User testing architectural design for behavioural patterns using a rudimentary WebVR system

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ABSTRACT

In many design disciplines, products tailored to the specific needs of a user group are being created. Architecture is at a time when data on user behaviour in a space, could be mined to drive a design process. Immersive Virtual Reality (VR) is a platform useful in visualising a design project and immersing users in it. It can be further empowered to obtain feedback on their experiences within.This research tries to establish an easy-to-use VR system to aid user testing architectural designs. A web VR environment with capabilities to track the users positions and actions, similar to building web analytics, is explored in this study. The systems ability to emulate the real world for the purposes of a behavioural study is tested by way of an experimental methodology. A VR environment based on an architectural design principle, modelled by architect and design theorist Christopher Alexander, is designed. 20 participants were allowed to explore the environment and their movements are tracked. Data collected from the experiment is compared with the behavioural expectations suggested by the design theory. The results show that the WebVR system is easy to use and the behaviour within the virtual environment corroborates with the real world.

Keywords: Virtual Reality, Web VR, VR Analytics, Architecture, Environment-Behaviour research, Christopher Alexander, Evidence-based design, VR Edge plugin for Rhino 3D.

Index Terms: H.5.2 [User Interfaces]: User-centered design; H.5.3 [Group and Organization Interfaces]: Web-based interaction; I.3.7 [Three-Dimensional Graphics and Realism]: Virtual Reality; J.5 [Arts and Humanities]: Architecture

1 INTRODUCTION

Architecture is the design discipline responsible for shaping and structuring our environment. In doing so, architecture directs human behaviour, defines users lifestyles and invokes peoples emotions. In this era of big data, design in almost every industry is driven by data. Architecture also follows this trend, in many ways, by using quantifiable environmental data for optimal building performance, structural data for form-finding, elaborate financial data for optimising costs; Data is also used to develop creative complex geometric forms. Architecture as a field has embraced data and has intertwined its use within different phases of the design process. However, decisions in design regulating human behaviour within a space principally rely on design principles and theories rather than quantifiable user behaviour data specific to a project. As Dr.Edelstein points out '*It is often suggested that the complexity of architecture makes impossible the reduction of the human interaction with built settings to measurable parts...Historically, architectural research relied on philosophical constructs or analysis of behavior patterns in order to relate human responses to design* ' [6]. Until recently it was not possible to observe human behaviour in architectural design other than in the form of post-occupancy evaluation. But with the advent of immersive Virtual Reality (VR), it is now possible to allow users to experience a building before its construction. This allows for testing a design for user impacts simultaneously during the design phase. The architect can observe the movements of a user immersed in the VR space just like in a traditional direct observation study.

Unlike movement of people in an environment, there are unobservable traits of human response that guide their actions; one of such being emotional response. Architectural space is too frequently seen as an entity purely for functional performance and designed for physical comfort disregarding the emotional aspect and temperament of the user. The mental comfort of inhabitants is as important as the functional performance to make a design successful. End users do not realise consciously how they react to a space. Hence such responses are hard to quantify and be incorporated into the design. Observing peoples behaviour through a particular discipline, be it social sciences, architecture, psychology or physiology, presents only a part of the picture. There is a need to link social, psychological and physiological research into environment-behaviour studies [29]. Biosensors have the potential to measure the emotional response of the user to a physical space. VR in conjunction with biosensors could act as a potential tool to investigate the effect of a physical environment on the mind and the resultant behaviour. This study aims at extracting user's behavioural data from virtual reality and validating VR as a tool to conduct behaviour studies. Incorporating biosensors to measure the emotional component of behaviour will be pursued in future studies.

The paper has been organised into the following sections. Section 2 discusses relevant background material including the motivation for this research, a literature review and current trends in VR technology. The objective of the research is clearly defined in section 3. Section 4 then goes on to describe the research methodology. The experiment procedure and research setup are discussed in detail here. Section 5 presents the results of the experiment and also includes a brief discussion on other observations when the experiments were conducted. Interpretations and findings are explained in section 6 which also contains the conclusions and hints for the way forward.

2 BACKGROUND

2.1 Motivation

Human behaviour is largely reactive to the built environment that surrounds them. Given how much power the built environment wields, the designers who shape them do not completely understand the effects of their design on the behaviour of the user. Warm thermal spaces with fire alcoves are incorporated in buildings and expected to function as a successful communal space with the knowledge that such spaces provide a sense of community and invite people in. [7]. Some spaces are designed with high ceilings to invoke a sense of freedom in its users and hence affect behaviour [19]. Human usage of space, studied as Proxemics, helps in creating a successful design for culturally different people by providing the right amount of space for them [11]. These are examples of documented intuitive responses of people in a physical setting, converted to a design component in architecture. Apart from the experience and intuition

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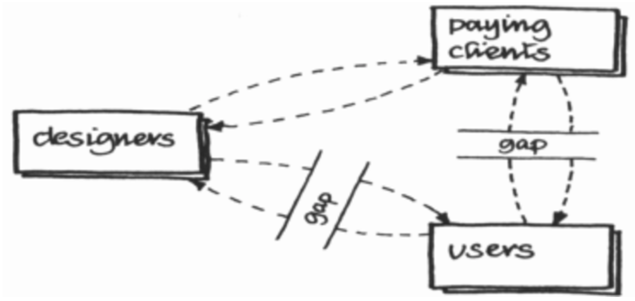

Figure 1: User-gap model defined by E-B researcher John Zeisel. [29]

of an architect, the design process is guided by such design theories so as to orient the events and functions in a space. After a project reaches completion, there is a generally accepted behaviour response to such a built setting based on the design principles used in its making.

In an attempt to better design a mass housing project, with respect to neighbours interaction, architect Brent Brolin decided to provide adjacent driveways to a pair of houses next to each other instead of same side driveways for all the houses [29]. But Herbert J. Gans, a sociologist, observed that such a layout of driveways contributes to negative interactions among neighbours in some cases because of previous disputes [9]. The conscious design decision made to improve the relationship among the residents of mass housing, in reality, had a reverse effect. The real-world cause and effect of the built space and behaviour is hard to predict accurately.

During the development of design, even when the user is known, their assumed needs and responses to the design is far from the actual. To add to this, there is a growing gap between the designer and the user as more often than not the end-user of a building is not the client of the project (see Fig. 1) [29]. In this state, the design problem during the development stage is narrowed down to the functional requirements of a building and not the intricate needs of the people.

Designers in practice rely on design principles and do not inquire into the needs of the specific users at hand for a specific context. This may result in the building having a negative effect on the lives of its inhabitants. This problem could be solved by approaching every design project as a research process, formulating context-specific hypothesis and proving it during the design phase so it can be implemented in manipulating user reaction. Such research is called Environment-Behaviour (E-B) research [29]. This can help ask the right questions about the users and uncover the true problems of a design solution.

Historically, post-occupancy evaluation of a building has helped the architect learn from his mistakes and better address the situation in future projects. Todays scenario of architectural practice can afford to constantly evaluate user response to a design parallel to the design process. With technological advancements made in simulating human behaviour and agent-based modelling, testing a design for behaviour patterns before its construction is made possible [17]. It requires programmers or technically sound designers to do such an analysis and not all design studios have the resources to take advantage of such techniques. Hence this method is not a common practice in the design sphere. **This paper explores the possibility of using immersive virtual reality as a platform to aid in the process of user-testing a design to gauge how the building design affects the users**.

