation. Therefore, the simulation task and area radius will be controlled to only last for a maximum of 20 minutes. Keeping the simulation duration under 20 minutes could reduce the emergence of VR motion sickness (Lo & So, 2001). Furthermore, this study will collect personal background information related to spatial ability, such as profession, travelling habits, and educational background. However, the data will be kept anonymous and not published, keeping the privacy of the data secured.

Following the involvement of human subjects in this research, risk and ethics evaluation should commence and receive approval from the Human Research Ethics Committee (HREC). The approval from HREC followed the stipulation of the TU Delft Regulation on Human Trials (2016). Figure 30 shows HREC ethics and risk assessment application process that needs to be done before commencing the research. The HREC ethical clearance would evaluate the submitted form, which observes the risk assessment and mitigation provided by the researcher. Ensure that research involving human subjects is executed following the research ethics regulation established in TU Delft.

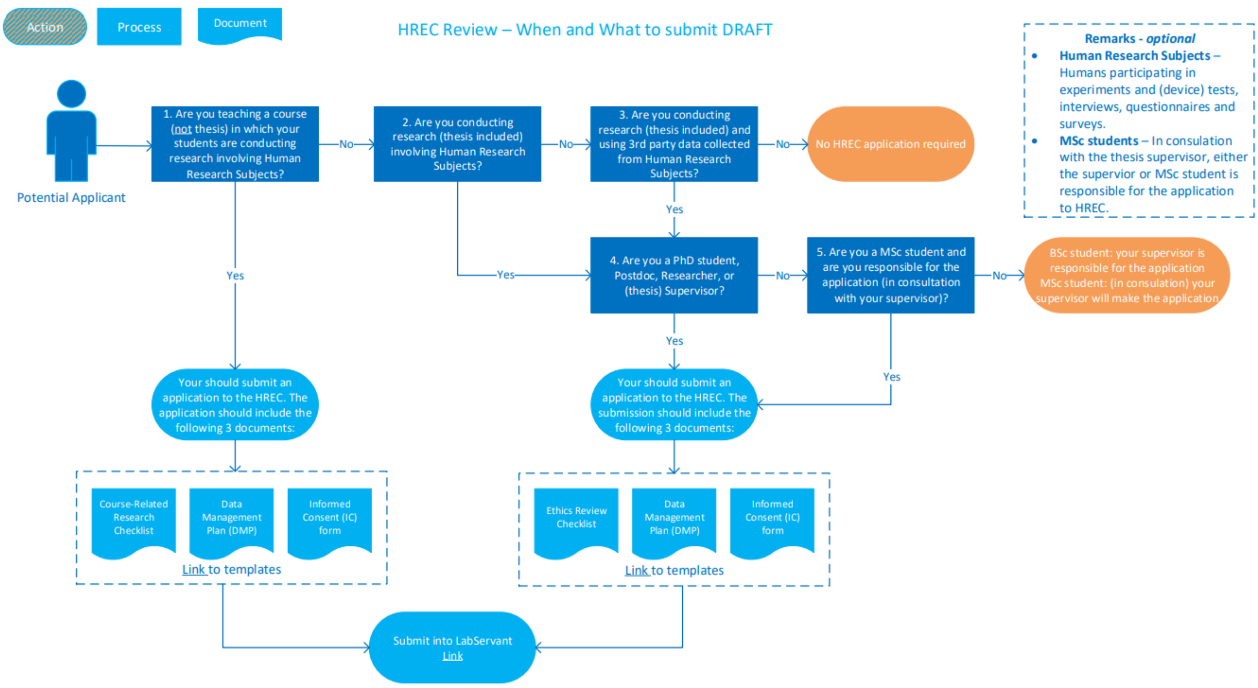

Figure 30. HREC ethics and risk assessment application process
Source: TU Delft HREC committee

4.6. Financial Support

The Indonesia Endowment Fund for Education Scholarship from the Government of Indonesia will financially support this research, covering the research expenses and parts of the publication fee.

5. RESEARCH PROGRESS

Along with preparing the GO/ NO GO meeting proposal, this research has begun its initial simulation testing the feasibility of the proposed research method. Various research processes that have been conducted are:

1. **Scanning parts of the A+BE building using ZEB Horizon Slam LiDAR scanner covering most of the A+BE ground floor area.**

   This process is part of the data collection stage, which involves environmental scanning of study cases. This data is fundamental for building the simulation environment. The data is collected using ZEB Horizon Slam LiDAR, which produces LiDAR point cloud data, capturing the 3D photorealistic environment of the A+BE ground floor area. The collected data have been reprocessed in Cloud Compare to integrate some building segments and reduce noises captured during the scanning process (figure 31). In this process, some parts of the buildings are also segmented to produce separate point cloud data highlighting potential building landmarks. The segmented data will be used for various analyses, such as investigating spatial features in specified landmark areas and VR validity verification study. The current data have captured most of the ABE building parts covering the main halls and various studios. More scanning is required to capture the rest of the building areas, including offices, classes, and various service areas.

Figure 31. Pre-processed LiDAR Point Cloud scan of ABE building

2. **Prior interpretation of wayfinding visual cues in ABE building**

Various landmarks are identified in this stage following LiDAR point cloud data collection results (figure 32). The analysis indicated initial information related to different categorizations of landmarks, such as global and local landmarks. Several parts of the ABE building play a significant role in district identification following the presence of global landmarks. Global landmarks signify the positioning relative to the overall building. Meanwhile, local landmarks signify positioning relative to smaller parts of the building. Hypothetically, not all buildings would possess global landmarks. Therefore, the result of this analysis will be further investigated by comparing it to the second study case, which will be collected at a later stage of the research.

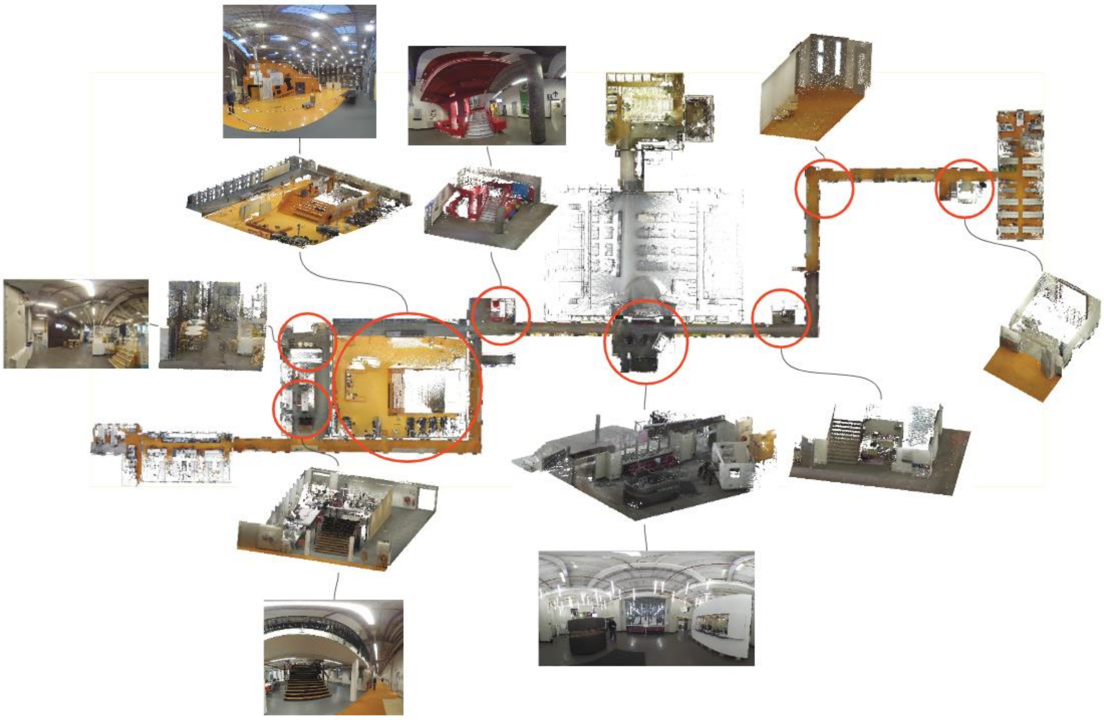

Figure 32. ABE building wayfinding landmark identification

3. **Testing visual quality of point cloud visualization in VR**

Some of the collected point cloud data began to be visualised in VR to evaluate its feasibility as a simulation environment. However, high-density point clouds could increase the computational density, reducing the system's performance. Therefore, this data is employed to evaluate the point cloud VR visual quality over several point densities. The point cloud data is modified into 6 different point densities and then visualised in VR. Furthermore, the visualization is recorded and analysed using canny edge detection to evaluate its ability to provide geometric information about the environment (figure 33). The image with edge detection is then compared with the ground truth edge image to evaluate its similarity in projecting the geometrical feature of the real environment. This data is applied to build a conference paper submitted to the AGILE Conference on Geographic Information Science.

