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Molecular & Cellular Biomechanics 2024, 21(3), 434.
https://doi.org/10.62617/mcb434

Article

Exploring the influence of body movements on spatial perception in landscape and interior design

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CITATION

Zhao P. Exploring the influence of body movements on spatial perception in landscape and interior design. Molecular & Cellular Biomechanics. 2024; 21(3): 434. https://doi.org/10.62617/mcb434

ARTICLE INFO

Received: 27 September 2024
Accepted: 14 October 2024
Available online: 8 November 2024

Abstract: This study investigates the influence of body movements on spatial perception in both landscape and interior design environments, focusing on how physical interactions shape spatial understanding beyond visual perception alone. Grounded in the theory of embodied cognition, the research examines how gait, posture, and movement dynamics affect spatial awareness. The study captures detailed data on movement patterns and visual engagement across different spatial contexts using a combination of real-world observations and Virtual Reality (VR) simulations, motion-tracking systems, wearable sensors, and eye-tracking technology. A total of 157 participants, aged 20 to 65, navigated both outdoor landscapes and indoor environments, with key variables such as surface materials, spatial layout, and lighting conditions manipulated to assess their effects on spatial perception. The study measured gait speed, step frequency, path deviations, time to destination, visual attention, and subjective ratings of perceived openness, ease of movement, and emotional response. Key findings include that surface materials significantly influenced gait speed and step frequency. For example, participants walking on concrete had a significantly faster gait speed (mean difference = 0.5220, $p = 0.001$) than those walking on gravel. In terms of spatial layout, the two-way Analysis of variance (ANOVA) results showed that winding paths led to more path deviations (F-statistic = 350.00, $p = 3.19 \times 10^{-8}$) and longer times to destination (F-statistic = 1744.00, $p = 2.39 \times 10^{-11}$) compared to straight paths. The environment type (landscape vs. interior) also significantly affected navigation, with landscape participants showing a more significant deviation from direct paths (F-statistic = 19.60, $p = 2.37 \times 10^{-3}$). Visual engagement data, analyzed through a chi-square test, indicated that vertical elements like walls approached significance in attracting visual attention (Chi-square = 2.88, $p = 0.0896$), while other elements like trees and benches had less impact. The Wilcoxon signed-rank test results showed significant differences between real-world and VR experiences in perceived openness (W-statistic = 0.0, $p = 0.001953$), ease of movement (W-statistic = 0.0, $p = 0.001953$), and comfort (W-statistic = 0.0, $p = 0.001953$), highlighting VR's limitations in replicating the full embodied experience of physical spaces.

Keywords: body movements; embodied cognition; virtual reality; spatial perception; motion tracking

1. Introduction

Spatial perception, how humans understand and interpret the space around them, is an essential aspect of landscape and interior design [1,2]. It goes beyond the visual to encompass how individuals move through and physically experience space [3]. Designers and architects have long understood the importance of creating aesthetically pleasing environments that functionally align with human movement patterns [4]. However, recent advances in cognitive science, particularly the theory of embodied cognition, have shifted the focus toward understanding how physical movements shape our perception of space [5,6]. This research delves into the intersection of body movement and spatial design, exploring how different environmental layouts, surface materials, and spatial configurations influence how people perceive and navigate natural and built environments.

The theory of embodied cognition suggests that cognitive processes, including perception, are deeply rooted in the physical body's interactions with the environment [6,7]. This contrasts with traditional views prioritising the brain as the central processor of sensory information [8]. Embodied cognition proposes that how we move through space—whether walking on a gravel path, ascending a flight of stairs, or navigating a winding corridor—profoundly shapes how we perceive that space [9]. In landscape and interior design, spaces are not passively experienced but actively engaged through physical movement [10,11]. Thus, spatial perception is influenced by visual, tactile, and kinesthetic feedback, all shaped by the body's interaction with the environment [12].

While much attention has been given to visual aesthetics in landscape and interior design, the role of physical movement in shaping spatial perception is less understood [13]. The path's texture, the room's openness, or the placement of vertical elements like trees or columns can influence how an individual moves through and experiences a space [14,15]. For instance, a person walking on grass may move differently than on concrete, and their perception of the space's openness, comfort, and flow may change accordingly [16,17]. These subtle yet impactful design elements underscore the need for a more comprehensive approach to spatial design that considers the entire sensorimotor experience [18–20].

In landscape design, natural elements such as terrain, vegetation, and surface materials guide movement in organic ways, creating a flow that is often more fluid and unrestricted than interior spaces [21–24]. The vastness of outdoor environments and the unpredictability of natural elements can evoke feelings of freedom or contemplation [25–30]. Conversely, interior design involves more confined, structured spaces where movement is guided by walls, furniture arrangements, and lighting [31–32]. The contrast between these two environments offers a unique opportunity to explore how different spatial dynamics influence movement patterns and spatial perception [33–35].

This study seeks to explore these dynamics in both real-world and virtual settings. With the rise of Virtual Reality (VR) as a tool for design visualization, there is increasing interest in whether VR can accurately simulate real-world spatial experiences [36]. Virtual environments allow designers to test and modify spatial layouts, surface textures, and lighting without the constraints of physical materials [37]. However, questions remain about how VR replicates real-world navigation's embodied experience [38,39]. By comparing real-world and virtual environments, this study aims to determine whether VR can effectively mimic the nuances of human movement and perception in physical spaces.

The research focuses on several key variables, including gait speed, step frequency, visual attention, and emotional responses, to assess how different design elements affect spatial perception. The study uses motion-tracking systems, wearable sensors, and eye-tracking technology to capture detailed movement patterns and visual engagement in landscape and interior environments. By integrating qualitative feedback from participants with quantitative data, this research provides a holistic understanding of how body movement influences spatial perception. Ultimately, this study aims to inform future design practices by highlighting the importance of considering human movement as a fundamental component of spatial perception. By understanding how design elements interact with the body's movements, architects and designers can create spaces that are not only visually appealing but also intuitive, comfortable, and engaging for users. Through a comparative analysis of real-world and VR environments, this research contributes to a deeper understanding of the embodied nature of spatial perception and offers valuable insights into physical and virtual design methodologies.

The article is presented as follows: Section 2 presents the theoretical framework; Section 3 presents the methodology; Section 4 presents the analysis; and Section 5 concludes the paper.

2. Theoretical framework

2.1. Embodied cognition and spatial perception

Embodied cognition is a theory that argues cognition is deeply rooted in the body's interactions with the environment, suggesting that our perception and understanding of the world are shaped not only by our mental processes but also by our physical experiences. In the context of spatial perception, embodied cognition highlights how individuals experience and interpret space through movement, posture, and physical interaction. The traditional cognitive view emphasizes the brain as the central processor of sensory information; however, the embodied cognition model suggests that the body is an integral part of this process. For instance, how we walk through a narrow corridor, climb a hill or explore an open plaza significantly affects how we perceive these spaces, as our bodily motions and constraints become a key factor in shaping our understanding of the surrounding environment.

From an architectural and design perspective, this means that space is not simply experienced visually or mentally but through the entire sensorimotor system. When we move through a space, our muscles, balance, and spatial orientation all contribute to our perception. For example, a well-designed pathway in a landscape may invite slow, contemplative walking, while a steep incline might encourage more rapid, energetic movement, each affecting how the space is perceived emotionally and physically. "We shape our buildings; after that, they shape us", Winston Churchill famously noted, emphasizing the profound interaction between our environment and movements. This highlights that our experience of space is a dynamic relationship, where the design of spaces can encourage or restrict specific movements, informing how we feel and think about those spaces.

In landscape design, the texture of the ground, the slope of a pathway, or the rhythm of tree placement can subtly guide movement, creating a sense of flow or resistance. Similarly, in interior spaces, the arrangement of furniture, the openness of a room, or the tactile quality of surfaces can lead us to move in specific ways, influencing how we perceive the comfort, scale, or even the purpose of the space. This notion of embodied perception aligns with the idea that our spatial awareness is visual and kinesthetic, as our sense of movement through space provides critical feedback on our surroundings.

