A COMPARATIVE ANALYSIS OF DIFFERENT LOCOMOTION IN VIRTUAL REALITY AND THEIR CONSEQUENCE IN SPATIAL COGNITION

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Abstract. Perception of space is deeply linked with our movement in space. In architectural design practices, this movement can be performed as a form of embodiment through the models of different scales and scoping into them with or without some apparatus. Leveraging the affordances of the model and the possibilities through the body architects perceive a scaled abstraction of the actual space. But in the case of virtual reality (VR), these movements bodily autonomy, and freedom are restricted due to the limitations of space and locomotion affordances. This paper will compare these three locomotion techniques and their effect on spatial cognition and navigation. We have developed a spatial navigation task for the participants of the architectural background to study the effect of different locomotive affordances. These different affordances have been utilised both in isolation and in combination with other affordances to study spatial navigation and cognition. Combining different guidelines aimed at reducing vection-induced motion sickness (VIMS) we have developed these environments and examined the degree of presence and spatial cognition concluding that a combination of different locomotive affordances can enhance the architectural experience and spatial cognition of the space.

Keywords. virtual reality, architecture, locomotion, movement, spatial cognition

1. Introduction

Human curiosity about representing a three-dimensional world onto a two-dimensional plane was satiated during the Renaissance in Italy through the development of the theory of perspective. Through this discovery, it was possible to emulate the depth dimension of the world onto a piece of paper. French philosopher Maurice Merleau-Ponty called depth the "most existential dimension of all" in the context of action and clarity on perception(Hale, 2017, p. 46). During the

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Renaissance, the observer's or the painter's eye was at the centre of everything that was reality and every line from reality merged into that centre. Through that painting observer was fixed in a place and was unable to move. But in the case of cubist painters, this was somewhat different. They moved around in the world around their subject and merged all those separate or continuous perspectives into one two-dimensional plane(Berger, 2008). Here the viewers are free in the world; their abstraction of the world through a continuous movement is expressed. Similarly, virtual reality (VR) also enables the viewer to move into and around a world as compared to a viewer with access to an image. Thus, VR holds an important role in the architectural perception of a built, unbuilt, or to-be-built space in various scales. However, the movement modalities in VR differ from the real world. It is not always possible to walk the virtual space in the real world as space is not always adequate in dimension and sometimes the other movement modalities offered by the VR tools are not enough to develop a sound perception. Room-scale movements are restrictive in cases like stairs, ramps and level difference and teleportation which is offered majorly in all the architectural VR toolkits is known for spatial disorientation(Das et al., 2023; Prithul et al., 2021). Architect Steven Holl has also inquired about the faculty of the judgement of space and bodily freedom of agency of movement through the overlapping perspective of the spaces during a continuous movement. Analogously, artist James Turrell has also invoked a sense of curiosity in his art installations simply by denying the observer the ability to enter a space or navigate through a space(Hale, 2017, p. 47).

Perception is argued as something that we do as contrary to something that happens to us(Noë, 2006). In the case of any shape and spatial properties, it is a function of movement(Clark, 2008, p. 172). Hence in the case of architectural entities, the movements should play a major role in spatial perception. In 1974, Donald P. Greenberg proposed a continuous sequence of images for "a realistic simulation of a walkthrough of a space"(Greenberg, 1974). Though he identified the need for simulation of motion for architects, technology was expensive and inadequate to simulate the walkthrough. Based on Greenberg's work, in 1986 Frederick Brooks Jr. attempted to implement a "moving view" and "user-steered pre-computed high-quality views". But state-of-the-art could only provide 9 updates/second. It was compared with what they believed to be real-time of 12 updates/second or better from the silent movies(Brooks, 1986). This was not beneficial for architects at that time and could potentially generate significant simulator sickness.