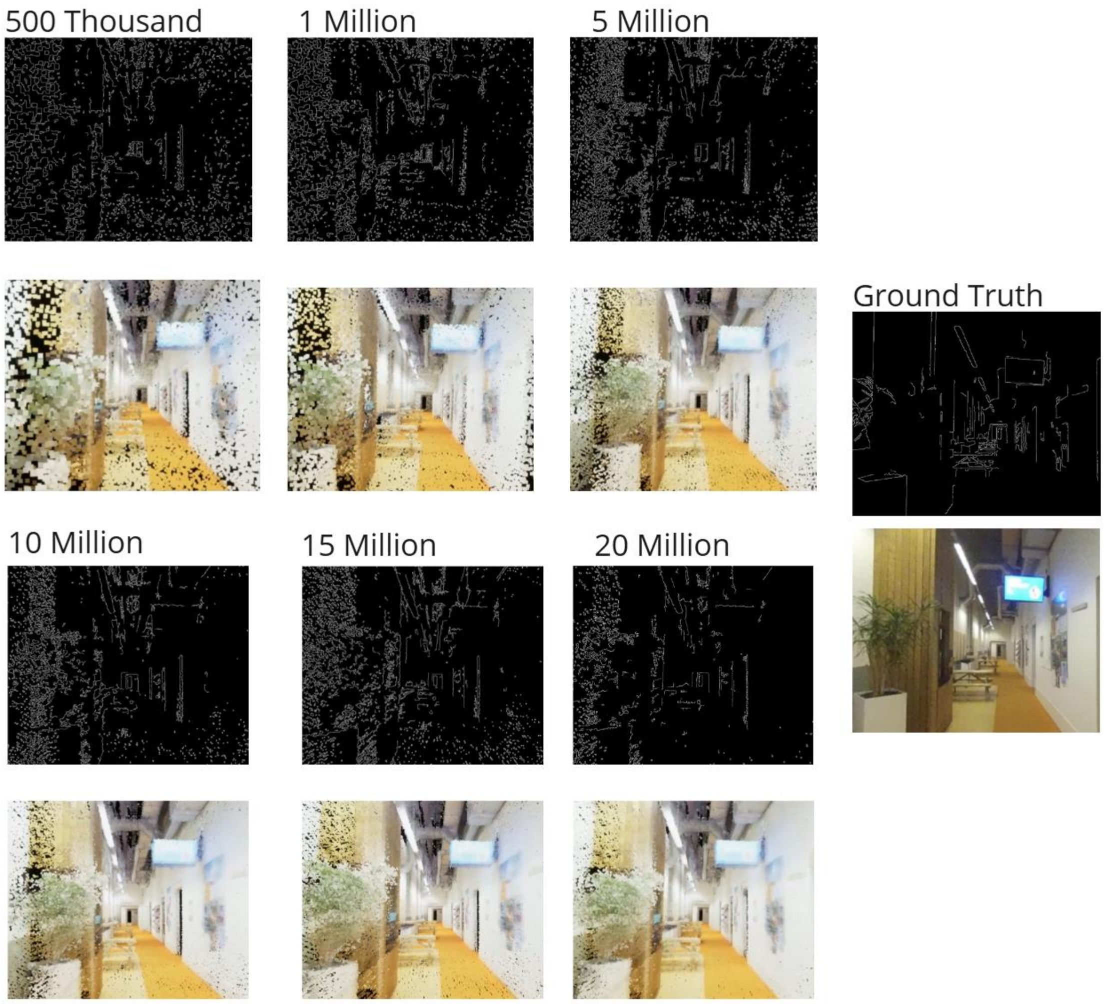

Figure 33. Result of pre-processed image using Canny Edge detection on various VR point cloud density and ground truth image

4. **Testing alternatives of point cloud visualization in VR (gaussian splatting)**

Gaussian splatting (GS) is explored in building a 3D photorealistic environment to evaluate its feasibility in being used as a VR environment in the wayfinding simulation. Some objects are tested to see the detail that GS could deliver. The initial test began by exploring detailed objects like the cactus (figure 34). The result showed that GS could provide a detailed visualisation of the cactus pricks. Furthermore, GDMC lab GS, with 7000 iterations, has been visualised in UE5 and showed promising GS scan results to be utilised as a VR environment (figure 35). The GDMC scan will undergo training again to produce GS from the 30000 iteration, which is supposed to produce a more seamless environment result than the 7000 iteration. Fox wall decoration GS has been tested using VR visualization, showing great detail that is well captured in VR (figure 36). These results indicate a great prospect of using GS to provide a 3D photorealistic VR environment for wayfinding simulation.

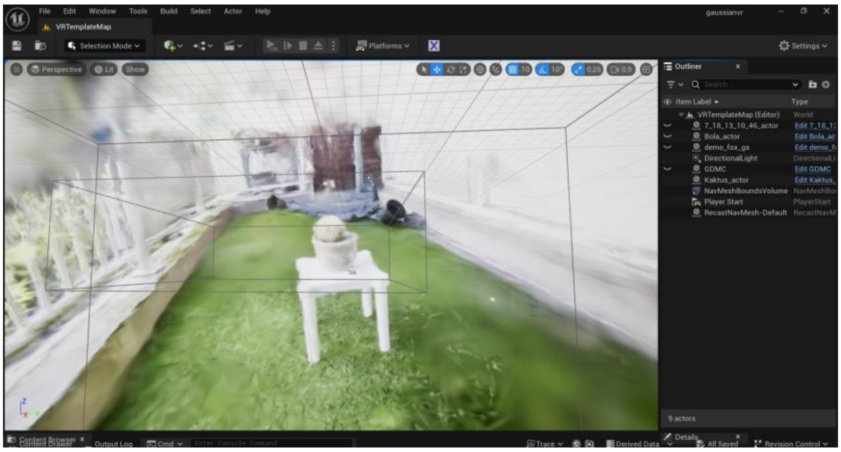

Figure 34. Gaussian splatting of cactus in UE5

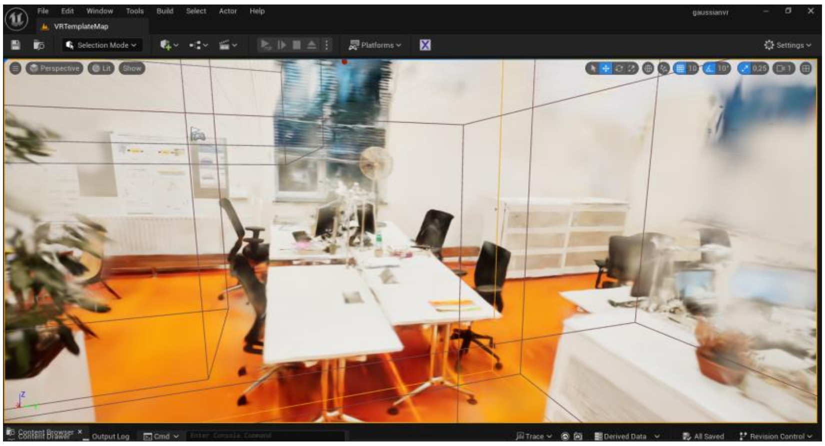

Figure 35. Gaussian splatting scan of GDMC lab in UE5

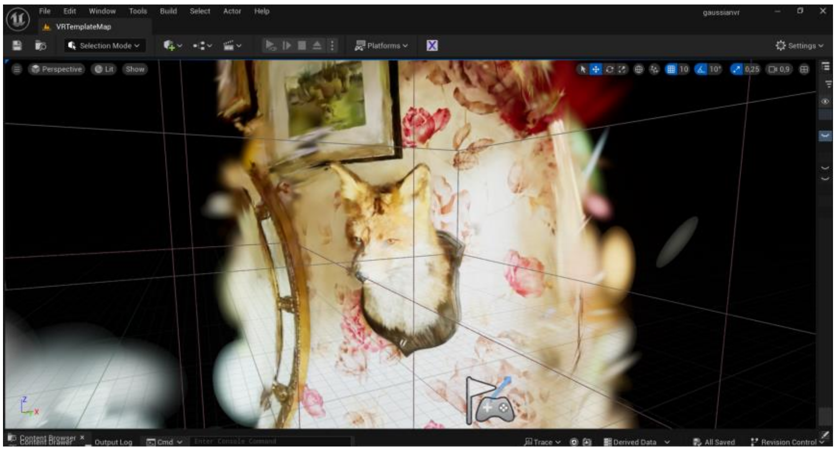

Figure 36. Gaussian splatting of Fox wall decoration in UE5

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APPENDIX A: Self-Reflection

Throughout this period, I have hit numerous research milestones and explored valuable insights related to my study. This section will express my self-reflection, described in key research achievements, technical and analytical skills gained, expanded knowledge and insights, completed milestones, and plans and next steps.