Architectural and design disciplines can leverage this understanding by designing spaces that align with natural human movement patterns, creating aesthetically pleasing environments and functionally attuned to the human body's natural tendencies. For example, curving paths in a park might intuitively guide people toward a focal point without the need for explicit signs, while an open-plan interior can encourage free movement and social interaction, enhancing the perception of openness and collaboration. This holistic approach, which integrates embodied cognition into design, emphasizes that moving through space is as important as seeing it, offering a richer, more interactive experience of our environments.

2.2. Spatial dynamics: Landscape vs. interior design

Spatial dynamics refer to how physical spaces influence movement, interaction, and perception. In landscape and interior design contexts, spatial dynamics differ significantly due to openness, boundaries, natural elements, and structural layouts. Understanding these differences is crucial for designers as they directly impact how people move through, experience, and emotionally connect with a space. Both landscape and interior environments have unique spatial dynamics that shape human behaviour, but they do so in distinct ways, influenced by the nature of the space—whether it is open, outdoor terrain or confined indoor structures.

In landscape design, spatial dynamics are primarily governed by natural elements and the lack of rigid boundaries. Landscapes typically provide more open, unconfined spaces, allowing for fluid and unrestricted movement. Terrain, vegetation, and pathways play significant roles in directing movement, as the topography may gently guide or impede mobility. For instance, a meandering path through a park invites leisurely exploration, while steep or uneven terrain challenges users to engage more physically with the environment. The openness of outdoor spaces also means that focal points like trees, water features, or sculptures become important in orienting individuals and guiding their movement, subtly influencing their spatial perception. The vastness of landscapes can evoke feelings of freedom, tranquility, or even insignificance, depending on how they are designed. Wide, expansive spaces can lead to slower, more contemplative movement, while narrower or enclosed pathways might prompt quicker, more focused navigation.

In contrast, interior design operates within more defined boundaries and often involves structured, confined spaces, which heavily influence movement patterns. Spatial dynamics indoors are shaped by walls, furniture arrangements, ceiling heights, and lighting, all of which contribute to the perception of space. For instance, a room with high ceilings and minimal obstructions may create an expansive, open feeling that encourages free movement and social interaction. On the other hand, rooms with lower ceilings or tightly packed furniture can evoke a sense of cosiness or constraint, channelling movement in specific directions. Interior spaces are also more likely to utilize vertical elements, such as stairs or mezzanines, which introduce a third dimension to spatial dynamics by engaging upward or downward movement, affecting both the physical experience and the psychological perception of space.

Another vital distinction between landscape and interior design is the role of materiality. In landscapes, natural materials like gravel, grass, and wood contribute to how people move through and perceive the environment. These materials often interact with the senses—such as the crunch of gravel underfoot or the coolness of grass—which can enhance the embodied experience of space. In interior design, materials like wood, concrete, fabric, and metal influence tactile experiences and shape acoustics and lighting, further affecting spatial perception. For example, the hard surfaces of an industrial interior might create a sense of coldness or echoing sounds that encourage swift movement, whereas soft furnishings and warm lighting can promote a slower, more relaxed pace of interaction.

The relationship between movement and spatial dynamics also varies between the two environments. In landscapes, movement tends to be more organic and dictated by the land's natural contours. People are free to move in various directions, and their perception of space is influenced by vastness, sensory engagement with nature, and elevation changes. In contrast, movement in interior spaces is often more controlled and linear, governed by the layout of corridors, doors, and furniture. This confinement to particular pathways affects how people perceive the scale of the space and their ability to navigate through it.

2.3. Human-centered design principles

Human-centred design (HCD) is a framework that prioritizes the needs, experiences, and movements of the end users in the creation of spaces, ensuring that the environments are both functional and intuitive. In the context of spatial perception, HCD focuses on how individuals interact with their surroundings and how design choices can facilitate natural, comfortable, and enjoyable movement through space. Whether applied to landscape or interior design, human-centred principles encourage designers to consider how spaces will be navigated, perceived, and experienced by different users, adapting elements to optimize their physical, psychological, and sensory engagement.

Empathy is at the core of the human-centred design, which calls for a deep understanding of the users' physical needs and preferences. In spatial design, this means considering factors such as accessibility, ergonomics, and usability. For instance, in a landscape setting, pathways must be designed with varying users in mind, from individuals taking a leisurely walk to those requiring wheelchair access. The slope, surface material, and width of the pathways all play a critical role in ensuring that the space is inclusive and accessible to everyone. Similarly, in interior design, ergonomic considerations influence the placement of furniture, doorways, and fixtures to create an environment where movement is effortless and natural, accommodating a wide range of users, from children to older people.

Another key aspect of human-centred design is flexibility. Spaces should be designed to adapt to different functions, movements, and needs over time. In landscape design, this might involve creating multifunctional areas supporting active and passive recreation, allowing users to engage with the space in various ways. A park could have open lawns for sports, winding paths for walking, and shaded areas for relaxation, catering to diverse physical activities and preferences. In interior spaces, flexibility might involve the use of modular furniture or movable partitions, allowing users to reconfigure the space according to their needs—whether for collaborative work, private reflection, or social interaction. This adaptability ensures that spaces remain functional and relevant as user requirements evolve.

The principle of intuitive navigation is also central to human-centred design. In landscape and interior design, users should be able to move through a space efficiently, understanding its layout without needing explicit instructions. This can be achieved through thoughtful spatial organization, where the arrangement of elements naturally guides users toward certain areas or activities. In landscape design, for example, using sightlines and landmarks, such as fountains or sculptures, can orient users and direct movement. In interior design, the flow between rooms or sections should feel logical, with clear pathways and open sightlines that help users understand where they are and where they need to go. Intuitive navigation improves functionality and enhances users' spatial perception, creating a seamless interaction with the environment.

Aesthetic and sensory engagement is also integral to human-centred design principles. Spaces should be functional and create a positive emotional response, stimulating the senses to enhance the user experience. In landscape design, sensory elements like the sound of rustling leaves, the texture of stone underfoot, or the smell of flowers contribute to a richer, more immersive experience. Designers might use natural elements strategically to evoke specific emotional responses, such as tranquillity or excitement. Similarly, materials, lighting, and acoustics can be carefully chosen in interior design to create comfortable and welcoming environments. Warm lighting, soft textures, and sound-absorbing materials can foster a sense of calm and relaxation, while brighter lighting and vibrant colors might energize and stimulate movement.

Incorporating user feedback and participation into the design process is another hallmark of human-centred design. Designers often engage with users throughout the design and implementation stages, seeking input on how spaces are used and experienced. This ensures that the design solutions reflect user needs and preferences rather than hypothetical or generalized assumptions. In landscape projects, this might involve surveying park visitors about their movement patterns and preferred activities, while in interior design, occupants' feedback can inform the furniture arrangement or the placement of amenities. This iterative process, where user feedback shapes the final design, leads to more functional and user-friendly spaces.

3. Methodology

3.1. Population

The study population for this research consists of individuals from diverse demographic backgrounds, focusing on participants who regularly engage with both outdoor landscapes and indoor environments. To comprehensively analyse how Body Movements (BM) influence spatial perception, the sample includes a broad range of participants varying in age, gender, and physical ability. Specifically, the study will involve 157 participants, comprising 87 males and 70 females, recruited from urban and suburban areas. The age range of the participants spans from 20 to 65 years, with an average age of 38.6 years. This broad age range allows a thorough examination of how different demographic groups perceive space based on their movement patterns in landscape and interior settings.

To ensure that the study captures a variety of spatial interactions, participants are categorized into three main groups based on their activity levels and familiarity with different environments. The first group comprises 55 individuals (35% of the total sample) who frequently use outdoor spaces such as parks, gardens, and recreational areas. This group includes individuals participating in activities like jogging, walking, and outdoor sports, allowing the study to capture dynamic movement patterns in landscape settings. The second group comprises 63 participants (40%) who primarily navigate indoor environments, including offices, homes, and public indoor spaces like malls and museums. This group will provide insights into movement within confined and structured spaces, exploring how furniture layout, walls, and ceilings influence spatial perception. The final group of 39 participants (25%) is a mixed group that regularly interacts with both outdoor and indoor environments, providing a comparative perspective on how movement across different settings affects overall spatial awareness.