Virtual Reality (VR) as a growing low-cost technology has the power to revolutionise the way designs are created by architects. VR is already being used as a problem-solving tool in varied disciplines, such as military training and scientic visualisation. In architecture, its possible applications are expanding. It is expected to soon become a mainstream design tool [5]. There have been several instances of VR applied to prototype designs in architecture and its advantage as a design tool has been repeatedly tested. Design visualisation and communication are some of the important applications of VR found in architecture. Building information modelling (BIM) along with its multiple layers of data were visualised in a VR system by Kieferle et al [3]. It was then used in team meetings of a construction project, to communicate the design problems among professionals from different disciplines [28]. By way of interviews, it was found that VR improves the mode of design communication. Another study showed that conveying architectural form and space to clients/non-architects with a VR model is an effective method than traditional 2D representations and physical models [16]. VR was used in this research project [4] to involve users in the early phase of a design so as to bridge the gap between architects and end-users. In a hospital interior design project, VR was used to involve the community to help make final design decisions based on their site-specific needs [27]. VR has also been utilised to benefit students in their architectural education by demonstrating room sizes and proportions. Some design studios are conducting research on using VR vs conventional design drawings to evaluate its impact on students creativity. [1] [15].

User-centered data-driven design is the core feature of designing a digital product. The design of such products uses human behaviour data to measure the impact of design on the user. Understanding the users is the main goal of using data in such a design process [14]. Extending this approach to architecture would allow for buildings that are more user friendly. Focus must be brought to make the building perform better with respect to user response as much as making the building perform better for the environment [6]. Architecture as a discipline has strongly relied on post-occupancy evaluation of a building to learn the mistakes that were made in the design decisions. Abundant and constant feedback from users, during the design evolution, will go a long way in moulding the design to meet the needs of the occupants. VR with its ability to simulate a physical setting and immerse users could be used in E-B (Environment-Behaviour) research which can be conducted simultaneously along with the design process to help improve the quality of the design. **This research paper investigates the potential of VR being used as a behaviour analysis tool to let architects user test designs for an iterative design process**. The tool designed for this purpose must be easy to implement in architectural practice and the data from such a tool must be reliable to enhance the design process.

2.2 Literature Review

2.2.1 Behavioural studies in architecture

Traditionally architecture relied on the knowledge of design practices that reflected the local needs culturally, sociologically, environmentally and technologically, accumulated over the years. This is called vernacular architecture where design principles were evolved through the method of trial and error and were passed on from generation to generation. As time went on, human settlements expanded, the scale of buildings grew bigger, technological advancements were made, and architecture and its theory too expanded.

Camillo Sitte, an Austrian architect, was one of the first few design theorists of his time. He tried to bridge the gap between modern city planning and artistic principles [25]. Of many concepts, Sitte was interested in the use of public plazas and the qualities that make them alive and successful. He travelled to many cities, directly observed and documented hundreds of plazas (see Fig. 2) and came to the conclusion that the public buildings in a plaza should be placed along the walls of the plaza. He theorised that people need to feel enclosed in a plaza and see its boundaries in order to use a plaza comfortably. This behavioural response was converted as a city planning principle because of its generalisability.

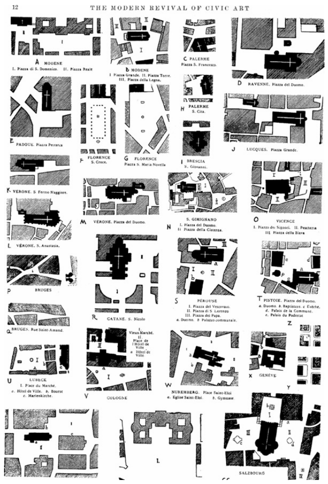

Figure 2: Plan of plazas recorded by Camillo sitte [25]

Kevin Lynch theorised how people orient themselves in a city. He observed how people's movement in city space and found the components of the mental mapping necessary for urban wayfinding. Path, edge, district, node, landmark were the five important architectural elements identified by Lynch [18]. It has helped in city planning to make cities more readable. Jane Jacobs was another author who, based on her empathetic observations of life in streets and parks, gave a new perspective to designing and programming cities [13].

Christopher Alexander studied behavioural patterns in buildings and cities [2] and formulated design patterns based on his practice, observations, innumerable case studies and scientific papers on human nature and the built environment. His patterns could be used as individual design solutions or as a combination to form a pattern language. He had a diagnostic research approach to support his theories. In his book [2], pattern number 110 talks about placing the main entrance of a building in such a way that it comes into view, to a person, as the building comes into their view (see Fig. 3). This is based on the behavioural facet of humans wherein they experience a sense of confusion and irritation when they are walking with no idea of destination in mind. People navigate space by automatically choosing a destination in order to orient themselves in a space and they consciously or unconsciously choose the shortest path towards it as mentioned by Tyrus Porter [22]. The behaviour of people is converted into a design principle that could be easily applied by other designers using his book.

Most recently, Bill Hellier criticizes how the 20th-century architectural theory has been largely standardising and weakly analytical [12]. His works among many others formed the basis of a set of architectural theories and methods called space syntax. Space syntax looks at buildings and cities as a configuration of many elements and expresses the relation between these elements mathematically. The aspect of integration of a room in a set of rooms or a street in a city is calculated by its distance to the other rooms / streets and is visualised graphically to understand the character and function of space in a building or a street in a city (see Fig. 4). Visual connection in this configuration is another value measured in space syntax. It is mapped and based on this value, movement of people is predicted. With space syntax, it is possible to quantify aspects like how navigable a space is. It is possible to predict even the social effects like crimes resulting due to the configuration of space. Space syntax is a quantitative study of the quality of spaces.

Nikos Salingaros talks about how human biology directs the behavioural response to the environment [24]. He argues why people hug the edges in a space-based on Gehls concept of edge effect [10] [23] and Ann Sussman and Justin Hollanders [26] mechanism of thigmotaxis, defined as how organisms move in response to edge conditions. He states how people intuit to walk along the edges of a space and tend to avoid the centre of open spaces.

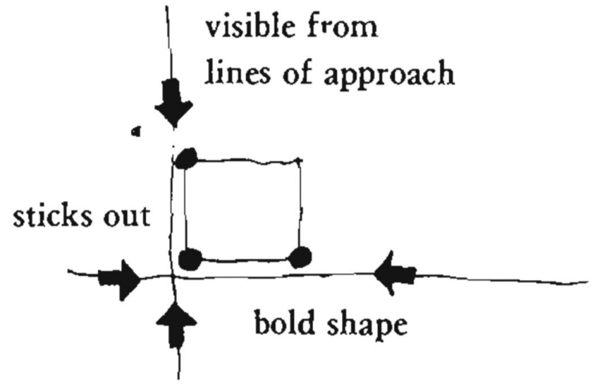

Figure 3: Pattern number 110 - Main entrance - pattern depicted by Christopher Alexander. [2]

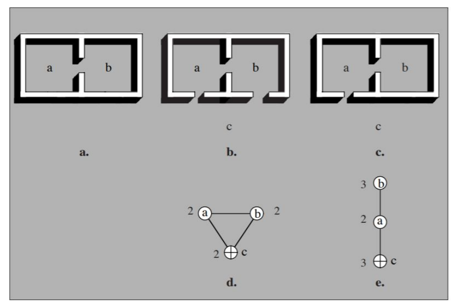

Figure 4: Integration of space according to space syntax [12]

All these theories are efforts to record human intuitions, their behavioural patterns and their response to a space. It has evolved from a qualitative to a quantitative study. With using virtual reality as a design tool to study behaviour, the aim is to record qualitatively and quantitatively the experience of the user in space.

2.3 VR in behaviour studies

Immersive virtual reality presents a graphical environment that resembles, to an extent, the real world and its objects. Therefore being immersed in VR results in the experience of inhabiting another world. The field of psychology is taking advantage of this technology in order to be able to present stimuli in 3D to test subjects. VR is also used to study phobias by simulating them in the virtual world. In traditional experiment contexts, the appropriate stimuli presented to the subject is controlled by the experimenter but he could not exercise full control over the surrounding environment. VR provides a larger control of the test environment and hence it is being preferred over other conventional methods [26]. It is believed that the ecological validity of an experiment is also greatly improved because of the use of VR [26]. Research was conducted to study human behaviour when faced with a moral dilemma, for example, the famous trolley dilemma [8].