Key Research Achievements

- *Theoretical context advancement*
  Building the contextual background of this research requires a rigorous literature exploration that covers various study subjects. In the wayfinding study, I explored spatial cognitive studies, which led me to the early hypothesis of cognitive development relation with learning mechanisms involving continuous wayfinding across environments. I also explore the potential role of access rights in spatial cognition, which will be one of the key findings of this research.
- *Discovery of various gap research*
  In building this report, I dive deep to find the most suitable methodology to execute this research and verify the validity of the research findings. Along the process, I discovered many research gaps that possess great potential to be addressed in this study or future follow-up studies. Such as methods of visualising 3D photorealistic in a VR environment, methods for verifying the visual quality of point cloud VR visualisation, methods for verifying the validity of VR wayfinding simulation, etc.
- *Exploration of LiDAR point cloud and Gaussian Splatting visualisation in VR*
  One of this study's key novelties is using a 3D photorealistic environment gathered from the real environment scan in wayfinding VR simulation. In order to do that, I have begun to explore various methods of bringing a 3D photorealistic environment into VR simulation. In this opportunity, I explored Gaussian Splatting, one of the most recent technological advancements of real environment scan models, and tested its visual quality in VR visualisation.
- *Deeper comprehension of human subject research data treatment and retrieval method*
  In preparing for the data retrieval, I must design an appropriate human subject research data retrieval method to explore spatial cognition during wayfinding without exposing the participants to potential harm. Therefore, I have enrolled in courses that expose me to various data retrieval methods and ethical data treatment for human subject research. As a researcher, I must treat my research subject carefully, ensuring the gathered data is treated with full responsibility and everyone involved feels safe.
- *Developed the initial draft of the paper*
  After gathering several leads of methods for visual quality assessment, I brought together several data built into a paper draft exposing the quality of the point cloud environment for VR wayfinding simulation. This study describes the possibility of point cloud application as a VR environment.

Technical and Analytical Skills Gained

- *Proficiency in Tools*
  During the point cloud exploration, I gained more proficiency in the tools required for point cloud data retrieval and visualizing it in VR. For instance, I have mastered using the Zeb Horizon LiDAR scanner, which captures the real environment and converts it into point cloud data. Furthermore, I have also mastered using HMD Quest 2, which is used to visualise immersive reality.
- *Proficiency in Software*
  In supporting the data processing, I have learned various new software essential in point cloud data handling and visualisation, such as FARO Connect Viewer, Cloud Compare, and Unreal Engine 5. Other than that, I also had a brief engagement with other software such as R Studio, Visual Studio, and PgAdmin.

Expanded Knowledge and Insights

- *Deeper comprehension of FAIR principles*
  In the course Data Management 101, I had the opportunity to learn about the importance of research reproducibility, which is one of the points in FAIR principles. The practice of FAIR principles is significant in the research data management of my study. I have created a data management system that allows me to store my data safely so that it can be used appropriately in accordance with the FAIR principles.
- *Presentation at NCG symposium*
  Over the event of the NCG symposium, I had the opportunity to present my research idea to GIS experts. During the event, I gathered valuable feedback and discussions, leading to a potential collaboration for this study.
- *Collaborative work with Synthesis Project master students*
  Synthesis project is a course involving Geomatic students preparing for their thesis studies. In this course, I have the opportunity to work collaboratively with the students to develop a navigation system which implements image-matching technology for indoor wayfinding. From this collaboration, I managed to collect the A+BE indoor point cloud dataset and the application system with image matching, which would be significant in the visual validity method for this study.
- *Doctoral Education part-completion*
  Within one year, I finished 20.5 GS credits, 45% of the required credits (45 GS) for PhD study completion. All the courses and work that I have done have contributed significantly to the knowledge and skills development required for this study.

Future Plans and Next Steps

Preparing for the upcoming years, I aimed to manage the research to be commenced in full commitment to the structured research timeline, meaning to produce research output and paper as scheduled. Furthermore, I look forward to and plan to commence collaborative study with various collaborators to produce a rigorous research outcome that could contribute significantly to studying spatial cognition, especially in a wayfinding context. Therefore, more collaboration plans are at hand, projecting future days ahead with productive and collaborative research.

APPENDIX B: Research Hypothesis

Main Research Question

"What factors contribute to spatial cognition development and wayfinding performance across indoor, outdoor, and transitional spaces, respecting access rights?

This research adopts a descriptive knowledge project, which focuses on describing the natural form of a particular scientific phenomenon (Zwart & de Vries, 2016). Therefore, the main research question aimed to describe the development of spatial cognition in a continuous wayfinding process within indoor, outdoor, and transitional spaces, considering the role of user access rights.

Hypothesis:

In continuous wayfinding, cognitive maps are formed through spatial cognitive processing of previously encountered environments. This process helps build the memory needed for spatial interpretation and navigation. In the indoor-to-outdoor simulation, people will be able to identify the visual cues, characteristics, and geometric forms of the indoor space, which will help them to reprocess the information for outdoor wayfinding. Transitional space will be a breakpoint where mental processing will occur before the path decision is built and navigation is executed. The building and outdoor environment characteristics will also affect the level of the wayfinding performance. Some buildings and outdoor areas will help increase the speed of the wayfinding process, while others potentially confuse the user during the route planning process. On the other hand, the access rights will be significant for spatial information retrieval during spatial exploration. Access rights context will boost memory processing, helping people build the cognitive map and resulting in a faster wayfinding process.

Sub Research Questions 1. What are spatial cognition and wayfinding visual cues in indoor, outdoor, and transitional spaces and addressing access rights?

This sub-question explores the theoretical foundation between spatial cognition, visual cues of wayfinding, and access rights, which is broken down into three questions below. The result of this question would become the fundamental background for analysis and data collection for the rest of the research.

Hypothesis:

Visual cues will provide prior information during spatial identification consisting of spatial geometric, signage, plan configuration, and landmarks, which will be kept as long-term memory. Long-term memory is collected during spatial exploration in wayfinding with access rights challenges. Intricate access rights will introduce an error-driven learning mechanism, which helps to foster spatial memory collection.

1.1 Which wayfinding variables are related to the visuospatial interpretation of indoor, outdoor, and transitional space?

Hypothesis: In indoor space, the visuospatial wayfinding variables emerge as architectural differentiation, plan configuration, signage and room numbers, and visual access following Weisman (1981) explanation of indoor architectural variables for wayfinding. Meanwhile, in outdoors, the visuospatial wayfinding variables emerge as paths, edges, nodes, districts, and landmarks (Lynch, 1960)*. On the other hand, the transitional space will adopt visual cues from the indoor or outdoor visual cues, which are accessible/ visible from the transitional space area*.

1.2 What is the role of intricate access rights in advancing spatial cognition development?

Hypothesis: Access rights context will limit the path accessibility, adding more spatial context information to the spatial memory collection. Adopting access rights will activate the error-driven learning mechanism, helping the development of a cognitive map.