The study also considers varying physical abilities to explore how individuals with different movement capabilities perceive space. Among the participants, 18 individuals (11.5%) report limited mobility, including the use of assistive devices such as canes or wheelchairs. This subgroup allows the research to examine how design elements like ramps, stairs, and surface materials impact spatial perception and navigation for those with mobility challenges. By including individuals with a range of physical abilities, the study ensures a more inclusive understanding of how body movement shapes the experience of space for all users. In terms of educational background, the participants are diverse, with 52 individuals (33%) having completed higher education (college or university degrees), 67 participants (43%) holding a high school diploma, and the remaining 38 participants (24%) having varying levels of education, including vocational training and primary education. This demographic diversity ensures that the study accounts for different levels of spatial understanding, which can be influenced by education, professional experience, and exposure to designed spaces. Participants are selected from urban (58%) and suburban (42%) areas, ensuring a balanced representation of environments where people interact with man-made structures and natural landscapes. The urban participants are primarily recruited from large metropolitan cities with shared access to well-designed public landscapes (such as city parks) and modern interior spaces. In contrast, the suburban participants interact more significantly with residential outdoor spaces and smaller-scale interior designs, offering valuable insights into how spatial perception varies across different living environments.

3.2. Apparatus

Various tools and technologies are employed in this study to measure body movement’s influence on spatial perception accurately. These apparatuses are selected to capture both qualitative and quantitative data related to participants’ movement patterns and their interaction with the designed spaces, whether in outdoor landscapes or indoor environments.

1) Motion Tracking System: The primary apparatus for tracking body movement is an optical motion capture system with infrared cameras. This system comprises 12 high-resolution cameras (OptiTrack Flex 13) positioned at key points in landscape and interior spaces to capture participants’ movements in three dimensions. The cameras are calibrated to record at a frame rate of 120 frames per second, ensuring precise data on how participants walk, turn, and navigate through space. Reflective markers are placed on the participants’ key joints (ankles, knees, hips, shoulders, and head) to record their gait, posture, and orientation within the environment. The system can track movements within a 10 m × 10 m area in interior spaces and a 20 m × 20 m area in outdoor settings, providing comprehensive coverage of the designed spaces.
2) Wearable Sensors: Besides the motion tracking system, participants are equipped with wearable sensors to record their movement patterns in more natural settings. These include inertial measurement units (IMUs), such as the Xsens MTw Awinda system, which can track acceleration, angular velocity, and real-time orientation. Each participant wears three sensors—one on the lower back, one on the right thigh, and one on the left wrist—to capture data on movement dynamics such as speed, balance, and range of motion. The wearable sensors are wirelessly connected to a central computer for live data collection, allowing researchers to analyze how participants’ BM changes as they navigate different terrains and spatial layouts.
3) VR System: To simulate and test spatial perception in controlled environments, a VR system replicates landscape and interior designs. The HTC Vive Pro VR headset is employed, offering participants an immersive experience of moving through virtual spaces. The VR system is integrated with 3D models of the studied spaces, enabling researchers to manipulate variables like path layout, surface materials, and object placement without altering the physical environment. The participants’ head movements and navigation within the VR space are recorded to analyze how spatial perception changes in response to various design elements. This VR simulation allows for a controlled exploration of spatial dynamics without external environmental influences such as weather or time of day.

4) Eye-Tracking Glasses: To gain insight into how participants visually engage with their surroundings during movement, Tobii pro glasses 3 eye-tracking technology is used. These lightweight, wearable glasses capture real-time eye movements, tracking where participants focus their attention as they move through different spaces. The glasses record data such as fixation points, saccades, and gaze duration, allowing the study to correlate visual attention with body movement and spatial perception. This data helps identify key design features that capture attention and influence navigation choices.
5) Survey Instruments and Questionnaires: To complement the quantitative data collected through motion capture and sensors, subjective data is gathered using a series of surveys and questionnaires. Participants are asked to complete surveys assessing their perception of space, comfort, and emotional response before and after navigating landscape and interior environments. The surveys are designed using a Likert scale, where participants rate their level of agreement with statements regarding spatial openness, ease of movement, and overall experience. This self-reported data provides valuable context to the quantitative findings, helping to understand how different individuals perceive space based on their BM.
6) Environmental Sensors: To ensure consistency in outdoor and indoor conditions, environmental sensors measure temperature, humidity, and lighting levels. These sensors, such as the Kestrel 5500 Weather Meter, are deployed in landscapes and interior spaces to control external variables that may influence spatial perception. For instance, changes in light or weather conditions may impact how participants move through outdoor spaces, while varying light intensity indoors may affect visual perception. The data from these sensors help standardize the conditions under which participants experience the spaces, allowing for a more accurate comparison of movement and perception across different environments.
7) Data Analysis Software: To analyze the large volume of data collected from the motion-tracking system, wearable sensors, and eye-tracking glasses, specialized software tools are used. Motion capture data is processed using OptiTrack Motive software, which allows for the analysis of joint movements, speed, and gait. Data from the IMUs is processed using the Xsens MVN Analyze software, providing detailed reports on participants’ movement dynamics. The eye-tracking data is analyzed using Tobii Pro Lab software, which generates heatmaps and gaze plots to visualize where participants focus their attention. All data are compiled and analyzed using SPSS and MATLAB to identify correlations between movement patterns and spatial perception.

3.3. Variables

In this study, quantitative and qualitative measurements are employed to analyze the influence of BM on spatial perception in landscape and interior design contexts. The primary focus is capturing detailed movement patterns and their correlation with participants' spatial awareness, comfort, and overall experience of space. Various variables, categorized as independent, dependent, and control variables, are measured to ensure a comprehensive understanding of the relationship between body movement and spatial perception.

3.3.1. Independent variables

The independent variables in this study are the design characteristics of the environments (landscape and interior), which are manipulated to assess their effect on participants' movement and perception. These include:

1) Spatial Layout: The organization of space in landscape and interior settings, including arranging paths, walkways, or corridors. In landscape design, variations in path curvature (e.g., straight vs. winding) and terrain type (flat vs. sloped) are tested. Different room configurations (open-plan vs. compartmentalized) and circulation routes are examined in interior design.
2) Surface Materials: The texture and type of surface materials, such as gravel, concrete, wood, grass, or carpet, can affect movement ease and perception. In landscapes, natural vs. artificial surfaces are compared, while in interior spaces, the effect of different flooring materials on movement comfort is analyzed.
3) Vertical Elements: Vertical design features, such as trees, sculptures, walls, or columns. These features may alter movement flow and spatial perception by creating focal points or barriers that guide or restrict movement.
4) Lighting Conditions: Lighting levels (bright vs. dim) and types (natural vs. artificial) are adjusted in both environments to observe their impact on movement patterns and spatial perception. Lighting can affect depth perception, movement speed, and comfort, especially in interior settings.
5) Spatial Boundaries: Defined as the degree of enclosure or openness in a space, this variable distinguishes between enclosed spaces (interior rooms with walls) and open spaces (landscapes or open-plan interiors). Spatial boundaries are expected to affect participants' sense of freedom in movement and their perception of space size.

3.3.2. Dependent variables

The dependent variables capture the participant's responses to the different spatial designs and measure how their movement patterns, perceptions, and experiences are affected. These include:

1) Movement Patterns:
    - Gait Speed and Direction: Measured using the motion tracking system, this variable captures the average speed at which participants move through different spaces. Directional changes and the smoothness of movement (e.g., straight or curved trajectories) are also recorded to analyze how the spatial layout influences navigation.

- Body Orientation and Posture: Changes in body posture (e.g., upright vs. leaning) and orientation (facing forward vs. turning frequently) are measured to assess how the environment encourages or restricts natural movement.
- Step Frequency and Stride Length: Collected from wearable sensors, this data measures how participants adjust their steps based on surface materials and spatial boundaries. For instance, participants might take shorter steps on uneven surfaces, while longer strides may be observed in open spaces.