In architecture, VR was used to study human movement and wayfinding in a CAVE (Cave Automatic Virtual Environment) VR simulation. The study found that this type of design analysis could be used predominantly in the design of hospitals to make wayfinding efficient and to find the destructive sounds interfering with the doctors attention in an operating room environment [6].

Most Virtual reality experiments were conducted using a CAVE setup before the advent of HMD (head-mounted displays). The CAVE is a five-sided virtual reality room created by 15 back-projection screens that enclose multiple viewers in a space that is 3 metres in diameter by 3.5 metres in height [6]. Such an immersive virtual reality installation is expensive to build and requires a dedicated space for its use. With the increasing availability and decreasing cost of VR headsets, mobile VR with HMD is used for this research.

2.4 Tools and trends to produce VR models

To study human behaviour in a virtual setup, a virtual reality model needs to be developed. There are many ways to transform an architectural 3D model into an immersive experience and the choice depends on the head-mounted display (HMD) applied in the interaction. One can use a desktop VR headset (Oculus Rift, HTC Vive, etc) or a mobile VR headset (Google Cardboard, Gear VR, etc). The VR scene for this research project is built for smart phones and is built as a WebVR experience (virtual experience built for the internet browser), which enables it to be shared and viewed online anytime, anywhere. Once the model is on the web, people's movement in the VR scene can be tracked much like how web analytics are built. Being easily shareable, more users can experience a scene, more data on their behaviour in the space can be collected. This can help an architect recognise patterns in the interaction of users with the design. VR is almost 6 decades old but it is still not included in mainstream architectural practice due to the perceived amount of resources, technical skills and the cumbersome process required to make a VR model. Using game engines like Unity and Unreal requires a specific skilled person and the workflow of modelling in such software is different from that of building architecture models. VR tools to transform 3d models built with the most-used 3D software in the world of architecture (3DS Max, Maya, Autodesk Revit and Rhino 3D) have been developed in recent years. And there are many applications and platforms, both online and offline, that allowone to make a 3D VR quickly and share the same with the client quite easily. Autodesks stingray is a 3D game engine and real-time rendering software that can be connected to 3DS Max and Maya. Iris VR and Fuzor are offline software that enable one to convert 3D models to VR experience with an easy workow. Some online platforms like Kubity, Visual Vocal, Insite VR, Sketchfab, Revit Live let users generate web VR visualizations. Dixie VR, an add-on for Grasshopper (a visual programming plugin for the 3D modelling software Rhino 3D), is a multi-user immersive platform, that allows many collaborators to work on an architectural project directly in VR. VR Edge is another Grasshopper plugin that produces VR ready models for the web by converting the Rhino 3D model into an HTML (HyperText Markup Language) format le. Rhino 3D and VR Edge are chosen for this research as the workflow to construct VR models seem straightforward and the HTML file can be uploaded to the web.

2.5 Limitations of the VR world

Using web-based VR as a behaviour testing tool has certain limitations as the virtual world is far removed from the real world in several aspects. Firstly, it is a hyper simplied version of reality catering largely to the senses of sight and sound but lacks the senses of smell and touch. Secondly, navigation within a VR scene is cursor controlled and does not mimic the way humans traverse across spaces. Humans might not want to incline towards hugging the edges when experiencing an environment in virtual reality. What helps in wayfinding in a city may not be necessary in a virtual world of exploration. It is important to investigate if the unique characteristics of a tool specific virtual environment affect the behaviour of people.

VR with its ability to be well controlled became a viable tool to do psychological studies. But in architecture, a vibrant environment with people is needed to resemble reality. The technological limitations of the chosen VR platform lead to questioning the behavioural response of the users in the virtual environment and if it corroborates with the real-world responses.

2.6 Hypothesis formulation

Using the recorded data of user movement from the virtual world to gain insight into the architectural design is only possible when the behaviour inside this articial world follows the basic human instincts in a real space. There is a possibility that the user behaviour within a virtual world can go against these primordial movement patterns discerned by architectural theorists, mentioned in the previous sections, because of the unique affordances of a VR world and its limitations to entirely mimic reality. The primary question raised when choosing VR for testing architectural theory is - **Does the user behaviour in a VR scene deviate from the normal behaviour owing to the new affordances that come with the virtual world ?**.

3 OBJECTIVE OF THE STUDY

The objective of this research is to embed human behavioural data in a given architectural design to evaluate the space for user response to evolve the design. Virtual reality is used as a medium to do that by creating a tracking app that can monitor user behaviour in the virtual environment. The position of the user in the VR and the time spent in each position is recorded by the app. This paper is the rst in a series of papers trying to realize this objective. The aim of this paper is twofold. Firstly, to report on the ease of the tool used in creating a VR model and collecting data from it. Secondly, to test an architectural design principle in the VR world to check for deviation of VR user behaviour from the expected behaviour dictated by the theory followed in planning a VR experience. This is the method by which the reliability of the behaviour data is tested.

4 METHODOLOGY

The proposed solution for user testing in architecture involves using VR to study human behaviour. The validity of using such a tool is tested using an **experimental methodology**. A 3D environment designed based on an architectural theory is presented to users to experience in VR. The data collected on their behaviour is compared to an expected behaviour map drawn out based on the architectural theory implemented to guide user behaviour in the design.

The research is a quantitative and qualitative study of user experience in a contrived VR environment designed to test a chosen architectural theory. To this end, a design principle that applies in the physical world, that is well documented and widely accepted is tested for its applicability in the virtual environment. The chosen design theory is a pattern from the collection of well-respected design practices for architecture and urban design modelled by design theorist Christopher Alexander [2]. The experiment was conducted on a random selection of 20 participants. The empirical data derived from the tracking app is supplemented by data obtained from a detailed questionnaire about their experience to better understand the perception of the VR scene and the difficulty of using Web VR during the experiments.

4.1 Tracking app and Properties of the VR scene

The VR scene is modelled using Rhino 3D. The output from the VR Edge plugin is an HTML file and multiple JSON (JavaScript Object Notation) files of the model. These files can be uploaded to the web. The reason for choosing this system of tools to create VR models are twofold. Firstly, many architects already use Rhino modelling software. A wide user base of architects would easily be able to access and use the new tool without specialized training. Secondly,

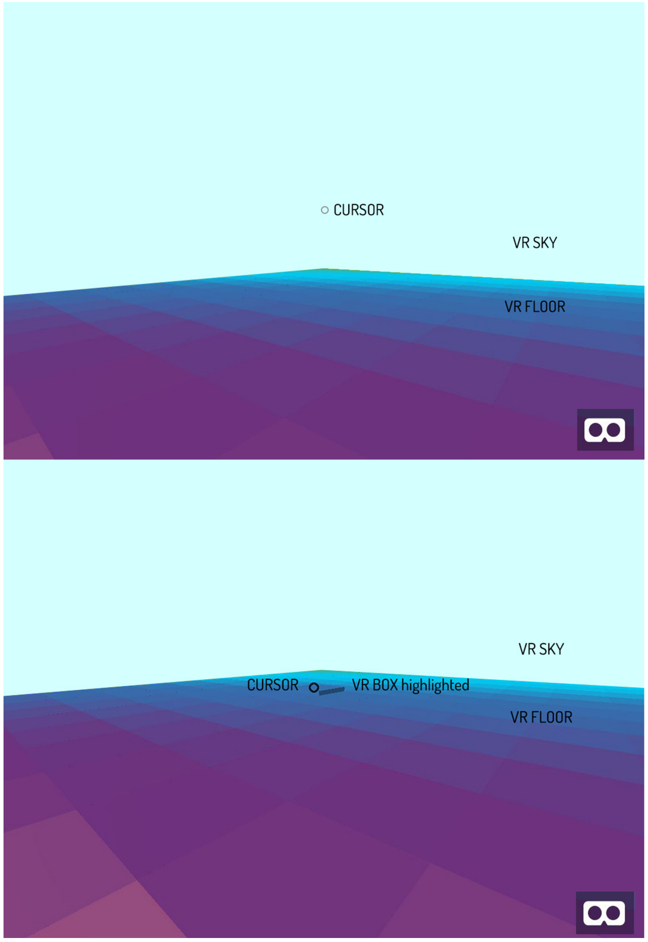

Figure 5: The image above shows the cursor in the center. The VR floor made of VR boxes is shown with colour gradient. The image below shows how a cursor highlighted VR box.

the produced HTML files can easily be manipulated to build the user tracking app and can be shared online.