1.3 In what way is the access right interpreted in wayfinding indoor, outdoor, and transitional space?

Hypothesis: Indoor space access rights can be interpreted as different room access following different user categories. Meanwhile, outdoor access rights can be interpreted in the access limitation following differences in transportation modes, traffic access, land ownership, and path obstruction. Meanwhile, access rights in transitional space will be interpreted contextually following access limitations, whether indoor or outdoor. Access rights will be used to identify the emergence of transitional space due to the nature of it being at the border of accessibility context between the space.

Sub Research Questions 2. Which VR simulation approach effectively captures the visual cues for wayfinding?

This sub-question aims to identify and build the required system for wayfinding simulation in a VR environment. Ranging from the simulation system to the quality of the environment, which effectively visualises wayfinding simulation.

Hypothesis:

VR simulation, suitable for capturing visual cues of wayfinding, requires a 3D photorealistic environment, which could cater to the identification of visual cues by utilizing visual capturing technology embedded in VR.

2.1 What digital environment (e.g. meshes, coloured point clouds or Gaussian splats) effectively captures details of spatial visual cues for wayfinding simulation?

Hypothesis: Point cloud digital environments, which are captured from the real situation, were believed to be most effective to be implemented for wayfinding in VR. This is due to its ability to capture environment details required to identify wayfinding visual variables.

2.2 What VR simulation systems must be implemented to capture visual cues of wayfinding?

Hypothesis: The wayfinding simulation study must consider movement behaviour and user experience. Catering to the need for movement behaviour by capturing visual cues and spatial layouts, wayfinding VR simulation must possess a visual capturing and path tracing system. Thus, VR wayfinding simulations must utilize eye tracking, path tracing, and head rotation recording technology. Furthermore, in recording user experience during wayfinding, the simulation must utilize Systematic Interviews, Thinking Aloud Protocols (TAPs), and questionnaires to confirm user experience with the expected hypothesis.

Sub Research Questions 3. To what extent does the significance of each wayfinding visual cue differ between indoor, transitional, and outdoor spaces with respect to access rights?

This sub-question aims to address the main finding of the research, which is the significance of wayfinding variables in each environment. The answer to this question would provide information on how spatial cognition performed in various wayfinding scenarios, especially with intricate access rights.

Hypothesis:

Visual cues of wayfinding in indoor and outdoor environments differ in different use levels of visual access between space and the utilization of landmarks. The scale of the environment also affects the user's wayfinding strategy. The utilization of a core building strategy is more common indoors compared to outdoors. However, outdoor wayfinding strategies are more toward direct strategy because the scale of the urban space forces the users to take immediate action, ignoring the centrality of space. In wayfinding performance, users exposed to intricate access rights tasks have better wayfinding performance or spatial understanding (meaning that they may not be faster in finishing the task but have better knowledge of the spatial environment). It was assumed that visual cues are rereviewed in intricate access rights task simulation that affects better spatial knowledge of the participant.

3.1 How do the visual cues affect wayfinding performance in each space?

Hypothesis: The visual cues are used as a spatial identificatory confirming various wayfinding variables such as districts, helping the development of spatial cognition. Transitional space with interacting views indoors and outdoors (such as glass windows) *uses cross-space visual cues to help the participant decide on a route plan faster during space transition wayfinding. Despite well-positioned signage throughout the building, the spatial configuration plays a significant role in the wayfinding performance, as indicated by the movement behaviours in different buildings.*

3.2 What are continuous simulation's implications for developing spatial cognition across integrated environments?

Hypothesis: The wayfinding in the first space becomes the foundation of spatial identification, helping the development of cognitive maps and memory collection. The collected memory will be used to find other spaces, helping to develop faster route planning.

3.3 How do access rights affect decision-making regarding wayfinding?

Hypothesis: Access rights play a role in an error-driven learning mechanism, helping the participant to learn the space better.

Sub Research Questions 4. How can we demonstrate optimized wayfinding, developed through the encouragement of spatial awareness, by exploiting gained knowledge on visual cues in a multi-environment setting?

This question aimed to build a virtual environment that could demonstrate optimized wayfinding that is developed through the encouragement of spatial awareness

Hypothesis: Optimized wayfinding could be demonstrated and built using an enhanced virtual environment, highlighting visual cues to build the user's spatial awareness.

4.1 What design guidelines should be established to develop spaces that integrate the gained knowledge to optimise wayfinding?

Hypothesis: The design guideline will integrate wayfinding variables according to the visual cues information collected from the previous simulations. The design guideline will also highlight the importance of transitional spaces as a spatial cognitive processing spot, which could significantly elevate spatial awareness in wayfinding.

4.2 What evaluation parameter can be implemented to validate the optimized wayfinding and spatial awareness demonstration?

Hypothesis: To validate the optimized wayfinding and spatial awareness demonstration, the study will implement a performance-based evaluation measuring time in finishing the *given task, evaluating the path efficiency, and observing the collected visual cues during the simulation. Following the simulation, semi-structured interviews will be commenced to analyse spatial awareness by investigating the visual cues for wayfinding decisions.*

APPENDIX C: Related Work

Wayfinding within individual circumstances

One of the determining factors of wayfinding performance also lies in the individual circumstances. These circumstances vary from gender differences, physical ability (e.g. visual impairment, disability, etc.), navigational aptitude, familiarity with the environment, age, personality, and even culture. Some individual circumstances are related to one another.

Gender has been believed to impact the wayfinding/ navigating strategy. Some studies mention that women and men have different strategies for wayfinding (Lawton, 1994). In the study done by Lawton, it was mentioned that two strategies in wayfinding signify the different wayfinding strategy references between men and women. Those two strategies are the Orientation strategy and the Route strategy. The orientation strategy focuses on understanding self-orientation towards the environment (e.g. using east, west, north, and south or cardinal direction as directional orientation). Route strategy focuses on the instruction to the destination also by acknowledging the relevant landmarks (e.g directed using left and right with landmarks as spatial cues) (Gärling et al., 1985). Among those wayfinding strategies, it was found that women tend to use route strategy instead of orientation strategy which men commonly use (Lawton, 1994).

However, a recent gender-related wayfinding study mentioned that the wayfinding strategy preferences are also affected by personality, which is not necessarily bound by gender (Muffato et al., 2024). Generally, the wayfinding process begins with spatial exploration, in which the person acquires spatial knowledge ranging from landmarks and routes to survey knowledge (Kim & Bock, 2021). Through this process, people build their cognitive map before deciding on their chosen path and begin navigating. However, the exploration stage, which is a crucial step that could determine the wayfinding performance, is affected by personal traits such as positive and negative beliefs in exploration (e.g. enjoyment in wandering and spatial anxiety) (Meneghetti et al., 2020). A low level of spatial anxiety could provide better wayfinding performance, a trait owned by people who enjoy exploring (Muffato et al., 2022). Furthermore, Muffato et al. (2022) explain that three of the five-dimensional traits (i.e. agreeableness, conscientiousness, emotional stability, extraversion, and openness) showed more significance in affecting the wayfinding inclination in men and women. The three personal traits that affect wayfinding inclinations are emotional stability, extraversion, and openness. Emotional stability is a personal trait associated with a small amount of impulse control and politeness. Regarding spatial exploration, emotional stability is related to the lack of spatial anxiety, which drives people to do spatial exploration (Pazzaglia et al., 2018). Extraversion is a personal trait related to the outgoing and enthusiastic character, which is related to a positive attitude in spatial exploration (McCrae & John, 1992; Wyllie & Smith, 1996). Meanwhile, openness is related to a curious and interesting character that caters to the enthusiasm for exploration (McCrae & John, 1992). Among the tested personal traits, openness and positive affect are the most significant traits that affect spatial exploration attitude regardless of gender (Muffato et al., 2024). Although the study explained that there are several impacts of personal traits that are specific to gender, such as the level of extraversion to the exploration attitude in men, the negative effect of spatial anxiety in men, and emotional stability in the level of spatial anxiety in women.

