eCAADe RIS 2019. Virtually Real. Immersing into the Unbuilt

Proceedings of the 7th Regional International Symposium on Education and Research in Computer Aided Architectural Design in Europe

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VIRTUALLY REAL

Immersing into the Unbuilt

7th eCAADe Regional International Symposium
Aalborg University

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Edited by
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Martin Kraus

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Virtually Real

Immersing into the Unbuilt

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Department of Architecture, Design
and Media Technology
Aalborg University

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Virtually Real

Immersing into the Unbuilt

Virtual reality technologies are currently experiencing rapid development and have matured significantly in recent years. As with other technologies, games pave the way for their introduction, but the VR technologies are increasingly put to professional uses, such as in training, manufacturing, design and architecture. And not surprisingly, the renewed interest in VR in recent years has also spilled into architecture and design, in practice as well as in research.

Basic VR systems consist of head mounted displays (HMDs), reminiscent of scuba masks, in which a screen is placed in front of the eyes. HMDs may be connected to sensors and a computer (either with a cable or wirelessly), they may simply hold a smartphone, making use of its built-in accelerometer, or they may be stand-alone systems with screens, sensors and computational power of their own. CAVE systems are a different form of VR which has been around for decades. Basically, they are room-size spaces with walls with full-size projection screens.

The relevance of VR technologies to architecture and design are manifold. In comparison to traditional forms of architectural representation – projection and perspective drawings, physical and computer models, VR systems enable a fully immersive experience of objects and spaces, whether yet to be constructed, or as simulations of real-life counterparts. VR models may be highly detailed or conceptual and may include sound to be experienced through headphones. In addition, VR systems may allow users to interact with the model by means of controllers, in order to move or otherwise activate elements in the model.

While the experience of architectural space is one obvious application of VR in architecture and design, VR may also be used pedagogically as instruction devices in architectural education. As vision is completely controlled in an HMD, one obvious advantage of VR is the capability to simulate light – something which is innately difficult with conventional forms of architectural representation, including

3D simulations on 2D displays. Finally, VR may be used to test perception, visual or aural, of architectural space, whether in terms of navigation and wayfinding, or the evaluation of different qualities of architectural space such as size, proportions, light conditions or soundscape.

The proceedings, like the symposium, is organised into six main topics; Interaction, Augmented reality, Navigation, Light, Education and Perception. These topics materialised in the process of scheduling the symposium. As such, they reflect the specific contributions to the symposium, but they might well be indicative also of the fields in which VR presents itself as most relevant to architecture and design.

Interaction

Apart from merely being present in a VR environment, the ability to interact with objects in that environment has obvious potentials, in general, as well as for architecture and design. Different interaction techniques exist, from simply gazing, or touching buttons on the HMD, to using automatically detected hand gestures. Interaction may serve different purposes. Most notably, interaction is used for changing position within the VR environment. As physical movement is mostly not a feasible way to move around in VR, hand-held controllers are typically used to point to positions in the VR environment in order to teleport the user around. In addition to movement, interaction may serve the purpose of moving objects, displaying information, or activating buttons and tools.

In their paper “Virtual Reality for prototyping compression-only structures”, Kontovourkis and Stroumpoulis (p. 5) present a methodological framework for prototyping compression-only structures such as arches and vaults and for investigating their assembly and physical behaviour prior to realization. In the presented VR system, users can modify and assemble virtual building blocks, which display real-world physical behaviour with regard to collision and gravity.

While the system has the obvious advantage of not involving real physical building blocks which are costly, heavy and take up space, such a system may have instructive value for the training of both builders and design students. While builders may learn how to actually construct compression-only structures, design students may train their understanding of the tectonic qualities and constructive potential of compression-only building techniques.

Latino et al. (p. 15) present a prototype for an indoor multi-stakeholder augmented reality (AR) application to support collaborative design in early stage urban planning. Much like the IKEA app that allows users to project virtual models of furniture in their home by means of a handheld device such as a smartphone or tablet, this prototype projects a virtual model of an urban environment onto a horizontal surface such as a floor or a table top by means of a similar device.

While still in the early phases of development, the idea of this system is to enable the visualisation of sensor and simulation data, as well as to allow users to modify elements in the model, which, in turn will impact simulations such as wind flows, sound, and patterns of movement. While the model can be examined only by moving around it and towards it (no zooming), it effectively functions as a virtual scale model in space.

Ever since the advent of CAD, one of the main challenges of any computer-aided design system has been to offer true sketching capability. Sketching – the act of ‘doodling’ loose drawings where lines are ambiguous, both with regard to their position and their meaning – is central to design exploration, yet very difficult to enable inside a computer system which essentially relies on specific coordinates in space in order to visualise inputs.

In “Sketching Immersive Information Spaces”, Vistisen et al. (p. 25) report on a couple of student workshops aimed at designing in and for VR, with a focus on design exploration. While VR seems to have some obvious potentials for early design exploration, sketching in VR, it seems, is not easily achieved. An attempt to apply hand-drawn equirectangular sketches – distorted 2D drawings which can be experienced as 360° environments in VR – turns out to be too much of a mental leap for the students to produce while still not offering a truly ‘sketchy’ work mode.

Augmented reality

While virtual reality offers interesting possibilities in architecture and design when it comes to immersing into completely computer-generated environments, augmented reality offers to superimpose computer-generated objects or spaces onto the physical world. This has obvious potential, both for experiencing objects in specific physical settings and for experiencing designs for the partial modification of the physical settings themselves.

Augmented reality often anchors virtual objects to the physical environment. In their paper “Mixed Reality and lost heritage”, Couceiro et al. (p. 37) engage this feature to facilitate the exploration of lost heritage. From historical photos, drawings and preserved objects, they aim to virtually reconstruct the Santa Monica monastery in Coimbra, Portugal, to its state before partial demolition in the 19th century.

The team applies two different digital technologies to reconstruct the lost spaces. Point cloud technology is used to 3D scan remaining building spaces and sculptures, and spaces are photographed using 360° stereoscopic photography. The two are combined to create a high quality stereoscopic 360° immersive experience. Ultimately, different VR-AR convergence experiences will be offered on site to future visitors of the monastery, enabling them to immersively explore states of the building complex which no longer exists.

Akin et al. (p. 47) address the visualisation of quantitative performance analysis in architecture. In essence, they aim to develop an AR tool which may allow designers to review architectural models and simulation results interactively through the integration of BIM and simulation data into an AR model. Focusing on daylight simulation, they use the Hololens HMD to project an architectural model in real space. The architectural model, in turn, is overlaid with a 3D column diagram indicating the amount of daylight in different parts of the model.

The tool supports visualisation, navigation, as well as interaction. Hence, apart from displaying the model and the daylight data visualisation, the model can be moved, scaled and rotated in space. Individual parts of the model such as trees, furniture and building parts may also be moved. The tool does have limitations though. As its workflow is unidirectional, passing data from the BIM software to the visualisation platform, the system does not offer feedback from interactions. Thus, moving parts in the model does not allow daylight simulation graphs to update.

Instead of allowing its user to immerse into the unbuilt, AR may be used the opposite way. In another tool development project, Schulz and Beetz (p. 57) use AR to position smartphones in space while using them to take survey photos of building interiors where GPS, WIFI and Bluetooth technologies cannot be used. In a clever setup, they use AR to simultaneously scan the spaces which are photographed. To locate the scans in absolute space, the starting point is picked on a map at the beginning of scanning/photo sessions.

Thus, photographs can be associated with metadata about the camera's position, orientation and angle as well as user annotations. While the photographs themselves may be stored using any cloud service, the metadata are combined and fed to a BIM database. But more interestingly, via the metadata, the photos are analysed and compared to a BIM model of the building using ray-cast. This way, it is possible not only to link the photos to the BIM model, but also to retrieve from the BIM model which building parts are visible in each photo and vice versa. And the surveyor may do all of this using a standard smartphone and without BIM expertise.

Navigation

How do you find your way around in virtual space? The possibility to actually walk in physical space in order to move around in virtual space may be limited by cables, sensors and the dimensions of the room where the VR system is set up. Moving around in continuous virtual space is therefore typically solved by using hand controllers to teleport oneself to new locations.

But virtual environments (VEs) are not bound by the same trivial three-dimensional constraints as physical space. VEs may be non-continuous, fold onto themselves, be inter-connected, and even change dimensions dynamically, in ways that transgress our experiences from the physical world. This redefines the notion of navigation and, in turn, calls for a whole set of metaphors for how to interact with VEs in order to navigate in them.

In a proposed research presented as "The use of virtual reality in exploring non-linear interpretations of literary architecture: an initial methodology", Liu (p. 69) very ambitiously outlines a VE based on interpretations of descriptions of architectural spaces in literature, such as Umberto Eco's The Name of the Rose, Italo Calvino's Invisible Cities, and Tu Fu's poem Meeting Li Kuei-Nien in the Southland. Working with architecture students and professionals, Liu aims to accumulate multiple drawn interpretations of the space descriptions as imagined by a host of contributors. These interpretations will form the basis for the design of a VE where the user may choose different scenarios, based on both tangible and intangible elements, in a non-linear fashion.

An important aspect of VR is the correspondence between actual physical movements (what your body feels) and simulated movements (the visual stimulation). This is called biomechanical symmetry. If, for instance, you turn your head wearing an HMD and the image inside it does not correspond, you are likely to get uncomfortable. This phenomenon is called simulator sickness, cybersickness, or VR sickness. While walking is difficult to simulate convincingly in VR, bicycling is easier to simulate. Bicycling, in other words, creates a higher level of interaction fidelity.

This is exploited by Bartas et al. (p. 75) in their study of presence in VR. Their experimental setup includes an exercise bike equipped with sensors enabling it to function as a VR controller. As the feeling of presence is associated with biomechanical symmetry, the experiment includes a simple game in two versions, one with a virtual body sitting on a bike, pedalling in sync with the real body of the user, and one without.

Light

While VR offers the possibility of immersing into unreal environments quite different from the physical world, in architecture and design you may also wish to simulate the real world as authentically as possible in order to evaluate the real-world qualities of proposed new objects and spaces. Thus, the ability to realistically represent visual aspects of built form such as materiality and light, or acoustic aspects such as reverberation or ambient noise in VR holds great potentials for architecture and design simulation.

Physics-based modelling and simulation is in constant development and it is possible to create computer-generated models which can realistically simulate real world environments. Nonetheless, traditional physical models may still be relevant for architectural representation in VR. In a daylight laboratory equipped with a mirror box artificial sky and a heliodon, Kreutzberg and Bülow (p. 81) have developed a technique for taking 360° photographs inside architectural scale models for daylight analysis.