VR Edge produces a scene that can be navigated by teleportation. The teleportation method of locomotion in a virtual space helps the user navigate from one point to another without actually traversing the physical space between them. The floor of the scene is a grid of boxes (see Fig. 5), each of which acts as a point in the scene that the user can move to. The point and click method of movement is where the user directs the cursor to where they want to move and then instantly materialise in the clicked spot. The cursor in the centre of the VR scene (see Fig. 5) also triggers a click when made to hover long enough on a box on the VR floor. The scene is a passive VR environment where the user cannot interact with the objects present. Currently, the scene is a single-user platform. The render quality of the VR scene is still primitive. Texturing and manipulating lights are not part of this version of the plugin.

The data of users' movement is extracted by developing an API (Application Programming Interface - a set of functions that allow the creation of applications that access the data of service) in Node.js (asynchronous event-driven JavaScript runtime). The coordinates of the points that are clicked on the screen are recorded in real-time along with the time stamp. This provides information on how a person navigates the architectural space and how long they spend in each location/VR box. Currently, the app runs on a local server and is accessed via a local port (see Fig. 6). The app will soon be

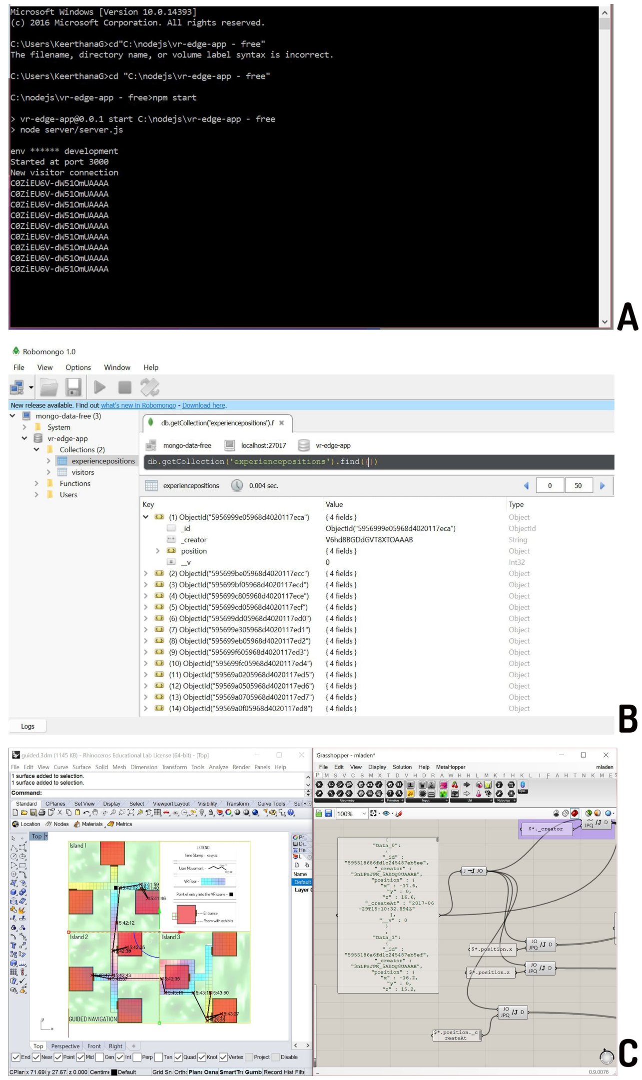

Figure 6: A - the command prompt running the tracking app.B - the database that stores the recorded data.C - the collected data is visualized using Rhino3D and Grasshopper.

deployed online to a dedicated server and will become accessible to users remotely.

4.2 Experiment Setup

The experiment scene is a model depicting the following design recommendation by Christopher Alexander [2] explained in the section Behavioural studies in Architecture:

- Selected design pattern: Main Entrance
- Explanation: The entrance must be placed in such a way that people who approach the building see the entrance or some hint of where the entrance is, as soon as they see the building itself..*Consciously or unconsciously, a person walking works out his path some distance ahead, so as to take the shortest path (Tyrus Porter, 1964).*
- Design Solution: ...the first step in placing the entrances is to consider the main line of approach to the site. Locate entrances so that, once the building(s) come into view, the entrance, too, comes into view....

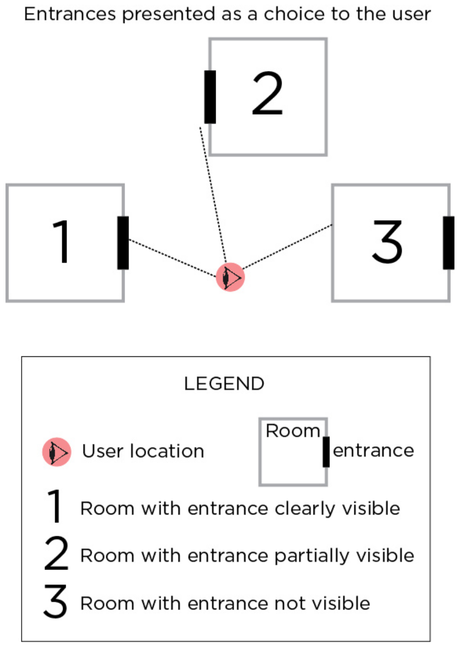

Figure 7: The types of entrances used in the experiment is depicted here. 1- fully visible entrance. 2 - partially visible entrance. 3 - entrance that is not visible to the user. The arrangement used to present the entrances as a choice is shown in the figure.

Three ways to position the entrance that exaggerates this point, as listed below, are identified and are presented as a choice to the user (see Fig. 7):

- Making the entrance fully visible.
- Making the entrance partially visible.
- Making the entrance not visible.

Based on the choice of entrance made by users in VR, inferences can be drawn on the extendability of the design rule to the VR environment.

A task-based VR Museum scene is designed wherein the users are asked to choose among the 3 types of entrances represented by different rooms. The scene is broken down into islands and in each island, all the rooms house the same exhibit so the user needs only visit one room (see Fig. 8). The choices made by the user in each island and their movement pattern was recorded.

The VR scene can be designed to provide free exploration to the user or a guided exploration (see Fig. 9). In the free exploration, people can navigate to any part of the constructed scene. While in the guided exploration the movement is restricted to a path. The floor of the VR is designed with a colour gradient to differentiate between the VR boxes for convenient cursor selection and teleportation.

4.3 Reconnaissance study

To refine the design of the VR environment, a reconnaissance study was done. This helped weed out any bugs in the tool as well as smooth the design of the VR scenes for the comfort and convenience of the users.Nielsen's usability engineering [20] suggests to test a small number of users to quickly analyze a tools usability. According to his mathematical model, testing six users will reveal more than 85% of the usability problems. Thus, these scenes were tested for quick feedback with six participants.