Since 2012, with the launch of the Oculus Rift, VR technology has developed significantly to a point where the recently launched Meta Quest 3 provides a 90Hz refresh rate while untethered. This hardware-level advancement potentially allows the researchers to implement the concepts developed in the early 70s or early 80s without any glitches. However, the VR toolkit available for architects does not yet contain any locomotion system that could allow for seamless movement within spaces(Ververidis et al., 2022). Often locomotion in VR has been linked with motion sickness and more specifically vection-induced motion sickness (VIMS). But it has been observed that vection has little to no effect on VIMS(Keshavarz et al., 2015). Rather there have been other factors like latency, resolution, optical flow, and prior knowledge of the system contributing to the VIMS(LaValle, 2023; *Motion Sickness in VR Explained – And Eliminated – Varjo.Com*, 2023).

Over the years there have been a multitude of locomotion strategies developed for VR, but it has been observed that controller-based locomotion systems have outperformed all the other locomotion systems(Cherni et al., 2020). Recent games like Assassin's Creed VR have challenged these locomotion restrictions and pushed the boundaries of immersive experiences through the incorporation of moves like parkour, continuous running and climbing. This game has also incorporated "comfort systems" to mitigate nausea, vertigo, and VIMS(*Assassin's Creed Nexus – Accessibility & Comfort Feature Manual*, 2023). These examples and studies add to the understanding of how locomotion systems can be an integral part of perception and how remedies can be incorporated into VR to mitigate motion sickness if needed.

In this pilot study, authors introduce three locomotion modalities in VR: controller-based movement, teleportation and a combination of teleportation and controller-based movement and study their effect on spatial memory, navigation, and cognition. The primary goal of this study was to introduce bodily autonomy in terms of movement in VR while experiencing spaces. In this paper, we will present the effects of different locomotion modalities on user perception over 6 scenarios consisting of 2 spaces and 3 locomotion modalities each for 10 participants.

2. Methods

In 1963 experimental psychologists Richard Held and Alan Hein experimented on two kittens to establish links between movement and perception of depth (Held & Hein, 1963). They found that perception is indeed a consequence of action, and this coupling of visual and bodily information was necessary for perception based on which Noë argues that there cannot be any passive or inert observer(Noë, 2006, p. 13). In VR architects can afford to see the built/unbuilt/to-be-built spaces on a 1:1 scale. During the Renaissance, there was a standard practice of making 1:1 mock-up model by architects Bernini or Michelangelo to move inside them to understand their spatial qualities better but currently, that is only possible in VR(Conforti et al., 2020). Thus, it was necessary to give the architects the agency and affordance of different locomotion modalities and then to observe their effect on perception.

Based on these previous examples, it becomes apparent that fully embodied walking, controller-based walking, and teleportation will have different perceptual notions of space and this study aims to find these.

2.1. SPACE SELECTION

The movement modalities needed to be tested on a set of spaces. In the experiment design, it was decided to use two different spaces with different degrees of complexity. It would have been possible to design two spaces with varying degrees of complexity, but it was decided to use two spaces designed by architects instead.

The first space with lower degrees of complexity is Aldo van Eyck's Sonsbeek Pavilion (Space A). The second space with a higher degree of complexity is a part of John Hejduk's Diamond Museum C (Space J). Both spaces are given a boundary to give the participants a sense of closure (Fig. 1). None of the spaces have any roofs and contain a set of walls, podiums, and columns which render a certain maze-like quality.

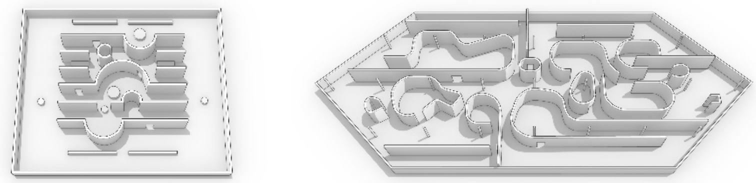

Figure 1: Left: Sonsbeek Pavilion Model, Right: Diamond Museum C

2.2. PARTICIPANT SELECTION

For this pilot study, 10 participants were selected (7 Male & 3 Female). Among the participants the following qualities were present: (1) all of the participants had a minimum of five years of architectural training and had a Danish equivalent of a master's degree in architecture; (2) Three participants were assistant professors, and one was an associate professor; (3) Five were research assistants working in architecture and urbanism; and (4) one was a PhD fellow.