Taking advantage of the recent advent of small, affordable 360° cameras, they have tested different ways of mounting such cameras inside scale models at different scales. Practical problems such as cast shadows from the cameras themselves, focal depths in physically small models, blur along the stitched edges of the two photos which the cameras use to create the 360° images, as well as the fact that camera mounts will inevitably be visible in a 360° image are examined, and ways to overcome them are devised. The reward is that it becomes possible to put oneself inside an architectural scale model Lilliput style and study light conditions by means of an HMD.

While Kreutzberg and Bülow investigate light in a mixed environment of 360° images of physical models, Hotta et al. (p. 89) investigate the perception of light in abstract virtual space in their paper “A Study of Perceived Spatial Depth in Relation to Brightness Level Evaluated by VR“. Taking on the ambition to provide a tool for the improvement of artificial indoor lighting in dense urban environments, they work from the notion that the visual perception of the size of spaces relates to the level and distribution of ambient light. In their experiment, they ask their participants to evaluate distances in a 10 x 10 x 3 abstract space under different lighting conditions, using an HMD.

In “The use of VR technologies to enhance methods for lighting design practice” Jelvard and Mullins (p. 97) not only wish to evaluate lighting conditions, but to design them. As lighting is notoriously difficult to ‘sketch’ by conventional techniques, they investigate the potentials of lighting design in VR. Thus, they have set out to develop an immersive VR tool for lighting design, allowing the designer to act in space rather than behind a screen. Using a game engine with relevant plug-ins, they manage to juggle the balance between real-time interaction and high demands for lighting realism in an early prototype tool allowing users to select and instantiate different light fixtures.

Education

As an educational tool, VR has already entered general education as well as professional training as a supplement to conventional teaching tools and as an enabler of new forms of learning. It seems more than obvious that VR holds great potentials for architecture and design education, both for theoretical, analytical, and design purposes. In VR, otherwise inaccessible spaces across time, space and matter may be investigated and interacted with.

As architectural drawing moved from paper to CAD, paper scale was replaced by a fluid continuum of zoom scales. This has led to an increasing difficulty for architecture students to understand the notion of fixed scales and their associated levels of detail. Taking their point of departure in architecturology, as defined by Phillipe Boudon, Velaora et al. (p. 103) take issue with this problem in their attempt to apply immersive techniques to the concept of scale in “Integrating Digital Reality into architectural education”.

Using an urban design teaching studio project for their case study, they ask students to design at different scales ranging from 1:2000 to 1:100, using either drawings or physical models as their design media. The students’ urban design proposals are transferred into an immersive environment which is subsequently populated with virtual actors which will interact with the design according to specific settings. In their further research, the authors intend to analyse how students may adapt their designs as a result of interacting with the immersive tool, and thus acquire an improved understanding of scale.

As opposed to the experiment by Velaora et al., Yıldan et al. (p. 115) have their students design inside the immersive environment. To this end they use the Google Blocks platform which allows the user to do 3D modelling in VR with operations similar to those of common 3D modelling software. The aim is to study the perception of topological relations in immersive VR environments, in comparison to traditional 3D modelling environments.

The experiment is twofold. In the first experiment, different forms inscribed in a 3 x 3 x 3 unit abstract cube, once monochrome and once color-coded, are analysed and participants are asked to recreate them from memory. In the second experiment, participants are asked to design simple models containing a series of spaces from fixed-size, color-coded unit blocks according to a brief. Ultimately, the results are analysed with regard to the participants' topological understanding and creativity, in immersive VR compared to the 2D screen of 3D modelers.

In a third study of VR for architectural education, "VRiC: Virtual Reality in Construction", Yucel and Alaçam (p. 125) propose an interactive VR learning environment for building construction courses. With an aim to encourage active learning and circumnavigate the dangers and impracticalities of construction site visits, they showcase an interactive, immersive building model prototype. In this prototype, students can move around and interact with different building parts and obtain both text-based and visual information about each part. They may view the model in an exterior finish view, or peel off any layer of the construction, in order to inspect otherwise hidden parts. They may even turn on an 'X-ray' mode and walk around the model as inside a technical drawing.

Perception

The ability of VR to simulate different spaces makes it ideal for studying and analysing spatial perception. One obvious advantage of VR is that of not having to physically construct a test space for the analysis of spatial perception or having to transport oneself to an existing and possibly remote physical space. But as virtual spaces need not be realistic, all sorts of conceptual spaces may also be conceived and used in VR.

In real life, spatial perception may encompass not only visual and aural stimuli, but also sensory stimuli such as humidity, wind, temperature and odour. While a large body of research exists about tactile stimuli in VR, many such stimuli may not typically be considered part of architectural experience. Maybe therefore, the works on perception in VR presented at the eCAADe RIS 2019 focus only on visual and aural stimuli in VR. Nonetheless, using HMDs and headphones in combination, the two enable fairly immersive experiences.

In his empirical study, Sanatani (p. 135) uses VR to examine whether there are any correlations between combinations of size, dimensions and brightness of different spaces and people's emotional responses to them. While wearing HMDs, test subjects are presented with a series of abstract spaces of varying sizes and proportions and with differently sized openings, all from a single vantage point. The test subjects are subsequently asked to self-evaluate with respect to the emotional attributes of valence (pleasure/displeasure) and arousal (activation/deactivation).

The hypothesis which Sanatani aims to test is whether emotional responses to space, which is generally regarded as ‘intangible’, may be quantified, or, in other words, if it may be generally asserted how people respond to large or small spaces, cubic or elongated spaces, bright or dark spaces, or any combination thereof. While Sanatani’s results may overlap with intuitive expectations (people seem to respond more to changes for small spaces and limited amounts of light than for large spaces and lots of light, and to generally prefer fairly lit spaces of human size and not too elongated proportions), they also indicate that testing such conditions using abstract VR spaces may actually present a way forward.

Similar in its aim, yet different in its method, the study “The Neurological Impact of Perception of Architectural Space in Virtual Reality” by Hermund et al. (p. 143) takes its test subjects through a sequence of architectural spaces, offering them to interact with them by means of hand-held controllers. While also interested in the test subjects’ emotional responses, they employ a brainwave recorder instead of self-evaluation. Although they overcome the technical challenges of simultaneously mounting two devices (HMD and head scanner) on the test subjects’ heads, other obstacles mean that they end up with relatively few samples.

The VR test space consists of a sketch model of an actual architectural space with minimum use of textures to avoid cognitive overload. The test subjects can ask questions to digitally modelled ‘dummy people’ which populate the VR model, and answers are given by real life staff present in the physical test space. Despite efforts to simplify the VR test space, it is still too complex to yield any conclusive knowledge, and the authors conclude that further research should be conducted using a 3D model ‘in the lab’, essentially more akin to that of Sanatani.

While the above studies focus on visual perception, Wyke et al. (p. 153) aim to simulate room acoustics in VR through auralization. Sounds are recorded in an anechoic room (absorbing sound reflections), and subsequently placed in the VR scenario using game engine-based auralization software. In the VR setup, test subjects equipped with an HDM in combination with headphones evaluate the realism of the system with respect to the recorded sounds, placement of sound sources, and sound perception.

In the test, speech and sounds from electronic equipment within the virtual space is played, as well as sounds from neighbouring indoor spaces and from outside through a door and a window. In parallel, an identical physical space furnished in the same way as the virtual space is used for comparison. Similar to Hermund et al., Wyke et al. conclude that interaction features represent a distraction. But contrary to what is the case for visual representation in VR, they also conclude that for aural simulation, a high degree of realism is imminent in order to effectively evaluate acoustic design.

Taken together, the papers presented at the eCAADe RIS 2019 demonstrate a significant breadth in the application of VR and AR technologies to architecture and design. From analysis to simulation, from education to construction, and from exploration to collaboration, VR and AR find very versatile applications in the field.

Enjoy!

Nicolai Steinø
Conference Chair


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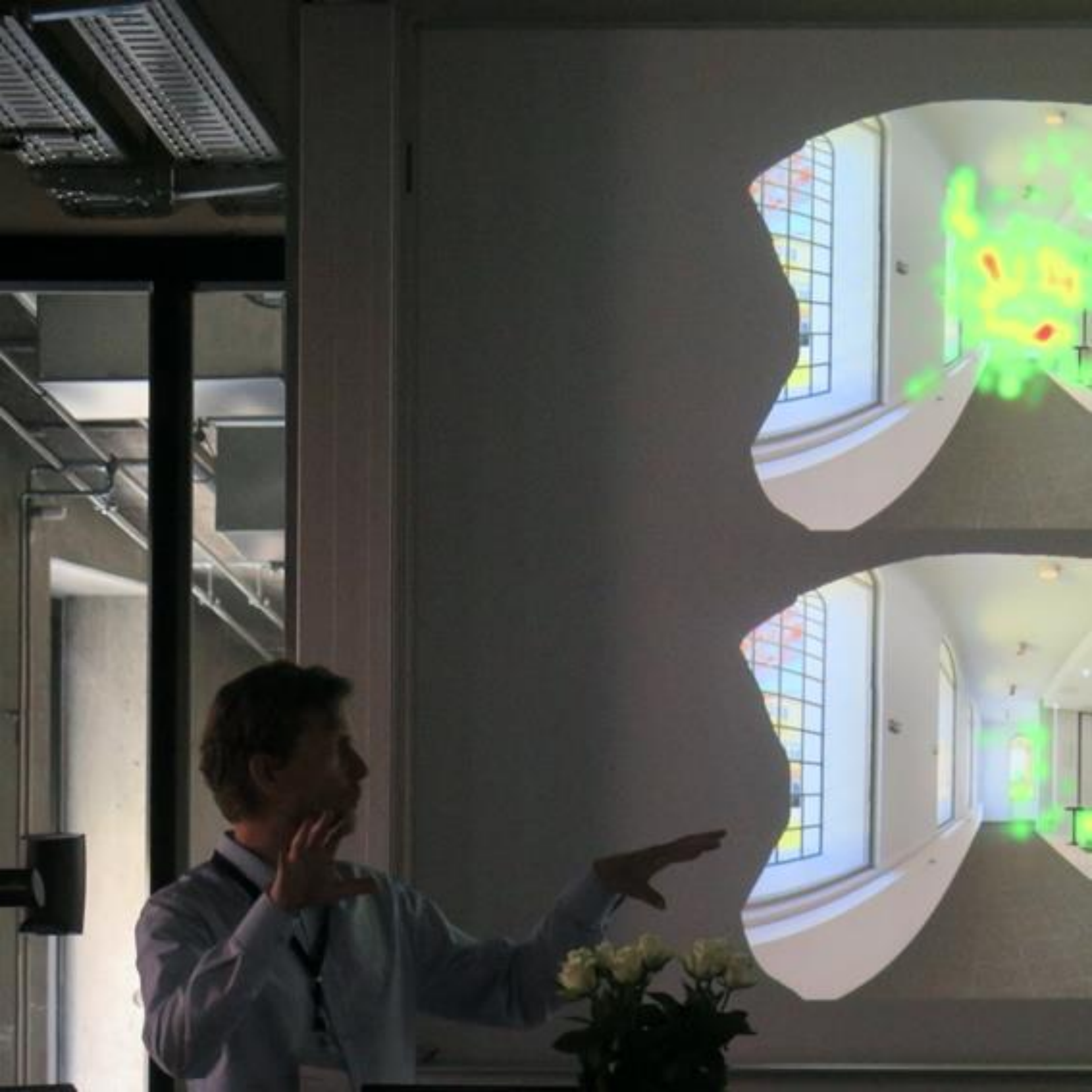
We would like to thank those who have contributed to the materialization of the 7th eCAADe Regional International Symposium in Aalborg. As an interdisciplinary department of architecture, design and media technology, virtual reality in architecture and design is highly topical. We are therefore grateful to the eCAADe council for entrusting us with organizing a symposium on this topic.