The designed scenes could not be loaded sometimes owing to the heavy meshes used as display objects in the VR museum set up

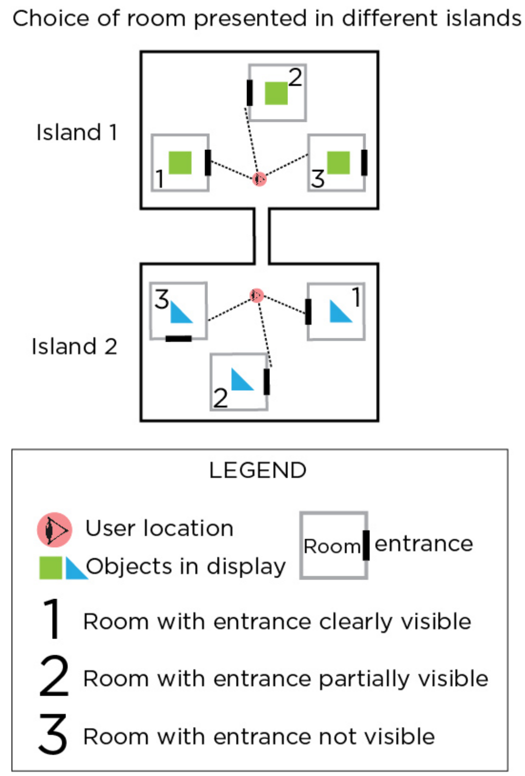

Figure 8: Islands 1 and 2 house 3 rooms each with different types of entrances based on visibility. The choice of room made by the user in each island is recorded.

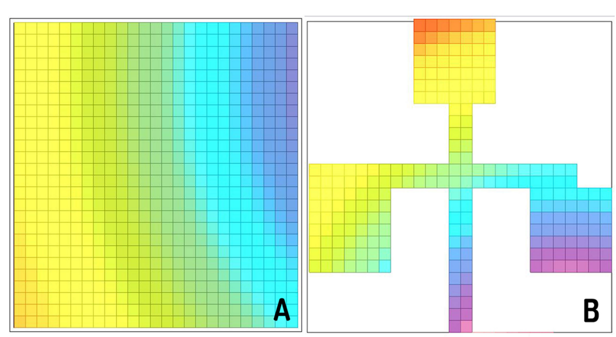

Figure 9: A - is a VR floor with free navigation. The user can move to any part of the scene. B - is a VR floor with guided navigation. It limits the user's movement to a region.

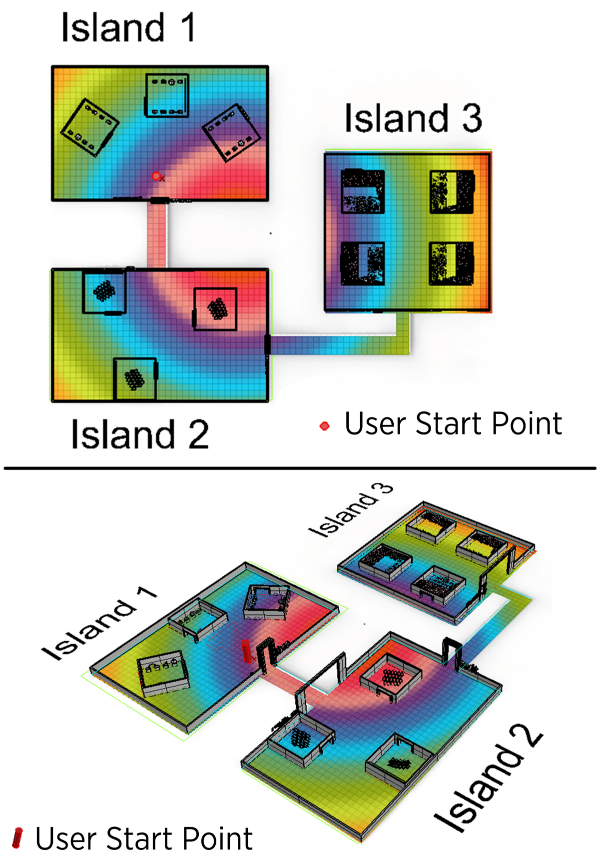

Figure 10: The image above shows the plan of Scene 1 with free navigation. It has 3 islands connected by pathways. The image below is a perspective view of the scene.

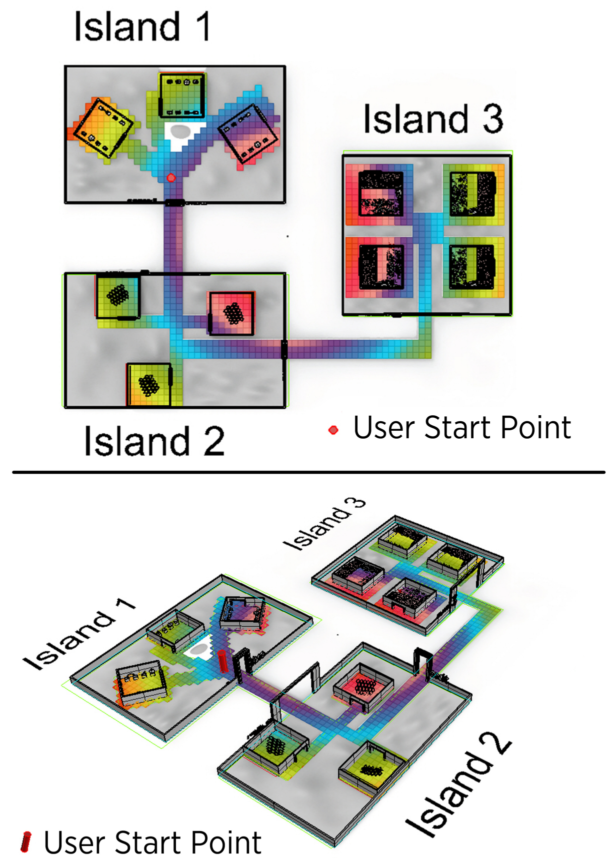

Figure 11: The image above shows the plan of Scene 2 with guided navigation. The grey patches outside of the coloured pathway is not accessible for users. The image below is a perspective view of the scene.

and the numerous VR boxes on the floor. This led to the redesign of the scenes to be smaller and with lighter meshes. Some of the users felt confused and lost in the VR scene. The final scene was designed with more signage to avoid confusion of users. Some users felt the experience was too long. Hence the number of islands in each scene was reduced to 3 from 4. Based on the feedback the scene was redesigned to improve the quality of data obtained.

4.4 Final 3D environment

The 3d model is divided into 3 islands with 3 rooms each with the same object displayed in all 3 rooms on an island (see Fig. 10). Only the design of the floor is changed for scene 2. It does not allow free movement of the user but restricts it to a pathway (see Fig. 11) (see Fig. 12). Exit and entry signs are placed in the scene to guide the users from one island to another (see Fig. 13). Room 1 in islands 1 and 2 has a clearly visible entrance, while rooms 2 and 3 have partially visible and completely non-visible entrances respectively. Island 3 has 4 rooms with hidden entrances so as to instil a sense of confusion in users. (Note: Island 3 is meant for future studies where the emotional response of users can be measured using biosensors that detect heart rate, brain waves etc,.). All the rooms in a given island are placed equidistant from the point of approach of the user so as to not let distance to an entrance affect its chances of being chosen.

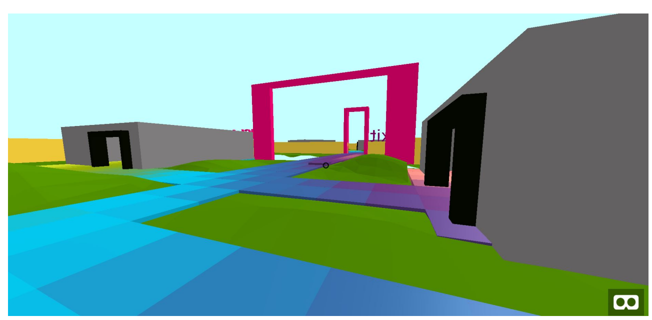

Figure 12: Restricted movement in scene 2. One cannot access or teleport to the green grass patch. The user movement is confined to the coloured VR floor.