Wayfinding in a Natural Setting

Since then, the study developed further on various environments, including the natural environment. One wayfinding study in the natural environment involved 15 experienced foot orienteers, in which the participants were asked to walk through a particular path and to communicate their path at the end of the race (Brosset et al., 2008). The study was conducted on a coastal and natural environment with an intricate path. The result of the study highlights the importance of landmarks in both settings and a linear feature (e.g. trails) that guides them along the path. Furthermore, unlike urban settings, wayfinding in natural settings relies more on cardinal directions. In terms of spatial description, the natural environment requires a more detailed description of the spatial features because of the intricate topographies and recurring features. Newcombe et al. (2015) explain that movement in complex topography situations is affected by the dynamic elevation of the slope, which is "perceivable by the kinaesthetic sense" (angle of the joints/muscular exertion), by the vestibular sense (sense of balance), and by the visual system (angles formed when a sloped terrain intersects a vertical plane)". Therefore, the rules of natural movement in complex topography potentially differ from those in flat topography, subsequently affecting the spatial cognition variable. Following this, visual interpretation is tested due to the angles formed at the intersection between sloped terrain and a vertical plane. As a result, distance is becoming a relative matter, while turns are more frequent due to limited access and the provision of the best possible shortcut to navigate to the top or the bottom.

Wayfinding in Building with Intricate Spatial Relationship

A wayfinding study done in a hospital showed the complicated spatial context due to intricate spatial relationships among departments, which are informed visually with signs and other cues (Baskaya et al., 2004). Additionally, hospitals presented different wayfinding behaviours due to different accessibility provided to the user. Patients and health care providers (doctors, nurses, staff, etc.) are exposed to the spatial situation differently, affecting their spatial familiarity. Patients are potentially exposed to disorientation due to unfamiliarity with the indoor situation (Allison & Carey, 2007; Devlin, 2014). Nonetheless, the healthcare providers could still undergo disorientation due to the dynamic spatial arrangement commonly happening in hospitals (Sevinç & Bozkurt, 2015). On the other hand, mobilisation in hospitals is mainly concentrated in corridors, indicating the time spent by the healthcare providers is mostly in wayfinding and navigating (Golembiewski, 2017). Therefore, it is important to provide an efficient space for navigating, especially for buildings with high mobility activity (Baskaya et al., 2004). This idea resonates with a study done by Peponis, Zimring, and Choi (1990), who highlighted the importance of a balance between good plan configuration and signage placement that will induce natural wayfinding.

In a building with more than one floor, the wayfinding strategy may differ in responding to different levels of the building. A study in a multilevel building highlights different wayfinding strategies following the wayfinding region that is being walked through (Hölscher et al., 2012). Generally, two alternative strategies are used in wayfinding. The first is the central point strategy, while the other is the direction strategy. The central point strategy is wayfinding, which focuses on remaining at the core of the building despite requiring to walk through indirect access, helping the person to securely self-orient in the environment (Holscher et al., 2007). On the contrary, the direction strategy effectively utilises a path that directly leads to the destination (Dalton, 2003; Hochmair & Frank, 2000). In addition to the general wayfinding strategy, multilevel wayfinding utilises floor strategy, which comprises the mobilising effort to the targeted floor (Holscher et al., 2007). Floor strategy specifically responded to self-orientation difficulties following a change of floors, utilising elevators or stairs (Soeda et al., 1997). The result of the study showed that novice users tend to use highly connected and integrated areas, which are interpreted as the core area of the building, showing utilisation of the central point strategy. On the contrary, experts utilize a direct strategy by following a steeper gradient of step depth reduction. Meanwhile, the experts also implement floor strategy more due to the spatial prior knowledge.

APPENDIX D: Conference Paper (paper draft 3)

Virtual Reality Visual Evaluation Through Edge Similarity in Various Point Cloud Density: An Early Study of Indoor GML Signification in Wayfinding Simulation

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Abstract. Wayfinding studies using Virtual Reality (VR) are growing significantly especially with the fast paced of technological development. VR has becoming one of the most reliable simulation technique due to the practicality of human subject research especially in indoor simulation. Meanwhile, VR simulation technology generally aim to achieve the best photorealistic environment for best immersive experience. This goal is also urgently needed for a more accurate wayfinding simulation which currently also supported by point cloud representation. However, wayfinding VR simulation with point cloud environment needs to overview its feasibility in fulfilling identification of wayfinding variables. Furthermore, it also needs to take into account how the simulation system could adhere to the standard of indoor spatial information such as IndoorGML. Therefore, this study aim to evaluate the visual feasibility of point cloud environment for VR wayfinding simulation. The study will analyse the visual quality of point cloud presentation in VR using various metrics such as SSIM (Structural Similarity Index Measure) and the edge similarity. Various VR point cloud density was assessed against the real situation image. The result indicated that the higher the density the better visual quality for the optimum VR simulation. Furthermore, it is shown that indoor GML component well aligned with wayfinding, indicating great potential to be used in practical used of wayfinding studies.

BoK Concepts. [CV4-7] Virtual and immersive environments, [TA14-2-1-1] Point clouds, [GC2] Spatial simulation modelling

Keywords. virtual reality, point cloud, wayfinding, indoorgml

1 Introduction

Various architecture and urban environment studies and projects adopt wayfinding framework as part of the design process and research parameters (Chen & Stanney, 1999; Fewings, 2001; Hölscher et al., 2012; Karimi, 2015). This is because wayfinding provide human spatial experience that depicts the spatial situation. Wayfinding is the human ability and process of going to the destined place, using the cognitive ability in respond to the spatial situation (Arthur & Passini, 1992). People will perform wayfinding differently in accordance to the spatial situation. For instance, a study in IKEA indicated how the spatial layout would affect the cognitive processing during shopping, potentially affecting the shopping behaviour (Penn, 2006). Spatial layout and the wayfinding respond to the space could affect urban development of a region (Vaez et al., n.d.). Furthermore, various emergency situation showed how wayfinding situation emerge on evacuation process (Fu et al., 2023). Therefore, it is important for architecture and urban subjects to consider wayfinding variables in the design process so that the design outcome will be produced as predicted.

Wayfinding simulation using Virtual Reality (VR) recently used more frequently in various study due to its ability to cater to the dynamic of human subject research (Dong et al., 2022). Human subject research which involve human respondent in the study, often produced unpredictable results. VR uses digital environment which can be modified whenever needed. In an intricate studies, such as emergency situation, VR could also simulate the situation without actually simulating real danger to the respondent (C.-H. Tang et al., 2009). For example, there are studies regarding emergency respond during building fire, that are easily simulated in VR simulation (Bernardini et al., 2023). Furthermore, there are also study to evaluate the spatial efficiency in health facilities which provided initial feedback of the designed building (Al-Sharaa et al., 2022).

Meanwhile, indoor wayfinding simulation system must also taking into account the standard of indoor spatial in formation in order to build an accurate indoor spatial representation. IndoorGML is an Open Geospatial Consortium (OGC) standard for indoor spatial information and modelling (Open Geospatial Consortium, 2019). It concentrates on providing model framework for representing and exchanging indoor spatial information which generally utilized in navigation aid applications. Indoor GML taking into account various indoor features such as rooms, stairs, and corridors which is significant in the spatial representation for navigation. Spatial information in IndoorGML is potentially possess remarkable integration with wayfinding variables in which can be utilized in practical use in wayfinding study and simulation. One of the earliest wayfinding theoretical framework consist of Paths, Edges, Districts, Nodes, Landmarks (Lynch, 1960). The wayfinding spatial classification align with IndoorGML spatial information that uses the spatial perception through relationships between nodes and edges. Furthermore, several studies had begun developing XML file which integrate visible landmarks in order to provide wayfinding assistance (Russo et al., 2014). The XML file are planned to be interpreted into other languages such as IndoorGML. Therefore, VR wayfinding simulation technical process would be best to adopt IndoorGML spatial standard so that it will not only visually accurate but also semantically meaningful.

On the other hand, with the rise of VR as wayfinding study method, more VR technology study are being developed. VR simulation strive to provide more photorealistic environment that could imitate the real environment. Point cloud is a 3D digital data that are presented with a collection of points. The points are positioned in local reference to provide 3d model of an object (FIGURE). Initially point cloud are presented without RGB data, but currently point cloud can provide a real image of the scanned environment. Some collection technique of point cloud are using LiDAR and photogrammetry. Both technique manage to provide photorealistic 3D digital object. Point cloud has great potential in providing real environment with detailed object for a more accurate virtual environment. Especially in wayfinding simulation, it is very important to provide close to real immersive reality to the respondent, so that the respondent could respond as natural as possible. With provided detailed shape and colour ambience that point cloud provided, studies that require real environment can provide more accurate results.