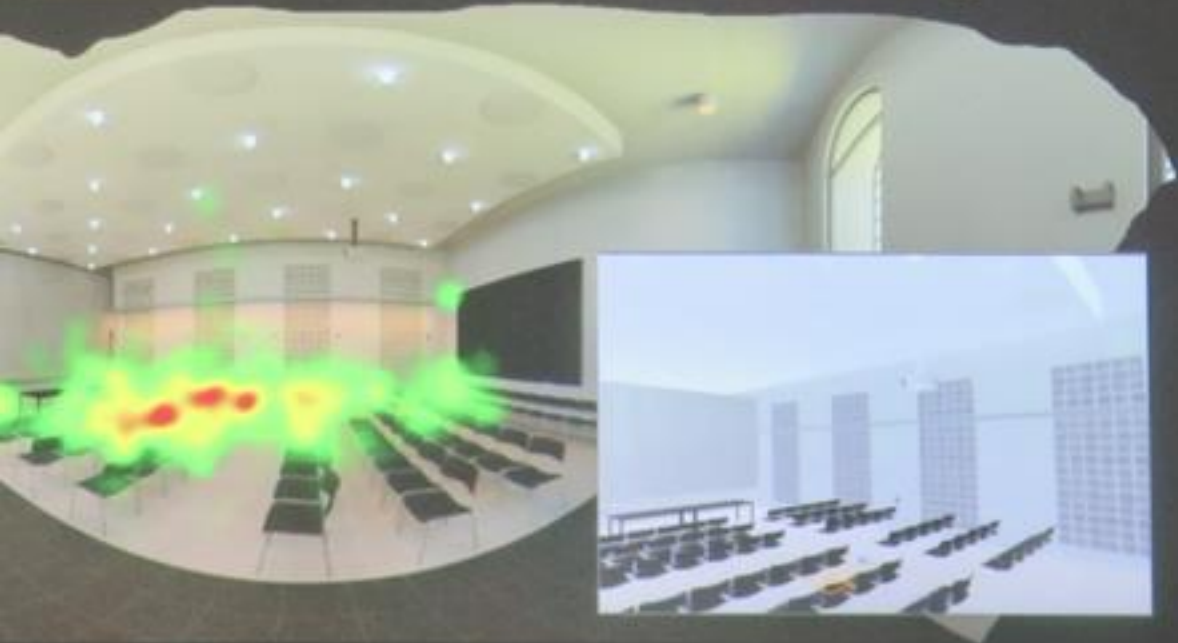
We would like to thank eCAADe council member Joachim Kieferle for facilitating our preparations, and organiser of the previous regional international symposium Odysseas Kontovourkis for sharing his experiences. Invaluable support was offered by Martin Winchester and Gabriel Würzer for setting up and supervising online systems for handling paper submissions, reviews, and graphic layout.

We would also like to thank the review committee for taking on the considerable task of reviewing the nearly forty submitted abstracts which ultimately resulted in the eighteen papers presented in these proceedings. In a time of increased performance requirements in academia, such work is in danger of depreciation. Yet without the dedicated efforts of voluntary reviewers, the conferences and symposia which foster and nurture our research community could not maintain their academic quality.

We are grateful for the financial support of the eCAADe which enabled us to invite the keynote presenter. Further financial support was generously offered by the local chapter of the Danish Architects' Association. Last but not least, we would like to thank the Department of Architecture, Design and Media Technology for their financial support, provision of premises, and practical assistance. Our gratitude also extends to our two volunteer student liaisons.

Nicolai Steinø & Martin Kraus
Conference Chairs





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SPOT

Keynote Speach: Social VR in Architecture

Tomás Dorta

Professor, Ph.D., director of the Design Research Laboratory Hybridlab, University of Montreal, Faculty of Environmental Design, School of Design

Tomás Dorta, architect and practicing designer, graduated from the Central University of Venezuela in Caracas in 1991, and undertook graduate studies at the University of Montreal in 1993. He obtained his Ph.D. (2001) by studying the impact of virtual reality as a visualization tool on the design process. His research interests include the mechanisms of the design process and co-design as well as the developments of new design techniques and devices using virtual reality. His research has been funded by large government research funding agencies from Quebec and Canada.

His research has been presented in various international scientific conferences and published in proceedings, including ACADIA, CAADRIA, eCAADe, EuropIA, SIGraDi, CAADFutures, IHM, DCC and SIGGRAPH, as well as in scientific journals such as Design Studies and International Journal of Architectural Computing. As a teacher, he became an assistant professor at the School of Design of the University of Montreal in 2003 and a full professor in 2017. He teaches PhD seminars and gives workshops and theoretical courses in industrial design on interaction design and co-design.

He is Director of the Design Research Laboratory Hybridlab. He is the lead designer of an innovative social virtual reality co-design system, the Hybrid Virtual Environment 3D, Hyve-3D.

Virtual Reality (VR) has got 50 years old since the invention of the Head Mounted Display. But VR can be understood beyond these VR headsets and become Social. Tomás Dorta's talk addresses the use of Social VR as design, pedagogical and research tool in the architecture and design disciplines.

Co-Design in HYVE-3D

Representational Ecosystem and Design Conversations

Organisers:

Thomás Dorta, Professor
Davide Pierini, PhD candidate
Hybridlab
University of Montreal

The aim of this workshop is to introduce the participants to the co-design approach using a Social VR system (without headsets): Hyve-3D (Hybrid Virtual Environment 3D) (Dorta, et al. 2016). The system affords simultaneous multiuser co-design (local and remote) using 3D sketches (exported as vectors) and imported 3D textured geometries, photogrammetry models and point-clouds. Participants will be trained to use the suitable representational ecosystem and the verbal protocols specific for co-design as a particular kind of collaborative design where each will be simultaneously ideating ad-hoc projects instead of cooperating (individual design to be put together in a later stage).

Dinner at the Table

VR/AR Convergence Applied to the 'Last Supper'

Organisers:

Mauro Costa Couceiro, Phd
Rui Lobo, Phd
António Monteiro, arch.
University of Coimbra, Portugal

Imagine you are sitting at the table with Christ and the Apostles. In an exercise of VR/AR convergence we will bring the human scale *Last Supper* terracotta ensemble (by Hodart, 1531-34), which belonged to the refectory of Santa Cruz Monastery, in Coimbra, to the dining room of the CREATE building, venue of the 7th eCAADe regional international symposium.

The goal of the workshop is to develop strategies for the conciliation between reconstructed Virtual Reality and the concrete reality (surveyed through 3D point-cloud and Stereo HD-VR Domes) in order to enhance the notion of continuity between both worlds. Thus, we will ask the participants to elaborate a 3D survey (both point-cloud and Stereo HD-VR dome) of the CREATE building dining-room, with state of the art technology, in order to build-in the *Last Supper* ensemble and to attempt a solid convergence between Virtual and Augmented Reality.


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Content

Unreal Game Engine for Architectural Lighting Visualization

Organiser:

George Palamas, Assistant Professor
Aalborg University

The world of visualization is changing rapidly and the lines across non-real time (e.g. 3ds Max) and real time (e.g. Unreal Game Engine), rendering applications are blurring with the former being used often for photorealistic, real time, visualizations.

This workshop is a systematic approach to explaining the different lighting models commonly used for real time rendering and how to use them inside of Unreal Game Engine. The course will be covering the basic principles of the lighting system of Unreal engine providing a practical understanding along with a basic design workflow on how to set up high quality lighting. Using case study scenes, we will create an interactive walkthrough with dynamic lighting, adaptive to user input.

Virtual Reality Room-Acoustics Workflows

Organisers:

Kjeld Svidt, Associate Professor, Aalborg University
Jesper Bendix Sørensen, CTO and owner, Epiito
Dario Parigi, Associate Professor, Aalborg University

In this workshop, you will be introduced to a Virtual Reality system with real-time auralization developed in an ongoing research project. You will learn how to import rooms with surface properties from an IFC model and set up sound sources for the VR model. The VR model can be experienced in a multi-user and multi-platform environment from epiito.dk.

The workshop is organized by researchers from Aalborg University and developers from Epiito. The workshop will take place in the CAVE at the construction site of the New Aalborg Hospital. Transport from the conference venue and back is included in the workshop.

Integration of Acoustic Simulations into Virtual Reality and its Usage in Architectural Design Practices

Organisers:

Finnur Pind, Industrial PhD fellow in acoustics Henning Larsen/DTU
Luís Vieira, Software Developer, Henning Larsen Architects

In this workshop an acoustics VR tool which is under development in Henning Larsen will be presented. The tool uses highly accurate pre-baked acoustic simulations, realized by a wave-based simulation algorithm under development in Henning Larsen/DTU. The tool is implemented as a plug-in into Revit and links 3D visuals created by Enscape and an audio processor implemented in Pure Data. Participants will be allowed to experience in VR some interesting test cases, including real design cases from Henning Larsen.