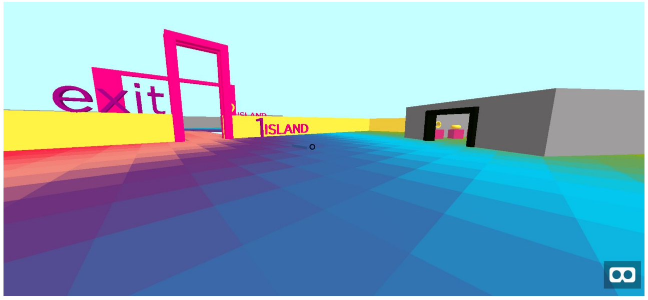

Figure 13: A view from the VR scene showing the exit signs placed in the scene to guide users from island to island. The screenshot is from scene 1 and the VR floor is not restricted by grass patches.

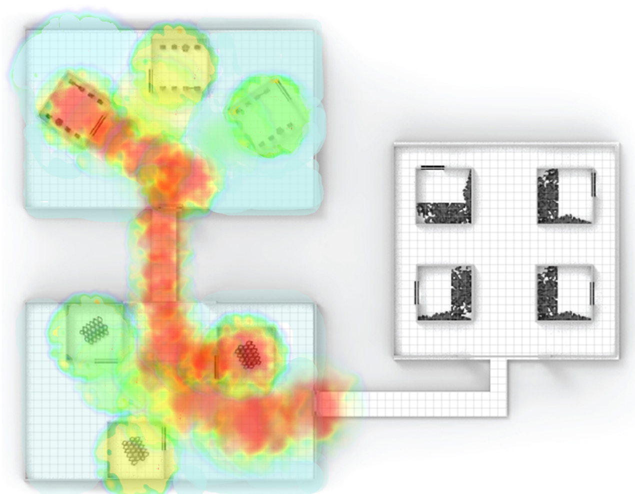

Figure 14: Expected Behavioural Map of scene 1.

4.5 The expected behaviour map

It is expected that most users will choose room 1 with the clear entrance in both islands 1 and 2 as the entrance will be immediately visible to users from their line of approach. Room 2 will be the next most selected and room 3 will be entered by the users sparingly as the entrances do not come into view as easily as that of room 1. The expected behaviour map is represented as a heat map (see Fig. 14) (see Fig. 14) where red shows the regions of the VR scene that will be most used or, in other words, most clicked and colour blue marks the regions with least visits.

4.6 Experiment execution

A set of 20 users participated in this experiment. Their ages ranged from 24 to 46 years. They were from different professional backgrounds namely architecture, engineering, design, management, media production and journalism. 7 out of 20 participants were first-time VR users, 8 users have been in VR for less than an hour, 5 were occasional users and 1 was a frequent user. Each scene was given to 10 participants. The experiment was conducted with each participant individually. The nature of the experience was briefed to the participant and the navigation method was explained to them. The HMD VR box was used. No input controller (a mouse-like device used to navigate a VR screen) was used during the experiment. Once the user is comfortable with the HMD, the phone with the VR scene was inserted into the HMD. Each participant was asked to move from island 1 to island 3 in order. The tracking data was collected throughout the experiment and the collected data was stored in a database with a unique user ID for each test subject. During the experiment, the emotional data was recorded using the Neulog GSR sensor for future use of emotional data analysis. After the experiment, the participant was asked to fill out a questionnaire that has questions on the users personal data, on the rooms selected in each island, the motivation behind the selection, on space perception and the general quality of the experience.

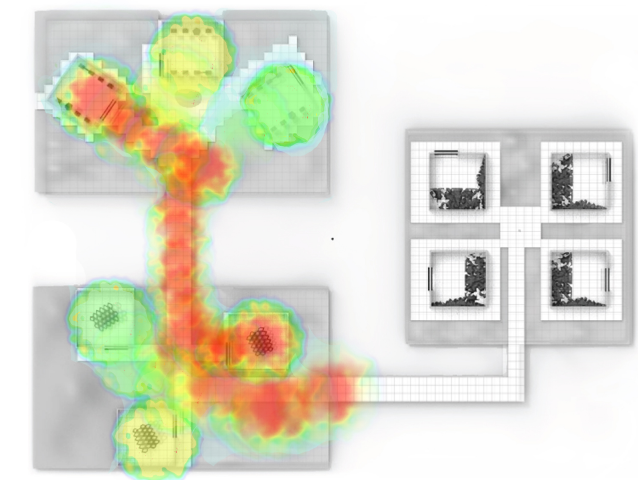

Figure 15: Expected Behavioural Map of scene 2

5 Results and Observations

The collected data consists of position coordinates, a unique creator id and the timestamp of each click. The stored data is of JSON format. It is parsed and the data is visualised (see Fig. 16) (see Fig. 17) using the Rhino plugin Grasshopper.

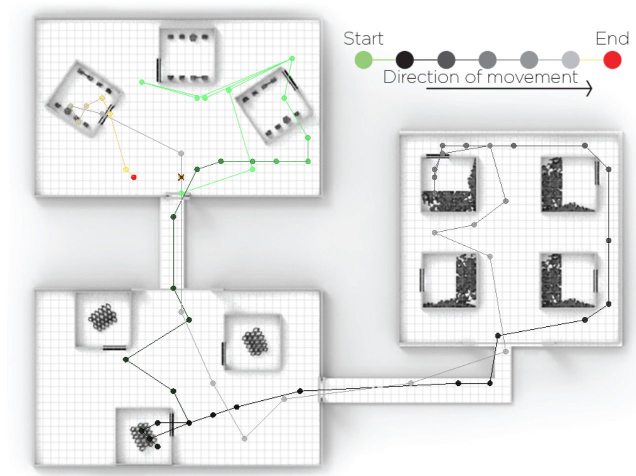

Figure 16: The movement pattern for 1 user of scene 1 is visualised in the above image where circles denote the clicks and the connecting lines help convey the chronological order of the clicks.

Table 1 summarizes the time spent and actions made by the user in each scene.

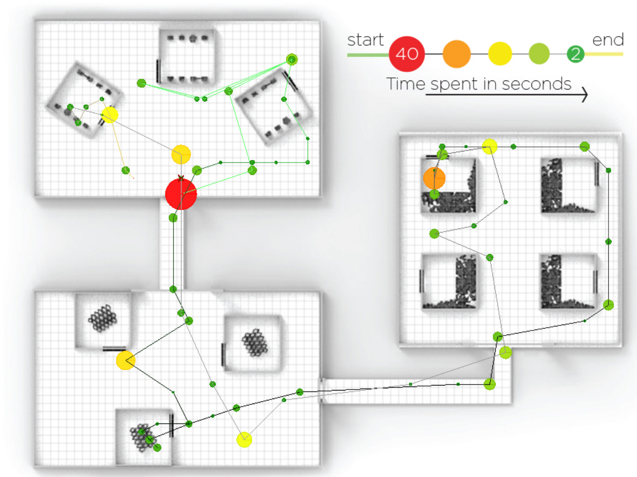

Figure 17: The time spent by the same user, as of the previous image, in each clicked location is visualised in this image for scene 1. More the time spent, bigger the radius of the circle and more warmer the colour is.

Scene	Max total time	Min total time	Max Clicks	Min Clicks	Max secs per click	Min secs per click
1	12min 57 secs	2 mins 27 secs	72	19	40	2
2	7 mins 23 secs	2 mins 23 secs	56	23	32	2

Table 1: Time spent and actions made by the user in each scene

None of the subjects felt the experience was too long or faced any frustration during the experience. More clicks were made in scene 1 and more time was spent there compared to scene 2. This could be attributed to the freedom that is available for users experiencing scene 1. It was also observed that more mis clicks were made in scene 1 than scene 2. This could be another reason for the difference in the maximum number of clicks between the 2 scene.

Table 2 shows the total number of clicks made by each user.