All the participants had some degree of experience with VR and a basic understanding of locomotion modalities. The participants were warned about potential motion sickness arising from the experiment. To reduce variables, motion sickness due to age and sex particularly was not analysed for evaluation but it was noted for all the participants.

2.3. CAD AND VR SETUP

From the plan of the spaces, a NURBS CAD model was generated in Rhinoceros and a mesh model was exported to be used with Unity. With XR Interaction Framework 2.5.1 with Unity, 2022.3.9f1 two custom scenes were created to be used with Meta Quest Pro. The viewers' movement was tracked through a custom C# script in Unity and position data was exported in a comma-separated text file (Fig.2).

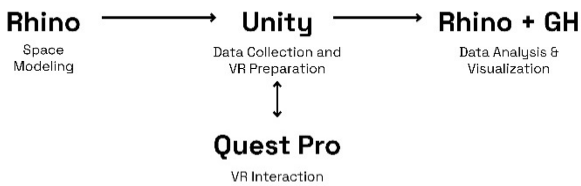

Figure 2:Experiment Structure

The model in Unity does not have any special material and only contains a white material as walls, the columns present in Space J have a red colour, the boundary limit for the space for navigation is an orange material with a white grid and the ground plane is of a black material with a white grid. All over this ground plane users can teleport freely.

For the locomotion modality, there are primary two options: controller-based continuous movement and teleportation. However, users were encouraged to walk on their own feet if deemed necessary. Through the left-hand controller thumbstick, the viewer could move freely forward and backward and strafe to left and right. To emulate a normal walking speed a speed limit of 1.3m/s speed was imposed to match with standard walking pace(Mohamed & Appling, 2020). By varying the pressure on the thumbstick users could control their speed. On the right thumbstick, two operations were imposed though only one could be triggered at any point: (1) thumbstick forward for teleportation and (2) thumbstick sideways for rotation of the camera.

3. Design Experimentation

3.1. EXPERIMENT STRUCTURE

The goal of this study is to find the relation between locomotion affordances and its eventual effect on spatial navigation and cognition. The participants had the option of three locomotion modalities and two types of spaces. Hence, they had to experience 6 different combinations. The participants were not informed about two different spaces. They were informed about six experiences and different modalities to avoid forming an information bias. The guardian was set up in a 5m x 5m area for the participants to move smoothly. The two spaces were shown to the participants alternatively and the order of the locomotion modalities was randomized for each set of experiments to avoid any learning bias towards the space.

First, they were informed about the experiment, about the data to be collected and warned about the possible occurrence of motion sickness. Then they were put in a trial environment for an average of 4 minutes to try the locomotion modalities to get habituated as a preparation for the main experiment. The next part was experiencing six individual environments for 2 minutes each with a break in between for the participants to complete a task for data collection. The detail of this data collection is described in the following section.

3.2. DATA COLLECTION

Throughout the whole experiment, several types of data were collected to make informed decisions about the relationship between modalities and their effect. The participants were asked to draw the plan of the space as they remembered after each experiment on an A4 paper with a dot grid.

During the experiment, three other data were collected: (1) photographs and videos of the participants to analyse how they behave in the real world while moving in the virtual world, (2) their movement trajectory in the VR in a plain text file, and (3) screen capture of their view to analyse what they are seeing and how they are reacting to the same. The trajectory data was further developed as a heat map through Kernel-Density Estimation (KDE) of their movement and was compared with their drawing and the photographic and video data of the participants were compared against the screen recording of the same participants.

3.3. STEPS FOR REDUCING MOTION SICKNESS

Lu and Mao suggested in their work to lean the body towards the direction of apparent motion in VR to reduce nausea(Lu & Mao, 2021). This suggestion was informed to the participants. This suggestion was also prescribed by Cherni et al in their review of movement modalities in VR(Cherni et al., 2020).