Following the presentation and demonstration a discussion among the participants will ensue, on how VR acoustics can fit into the architectural design process and what added value it can bring to the table. Technical aspects of VR acoustics will also be discussed, e.g. different approaches for realizing acoustic VR and their respective pros and cons (different simulation techniques / pre-baked vs real-time simulations / different game engines running the visuals / integration into different CAD software / different usage requirements need / etc


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Contents

Papers

Virtual Reality for prototyping compression-only structures

Odysseas Kontovourkis[1], Andreas Stroumpoulis[2]
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The development of compression-only structures consisting of units requires a number of important and demanding steps including form-finding and innovative assembly of parts during construction. Although, computational design techniques for structures' form-finding are well established and applied effectively, the simulation of their assembly and generally their physical production are still in an early stage of investigation with less examples to be found. This paper attempts to provide a methodological framework based on Virtual Reality (VR) for prototyping compression-only structures and particularly for investigating their assembly and physical behavior prior to their realization. The suggested methodology is validated using three case studies with different level of difficulty in terms of their geometry and process of simulation. In the first case, an arch-like structure with single curvature and in the next two cases vault structures with double curvature are applied, highlighting the limitations that arise in each case. At the same time, the work aims to open the discussion on the role of VR, as an approach implemented in research and teaching for pre-construction stage investigation.

Keywords: *Virtual Reality, compression-only structures, prototyping, assembly, physics-based modeling, collision*

INTRODUCTION

Nowadays, the design and analysis of shell structures are of great interest among architects and engineers. However, a number of obstacles appear in physical realization stage, mostly related to their assembly and erection, due to their increased construction complexity, time and cost (Deuss et al, 2014). In most cases, the solutions proposed in the actual implementation phase refer to conventional erection of their parts, such as the use of formworks in the entire system, which leads to costly and time consuming results. In order to overcome such issues, different computational techniques for assembly and erection have been developed (Quinn et al, 2015). These have been mostly conducted by using digital tools in order to predict the construction sequence or by applying small scale physical examples to test the feasibility of suggested approaches (Deuss et al, 2014; Quinn et al, 2015). On the other hand, the application of VR tools allows the prediction or inspection of the behavior of building and structures prior to their construction (Li et al, 2018), but little research has been done in relation to the control of the actual behavior of freeform shell structures including compression-only systems during their assembly or erection. VR and accompanied technologies allow several features to be integrated including gestures, haptics and physics-based simulation in a single environment. This offers direct involvement of users in the assembly and construction processes, which could provide reliable evaluation of their physical behavior prior to their actual production, resulting in time and cost reduction but also in better understanding of the process involved (Kontovourkis et al, 2018).

The introduction of VR in the construction industries has been unleashed from simple visualization and inspection of the final result or 4D simulation of construction [3], and over the last two decades a rapid development and a new level of sophistication is observed (Seth et al, 2011), mostly towards the contribution of mechanism for faster and more effective decision-making (Bryson, 1996). Thus, today the process of prototyping, that is, the development of prototype structures before their implementation in actual scale, can move beyond 3D modeling using conventional or parametric tools for geometrical control, towards more sophisticated processes that can incorporate VR combined with multiple human-computer interfaces (gestures, haptics, etc.). These allow, beyond the perception and sense of the presence of users in space, the interaction with space and structures, enabling the control, the experience and the evaluation of manufacturing process as close as possible to real conditions. Such an area of exploration deals with the ability of technology to simulate the positioning and assembling of objects or construction parts by users in real time, so comprehensive prototypes can be developed in virtual environment and their physical properties can be explored in simple, rapid and economic way.

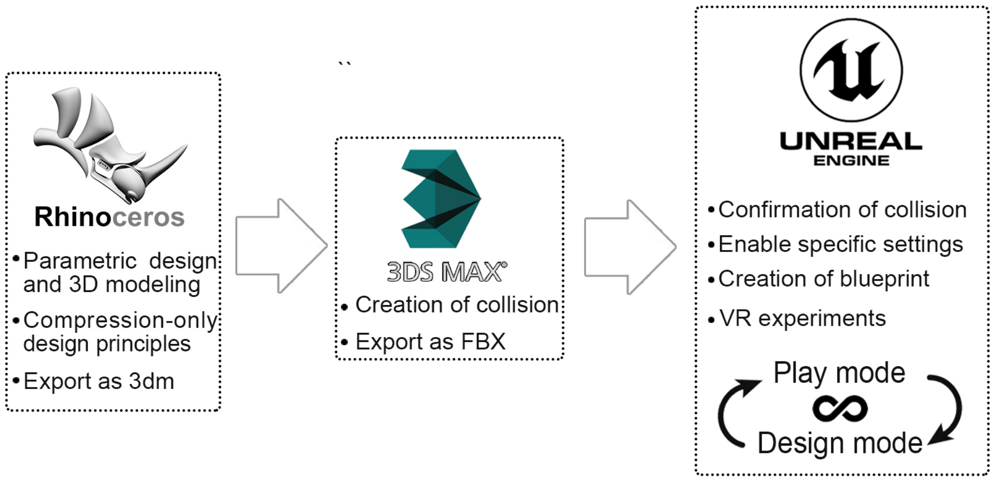
Such techniques have been observed in other disciplines such as the manufacturing industry with interesting results, for instance the work by (Jayaram, 1999), alongside development and deep investigation of other associated issues including collision detection, inter-part constraint detection and management, realistic physical simulation, data transfer between CAD and VR systems, and intuitive object manipulation (Seth et al, 2011). As it has been already said, although VR has been used in the building industry for building perception and construction planning, its application in the early stage of development of compression-only structures with single and double curvatures, which have particularities in regard to the complexity of their assembly and construction, have not been sufficiently explored yet.

This paper aims to deepen into this research direction through an evolving experimentation and control of the capabilities afforded by this technology and through the formulation of a methodological framework using VR for prototyping compression-only structures prior to their physical realization. The suggested method is described in the following chapter. Then, the methodology is applied in three case studies, aiming to demonstrate the proposed procedure and to discuss outcomes related to its ability, effectiveness and reliability to be used in pre-construction stage. Finally, conclusions are drawn and discussion regarding future developments is provided.

SUGGESTED METHODOLOGICAL FRAMEWORK

This exploration focuses on the capabilities given by the gaming platform Unreal Engine 4 [1], which emphasizes the perception of virtual elements by providing physical properties in real time through simulation. The selection of specific software is due to the functions involved that provide a series of advantages. Initially, through a programming process, the default VR mode can connect and enable operation of the VR Head Mounted Display (HMD), in this case Oculus Rift [2], and Controllers. Through these devices it is possible to navigate and to immediate experimental actions in the virtual space. In turn, the VR mode is divided into two categories: Play mode and Design mode. Starting with Play mode, the user can use the VR to enter the virtual world and the

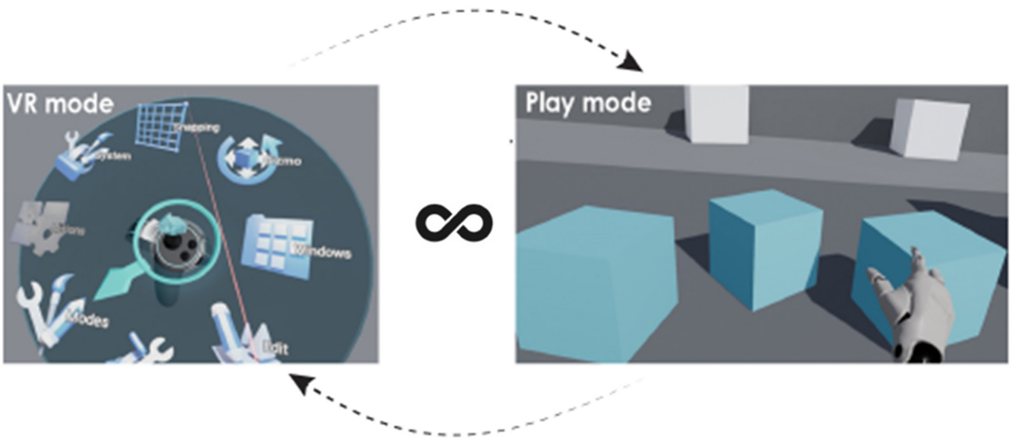
Figure 1
Flow chart of the suggested VR-based prototyping process



Controllers to navigate and play with the elements in space. Subsequently, the Design mode allows users to redefine the existing elements or the environment by conducting design changes in real time. The functional use of tools is achieved through a wide range of options directly implemented by the Controllers.

As it has been mentioned, the goal of this research is to prototype and to test in experimental context the behavior of single and double curvature systems under compression forces. This is done by

Figure 2
Loop logic between VR and Play mode



allowing users to interact with the structural components and the overall system in space through the use of VR and available Controllers. Initially, the design investigation that involves form-finding and subsequently the production of 3D models is conducted in parametric design environment Grasshopper [3] (plug-in for Rhino [4]), in order to achieve the design of compression-only systems. Then, in 3ds Max [5], files are converted from 3dm to FBX. The structure is programmed to incorporate collision properties, which is responsible, in a later stage, to allow the physical behavior of elements close to reality. Then, the file is imported to Unreal Engine in the form of static mesh for technical and programmatic processing. In this process, the structural elements are appeared in the form of static meshes with collision properties due to their previous processing and then, through simple selection, they acquire physical properties for instance gravity in the virtual space. The behavior of objects is achieved by their programming in C++ language, which is used in the form of Blueprint, a visual programming interface embedded in Unreal Engine. In this way, an easy programming environment is provided to the users, who might not have pre-existing experience in C++. Through Blueprint, the Pick actor interface activation is obtained, which is addressed in order to manage movement and repositioning of structural elements in space having physical properties, for instance weight. This process is tested in several case studies within a cyclically iterative loop procedure between Design and Play modes for direct processing and experimentation regarding the behavior and generally the process of prototyping the structures. Figure 1 demonstrates the workflow of the suggested VR prototyping procedure that incorporates design development and VR assembly demonstration. Figure 2 presents the loop procedure between VR and Play modes based on respective screenshots.

CASE STUDIES

The experimental process aims to deepen into different research issues related to the VR prototyping of compression-only structures. Firstly, it focuses on controlling the behavior of curved-like systems, operating under compressive forces and secondly, on developing a VR environment where ‘physical structures’ and users can interact using the available HMD and Controllers.