5.1 Ease of use of the tool

The workflow to produce a VR scene from Rhino 3D and VR Edge plugin is straightforward and easy to understand. A simple tutorial can guide one through the process and it requires a relatively short time to change a rhino model to a VR model. The app used to track users movement in the VR scene required some technical knowledge, on the part of the experimenter, to be able to collect and store data. But this feature is to be included in the plugins next version and hence the data collection method will be of a plug and play format. This will enable anybody to use this tracking app and recover data about their design.

5.2 Space perception and ease of use of VR for the users

80% of the users found the scale of the virtual scene similar to that of a physical setting. The users who reported otherwise found the height of the entrances too low mainly because the users were tall and they felt the urge to duck when entering a room. The method of navigation was easy to understand for all subjects and they had no problem in implementing it in the experience without prior practice. Including the 35 % of new users with no prior VR experience had no problems navigating the scene. 55% of users reported that the pace of movement was normal whilst 30% found it slow and 15% found it fast. Simulator sickness which is a common problem associated with VR experiences was also tested for, but 90% of the users reported no nausea, dizziness or other symptoms normally associated with simulator sickness. Overall, VR scene from VR edge proves easy for the users to navigate and it is comparable to reality.

Range of clicks	No of users in Scene 1	No of users in Scene 2
70 - 80	1	0
60 - 70	2	0
50 - 60	2	4
40 - 50	3	3
30 - 40	1	1
20 - 30	0	2
10 - 20	1	0

Table 2: Total number of clicks made by each user

5.3 Movement pattern

The movement pattern of scene 1, in 4 cases, resembled close to that of scene 2 - more controlled and guided in spite of the ability to move anywhere (see Fig. 18). In other cases, there were many unexplainable random clicks in the scene. Long distances and erratic jumps were made by users in scene 1. Particularly one user focused more on making jumps between islands which were not connected by VR floor than trying to move towards a destination. This behavior of VR users renders the data not reliable for assessing behaviour and informing the design as they are not representative of the real world.

5.4 Testing of the architectural theory

Table 3 shows the choice of rooms made in each island in each scene by each user.From table 3, one can see that room 1 with a prominent entrance was chosen majorly in both islands in both the scenes. The heat map of the obtained data is shown in image (see Fig. 19) (see Fig. 19) along with the expected behavioural map. The rooms 2 and 3 were chosen as expected (room 2 greater than room 3) except in island 1 of scene 1 where room 2 was not chosen by any user. In island 1 of scene 2, rooms 2 and 3 were chosen equally. This deviation from the expected behaviour was analysed further by studying the user responses to the questionnaire. The survey included questions trying to unravel the motivation behind the choosing of an entrance by the user.

The reasons given for choosing a particular room in island 1 were, in some cases, contradictory to the reasons given by the same user for a similar action in island 2. For instance, one user mentioned the motivation behind the room selection was that the entrance was not visible. The user wanted to roam around and explore than to choose a room with a clearly visible entrance. The same user chose room 1 in the next island stating the reason that the entrance was clearly visible. The reasons behind why people choose a certain room is hard to assess and, sometimes, are contradictory. For scenes 1 and 2, 6 out of its 10 participants provided consistent reasons for their drive behind entering a room whilst the others exhibited the urge to wander around in some places and the lack of it in other instances.

5.5 Data reliability

At a cursory glance, the movement pattern of people in the VR world is as expected and close to the real world but more points

User	Scene	Choice of room in Island 1	Choice of room in Island 2
1	1	3	1
2	1	3	2
3	1	3	1
4	1	3	1
5	1	1	1
6	1	1	1
7	1	1	1
8	1	1	2
9	1	1	1
10	1	1	3
11	2	1	2
12	2	3	3
13	2	2	1
14	2	1	1
15	2	2	1
16	2	1	1
17	2	3	2
18	2	1	1
19	2	1	2
20	2	1	3

Summary of choices	Island 1	Island 2
scene 1	Room 1- 70% Room 2 - 0% Room 3 - 20%	Room 1- 70% Room 2 - 20% Room 3 - 10%
scene 2	Room 1- 60% Room 2 - 20% Room 3 - 20%	Room 1- 50% Room 2 - 30% Room 3 - 20%

Table 3: Choice of rooms

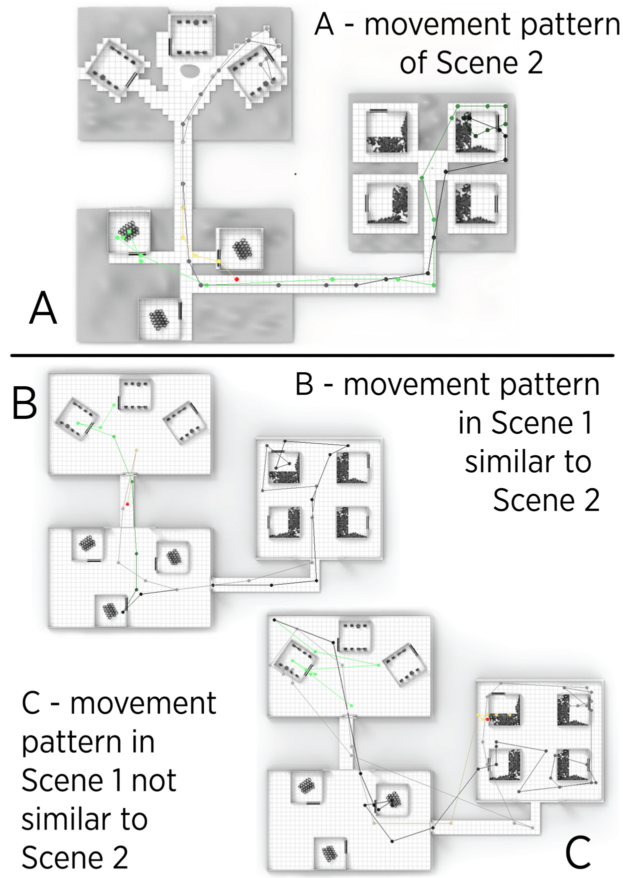

Figure 18: Image A shows the movement pattern of a user in Scene 2. Image B shows a similar pattern restricted to a linear path observed in Scene 1 where there is no constraints in the spaces one could teleport to. Image C shows the user taking advantage of the free space. A random behaviour is discerned in this case. .

were observed through survey and analysing the movement pattern click by click. 5 out of 10 subjects reported having moved through the walls in scene 1 but only 2 out 10 reported the same for scene 2. This shows, more the VR boxes, more chances of it being selected by the cursor through the walls unintended by the user. This propels the user to jump through walls unintentionally in most cases. Once it occurs by accident, some users try to do it again for the fun of it. This hinders the reliability of the data collected on movement and the motivation behind it.

The addition of rotation data - ability to see what a user sees in each location - can help answer a lot of questions that raise when studying the movement pattern. The time spent in a location is able to convey if the person is just passing through a location or is pausing to look around or deciding on the next click. Similarly having rotation data can help in knowing if the user is looking in the places as one would expect and place the entrance in a clearly visible location. An example is used to prove the need for a richer data (see Fig. 21). In the figure, the user enters the island 2 of scene 1 and first goes towards room 3 and spend a little time outside the entrance but does not enter the room. Instead, the user moves to room 2 and adds to the expected behaviour pattern. The rotation data will infer the experimenter if the user had his/her back to the entrance or if the user clearly saw the entrance but avoided to enter the room for reasons unknown. There is a need for a richer data that

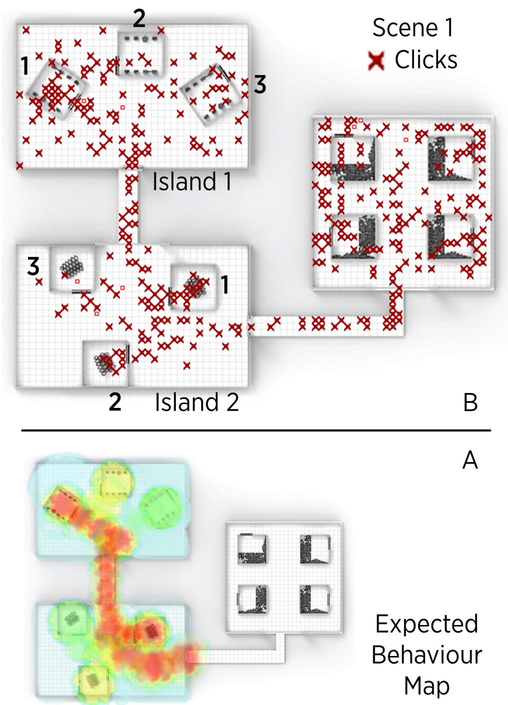

Figure 19: Image A - Expected behaviour pattern of scene 1. Image B - distribution map of movement pattern/clicks for scene 1.