2) Visual attention
    - Fixation Points and Gaze Duration: Eye-tracking data captures where participants focus their attention as they move through the space. Key metrics include the number of fixation points (areas of interest) and the gaze duration at specific objects or features, indicating which design elements capture the most attention.
    - Gaze Shifts: The frequency and speed of gaze shifts (moving the eyes from one focal point to another) are also measured. Rapid gaze shifts may indicate difficulty processing the space, while sustained focus may suggest a comfortable and engaging environment.
3) Spatial Perception
    - Perceived Space Openness or Enclosure: Measured through post-navigation surveys where participants rate their perception of how open or enclosed a space felt during movement. Higher openness ratings are expected in more expansive landscapes, while lower ratings may be given to confined interior rooms.
    - Perceived Ease of Movement: Participants rate how easy or difficult it was to move through the space, with specific attention to surface materials, terrain, and spatial layout. The goal is to correlate these perceptions with objective movement data such as gait speed and step frequency.
    - Emotional Response: Participants’ emotional reactions to the space (e.g., feelings of calm, excitement, or discomfort) are captured through a Likert-scale questionnaire. This provides insight into the psychological impact of different spatial features.
4) Navigation Efficiency
    - Time to Destination: The total time it takes for participants to navigate from one point to another is recorded. Faster navigation times are expected in spaces with clear sightlines and unobstructed pathways, while longer times may indicate more complex or disorienting spatial layouts.
    - Path Deviations: The frequency and extent of deviations from a direct path (measured by the motion capture system) are analyzed to determine how design elements such as curves, obstacles, or landmarks affect navigation choices.

3.3.3. Control variables

To ensure that the results are not influenced by external factors, several control variables are monitored:

1) Environmental Conditions: For outdoor environments, weather conditions such as temperature, humidity, and wind speed are controlled or measured using environmental sensors to account for their potential impact on movement. In interior environments, factors like temperature, ventilation, and noise levels are standardized across all participants.
2) Physical Ability: Participants’ mobility levels (e.g., those using assistive devices vs. those without) are accounted for in the analysis to avoid skewing the results. Data from participants with limited mobility are analyzed separately from those without mobility challenges to provide accurate insights.
3) Time of Day: To control for variations in perception due to lighting or fatigue, all measurements are conducted at consistent times of day, either in the morning or early afternoon, ensuring uniform natural light in outdoor spaces and consistent lighting conditions indoors.

3.4. Data collection methods

The data collection for this study is carried out through quantitative and qualitative approaches designed to capture detailed insights into how BM influence spatial perception in landscape and interior environments. The collection process involves three key phases: observational data gathering, movement tracking using advanced technological tools, and participant feedback through surveys and interviews.

3.4.1. Observational data gathering

The first step in data collection involves direct observation of participants as they navigate through selected landscape and interior spaces. These observations are conducted in natural settings (e.g., parks, gardens, office buildings, and residential interiors) and controlled environments (e.g., VR simulations). Researchers observe how participants move within the space, noting deviations from expected movement paths, hesitations, or exploration patterns. Observations focus on conscious actions, such as deliberate turns or stopping to engage with a particular design element, and unconscious behaviours, such as posture shifts or gait adjustments in response to changes in terrain or flooring. These observations are documented with video recordings to ensure accurate post-analysis.

3.4.2. Motion tracking and sensor data collection

Data is collected using a comprehensive motion capture system and wearable sensors to quantify movement patterns. Participants wear reflective markers on key joints (ankles, knees, hips, shoulders, and head), and their movements are tracked using 12 high-resolution infrared cameras positioned around the study area. This system captures detailed data on gait speed, direction, body orientation, and posture as participants move through the landscape or interior environment. The data is recorded at a frame rate of 120 frames per second, ensuring precise tracking of movement dynamics in real time.

In addition to motion capture, participants are equipped with wearable inertial measurement units (IMUs) attached to their lower back, right thigh, and left wrist (**Figure 1**). These sensors track acceleration, angular velocity, and orientation, allowing for the analysis of balance, step frequency, and stride length. The wearable sensors also provide valuable data on how participants respond to different surface materials and terrain types, offering insights into how environmental factors such as gravel, grass, or carpet influence movement ease and comfort. All sensor data is wirelessly transmitted to a central system for real-time monitoring and is later processed using specialized software to identify movement patterns linked to spatial perception.

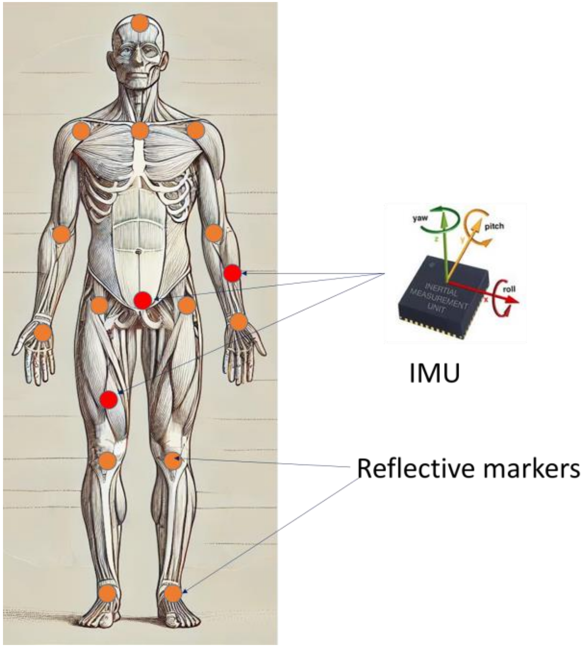

Figure 1. IMU and reflective marker placement.

3.4.3. Eye-tracking and visual engagement data

To complement the motion-tracking data, participants wear eye-tracking glasses to monitor visual engagement with the space. Tobii pro glasses 3 (**Figure 2**) captures where participants direct their gaze, the duration of their focus on specific elements, and how frequently they shift their visual attention between objects or areas. The eye-tracking data helps to correlate body movement with visual perception, identifying key features of the space (e.g., pathways, obstacles, or focal points like sculptures) that capture participants' attention. This data is essential for understanding how design elements guide or disrupt natural movement and spatial awareness.

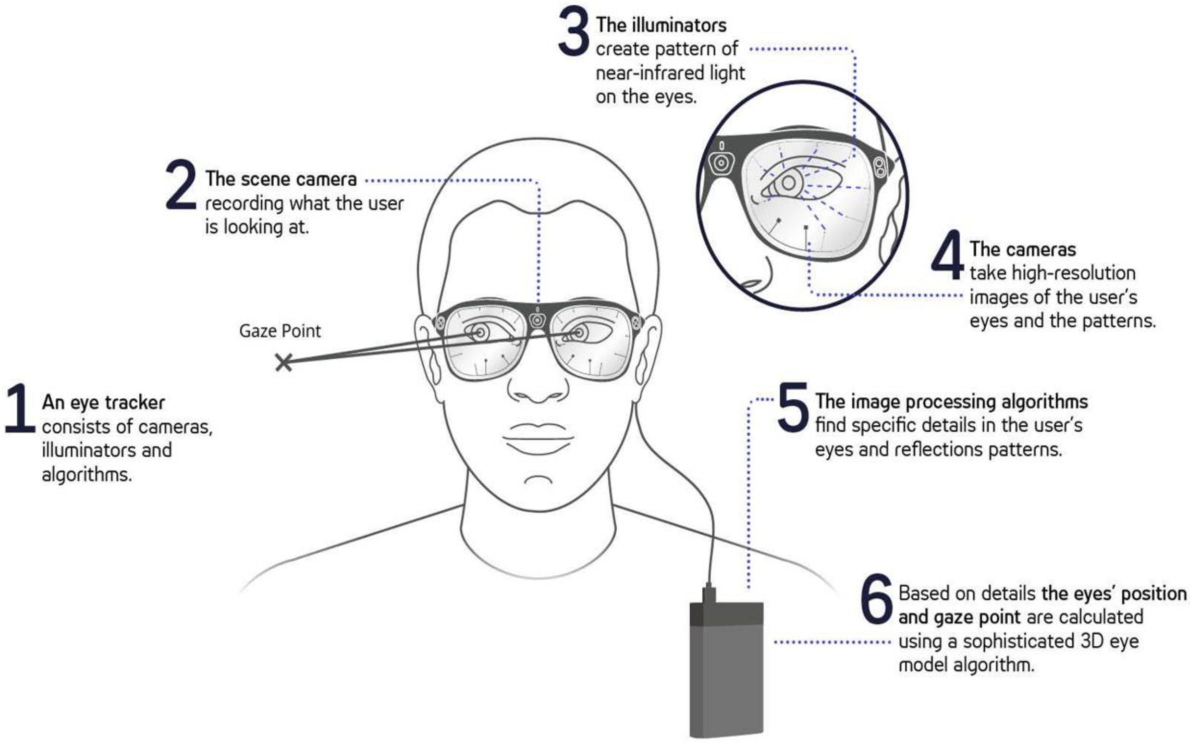

Figure 2. Tobii pro glasses 3.