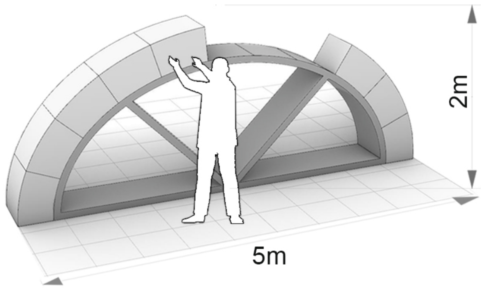


Figure 3
Arch-like structure and human scale

In order to achieve satisfactory results, the design of structures needs to follow a certain development logic, which is influenced by a number of constraints associated with the use of Unreal Engine 4. In general, the design of case study experiments refers to unit structures, and more specifically, to geometrical configurations consisting of modular elements, aiming to provide an ease execution of pick-and-place procedure in the VR environment by the users. In addition, the design takes into account other important criteria that include the static adequacy of structure under investigation, the amount of unit elements consisting the overall structure, the gaps between the units that are associated with their collision behavior and the scale of structure that is related to the user and its ability to undertake the predetermined tasks. As it is demonstrated in the workflow of this paper (Figure 1) and in order to implement the experiments, after the design of each structure under investigation is decided, the procedure involves different 3D modelling (Grasshopper, Rhino and 3ds Max) as well as VR settings and programming steps/platforms (Unreal Engine 4), enabling the user to be involved in a real-time prototyping process based on VR technology. This needs to be accompanied by simulation of the physical behavior of constituent elements as close to the reality as possible and includes gravity and collision avoidance of the units as well as manipulation by users close to gesture-like behavior together with VR perception of users in real scale.

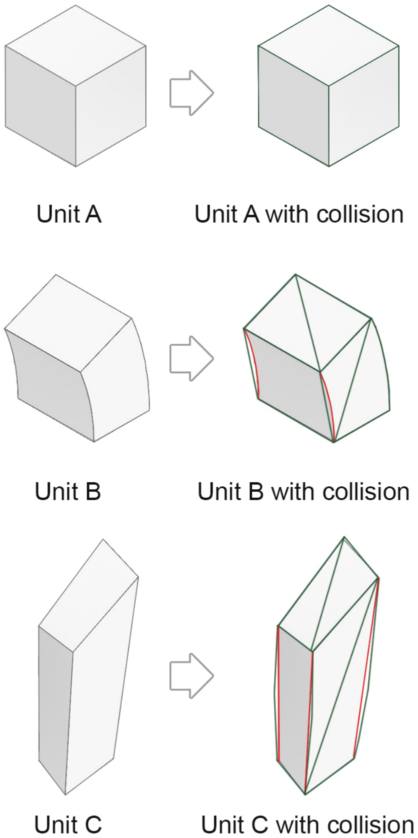


Figure 4
Diagrammatic representation of collision behavior adjustment

Case study 1

In case study 1, Rhino is used to design a 3D model for an arch-like structure with single curvature that is symmetrical to the vertical axis and consists of 11 unit elements (Figure 3). The symmetry allows efficient balance and static adequacy of the structure. Respectively, the selection of specific number of elements is related to the ease of carrying out the assembly process by the user. Also, a supporting structure is designed and incorporated into the 3D model, which is used to assist the user during the real-time VR prototyping process. Finally, as far as the geometry is concerned, no gaps between units are defined due to their single curvature, which allow the collision mesh to be precisely integrated in the perimeter of the units.

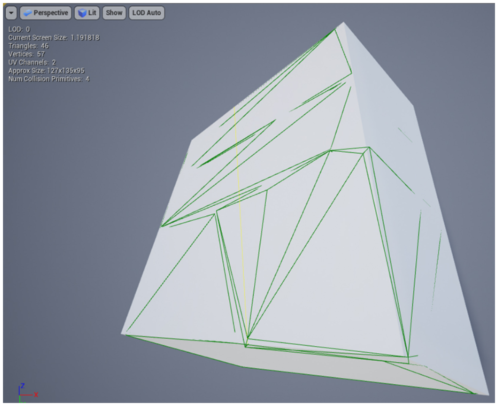


Figure 5
Collision settings extracted from the Unreal Engine 4 software

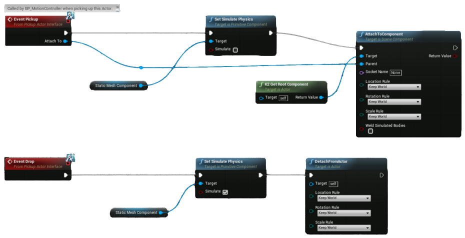


Figure 6
Representative physical behavior programming of one unit through visual scripting (Blueprint)

Before the 3D model is imported in Unreal Engine, an intermediate step is conducted in 3ds Max, which is responsible for two basic adjustments. Firstly, to convert the file into 3ds format and secondly, to get collision-based processing that is responsible for identifying virtual elements as objects with physical data, i.e. the user can interact with a particular element where he/she can touch and reposition the units in virtual space. Specifically, the collision behavior is created by cloning and renaming new units, around which a mesh is created, allowing the user to touch them with his/her controllers-hands in the virtual space.

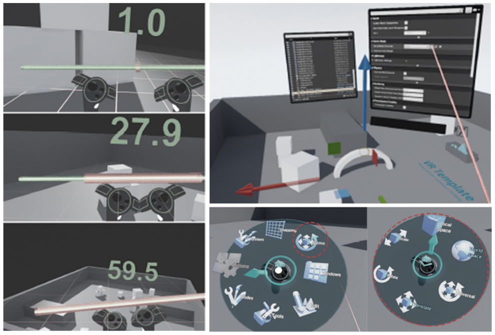


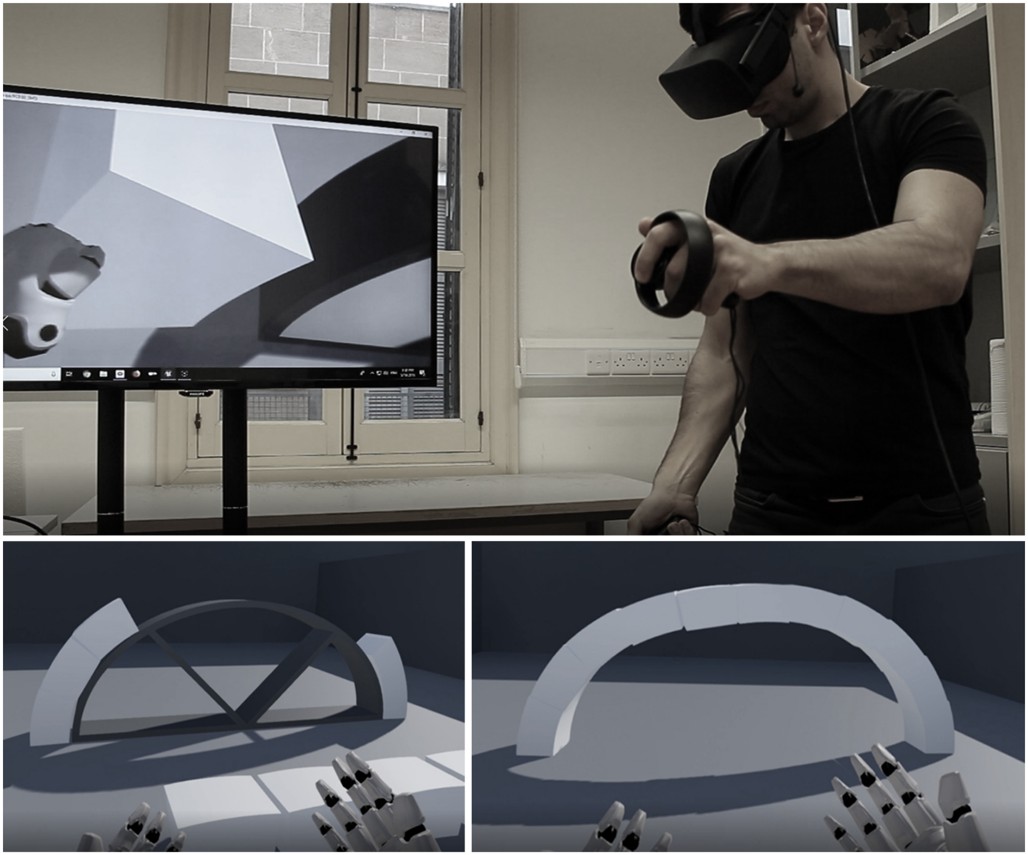
Figure 7
Screenshot of the Design mode through user's visual perception

By importing the file to Unreal Engine, the 3D model receives three processing steps. The first step confirms the adequate collision behavior of each unit created in 3ds Max (Figure 4 and 5), the second step activates simple adjustments that include movable, simulate physics, simulate generate and simulation overlap events, as well as adjustments related to the weight of each unit and hence the static behavior of structure. Finally, in the third step, each unit goes through a separate programming procedure, where the C++ programming language is used in the form of Blueprint (Figure 6). In this stage, the system is decoded and converted to visual scripting environment for its ease use by the designer. This process aims to associate the static elements of the structure with the environment and the user in order to support a system where the people can interact with the given units, allowing repositioning in space.

Focusing more specifically on the use of VR HMD and Controllers, emphasis is given on the interaction choices provided to the user in the VR environment. Initially, based on the two modes, the user can interact, firstly through Play mode where the user can define and reposition the elements in space and, secondly through VR mode or Design mode where the user can be involved in a design process by modifying (move, scale, rotate, etc.) and by adjusting properties (weight, materials, etc.) (Figure 7). In this case, the use of keyboard and computer is replaced by a projected interface that is visible in VR and where choices can be made through Controllers. In addition, through the two provided modes, a real-time loop can be achieved, where the user with the assistance of Controller has the ability to modify the design of a structure in the VR mode, to test its physical behavior in Play mode and vice versa. Through this process, users can be easily engaged and experiment in a procedure where structures are regenerated and evaluated having physical characteristics such as gravity and collision.

The 3D model adjustment is followed by real time demonstration of VR prototyping and particularly assembly. Initially, the Play mode is selected and the user is immersed in VR space with given elements to include the supporting frame structure and the units for the realization of the arch-like structure. The assembly methodology implemented in the first case study is based on a typical masonry arch geometry consisting of units, based on which the user starts to build this from the edges of the arch and upwards (Figure 3). In order to control the system in a satisfactory level and to achieve static equilibrium of the units, the reduction of the weight of the units in relation to their height was decided. The time to complete the process including assembly and implementation in the VR world was 7min in total. During the first experiment, malfunctions during the placement of the first three units have been observed. Also, it has been noticed that a prerequisite for the proper installation of the second unit was the simultaneous and tangent positioning with the first one. Then, a careful and slight placing of the two units on ground was required. The same process was followed in the case of positioning the third unit in relation to the second one. In this case study, the required total time for programming and then assembling was approximately 30min (Figure 8).