It has been observed that vection can be weakened by offering sensory cues related to the real world and an increased field of vision can strengthen the vection cues by projecting a large image on the retina(LaValle, 2023, p. 243). Meta Quest Pro comes with two partial light blockers. According to Health and Safety Warning provided by Meta, by removing those light blockers, a better awareness of real-world surroundings can be achieved(*Health and Safety Warnings | Meta Quest | Meta Store*, n.d.). Hence for this experiment, these two light blockers were removed to give the participants a better understanding of their surroundings (Fig. 3). Despite all the precautions one participant reported light motion sickness at the end of the six experiments and another participant reported motion sickness throughout the experiment but completed all six experiments.

Figure 3: Removal of Partial Light Blockers for surrounding awareness.

Pieces of ginger candy were offered to all the participants to alleviate the symptoms of nausea if they experienced motion sickness during the experiments.

4. Results

This experiment was designed to gain insight into how locomotive modalities affect our perception of space. These insights can be classified into the following categories: (1) the relationship between seeing and moving, (2a) spatial memory and spatial perception, and (2b) the area covered as an effect of locomotion modality.

4.1. RELATIONSHIP OF SEEING AND MOVING

Previously it was mentioned that the majority of the VR tools for architectural design offer only teleportation as the only locomotion modality. Teleportation works only if the person can see the space where they would like to travel. Here the ability to move turns to be entirely ocular-centric; that is if one can see the space then one can move into the space. This is not a continuous image of the space but many discreet images of the space that need to be stitched to form a complete image.

This is opposite to what fully embodied walking or controller-based movement could offer. The bodily autonomy of the agency of movement is upheld in those two scenarios either by the body itself or through technological mediation. As James Gibson has mentioned vision depends on the eye but the eye is in the head which is eventually on the body(Noë, 2006, p. 209). Teleportation has its benefits, but it limits the bodily ability to move in space ergo it limits the perception of the space.

On the contrary, embodied walking and controller-based walking retain both the agencies of vision and movement of the user. The user need not see the exact place they are travelling to; they can discover/reveal at their own pace. This also echoes the arguments by Steven Holl about how overlapping perspectives formed in space from bodily movement help in spatial perception(Hale, 2017, p. 48). Photographic data has revealed that participants have leant in real life to look around the corner in VR before moving forward in the case of these two modalities like how one would probe a space in real life. This similarity in movement helps the participants to carve a more accurate description of the space.

4.2. SPATIAL MEMORY, SPATIAL PERCEPTION & AREA TRAVERSED

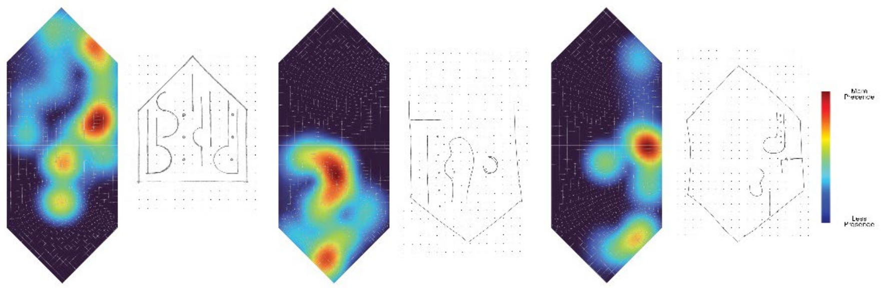

Figure 4: Drawing Similarity with Heatmap and Coherence with Ground Truth

Upon studying the drawing and the movement trajectory an interesting pattern emerges. Architects are trained to develop spaces and this training involves a seamless transition from a two-dimensional entity to a three-dimensional entity. In this experiment, participants have drawn the part of the space they have only experienced, but the drawings have varying degrees of coherence with the ground truth (Fig. 4).