3.4.4. VR simulations

In addition to real-world observations, VR simulations study how participants move through and perceive spaces under controlled conditions. Participants wear an HTC Vive Pro VR headset and are immersed in virtual landscapes or interior designs modelled after real-world spaces. In the VR environment, researchers can manipulate variables such as path layout, surface materials, and lighting conditions without the physical constraints of real-world environments. The participants' movements and visual engagement in the virtual space are recorded and analyzed to understand how specific design features influence spatial perception. The use of VR allows for greater flexibility in testing various design scenarios and ensures that environmental variables (such as weather or noise) are controlled.

3.4.5. Participant surveys and interviews

After each navigation session, surveys and interviews were conducted to gather qualitative data on participants' perceptions. The surveys are designed using a Likert scale, where participants rate statements regarding their experience of the space. Questions address the ease of movement, the perceived openness or confinement of the space, and emotional responses such as comfort, stress, or engagement. This subjective feedback is crucial for understanding how participants interpret the space beyond the measurable physical data. It also provides insights into psychological aspects of spatial perception, such as feelings of safety, tranquillity, or stimulation in response to the design.

Following the surveys, semi-structured interviews are conducted with a subset of participants to delve deeper into their experiences. These interviews focus on understanding why participants made confident navigation choices, how they felt about specific design features, and what improvements or changes they would suggest to enhance spatial experience. The interviews also explore spatial perception's emotional and cognitive aspects, offering more prosperous, detailed insights than surveys alone.

3.4.6. Environmental data collection

In outdoor environments, environmental data such as temperature, humidity, and lighting levels are recorded using sensors to control for external variables that might affect movement and perception. A Kestrel 5500 Weather Meter monitors weather conditions in real-time, ensuring that changes in environmental factors are accounted for when analyzing the participants' movement data. Consistent lighting and climate control are maintained in interior spaces to ensure a standardized experience for all participants.

In conclusion, the data collection methods used in this study employ a multi-dimensional approach, combining direct observation, advanced motion tracking technologies, eye-tracking, VR simulations, and qualitative feedback from participants. This combination of quantitative and qualitative data ensures a comprehensive understanding of how BM influence spatial perception across landscape and interior design environments. The meticulous data collection allows for robust analysis, providing valuable insights into the dynamic interaction between human movement and spatial design. **Table 1** shows the data collected in this study.

Table 1. Types of data collected in the study along with the corresponding units.

Data Collected	Description	Measurement Unit
Gait Speed	The average speed of participants' movement through space	Meters per second (m/s)
Step Frequency	Number of steps per second	Steps per second (steps/s)
Stride Length	Distance between consecutive steps	Meters (m)
Body Orientation	The direction in which the body is facing during movement	Degrees (°)
Posture Changes	Adjustments in body posture during navigation	Qualitative observation (NA)
Movement Path	The actual path followed by the participant	Meters (m)
Time to Destination	Time taken to navigate from point A to point B	Seconds (s)
Path Deviations	Number of deviations from the most direct route	Count
Acceleration	Change in speed during movement	Meters per second squared (m/s^2)
Angular Velocity	Speed of rotation of body segments (e.g., hips, shoulders)	Degrees per second (°/s)
Gaze Fixation Duration	Time spent focusing on a specific object or area	Seconds (s)
Gaze Fixation Points	Number of distinct areas or objects participants focus on	Count
Gaze Shift Frequency	Number of shifts in gaze from one object to another	Count per second (s^{-1})
Perceived Openness	Participants rated how open or confined the space felt	Likert scale (1–5)
Perceived Ease of Movement	Participants rating of ease or difficulty in navigating space	Likert scale (1–5)
Emotional Response	Emotional reactions (e.g., calm, stressed) during navigation	Likert scale (1–5)
Temperature	Ambient temperature in outdoor environments	Degrees Celsius (°C)
Humidity	Humidity level in outdoor environments	Percentage (%)
Lighting Level	Brightness in indoor or outdoor environments	Lux (lx)

3.5. Experimental design

The experimental design for this study is structured to systematically analyze how BM influence spatial perception across both landscape and interior environments. The experiment has two phases: real-world navigation in selected landscape and interior settings and a controlled VR simulation of similar environments. A within-subjects design is employed, meaning each participant navigates through all experimental conditions to provide comparative data on their movement patterns and spatial perception.

3.5.1. Phase 1: Real-World navigation in landscapes and interior spaces

1) Participant Preparation Upon arrival, each participant is briefed on the purpose of the study and the procedures involved. After obtaining informed consent, participants are fitted with the necessary motion-tracking equipment, including reflective markers attached to key joints (ankles, knees, hips, shoulders, and head), as well as wearable inertial measurement units (IMUs) placed on the lower back, right thigh, and left wrist. These devices capture real-time data on movement patterns, such as gait speed, step frequency, and posture changes. Participants are also fitted with Tobii Pro eye-tracking glasses to monitor visual engagement with the environment as they move through the space. The eye-tracking glasses record where participants focus their attention, how often they shift their gaze, and the duration of fixations on specific objects or areas.
2) Experiment Setup The experiment is conducted in two distinct types of environments: one outdoor landscape setting and one indoor setting.
    - Landscape Environment: A 500-m-long section of a public park is selected, featuring varying terrain (flat, inclined, and uneven), different path materials (gravel, grass, concrete), and natural landmarks such as trees, benches, and water features. The layout includes straight and winding paths designed to test how participants navigate different spatial configurations and surface materials.
    - Interior Environment: The indoor setting consists of an ample, open-plan office space, with defined sections for meeting areas, private offices, and open corridors. Furniture is arranged to create different navigation challenges, including narrow hallways, wide open spaces, and areas with vertical elements such as columns. The lighting is carefully controlled, with some areas featuring bright lighting and others dimly lit to observe its effect on spatial perception.
3) Task Instructions: Participants must complete a navigation task in both environments. They are provided with a starting point and an endpoint, and their goal is to navigate the space as naturally as possible without any specific instructions on how to reach their destination. They are told to pay attention to their surroundings and to move at their own pace. The natural movement allows the experiment to capture participants' intuitive navigation choices, gait adjustments, and engagement with design elements. In both environments, the time taken to complete the task is recorded, along with the number of path deviations (if participants stray from the most direct route). The motion tracking system captures movement data such as gait speed, step frequency, body

orientation, and any posture adjustments in response to environmental features (e.g., uneven surfaces or narrow spaces).

4) Visual Engagement: Participants’ eye movements are recorded throughout the task to track their visual engagement with the space. The eye-tracking glasses capture data on fixation points (specific elements that capture their attention), gaze shifts, and focus duration on different objects or areas. This data is used to identify which design features (e.g., pathways, lighting, vertical elements like trees or columns) guide or disrupt navigation and spatial perception.
5) Post-Navigation Surveys After completing the navigation task in each environment, participants are asked to complete a survey. The survey uses a Likert scale to assess their perception of the space, including how open or confined it felt, how easy it was to move through, and their overall emotional response (e.g., whether they felt calm, stressed, or engaged). The survey also asks participants to comment on specific features of the environment, such as surface materials, lighting, and path layout, and how these influenced their movement and spatial awareness.

3.5.2. Phase 2: VR simulation

To ensure that environmental variables such as weather, temperature, and noise do not influence participants’ movement and perception, the second phase of the experiment is conducted in a VR environment. The VR simulation replicates the real-world landscape and interior spaces but allows researchers to manipulate specific design elements without external interference.