Figure 8
Assembly process in VR environment



Case study 2

In the second case study, the general preparation and programming of the 3D model remains the same. However, differences related to the geometry of structure are occurred. Specifically, in this experiment, a double curvature is selected with three edges on the ground and with one edge to formulate an arch-like opening, a structural system symmetrical on the vertical axis of its arch-like face. The design was accomplished in Grasshopper plug-in and was generated using Catenary arches in the principle of Hooke's hanging chain models. This specific curve formulates the actual shape of an ideal arch that depends on its length and on its edges distance. An inverted chain that is included within the boundaries of an arch ensures that the particular structure can carry its own weight (Heyman, 1995) and therefore it functions as a compression-only structure.

The scale of structure remains similar to the first one with a fixed height at approximately 2m but the number of units, due to the investigation of a double curved structure and hence its expansion is space, is increased to 75. The distribution of weight was increased again from the bottom to the top (Figure 9). The structure was designed with 4cm gap between units because of the double curvature of morphology and the structural elements' distortion. This resulted in an inaccurate integration of collision mesh into the perimeter of the unit. As a consequence, intense forces of repulsion in areas where the units penetrated each other were observed.

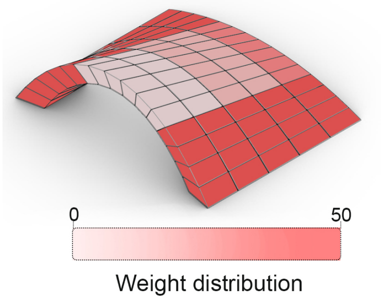


Figure 9
Increasing weight according to the position of units on structure

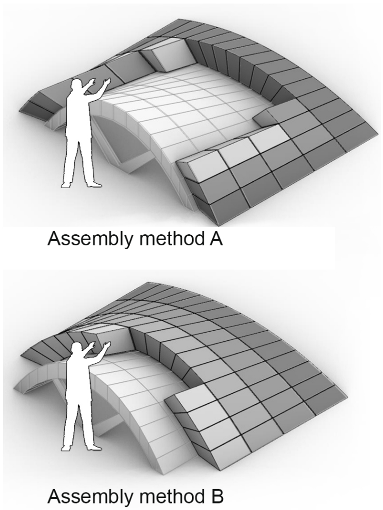


Figure 10
Methods of assembly performed by the user

Initially, the control through Play mode was performed and this proved that the structure was adequate in terms of its static behavior, functioning as compression-only system that is supported by its own weight. During the assembly process, two different techniques were applied; in the first case, the units were assembled one by one, starting from the two foundation edges of the structure on the floor. In the second case, the assembly of each arch formulating the whole structure was performed separately (Figure 10). The assembly time was 90min and 70 units out of 75 were successfully placed. Possible reasons for not fully completing the experiment include errors due to the specific division of units and the size of the gap between them, but also due to the VR programming malfunctions that was related to the collision behavior properties of the units. Finally, due to the inaccurate handling and placing of each unit by the user. The required time for programming was 120min, for VR assembly 70min and the procedure took 210min in total (Figure 11).

Case study 3
In the third experiment, the technical and programming process remains the same as in the two previous procedures but differences occur with regard to the design of the structure to be investigated. In particular, the structure is derived from the parametric algorithm based on Catenary curves, whose principle has been explained in the previous section of this paper. More specifically, the structure is a vault with double curvature and with symmetry in the diagonal axis of structure's plan view. Also, two adjacent sides are grounded and two others shape arch-like curves, formulating a surface where 36 units are distributed with 4cm gap between them in both directions.

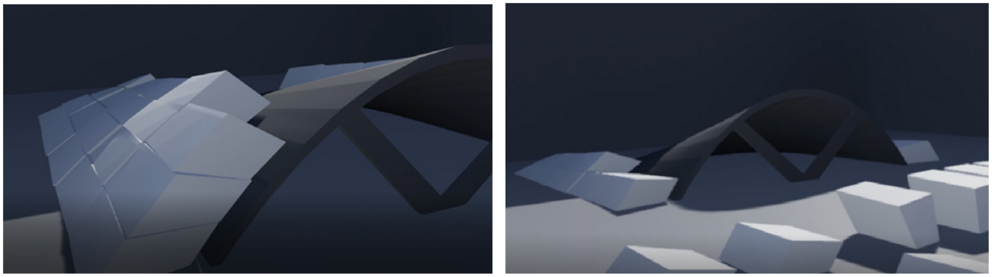


Figure 11
Assembly process in VR environment

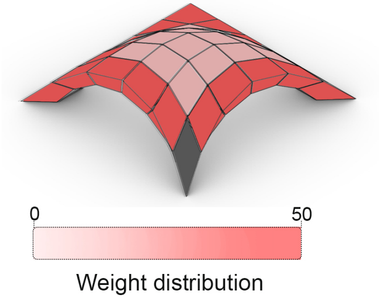


Figure 12
Weight distribution of structure with double curvature

In this case, static mesh properties were incorporated into the common unit that holds the two curves to remain rigid, indicating its possible consolidation on the ground, which can happen in a real case construction scenario. The weight distribution is demonstrated in Figure 12. The static behavior of the structure has been successfully controlled in Play mode (Figure 13), but due to its complex double curvature, 33 out of 36 units were positioned during the assembly process in 25 min completion time. Similar to the case study 2, the reason for not completing the process was related to the way units were divided due to the complex geometry of structure, which affected the process of incorporating collision behavior. Also, an important factor in the successful conclusion of the process is the accuracy during handling and placing the units by the user, a task that requires a great degree of attention but also an efficient handling of controllers during the pick and place process.

In summary, Table 1 shows information regarding the three case studies. It is observed that in all cases, although with different degree of difficulty, the static simulation results were successful. By increasing the degree of structures' complexity, there was an increase in both, programming and assembly time, which was associated with the number of units. This gradual increase of complexity resulted in the unsuccessful completion of the last two case studies, since

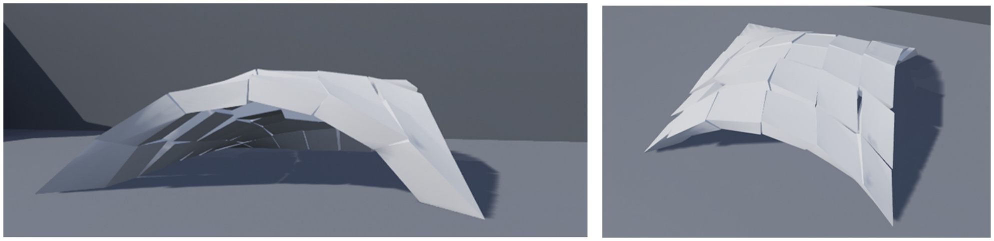


Figure 13
Static behavior of the structure in Play mode

	Case Study 1	Case Study 2	Case Study 3
Complexity of form (1-5)	1/5	3/5	5/5
Number of units	11	75	36
Programming time (min)	25	120	90
Static performance	Successful	Successful	Successful
Assembly proces	All units	70/75 units	33/36 units
Assembly time (min)	7	90	25

Table 1
Results related to the three case studies

other factors might influence the process including the inaccurate pick-and-place process of each unit by the user.

CONCLUSION

This work aimed to introduce a methodological framework for virtual prototyping of compression-only structures using VR technology. Through an analytical investigation of three case studies, the proposed approach intended to examine their physical behavior during design, static performance and assembly stages in virtual environment, examining in parallel the effectiveness of the process to be implemented by users in pre-construction stage and prior to the fabrication of systems in actual scale. Also, the suggested methodology and the results obtained were discussed in terms of their ability to provide reliable information by combining, in an integrated manner, parametric design that involves form-finding with physical behavior approaches.

Future studies will continue towards the exploration of the potentials provided by the specific process in the VR environment, in an attempt to reduce as much as possible, the errors that occur during the physical behavior simulation as well as in the gradual placing and assembly of units in different construction systems. Such a process might offer an investigation into the behavior of compression-only structures close to real case scenarios prior to their physical realization, both at research and teaching level.

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Virtual City@Chalmers: Creating a prototype for a collaborative early stage urban planning AR application

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Contemporary urban planning require multi-stakeholder collaboration to create liveable, accessible and resilient cities. Information and communications technologies can play an important role. This paper presents and discusses the development of a prototype for an indoor multi-stakeholder augmented reality (AR) application to support collaborative design in early stage urban planning. The prototype is integrated into VirtualCity@Chalmers, a platform for modeling, simulation, and visualization of urban environments. Based on a user-centered approach, four main steps were carried out: literature study, interview study, development of guidelines, and development of the first version of a collaborative AR prototype. The guidelines for the prototype development address design and layout, collaboration, analysis, and object creation and manipulation. At the current state of development, the AR application allows users to visualize a projection of three-dimensional assets over a flat surface. Further research will focus on user testing and integration of simple Computational Fluid Dynamics simulations.

Keywords: *AR, urban planning, prototype, simulation, collaborative platform, participation*

1. INTRODUCTION

Urban planning and design deal with complex problems and require collective knowledge in order to understand, communicate and collaborate between stakeholders for a higher quality outcome. Global and regional policies strongly encourage citizen engagement in urban planning processes (European Commission, 2011; United Nations, 2017). Thus, contemporary urban planning and design require multi-stakeholder collaboration, between professionals, but also between professionals and citizens. Information and communications technologies (ICT) can play an important role in this, for better outreach to citizens through mobile, social media and inclusive multichannel service strategies (UNPAN, 2014) but also for improved multi-stakeholder dialogues.

With increasing digitalization of urban planning and design processes, more advanced technologies are considered both an opportunity and a challenge for participatory urban planning (Kahila and Kyttä, 2010; Billger et al, 2017). Digital 3D-models with a high degree of interactivity offering advanced simulation and visualisation can facilitate this (Senbel & Church, 2011). However, visualisation in an urban model is challenging, relating to the appropriate levels of realism and detailing (Billger et al, 2017). Few studies exist that truly combine multimodal analysis and information visualisation (O'Halloran et al, 2018). It is also a challenge to expand the level of participation beyond information and consultation into collaboration and co-creation. There are promising efforts to develop new forms of engagement, participation, and collaboration using digital technologies, including visualization and gamification, cloud computing, social media, and mobile technologies.

At Chalmers University of Technology in Gothenburg, Sweden, a research and innovation project named VirtualCity@Chalmers (VC) (www.virtualcity.chalmers.se) has recently been established with the aim to compile research expertise in modelling, simulation, urban planning, computer science and other research fields to build a dynamic and interactive virtual city platform. Central to the project is the development of a 3D-platform that allows the integration of different simulation models and data into a single entity. During the first project phase in 2018, digital twins of the two University campus sites were created in the form of an immersive 3D world (Figure 1). The platform is already serving as a multipurpose arena for researchers featuring both First Person and Bird's Eye user perspectives, as well as real-time coupling of simulations and data. In addition, augmented reality (AR) capabilities can be used to enhance the user experience. The current version of VC encompasses high-quality data for a large portion of the City of Gothenburg, with more detailed data for the University campus. VirtualCity@Chalmers supports a small number of cloud-based simulation backends, e.g., for urban wind simulation, and provides advanced interactive visualisation through Unreal Engine. So far, mainly applications for single expert users have been developed. A key research question is: How can the digital infrastructure created by VC for urban modelling and simulation be translated and utilised as a transdisciplinary platform for decision making, participation, and collaborative design?