Despite great potential point cloud environment for VR simulation, VR simulation using point cloud are quiet uncommon, although many had begun to explore the merging and compatibility of point cloud and VR visualisation in various scenarios (Michalas et al., 2024; Yasar et al., 2024). Therefore, this study aim to provide an approach on point cloud for VR wayfinding simulation by evaluating the visual quality of point cloud in VR simulation. VR simulations can be conducted in many context, nevertheless this study will focus on wayfinding simulation which consider edge as one of the wayfinding variables. Edge generally represented in the geometrical border of spatial environment that normally appear in the form of floor and walls. This study will evaluate the feasibility of point cloud VR visualisation by analyse the edge identification across different point density. The result will indicate which level of density will be appropriate for VR simulation. One of IndoorGML key feature requires clear segmentation of the spatial data (L. Tang et al., 2018). Therefore, the visual evaluation will provide early evidence of the IndoorGML potential to be integrated in Wayfinding simulation system by having clear understanding of visual clarity for spatial data model.

2 Related Work

2.1 Wayfinding in Indoor Spaces

Indoor wayfinding has becoming a critical study field due to its relevance to various navigation challenges such as emergency situation, accessibility, mobility efficiency, and spatial cognition. All those challenges often occurred in essential building such as hospital, train station, or educational building which are often challenging specific group of people (Abu-ghazzeh, 1996; Ahn et al., 2017; Al-Sharaa et al., 2022). Wayfinding study first initiated from a cognitive map which involve animal as the study subject. The study explained that spatial exploration could contribute to the development of cognitive map (Tolman, 1948). The exploration of cognitive map leads to wayfinding study which is first introduced by Kevin Lynch from the study of mental image of a city (Lynch, 1960). In the study, Lynch mentioned several wayfinding framework which affiliated to the city spatial features such as Paths, Edges, Districts, Nodes, and Landmarks. These wayfinding framework has been interpreted in may indoor studies, ranging to the implementation of signage, indoor landmarks, and spatial borders.

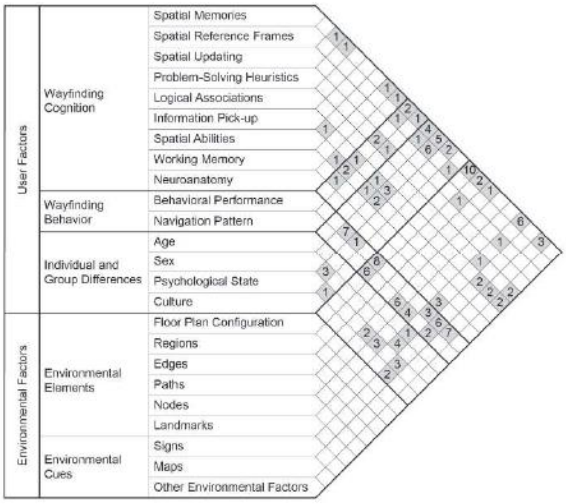

Figure 1. Relationships between different sub-domains (i.e., intersecting domains) are shown in this folded matrix. The numbers in the cells indicate the number of articles in each intersecting domain. Some studies examined more than two sub-domains; hence they can fit into multiple pairs of sub-domains.

Source: (Jamshidi et al., 2020)

Although the early theoretical foundation of wayfinding occurred from spatial traits, it is mentioned that user factor also play a significant role in the wayfinding performance (figure 1). Furthermore, there are nine major sub domain of wayfinding cognition that affect the wayfinding performance which are "spatial memories, spatial reference frame, spatial updating, spatial problem solving heuristics, logical associations, information pick-up, spatial ability, working memory, and neuro anatomy" (Jamshidi et al., 2020).

On the other hand, technological development have explored improvements for traditional wayfinding research methodology. Virtual reality and augmented reality began to developed as simulation tool which could optimized the user experience in wayfinding simulation (Goldiez et al., 2007; Vilar & Rebelo, 2010). Which is an alternative of simulation tool in addressing sensitive and dangerous issues such as fire evacuation (Bernardini et al., 2023). Wayfinding simulation utilizing deep learning and agent based also explored presenting another advancement of wayfinding study (Afif et al., 2021; Jonietz & Kiefer, 2017).

2.2 Point Clouds in VR Simulations

The use of VR had increased over the past years in various study due to the ability in simulating many situation. The development of VR devices also rapidly advancing along with the fast forward technological advancement. This situation also affect how the wayfinding simulation is being conducted, simulating various scenarios that is difficult to commenced in real simulation. For instance, many study related to emergency scenarios are able to be conducted using VR (Ren et al., 2008). There are also studies related to behaviour observation that are managed to be done effectively due to the ability of environment control in VR simulation (Schneider & Bengler, 2020).

In responding to the demand of more realistic virtual simulation, photorealistic environment are also developed in many studies. More render technique and advanced real environment scanning technique are currently developed. For instance environment scanning technique such as photogrammetry and LiDAR are currently able to brought photorealistic 3D digital object which can be viewed in many visualisation platform. Photogrammetry and LiDAR manage to produce various 3D digital object such as mesh and point cloud, in which each serve different purposes in various studies (Li-Chee-Ming et al., 2009; Nebel et al., 2020). For instance, photogrammetry manage to create mesh 3D object of a urban buildings (Liang et al., 2017). Although mesh objects often left out several detailed shape that might be needed in various study. Meanwhile, point cloud uses points in building spatial objects making it able to create detailed objects.

Detailed aspects of point cloud 3D object could be beneficial for wayfinding study which require attention to detail during the simulation. Several studies related to the utilization of point cloud in VR visualisation showed promising result in terms of providing accuracy of environmental visualisation. A study done by Michalas et al compare the ability of point cloud virtual environment with omnibase by doing measurement task to see its visual quality in providing accurate measurement (2024). Meanwhile other study showed the point cloud visualisation for emergency real time indoor navigation (Yasar et al., 2024).

2.3 Indoor GML

IndoorGML and wayfinding entities serves different purposes. Generally, wayfinding entities implemented directly in the real-world in the form of signages, specific building design, etc. Despite possessing similar entities, IndoorGML is presented as a model for indoor space representation in the form of XML file, which can be implemented as indoor spatial reference system. In IndoorGML there are several aspect which is part of the indoor constraint, those are cellular space, semantic representation, geometric representation, topological representation, and multi-layered representation (Open Geospatial Consortium, 2019). Cellular space serves as physical entity of a space such as room, corridors, or doors. Meanwhile, semantic representation serves as labelling of each of the space. Geometric representation contain detailed geometric information if indoor entity, such as space, size, and shape. Topological representation is serves as the relationship that are created between spaces. For instance how each space are connected to one an another, which provide clear connected space sequence. Multi-layered representation possess multiple layer of information which needs to be separated from one and another.

Some studies utilising indoorGML for wayfinding have been published showing the potential integration of wayfinding framework being supported by spatial system in IndoorGML. A study mentioned the utilization landmarks as a means to navigation aid which can be translated into IndoorGML (Russo et al., 2014). Other study mentioned geometric model and symbolic model which is a classification of indoor spatial data models (Kang & Li, 2017). This model aligned with wayfinding entities which considers geographical entity such as edge and also symbolic entity such as district which represented in signages. On the other hand a study suggested IndoorGML data model for people with disability (Park et al., 2020). This study cloud align greatly with various study of wayfinding of people with disability (Gupta et al., 2020; Karimi et al., 2014).

3 Methodology

The study will be conducted by evaluating the point cloud scan of a hall in the faculty building, which is visualized in Unreal Engine 5 (EU5) using LiDAR Point Cloud plugin. The point cloud will be viewed in VR using Quest 2 Head Mount Device (HMD) evaluating the visual clarity of point cloud visualisation using several metric.

There are 4 process in this study which began by data collection, pre-processing, simulation, and analysis and statistical evaluation. All the process is completed with specific tool raging from ZEB Horizon with Zeb Vision LiDAR scanner, Quest 2 VR Head Mount Device, and High specification computer (table 1). ZEB Horizon is used due to the practical use and fast processing LiDAR scan result. Furthermore, in order to appropriately run VR simulation there are several computer specification criteria that must be followed according to the specification standard mentioned by Unreal Engine 5 and Quest 2. Some of the minimum requirements are Windows 10 64-bit operating system, CPU with Quad-core Intel or AMD processor, 2.5 GHz or faster, 8 GB Memory (RAM), DirectX 11 or DirectX 12 compatible graphics card, and 256 GB SSD. By fulfilling the required criteria the simulation is expected is running in accordance to the visualisation standard. Furthermore, in this study there are various software used for the data processing which are Faro Connect , Cloud Compare, Unreal Engine 5, and Google Collab (table 2). Faro connect is used to Slam data Processing which turning Slam into Laz. Cloud compare are used to cleaning point noises and integrating point data. Unreal Engie 5 is used to visualised and running the VR simulation. Google Collab are used for running the Edge image identification, analysis, and statistical processing.