1) VR Setup Participants wear the HTC Vive Pro VR headset, which immerses them in a 3D virtual environment. The VR system is integrated with motion-tracking technology to capture their movements in the virtual space. The same reflective markers and wearable sensors used in the real-world phase are employed in the VR phase, allowing consistent data collection across both experiment phases.
2) Simulated Environments the VR environment is a virtual replica of the real-world landscape and interior spaces. This includes the same path layouts, surface materials, lighting conditions, and vertical elements as the real-world experiment. However, researchers can manipulate variables more quickly in VR to test different design scenarios. For example, the terrain in the virtual landscape can be adjusted from flat to inclined, or the lighting in the interior space can be instantly dimmed or brightened without physically altering the environment.
3) VR Task Participants are given the same navigation task as in the real-world phase. They are instructed to navigate from a starting point to an endpoint in both the virtual landscape and interior environments, moving as naturally as possible. The same data (gait speed, step frequency, body orientation, visual engagement) is recorded as they move through the virtual space.
4) Manipulation of Design Variables in the VR phase, researchers can introduce subtle environmental changes to test how these modifications affect movement and spatial perception. For instance, they can slightly alter the curvature of a pathway, change the texture of a surface, or shift the position of vertical

elements like trees or columns. These manipulations allow for a controlled comparison of how small design changes influence participants' navigation choices and spatial awareness.

5) Post-VR Surveys After completing the VR navigation task, participants are again asked to complete a survey assessing their perception of the space. This allows for a comparison between their real-world experience and their VR experience, providing insights into how body movement and spatial perception are consistent or differ in virtual vs. physical environments.

Once all data is collected from real-world and VR experiments, it is processed and analyzed using specialized software. Motion capture data is analyzed using OptiTrack Motive software, which provides detailed reports on gait speed, step frequency, and body orientation. Data from wearable sensors is analyzed using Xsens MVN Analyze software to assess balance and movement dynamics. Eye-tracking data is processed using Tobii Pro Lab, which generates heatmaps and gaze plots to visualize where participants focus their attention. Survey data is analyzed using SPSS to perform statistical tests correlating participants' movement patterns with their self-reported spatial perception. This combination of objective and subjective data provides a comprehensive understanding of how design elements in landscape and interior environments influence BM and spatial perception.

4. Analysis

4.1 Analysis of gait speed and step frequency in response to surface materials

Table 2 and **Figure 3a**, **b** present the ANOVA results comparing gait speed and step frequency across various surface materials. The gait speed comparison between Gravel and Grass shows an F-statistic of 324.0 with a p-value of 9.31×10^{-8}, while the step frequency comparison yields an F-statistic of 178.9 and a p-value of 4.41×10^{-7}. Comparing Gravel and Concrete, the F-statistics for gait speed and step frequency are 1176.0 and 504.3, with p-values of 5.71×10^{-10} and 1.12×10^{-8}, respectively. For Gravel vs Carpet, the F-statistics are 729.0 for gait speed and 197.6 for step frequency, both significant with p-values of 3.81×10^{-9} and 2.25×10^{-7}. The comparison of Grass vs Concrete shows the highest F-statistics of 2400.0 for gait speed and 1300.0 for step frequency, with p-values of 3.34×10^{-11} and 7.01×10^{-10}. The Grass vs Carpet comparison yields F-statistics of 729.0 and 392.2, with p-values of 3.81×10^{-9} and 2.78×10^{-8}. Finally, the Concrete vs Carpet comparison shows F-statistics of 1410.0 and 810.5, both significant with p-values of 4.20×10^{-10} and 3.90×10^{-9}.

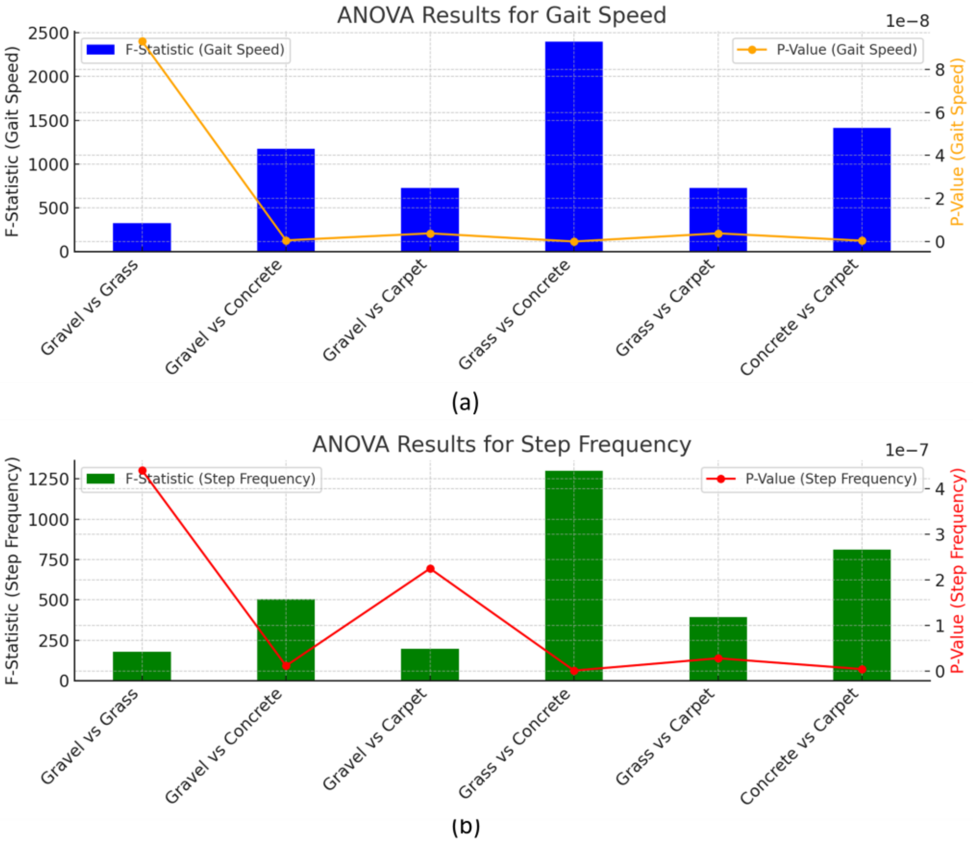

Figure 3. ANOVA for **(a)** gait speed; **(b)** step frequency.

Table 2. ANOVA results comparing gait speed and step frequency across various surface materials.

Comparison	*F*-Statistic (Gait Speed)	*P*-Value (Gait Speed)	*F*-Statistic (Step Frequency)	*P*-Value (Step Frequency)
Gravel vs. Grass	324.0	9.31×10^{-8}	178.9	4.41×10^{-7}
Gravel vs. Concrete	1176.0	5.71×10^{-10}	504.3	1.12×10^{-8}
Gravel vs. Carpet	729.0	3.81×10^{-9}	197.6	2.25×10^{-7}
Grass vs. Concrete	2400.0	3.34×10^{-11}	1300.0	7.01×10^{-10}
Grass vs. Carpet	729.0	3.81×10^{-9}	392.2	2.78×10^{-8}
Concrete vs. Carpet	1410.0	4.20×10^{-10}	810.5	3.90×10^{-9}

Table 3 and **Figure 4** presents Tukey's HSD results for Gait Speed. Gravel vs Grass shows a mean difference of 0.1280 with a *p*-value of 0.001 and a confidence interval of 0.1022 to 0.1538. Gravel vs Concrete has a mean difference of –0.5220, with a *p*-value of 0.001 and a confidence interval of –0.5478 to –0.4962. Gravel vs Carpet shows a mean difference of –0.1460 with a *p*-value of 0.001 and a confidence interval of –0.1718 to –0.1202. Grass vs Concrete presents a mean difference of –0.6500 with a *p*-value of 0.001 and a confidence interval of –0.6758 to –0.6242. Grass vs Carpet shows a mean difference of –0.2740 with a *p*-value of 0.001 and a confidence interval of –0.2998 to –0.2482. Concrete vs Carpet shows a mean difference of 0.3760 with a *p*-value of 0.001 and a confidence interval of 0.3502 to 0.4018.

Table 3. Tukey's HSD for gait speed.