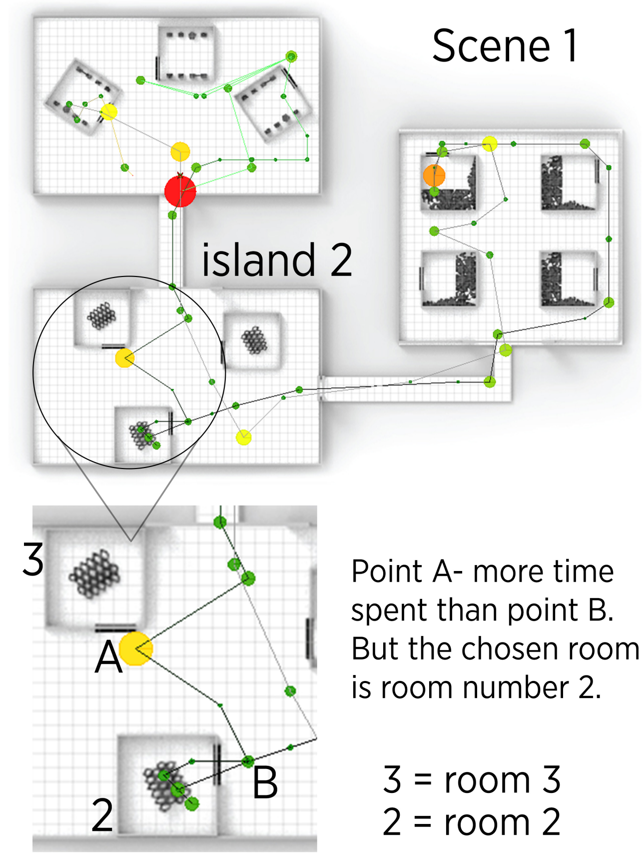

Figure 21: The user entering island 2 in scene 1 is almost close to choosing room 3 over room 2. But more data on the behaviour is needed to assess the reason why the user moved away from room 3 to room 2.

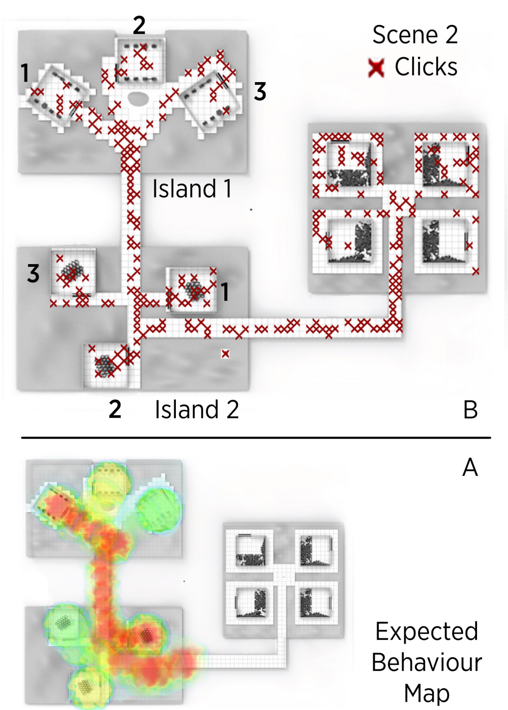

Figure 20: Image A - Expected behaviour pattern of scene 2 . Image B - distribution map of movement pattern/clicks for scene 2.

should be extracted from the VR scene to make it a stronger tool for behavior analysis.

6 Conclusion and Way forward

In the field of architecture, there exists a wide gap between the designer, i.e. the architect and the end user in terms of their tasks, expectations and their context. Literature has provided ample examples of cases where the aim and intent of the designer have been thwarted completely by the design having the direct opposite of the desired effect on the user behaviour. This emphasizes the need for a systematic usability testing to inform the architect and continually modify the design [21]. Traditional methods of evaluating and understanding user behaviour to try and design for the user, like surveys, interviews or simulation methods have been found to be either underwhelming and not very effective or to be elaborate and resource consuming. Thus there has always been a demand for a balanced tool that is cheap and easily available but is also efficient and effective. Many applications for user testing in architecture involve the design of communal spaces and public buildings and thus a tool that offers widespread usability and simultaneous testing would be highly desirable.

In this research movement pattern of people in a contrived VR environment was observed and analyzed. The collected data gives an insight into the natural movement of people, the supplementary survey serves to help understand the motivation behind some of the choices the subjects made in the VR world. The choices were expected to follow the architectural theory on **Main Entrances** given by Christopher Alexander wherein the room with a clearly visible entrance should be chosen most number of times by most number of user.

Based on the experiments conducted and the data collected, the VR tool even in its primitive stage with rudimentary graphics and design elements does an outstanding job at emulating the real world for the purposed of behaviour testing architectural designs. The feedback from the subjects and the comparison between the observed and expected behaviours were the two main ways of establishing the validity of the WebVR system as a behaviour testing tool. This suggests for more than half the users, neither the low render quality nor the teleportation mode of locomotion or any of the other affordances of the VR environment distract or divert the user from acting as they would in the real world. Some people chose to travel along the shortest paths and made decisions consistent with that objective even when they realised that they could travel freely to any point in the environment. The widespread applicability of the tool is also proven by the fact that users of varying ages and prior VR experience (including first-time users) were comfortable with the VR system and could quickly learn to navigate within the simulated environment. Revisiting the hypothesis, the experiment and the data collected at first glance suggests taking the position that the user behaviour in a VR scene **does not deviate** from the normal behaviour owing to the new affordances that come with a virtual world. Further research with more participants and a variety of scenarios is required before this can be definitively concluded. The VR floor of scene 2 with guided navigation proved more effective in producing valuable data than that of scene 1 as the number of misclicks and the jumping-through-the-wall phenomenon were remarkably minimised in scene 2. A focused movement pattern was observable more in scene 2 than in scene 1.

The analysis of the collected data revealed interestingly the importance of also capturing rotational FOV data of the subject, i.e. the direction in the subject is facing at each point of the experiment. This data in addition to the position and time data would help in reconstructing not only the movement pattern of the subject but also areas of interest, visibility and the impact of signage and a peek into the navigation strategy the subject employs. Emotional data also was collected during the experiment, using a skin conductance sensor to measure the emotional sweat of users on their fingers, but was not analyzed or presented due to poor quality. This is another area of improvement that has been identified as emotional data adds a completely new dimension to the capabilities of the WebVR system. Measuring stress levels and attention levels could help decipher areas where subjects feel lost or confused, areas that attract users and kindle their curiosity, and locations or exhibits that calm/relax people. With the online deployment of the tool, it would be possible to simultaneously let multiple users experience the VR environment and collect data from their experiences. This would benefit countless projects that value feedback from the community. WebVR being compatible with multiple platforms and a lightweight tool, can run on most modern age smartphones and hence reach out to a multitude of users. The WebVR system suggested is still in its infancy at the time of writing this paper and hence extensive testing is required to ensure repeatability of the data. Continual improvement by means of modifications and fine tuning is also expected as the tool is still quite a way from a product stage. Further research and improvements to the tool, not only would serve to justify the WebVR system as the new standard for behaviour testing but also introduce evidence based design to the field of architecture.

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