Table 1. Hardware tools specification used in the study

Stage	Tool	Specification
Data Collection Simulation	ZEB Horizon with Zeb Vision	Resolution: 4K RGB sensor Field of View (FoV): 360 ° panoramic image
	Computer	Processor: AMD Ryzen 7 7700 8-Core Processor 3.80 GHs Memory: 32 GB Operating System: Windows 10 ENterprise
	Meta Quest 2 (HMD)	Processor: Snapdragon XR2, octa-core, Kryo 585 (1 x 2.84 GHz, 3 x 2.42 GHz, 4 x 1.8 GHz), 7 nm process technology Memory: 6 GB Operating System: Android 10

Table 2. Software

Stage	Software
Pre Processing	Faro Connect Cloud Compare
Simulation	Unreal Engine 5
Analysis and Statistical Evaluation	Google Colab

3.1 Point Cloud Representation Preparation

Point cloud data preparation begin by the data collection by doing the spatial scanning. The point cloud data was acquired using ZEB Horizon with Zeb Vision LiDAR point cloud scanner. The ZEB Horizon operate using Zeb Vision which is a 360 camera to capture imaging data of the scanned area, resulting point cloud with RGB imagery. The point cloud scanning was done during night time to reduce the point cloud noise due to reflection in the window. The data was collected in different segments, collecting different parts of the building on each of the segments.

After the scanning process, the point cloud representation undergone data processing process which are .slam data processing, noise reduction, and integration between segments. The data was first collected in the form of .slam data file and then processed into Laz using Faro Connect software. After turning the file into .laz, the data is going through noise reduction and integration process using cloud compare software. In this process, noise points are deleted. Furthermore, separated data are then combined into one showing a complete point cloud environment which is ready to be visualised in VR. Before VR visualisation, the point density is reduced into several level of density using segment feature in Cloud Compare. The density reduction is random, producing different density from 500 thousand, 1 million, 5 million, 10 million, 15 million, and 20 million. Six (6) level of density is intentionally created to overview the impact of point density to the visual quality in VR. Therefore, future researcher are able to decide which density suitable to be used in the VR simulation research.

3.2 Visual Quality Evaluation

After the density point cloud representation has been produced, the point cloud file then visualized in VR for further evaluation using Unreal Engine 5 (UE5). In order for the software to read point cloud representation , LiDAR Point Cloud plugin of UE5 is installed. Once the point cloud representation is inserted, VR tools are prepared such as Steam VR and Meta Quest Link which linked VR HMD into UE5. The simulation process is then recorded and captured as .jpeg file and then pre-processed using Canny Edge detection to produced edge structure of the image. Canny Edge detection is a image processing technique to detect edges created by an image (Tasneem & Afroze, 2019). The detection process involve several steps such as noise reduction, gradient calculation, non-maximum suppression, double thresholding, and edge tracking. The processed image then further evaluated using Structural Similarity Index Measure (SSIM) and Edge similarity by comparing the VR point cloud image with the real picture image that serves as the ground truth.

SSIM is used to evaluate the level of similarity between two images which are expected to adhere to human visual system (Wang & Bovik, 2002). The method use three main factors which are Luminance Comparison, Contrast Comparison, and Structure Comparison (Wang et al., 2004). While the point cloud image was analysed with using SSIM, it is also assessed with Edge similarity metric. In the similarity assessment process, the precisions are computed by comparing the pixel of the edge maps (point cloud and real picture edge image). The score indicated fraction of pixels that are identical, showing measurement of edge interaction.

The analysis is focusing on edge interaction in order to depicts visual accuracy for utilization of wayfinding and indoorGML element. Edge is one of the key elements of wayfinding variable which represent spatial boundary such as wall, barriers, etc. Meanwhile in IndoorGML, edge serves as a boundary class that separates spaces in building. Using edge as the ground data could identify feasibility of point cloud as wayfinding simulation while estimating the usability of IndoorGML for wayfinding application.

3.3 Data and Software Availability

Point cloud data presented in this study is openly available under a permissive CC-BY-SA 4.0 licence with DOI **10.4121/1ccabad8-d891-4dd4-90e7-49d5e329f980.** The files could also be access through the following link https://data.4tu.nl/private_datasets/Bnlz1ZnfHJr3FWTyWCnXunfJOq8xnyu_Ovud91pG_y8.

4 Results and Analysis

This study is focusing on visual assessment of point cloud environment in VR visualisation by analysing different point density and visual quality of the environment. Six level of density that are being tested are 500 thousand, 1 million, 5 million, 10 million, 15 million, and 20 million. The original point cloud density collected from LiDAR scanning is 20 million in .laz format. The point cloud density is then reduced using segment feature in cloud compare with random point reduction.

Different density of points in VR visualisation apparently significantly affect how the points are presented in the HMD. The lesser the points the more coarse edges created by the points. On the contrary, the denser the points the smoother the surface created by the points will be. By default, UE5 would fill the gap created in sparse point cloud, thus creating bigger points in less dense point cloud representation which can be seen in the 500 thousand point image (figure 2). Meanwhile, Point cloud visualisation in the 20 million points image, showed smaller point due to the great number of points embedded in the object area.

Furthermore, as we observe in detail at figure 3, it is noticeable that the closer our view to the surrounding the space, the greater the voids between the points especially with low-density point cloud representation , such as 500 thousand point to 1 million point. However, beginning 5 million point cloud density, the voids in closer view are relatively smaller and even getting smaller along with the increase of the density. Meanwhile, at the farther view the voids are generally non-existent, creating a well-defined surface in all point density.

Generally, despite the visual differences by different density, the corridor representing edge wayfinding variables and indoor GML component are still well defined, providing clear path for wayfinding. Clearly defined edges and objects of virtual environment are very important in order creating an optimum user experience of wayfinding. In wayfinding, user are expected to be able to identify several spatial traits, from edge, path, landmarks, which is represented in signage, districts, and nodes. Thus, the key to the identification process began by having clearly defined visual geometry of the environment. Furthermore, good presentation of point cloud environment is significant in creating similar ambience of the immersive reality with the real environment which can also be represented in good colour, lighting, and shadow. Greater similarity ambience with the real environment could induced a more natural wayfinding movement for the simulation participant.

4.1 SSIM and Edge Similarity Assessment

This study is focusing on visual assessment of point cloud environment in VR visualisation by analysing different point density and visual quality of the environment. Six level of density that are being tested are 500 thousand, 1 million, 5 million, 10 million, 15 million, and 20 million. All the six different density are then compared to the real environment image using 2 metrics which are Structural Similarity Index Measure (SSIM) and Edge Similarity (%). Image which are used in the SSIM and Edge Similarity evaluations are pre-processed using Canny Edge detection to retrieve its edge feature (figure 4). The edge retrieval result showed significant edge detection on voids between points, especially on closer VR view. Nonetheless, on surfaces with dense points, edges are emerges in the appropriate objects such as TV, doors, lamps, and chairs. However, the edges that supposed to define walls and floors are not detected. This situation occurred not only the VR visualisation point cloud image, but also on the real picture image which also acted as the ground truth. There are several potential possibilities that causing this occurrence, such as similar colour contrast between wall and the floor and the lack of shadow-cast area on the floor and wall areas (Tasneem & Afroze, 2019).