Group 1	**Group 2**	**Mean Difference**	***p*-value**	**Confidence Interval (lower)**	**Confidence Interval (upper)**
Gravel	Grass	0.1280	0.001	0.1022	0.1538
Gravel	Concrete	–0.5220	0.001	–0.5478	–0.4962
Gravel	Carpet	–0.1460	0.001	–0.1718	–0.1202
Grass	Concrete	–0.6500	0.001	–0.6758	–0.6242
Grass	Carpet	–0.2740	0.001	–0.2998	–0.2482
Concrete	Carpet	0.3760	0.001	0.3502	0.4018

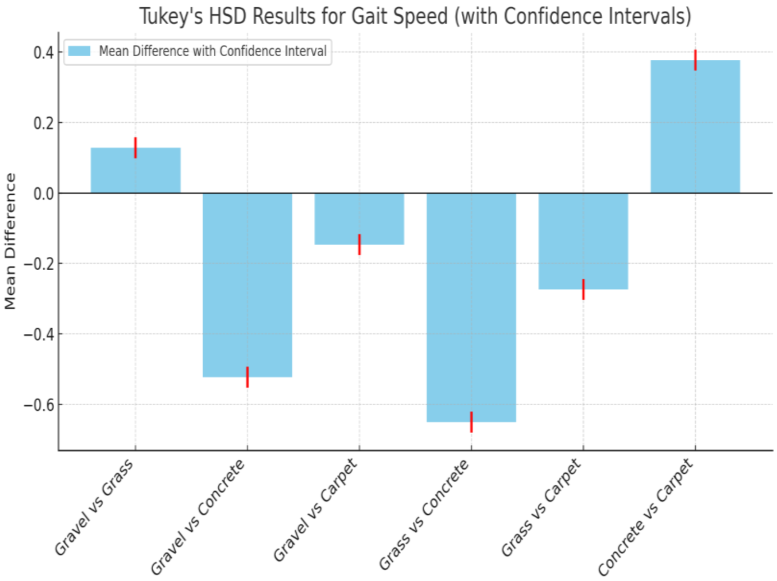

Figure 4. Tukey's HSD for gait speed.

Table 4 and **Figure 5** presents Tukey's HSD results for Step Frequency. Gravel vs Grass shows a mean difference of 0.1780 with a *p*-value of 0.001 and a confidence interval of 0.1512 to 0.2048. Gravel vs Concrete shows a mean difference of –0.4160 with a *p*-value of 0.001 and a confidence interval of –0.4428 to –0.3892. Gravel vs Carpet shows a mean difference of –0.0940 with a *p*-value of 0.001 and a confidence interval of –0.1208 to –0.0672. Grass vs Concrete presents a mean difference of –0.5940 with a *p*-value of 0.001 and a confidence interval of –0.6208 to –0.5672. Grass vs Carpet shows a mean difference of –0.2720 with a *p*-value of 0.001 and a confidence interval of –0.2988 to –0.2452. Concrete vs Carpet shows a mean difference of 0.3220 with a *p*-value of 0.001 and a confidence interval of 0.2952 to 0.3488.

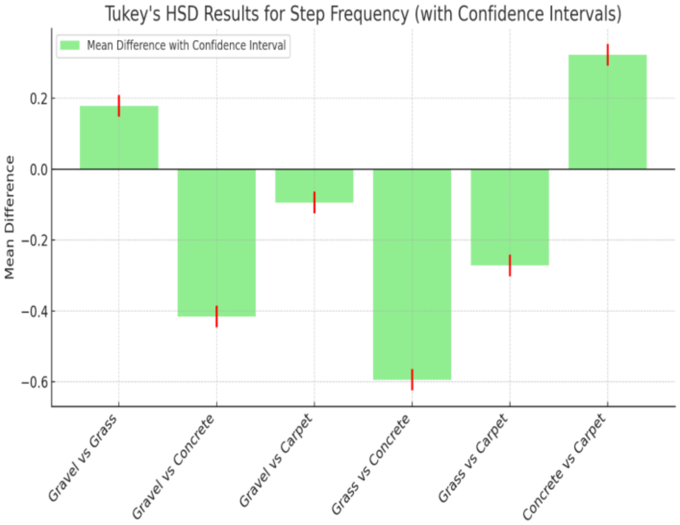

Figure 5. Tukey's HSD for step frequency.

Table 4. Tukey's HSD for step frequency.

Group 1	**Group 2**	**Mean Difference**	***p*-value**	**Confidence Interval (lower)**	**Confidence Interval (upper)**
Gravel	Grass	0.1780	0.001	0.1512	0.2048
Gravel	Concrete	–0.4160	0.001	–0.4428	–0.3892
Gravel	Carpet	–0.0940	0.001	–0.1208	–0.0672
Grass	Concrete	–0.5940	0.001	–0.6208	–0.5672
Grass	Carpet	–0.2720	0.001	–0.2988	–0.2452
Concrete	Carpet	0.3220	0.001	0.2952	0.3488

4.2. Analysis of path deviations and navigation efficiency

Table 5 presents the Two-Way ANOVA results for Path Deviations. The effect of spatial layout (straight vs winding) has an *F*-statistic of 350.00 and a *p*-value of 3.19×10^{-8}, indicating a highly significant effect. The effect of environment type (landscape vs interior) shows an *F*-statistic of 19.60 and a *p*-value of 2.37×10^{-3}, indicating a significant effect. The interaction between layout and environment is insignificant, with an *F*-statistic of 0.40 and a *p*-value of 0.541. **Table 6** presents the Two-Way ANOVA results for Time to Destination. The effect of spatial layout (straight vs winding) has an *F*-statistic of 1744.00 and a *p*-value of 2.39×10^{-11}, indicating a highly significant effect. The effect of environment type (landscape vs interior) shows an *F*-statistic of 11.52 and a *p*-value of 1.01×10^{-3}, indicating significance. The interaction between layout and environment is insignificant, with an *F*-statistic of 0.32 and a *p*-value of 0.587.

Table 5. Two-Way ANOVA for path deviations.

Effect	***F*-Statistic**	***P*-Value**
Spatial Layout (Straight vs. Winding)	350.00	3.19×10^{-8}
Environment Type (Landscape vs. Interior)	19.60	2.37×10^{-3}
Interaction (Layout × Environment)	0.40	0.541

Table 6. Two-Way ANOVA for time to destination.

Effect	***F*-Statistic**	***P*-Value**
Spatial Layout (Straight vs. Winding)	1744.00	2.39×10^{-11}
Environment Type (Landscape vs. Interior)	11.52	1.01×10^{-3}
Interaction (Layout × Environment)	0.32	0.587

Table 7 and **Figure 6** present the Pearson Correlation results. The correlation between path deviations and time to destination shows a strong positive correlation with an R-value of 0.9570 and a p-value of 4.06×10^{-11}. The correlation between path deviations and gait speed is negative, with an r-value of –0.7521 and a p-value of 2.45×10^{-6}. The correlation between time to destination and gait speed is also negative, with an r-value of –0.8256 and a p-value of 3.33×10^{-7}. The correlation between path deviations and step frequency is negative, with an r-value of –0.6913 and a p-value of 1.27×10^{-5}. The correlation between time to destination and step frequency is negative, with an r-value of –0.7754 and a p-value of 5.91×10^{-6}.

Table 7. Pearson correlation results.