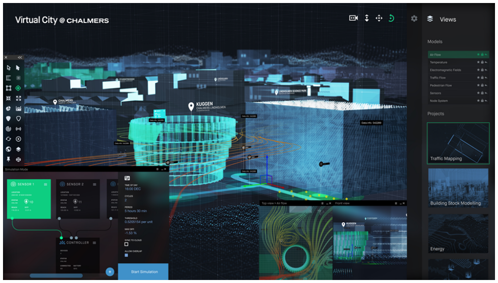

Figure 1
VirtualCity@Chalmers is a an immersive 3D-platform that allows the integration of different simulation models and data into a single entity.

Aim and scope

The aim of this paper is to present and discuss the development of a first prototype for an indoor multi-stakeholder augmented reality (AR) platform to support collaborative design in early stage urban planning integrated into the VirtualCity@Chalmers platform. A particular focus is on the formulation of requirements for such a prototype and on the exploration of the technological requirements.

In the current prototype, features are limited to a selection of building elements, simplified representations and basic shapes supporting user interaction. The prototype does not yet include additional environmental information such as rain, shadow casting and sun exposure. The intended target groups of the platform are both professionals such as urban planners and designer teams, multi-stakeholders with different professional competencies, and citizens. For the prototype, the main target groups are professionals. Augmented table projections are used to support a shared understanding through collaborative design.

2. BACKGROUND

Some of the previous work that informed the development of our collaborative AR prototype are the Luminous Table (Ishii et al., 2002), the Urban CoBuilder (Imottesjo & Kain, 2018), the Quick Urban Analysis Kit (Mueller et al., 2018) and commercial softwares such as InPlan or CityEngine.

The Luminous Table is an "Augmented Reality Workbench" (Ishii et al., 2002) that combines physical and virtual representations in urban design, namely sketches, physical models and computational simulations, into a single information space. The application demonstrates how a simultaneous use of diverse media supported a more holistic design process. By interacting around a table, participants are active agents in the design process, and can change the model simultaneously. The interactive table encourage users to communicate directly in reference to the representations of their plans while allowing to simultaneously engage in the design process, in contrast to a standard computer interface that aims at single users and can discourage collaboration around the same screen.

The Urban CoBuilder is a mobile augmented reality outdoor app that builds on communicative planning and agent-based modelling approaches and aims to explore urban design solutions (Imottesjo & Kain, 2018). The application invites people to collectively build their city using game-based planning rules. Each participant can interact with the site and save the changes, which then serves as a base for the next user who can edit the given scene. Urban CoBuilder is an on-site collaborative AR tool for urban design for multiple stakeholders, but only one user at a time can shape the built environment.

The Quick Urban Analysis Kit, explained by Mueller et al. (2018), is a tool for participatory design, in which non-experts can place geometric objects on a surface via a web browser interface (www.qua-kit.ethz.ch). The objects represent different building uses, such as residential or commercial volumes, which come together to form the user's own vision of an urban area. Logged in users can work together on a single design problem, share ideas and design proposals, and view and discuss works of others. Local clients can use qua-kit as a presentation tool. By making the tool simple enough for the general public to use, urban planners and designers can better understand what the citizens prioritize in an urban development project. The platform is an open source project, therefore, everyone is welcome to contribute.

InPlan (www.inplan.se/home) is commercial software for urban planners, urban designers, and other stakeholder involved in urban planning processes to support visualisation of urban visions, master plans and detailed plans. The users interact through large touch screens on a table together with virtual reality goggles. InPlan supports preparation of presentation material, collaborative discussion in early-stage projects, and citizen communication during urban planning processes.

Esri CityEngine (www.esri.com/en-us/arcgis/products/esri-cityengine) is a commercial 3D modelling software using procedural modelling to generate large-scale buildings and virtual cities. The application supports manipulation of shapes in 2D and 3D volumes via a shape grammar, and can import different types of geospatial datasets. CityEngine can be used in participatory design settings but has to be operated by one expert user and is thus not accessible to non-professionals.

All of the above presented platforms and softwares support collaboration in early-stage planning processes in different ways. Some of them combine representations of virtual and physical objects presented on a table to encourage discussions (Luminous Table). Others support on-site collaboration of multi-stakeholders, but with only one user at the time (Urban CoBuilder). Some of the platforms need expert users (Esri CityEngine), while others are accessible to non expert users with basic ICT knowledge. Different technologies for interactions are used, such as web browser, AR, VR, large horizontal touch screens, desktops, tablets or mobile phones. Shapes and geometries are simple and can be easily moved around or changed in an interactive way. However, none of the platforms includes additional parameters (wind flow, sound, movements patterns) that simulate the consequences of the design choices, moving elements or changing the shape and height of buildings, on the local climate and perception of the living environment.

3. METHODS

For the development of the AR prototype presented in this paper, a user-centered approach has been chosen (Lowdermilk, 2013). The research has been carried out in four main steps: literature study, interview study, development of guidelines based on three iteratively developed prototypes, and development of a first version of a collaborative AR prototype.

The literature review has focused on interactive and dynamic applications that facilitate participatory and collaborative design in urban planning, and was used to prepare the interview study. Nine different interviews were conducted with urban planning experts and presumed users. Based on the interviews and three iteratively developed prototypes, a set of guidelines were prepared, illustrating the needs for the design of an early stage user interface for collaborative urban planning. The interviews informed the design choices, and the purpose of the three prototypes was to create and test the guidelines. The first prototype for testing and evaluating the guidelines was a low-fidelity prototype (paper prototype), the second one a medium fidelity prototype (a simple web-based, single user prototype on a tablet), and the third one was a high-fidelity prototype (web-based, single user, interactive prototype). The three initial prototypes have been evaluated by both human-computer interaction experts and urban planning experts and resulted in the formulation of the final guidelines. This preparatory work was carried out by Öhrn (2019) as part of his Master thesis, and the the first AR prototype for collaborative planning was created and evaluated as part of the current work.

4. RESULT AND DISCUSSION

4.1 Guidelines

In order to reflect on what to consider when designing an application for early stage urban planning, a set of guidelines has been formulated. The guidelines derive from interviews and the work carried out by Öhrn (2019) and address four main areas: design and layout, collaboration, analysis, and object creation and manipulation.

Design and layout.

- Planning process is iterative. The capability to view previous work and reference images while using the application could be useful.
- Follow application conventions. Include and build upon commands and functionalities that are already implemented in similar applications and that the user is familiar with.
- Keep it simple. Users desire a simple interface that is easy to learn. Consider including tools to help the user familiarise with the application.
- Provide a menu that is easily accessible yet lets users maintain their focus on the design area. The menu can be triggered by commands such as long-pressing or right-clicking and may include tool and type selection.
- Use off-the-shelf products. Interviews show that

low cost and familiar tools are preferred over expensive and specialised hardware solutions.

Collaboration.

- Design for collaboration. While designing the application, consider how two or more users can make use of it and choose hardware accordingly, to support collaborative design and joint interaction.
- Enable comments and feedback. Consider implementing a way for the user to give written input via comments or other feedback.
- Enable image import. Some work might be made previously by other stakeholders in an earlier stage of the process by using media such as pure pen-and-paper sketches. These documents can be traced or used as reference. Enabling the import of such images supports continuation and collaboration in the design process.

Analysis.

- Display detailed information on demand. Showing relevant information when selecting an object or hovering over it helps the user get an immediate general feedback from the design.
- Include design statistics. Consider showing the total number of elements belonging to the same category, such as building elements or total area of the same area type. This will be likely to benefit the users when performing cost analysis or further analyses later in the process.
- Provide early error prevention, to a degree. Warning the user for potential difficulties with the design can save costly adjustment work later on in the process. The user should be able to disable this feature as it happens that urban planners need to circumvent outdated regulations.
- Provide real-time analysis both as an overlay as well as detailed information extraction. This can help users make design decisions and analyses quickly and iteratively. Analysis can be limited to simpler simulations to be run in real-time. Users would want to know the origin of the data and adjust parameters such as time of day.

Object creation and manipulation.

- Consider integrating free-hand sketching or a line tool. Many users prefer pen-and-paper sketching, while others are familiar with digital sketching tools, using key points and curvature options similar to the line tool in Adobe Illustrator.
- Created objects should be distinct. Users expect objects to be selectable individually, e.g., each on its own layer. For multi-selection, consider supporting multi-press and lasso selection tool.
- Design for 2D, allow for 3D. While it can be beneficial to limit the number of dimensions to two for sketching, some users need to add and view height for proper analysis. Even if 3D (and VR/AR) may not highly desired in the sketching phase, it can be beneficial for stakeholder participation and participatory design.
- Include a customisable background map. The application should connect to a map to show for instance terrain morphology. The location can be specified by the user. Consider that users may want to add GIS data layers, so the application should support this.
- Land use instead of buildings. In urban planning land use is often more relevant than individual buildings. Consider a design mode for land use that features sub-categories, such as specific housing typology area for residential areas.

These 17 guidelines guided the development of the collaborative AR prototype for early stage urban planning and design processes.

4.2 Prototype and design implementation

For the development of the AR prototype for early stage urban planning, we applied a double diamond design process (DDDP) consisting of four distinct phases:

- A. Discover, which involves the process of researching the topic by field and literature studies and any other source of available data.
- B. Define, in which the developer combines and analyses the findings leading to the definition of the actual design challenge.
- C. Develop, in which the actual iterative development of different concepts is happening in order to test and evaluate.
- D. Deliver, where the prototype is reaching its final form.

The current prototype is a work in progress and is currently in the development phase (C) of the DDDP sequence.

The implementation of a user application on an augmented reality (AR) device can be a cumbersome and very demanding task, both in terms of resources and the ingenuity required (Mekni et al, 2014). A particular challenge lies in that AR is a relatively new technology and both toolkits and hardware are still immature, leading to long development and testing cycles.