In SSIM analysis, the smallest number showed score of 0.3890 which came out from 500 thousand point cloud density (table 3). While the highest score showed 0.519 coming from 20 million point density. SSIM evaluates the structural information created from the image luminance and contrast which evaluation metric ranges from -1 to 1. Score 1 means that the image has perfect structural similarity. Zero (0) score mean that it has no structural similarity. While negative value would mean that the images has dissimilar structure. SSIM score result of the tested images are ranging from 0.3 to 0.5 with 0.3 has the lowest density (500 thousand) while 0.5 has the highest density (20 million), indicating low to moderate structural similarity. This indicated that the higher point cloud density are well identified while the lower ones are generally still identifiable although not as clear. Additionally, the low result signify that the structural image detail between VR visualised point cloud compared to the real environment photo differs significantly. Nevertheless, the significant difference could also affected due to difference in the feature representation, lighting, or even resolution. Furthermore, the image clarity identification would still needs to consider data from Edge Similarity analysis. Because the combination of lower score of one matric with higher score on the other matric could resulting an acceptable image visualisation.

The analysis result of Edge Similarity percentage showed similar steady trend ranging from 92 to 95 % (figure 5). Although points with the highest density (20 million) showed the highest percentage of edge similarity, but the overall percentage are relatively high with similarity above 90%, indicating good structural outline (table 3). The data are collected from comparing extracted edges of both the VR point cloud image with the image of the real environment. Key boundaries of both images are identified using edge detection algorithms. The result showed that despite difference in density, all possess clear edges to help identified clear border.

Figure 2. VR visualisation of different point cloud density

Figure 3. VR visualisation of near and far point scarcity in different point cloud density

The image density analysis result showed a general increase of score along with the increase of density. The SSIM and edge similarity analysis together could indicate feasibility aspect to the visual quality of point cloud VR environment. In 500 thousand points SSIM result indicate poor structural similarity which affect to the insufficient detail and lack of visual quality. With this result object and landmark recognizability will be difficult. Furthermore edge similarity score result showed moderate similarity. It indicated that there might be incomplete edges due to the lack of density but the outline and object edge are still recognizable. By considering both metric 500 thousand points, it can be stated that 500 point density is not sufficient for task which requires high fidelity such as VR wayfinding. In 1 million point density, the result showed that there is a slight improvement in SSIM score, which indicating still lack of visual quality and resemblance to the real photo image. Edge similarity score showed a slight drop indicating the emergence of noise and irregularities, which causing less noticeable edge. This score indicated a slight better visual quality compare to the 500 thousand points although still insufficient for task with high fidelity. In 5 million point density, the SSIM score does have an increasement but not significant in comparison with the increase of point density. This mean that the visual fidelity is still considered to be low. On the edge similarity score, there is a decline of score which interpreted as insufficiency for sharp transition. Both score interpreted that there's a decrease in visual quality despite and lack of precision in navigational feature. Meanwhile score in 10 million points showed a great increase in SSIM score, supported by the increase of edge similarity. Indicated an improve in edge and visual quality making it sufficient for immersive task. Interestingly in 15 million score result showed a slight decrease which might be caused by a distorted image quality provided for 15 million density. Finally, in 20 million points SSIM result showed best visual fidelity in which the structure and detail are well captured, making it most suitable for high-fidelity VR task. Furthermore, edge similarity showed best edge preservation. Thus, 20 million point density can be deemed as the most ideal density for wayfinding simulation.

Figure 4. Result of pre-processed image using Canny Edge detection on various VR point cloud density and ground truth image

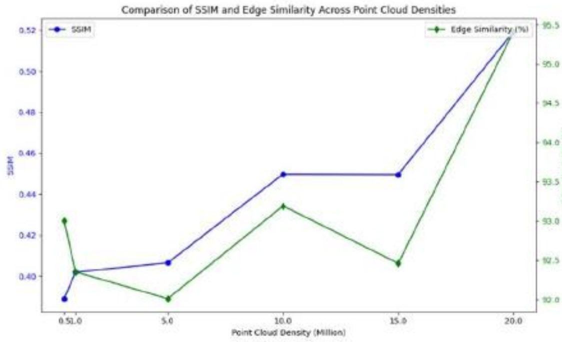

Figure 5. Comparison of SSIM and Edge similarity across point cloud densities

Table 3. SSIM and Edge similarity score across density

No	Number of Point (Density)	SSIM	Edge Similarity (%)
1	500 thousands	0.3890	93.00
2	1 million	0.4019	92.35
3	5 million	0.4065	92.01
4	10 million	0.4497	93.19
5	15 million	0.4496	92.46
6	20 million	0.5193	95.41

5 Discussion

The SSIM and edge similarity analysis indicating visual quality for wayfinding task which resulting 20 million point density as the best point density for wayfinding task. However, the higher the density the more it will affect the computational efficiency. Therefore, the simulation needs to use best computer system should the highest density were expected to be used in the wayfinding simulation. Nonetheless, the result showed lesser point density as low as 10 million points to be well sufficient for VR simulation. Although the point scarcity image showed rather large void in close view in comparison with 15 and 20 million point density. Therefore, it is best to find balance between user experience and visual fidelity for wayfinding task.

With the result that is apparent from the point cloud VR visual quality, it is shown that in some density images are identifiable making it possible to be segmented for better wayfinding simulation system. Furthermore, the use of edge as wayfinding boundary in VR could well integrated with IndoorGML which serves as a spatial information standard for indoor navigation system. Thus, the development of IndoorGML usability could be enhanced by inducing the edge quality metric to the IndoorGML schema.

6 Conclusion

The increase of wayfinding VR simulation encourage more development of photorealistic environment to the immersive reality. Point cloud which possess great potential of providing photorealistic environment, should be evaluated further to analyse its feasibility for supporting wayfinding simulation task. This study evaluate the visual quality of point cloud VR visualisation in different point density. The evaluation consider several aspect and metric which are the point scarcity, visual clarity in close and far view, SSIM metric, and edge similarity. The result showed 10 million point as the lowest point density for appropriate visual fidelity. Meanwhile, 20 million points has the best visual quality, yet might cause greater computational load due to demand of higher computer specification. On the other hand, the visual analysis result also indicated the possible use of IndoorGML for point segmentation due to the clear edge of wayfinding objects. Furthermore, due to the similar entities, it is ideal that VR wayfinding simulation to take into account IndoorGML as part of spatial system in the simulation.

In the future, the study could extend to other wayfinding framework and identify the potential alignment wayfinding entity with other IndoorGML components. There are 4 other wayfinding framework that has not been addressed in this study which are nodes, district, landmark, and path. By exploring these parameter in VR point cloud visual evaluation, strategies for wayfinding simulation could be optimized.

APPENDIX E: Experiment Design Criteria

To execute a simulation experiment that can validate the VR simulation result, experiment design criteria are developed to establish consistency, reliability, and validity in the evaluation process.

1. **Environment Criteria:**
   - **Photorealistic environment**: The virtual environment embedded in the VR must be able to represent real-world visual fidelity accurately.
   - **Visible signages**: Clear and distinct signage must be available to support the identification of wayfinding visual cues.
   - **Seamless walkthrough interface**: A joystick-based movement system must be implemented as a navigation tool to maintain intuitive and smooth locomotion.
   - **Interactive elements:** Interactions with various indoor and outdoor elements, such as doors and traffic lights, should be built to accurately real-world representation
   - **Technical consistency**: The virtual simulation frame rate must be kept at least 60 fps to reduce the risk of motion sickness and maintain fluid visual rendering.
2. **Participant Criteria:**
   - **Sample size**: 20-30 participants per-simulation
   - **Participant eligibility**:
     - No prior knowledge of the tested environment
     - Participants from The Netherlands will navigate the Indonesia environment, while Indonesia participants will navigate in The Netherlands environment.
     - Minimum participant age: 18 years old
     - Participants must have an appropriate health condition that will not undergo severe motion sickness or epilepsy during wayfinding simulation
3. **Simulation Task Criteria:**
   - **Time limit**: Each simulation session should not exceed 20 minutes to reduce the risk of motion sickness
   - **Scenario design**:
     - **A control scenario**: Wayfinding task without any modification to the environment interaction
     - **Experimental scenario 1**: Wayfinding task with modification to the access rights to test the impact of access rights on spatial cognitive development
     - **Experimental scenario 2**: Wayfinding task with enhanced 3D digital environment to test optimized wayfinding performance
   - **Wayfinding objectives**: Simulation participants must be able to do wayfinding to the predefined destination mentioned in the task
   - **Navigation Metrics**: The data will be collected from:
     - Task completion time

- Number of directional errors
- Instances of hesitation or backtracking
- Interaction with signage and environmental cues

APPENDIX F: List of Figures

APPENDIX G: List of Tables