Drawings after the teleportation modality are the least coherent and mixed modality has the highest degree of coherence. This lower degree of coherence does not relate to the area covered by the participants. Often, they have traversed more areas in teleportation than the other two modalities (Fig. 5). In the other two modalities even if the participants have traversed less distance the drawings are much closer to the ground truth.

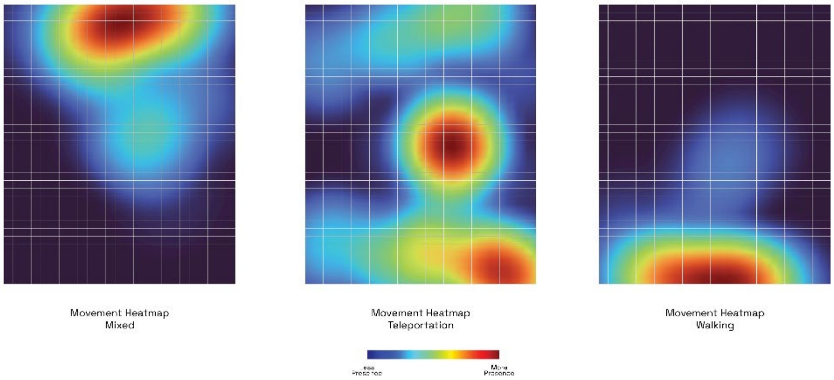

Figure 5: Difference in Nature of Heatmaps: Mixed, Teleportation, Walking (L-R)

5. Discussion

According to Mearleu-Ponty, perception is not a total of individual senses like visual, tactile, and auditory cues but perceived with the whole body which is an echo of Gaston Bachelard's "polyphony of senses". Ocular-centrism restricts our perception to only what we can see thereby disregarding all the other sensory inputs (Pallasmaa, 2012). However, movement stitches the change in perspectives and helps the body to perceive the space in its totality. Thereby movement becomes an important constituent of spatial perception in VR.

VR has been present in the architectural context for at least thirty years. There have been several research about how to use these tools in an architectural context since the early 90s(Dagit, 1993; Dirk & Regenbrecht, 1996; Donath & Regenbrecht, 1995). However, a recent study conducted by the Architects' Council of Europe has revealed that only 5% of the architectural practices in Europe used VR in 2022. This was a 2% reduction from 7% of architects from 2020. Even the customer request for VR has fallen from 15% in 2020 to 11% in 2022(*ACE Observatory/Observatoire Du CAE*, 2023).

One of the possible reasons for this could be the lack of fulfilment of architectural needs through these VR tools. A review by De Freitas and Ruschel presented that the majority of the research and development for architectural VR and augmented reality (AR) tools were published in journals that were out of the scope of architectural design research(De Freitas & Ruschel, 2013). There are many reasons why VR in architectural design practices is not integrated and one of the key reasons is it is not embedded into architectural education. Thus, the modalities and habitual niches of this technology are vastly unknown to architects.

The experiment deals with spaces with varying degrees of spatial complexity between them. Hence, it was observed that in the given time it was not possible to explore both the areas in its entirety. Proportionally more area has been covered by the users in Space A than Space J in this experiment. But in the case of one participant with a high degree of experience in computer games has proved to be otherwise. Even through teleportation, this participant has traversed a large amount of space along with a drawing of the space with higher coherence to ground truth. However, this was an apparent exception in this experiment. However, according to LaValle, first-person shooter computer games reduce the sensitivity towards vection and help in navigation in VR (LaValle, 2023, p. 293).

In this experiment, the authors have touched upon a small, yet important aspect of VR used in architectural design. This experiment shows that spatial memory and cognition become different with the change in movement modalities. By introducing these extra movement modalities in a VR environment, we are thus proposing a paradigm change in how VR tools are being developed for architects. However, from this experiment, it is not possible to predict if the spatial quality appears differently with the change in locomotion. One of the future tasks based on this experiment could be to investigate whether spatial quality is a function of locomotion modality.

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