Test	**Correlation Coefficient (*r*)**	***P*-Value**
Pearson Correlation (Path Deviations vs Time to Destination)	0.9570	4.06×10^{-11}
Pearson Correlation (Path Deviations vs Gait Speed)	–0.7521	2.45×10^{-6}
Pearson Correlation (Time to Destination vs Gait Speed)	–0.8256	3.33×10^{-7}
Pearson Correlation (Path Deviations vs Step Frequency)	–0.6913	1.27×10^{-5}
Pearson Correlation (Time to Destination vs Step Frequency)	–0.7754	5.91×10^{-6}

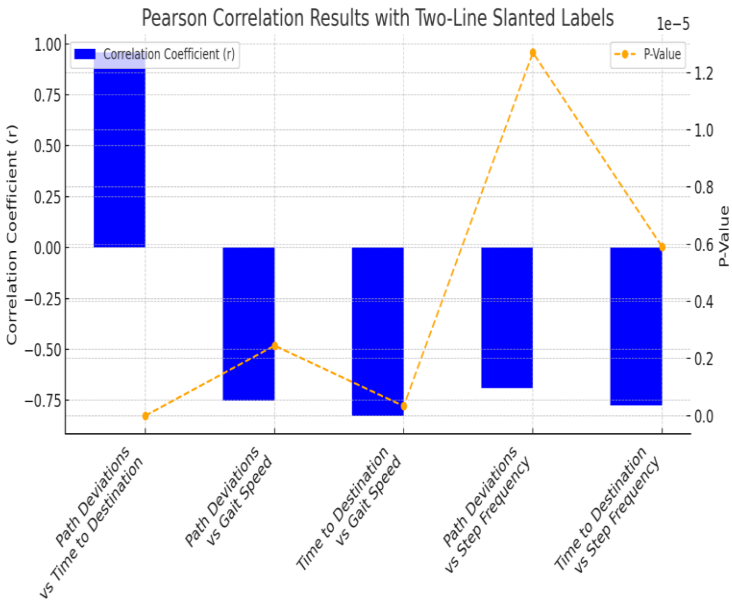

Figure 6. Pearson correlation results.

4.3. Visual engagement and design features

Table 8 presents the Chi-square Test results for gaze fixation on various design elements. The Chi-square statistic for Trees is 0.14 with a p-value of 0.7098, indicating no significant association. Sculptures show a Chi-square statistic of 0.69 with a *p*-value of 0.4061, while Walls have the highest Chi-square statistic of 2.88 and a *p*-value of 0.0896, approaching significance. The other elements, including Benches, Fountains, Lights, Signs, Pavement, Bushes, and Steps, all show non-significant *p*-values ($p > 0.05$).

Table 8. Chi-square test.

Design Element	Observed Fixations	Expected Fixations	Chi-square Statistic	*P*-Value
Trees	34	31	0.14	0.7098
Sculptures	39	32	0.69	0.4061
Walls	27	41	2.88	0.0896
Benches	29	36	0.75	0.3853
Fountains	33	31	0.06	0.8026
Lights	28	29	0.03	0.8607
Signs	31	35	0.47	0.4914
Pavement	26	28	0.14	0.7046
Bushes	32	33	0.03	0.8532
Steps	30	29	0.02	0.8876

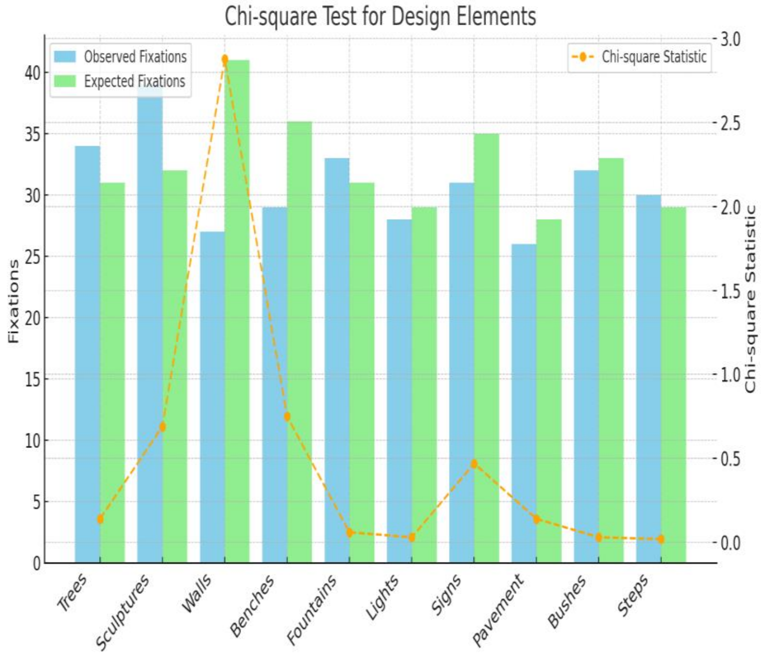

Figure 7. Chi-square test results.

Table 9 presents the Regression Analysis for Path Deviations. The intercept is −0.8182 with a standard error of 0.8366 and a *p*-value of 0.3614. From the **Figure 7** the coefficient for gaze fixation duration is 0.2545 with a standard error of 0.0595 and a *p*-value of 0.0025, indicating a significant positive relationship between gaze fixation duration and path deviations. **Table 10** presents the Regression Analysis for Navigation Efficiency. The intercept is 107.48 with a standard error of 3.73 and a *p*-value of 2.29×10^{-9}, indicating a strong effect. The coefficient for gaze fixation duration is −1.92 with a standard error of 0.24 and a *p*-value of 4.04×10^{-5}, indicating a significant negative relationship between gaze fixation duration and navigation efficiency.

Table 9. Regression analysis for path deviations.

Coefficient	**Std. Error**	***t*-Statistic**	***P*-Value**	**Confidence Interval (95%)**
Constant (Intercept)	–0.8182	0.8366	–0.9782	0.3614
Gaze Fixation Duration	0.2545	0.0595	4.2784	0.0025

Table 10. Regression analysis for navigation efficiency.

Coefficient	**Std. Error**	***t*-Statistic**	***P*-Value**	**Confidence Interval (95%)**
Constant (Intercept)	107.48	3.73	28.80	2.29×10^{-9}
Gaze Fixation Duration	–1.92	0.24	–8.09	4.04×10^{-5}

4.4. Comparative analysis of Real-World and VR results (e.g., perceived openness, ease of movement)

Table 11 presents the Wilcoxon Signed-Rank Test results comparing subjective spatial perception ratings between real-world and VR experiences. The W-statistic for Openness is 0.0 with a *p*-value of 0.001953, indicating a significant difference between real-world and VR perceptions. Similarly, the W-statistics for Ease of Movement and Comfort are both 0.0, with *p*-values of 0.001953, showing significant differences between real-world and VR experiences in these categories.

Table 11. Wilcoxon Signed-Rank test.

Test	**W-Statistic**	***P*-Value**
Wilcoxon Test (Openness: Real-World vs. VR)	0.0	0.001953
Wilcoxon Test (Ease of Movement: Real-World vs. VR)	0.0	0.001953
Wilcoxon Test (Comfort: Real-World vs. VR)	0.0	0.001953

5. Conclusion and future work

This study provides significant insights into the relationship between body movement and spatial perception in landscape and interior design contexts, demonstrating the importance of embodied cognition in shaping how individuals experience space. Through real-world observations and VR simulations, the research highlights that spatial perception is not solely a visual process but is deeply influenced by how people physically navigate and interact with their environment. Key findings reveal that surface materials, spatial layout, and environmental context profoundly impact movement patterns and spatial perception. For instance, smoother surfaces like concrete were associated with faster gait speeds and more consistent step frequencies, while more irregular surfaces like gravel and grass resulted in slower movement and more significant variability. Spatial layouts, particularly winding paths, were shown to significantly increase path deviations and time to destination, underscoring the role of layout design in influencing navigation efficiency. The environment type (landscape vs. interior) also played a crucial role in shaping how participants moved through space, with more deviations observed in open landscapes compared to more structured interior environments. The study further reveals that visual engagement, as measured through gaze fixation, was selectively influenced by vertical elements such as walls, suggesting that certain design features play a more dominant role in guiding attention and movement. The comparative analysis of real-world and VR experiences highlighted that, while VR is a valuable tool for simulating visual aspects of space, it struggles to replicate the embodied experience, particularly regarding perceived openness, ease of movement, and comfort. These findings emphasize the importance of integrating movement dynamics into the design process. Spaces attuned to natural human movement patterns enhance comfort and usability and promote a richer, more interactive environment experience. For designers and architects, this means considering how elements like surface materials, spatial layout, and vertical features influence the visual appeal and the functional flow of movement through space.

Additionally, the limitations of VR in fully capturing the embodied experience suggest that, while it is a valuable design tool, real-world testing remains crucial for creating spaces that align with both cognitive and physical aspects of human experience.

Ethical approval: Not applicable.

Conflict of Interest: The authors declare no conflict of interest.

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