VC uses a bottom-up approach in development, seeking to combine different data, models, and simulations into one common platform, thus ensuring that there are solid development foundations for any User eXperience (UX) endeavors. For the implementation of the AR prototype for the current work, many software components already existed as part of the VC platform, such as the 3D city model, basic user interaction, and the connection to the cloud computing server for modeling and simulation. For the extension to AR, we made use of Google's ARCore toolkit (docs.unrealengine.com/en-us) through Unreal Engine (UE) (developers.google.com/ar/reference). Both software development kits (SDKs) are golden standards for a wide array of scientific applications (Boyd et al, 2017; Martin, 2018; Qiu & Yuille, 2016; Linowes & Babilinski, 2017), escaping the realm of gaming and entertainment for which they are mainly designed and developed.

Figure 2 illustrates the design of the current prototype. VCCore (server) acts as a hub for data management and processing, including geodata, sensor data (IoT) and data generated through modeling and simulation. VCCore is also the hub for modeling and simulation, acting as the driver of a range of different simulation backends running on the cloud server. Data is communicated from VCCore to user clients, which may be desktop computers, smart phones or other AR/VR devices. For the current work, the devices is an Android smartphone running an ARCore/UE application. The Server/Client communication is two-way, meaning that developers can provide collaborative features to the users, since the UX endpoints can communicate to each other through the platform.

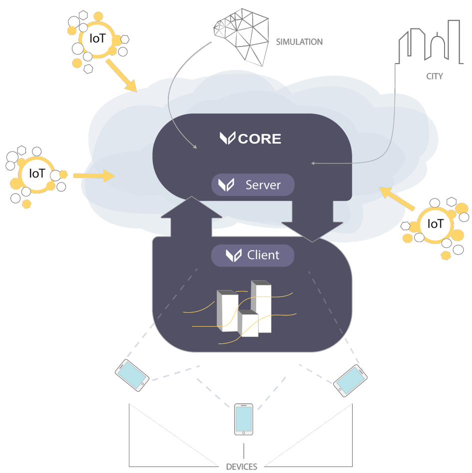

Figure 2
Diagram of the design of the AR urban planning application.

Figure 3 shows a snapshot of the development status of the prototype. The User Interface (UI) is heavily based on existing Unreal Engine ARCore templates and the debug menu on the bottom right side of the screen offers mostly development related information. In the middle of the screen, parts of Lindholmen Science Park and Chalmers University of Technology campus are visualised as 3D holograms placed on a conference table. The geometries for the visualisation are obtained through the data interface of the VC platform. The data interface allows the creation and visualisation of additional layers such as sensor data or simulation data (wind flow, temperatures, traffic flow, pedestrian flow etc.) to enable collaborative exploration of data and simulation results. The addition of user interaction for manipulation of 3D assets (adding or moving streets and buildings) is work in progress.

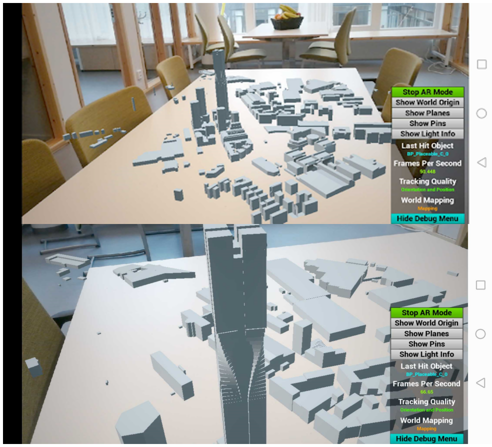

Figure 3
a-b. Screenshot of the prototype application running on an AR-enabled smartphone.

4.3 Data preparation and processing

VC is an open-source platform for interactive city modeling and simulation and relies, as much as possible, on open data formats and open data sources. A strong focus is placed on developing an automatic pipeline from raw data sources such as national databases to modeling, simulation, visualization, and user-interaction. Such data sources are available in Sweden from the Swedish mapping, cadastral and land registration authority (Lantmäteriet; www.lantmateriet.se), which has been responsible for providing geodata for Sweden since 1628.

Main data sources are vector-based property maps providing the 2D footprints of buildings in Sweden to a high-accuracy, together with digital elevation maps (Digital Surface Models, DSM) in the form of high-density point clouds obtained by aerial LiDAR scanning. From these two data sources, the VC platform generates 3D tetrahedral computational meshes for modeling and simulation, as well as 2D triangular meshes for visualisation and user interaction.

In addition to this automated pipeline generating low level of detail (LOD1) models suitable for large-scale city modeling and simulation (Biljecki, Ledoux, et al., 2014), VC provides high level of detail (LOD2) models for selected regions (the University campus sites) and even higher level of detail (LOD3) models for selected buildings and monuments. The higher LOD models are only used for visualization, not for modeling and simulation.

4.4 Representation and Interaction

As discovered during the evaluation of the sketching interface by Öhrn (2019), a 3D view can serve at least two concrete purposes in early-stage urban planning projects. First, it can serve as a tool for urban planners to enable input of, among other attributes, average building heights. Second, the possibility of viewing a sketch in three dimensions facilitates the communication of ideas to stakeholders, such as the general public, who might find 2D sketches too abstract and difficult to interpret. In both scenarios, the overlay of simulations models and data sets support knowledge exchange and horizontal discussion between stakeholders of different professions and expertise.

At the current state of development, the AR application allows users to visualise a projection of 3D assets over a flat surface. A 3D urban model can be visualised on a table or a floor surface and users can navigate the scene by physically moving in the room and around the virtual projection. Users require a mobile mixed-reality device to use the application. The prototype utilises the rear camera of the device to identify a horizontal surface on which the model can be placed; see Figure 4. Several surfaces might be identified and the user must therefore select a suitable surface by clicking on it. The model will appear on the selected source and will remain anchored to it. At this stage, users can explore the model by physically moving around the projection. Zooming in and out is carried out by moving closer to or further away from the model. This movement is likely to reinforce the feeling of immersion experienced by the users. Collaboration is enforced by enabling multiple users to view and explore the same model as shown in Figure 5 (currently requiring manual placement and calibration).

At this stage, the prototype provides indoor AR projection accessible via mobile device and basic user interaction and aims to support design manipulations common in desktop-based applications, in a multi-stakeholder framework. In the next development phase, participants will be able to move and edit geometries and add new elements via their augmented reality mobile devices. The application will also support the overlay of visualisations of simulation data or sensor data in the form of, e.g., heat maps and streamlines. Any manipulation of the projected environment will influence the result of environmental simulations, such as windflow, and it will be visualized in real-time. The scene projected aims to be immersive and dynamic.

Since the application relies on virtual projections rather than physical tools that may clutter the working surface (Ishii et al, 2002), the application will allow the simulation of complex urban scenarios integrating different types of information layers. The scale of the virtual model can also be adjusted to specific needs, which means that the projection of dense real-world design arrangements of buildings and infrastructure can be supported.

Figure 4
Screenshot of the prototype application showing several buildings placed on a conference table.

Figure 5
Illustration of three participants exploring and discussing a design proposal using the prototype AR application.

4.5 Link to VirtualCity@Chalmers platform

The prototype presented in the current paper exemplifies how a collaborative research platform such as VirtualCity@Chalmers can be used to support collaborative urban planning. However, many of the features developed as part of the current work (data processing pipeline, modeling, simulation, visualization, AR user-interaction) are useful in many other contexts. Thus, VirtualCity@Chalmers functions as a research infrastructure that may support not only research focusing on end-users such as urban planners, but also functions as an infrastructure for visualisation, presentation and dissemination of basic research in large-scale city modeling, such as simulation of urban wind comfort, traffic flow, pedestrian flow, flooding, and more; see Figure 6.

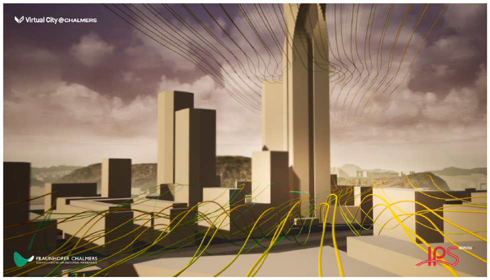

Figure 6
Simulation and visualisation of urban wind comfort as part of Virtual-City@Chalmers.

5. CONCLUSION AND FUTURE WORK

In this paper, the development of a first AR implemented prototype for collaborative urban planning and design has been presented. The prototype application allows users to visualise a virtual model and bring changes to the scene by adding and removing three dimensional elements.

The application is intended as a tool for urban and city planning that aims at enhancing collaboration, supporting communication and knowledge exchange between stakeholders. So far, the AR prototype has only been tested by the development team and not by domain specific users (urban planners and designers). Still, from the work with the guidelines and the related evaluations it can be assumed that the platform could improve participatory planning processes and collaborative design practices as it would considerably help participants in communicating their design intentions and understand the effect of their design choices. By that, the application can provide added value for the early stage of a design process. Further, the possibility of creating a three-dimensional design helps participants getting a better sense of spatial implication of their design choices. Multiple simultaneous representations make it easier to understand the dynamic interdependence of planning issues (Ishii et al., 2002). Involvement of multiple stakeholders in urban planning processes is seen as a way to enhance urban resilience (ISDR, 2005) by better reflecting the diversity of needs and opportunities and increasing ownership of decisions [1].

VirtualCity@Chalmers is in the early stage of development and it requires both technical and social design improvements. Future research will include visualisation of additional dynamic factors such as drainage vectors, microclimate analysis, topographical information, auditory mapping, pattern of movements such pedestrian and traffic flow modelling (Space Syntax), but also more qualitative aspects such as perception of places. A more advanced version of the platform will also provide a wider selection of building modules to choose from.

The collaborative potential of Virtual-City@Chalmers will be tested and evaluated in user tests with both professionals in urban planning and students in related subjects. User testing will provide relevant and necessary feedback to develop the application further.

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Sketching Immersive Information Spaces

Lessons learned from experiments in 'sketching for and through virtual reality'

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This paper presents the lessons learned from a design workshop exploring methods for early exploration of immersive information spaces, such as Virtual Reality (VR). The methods explored cover design situations both designing for VR, and designing through VR, in varying degrees of fidelity. The workshops shared the common factor of attempting to enable a feedback loop between sketching activities and the more didactic and time consuming prototyping processes. From our analysis, we found that to achieve true `sketchiness' in an immersive VR settings, tool proficiency naturally becomes a decisive factor, since a lot of new techniques needs to be learned and gained experience with. Furthermore, it is evident that the mental shift, from flat to 360 degree design, was challenging, but also the enabler of new creative constraints from which the designer can explore the boundaries of the design space. We conclude by arguing for the development of more formalized patterns, materials and tools to not just enable immersive sketching, but also enable grasping the immersive design space itself by motivating the explorations and happy accidents when `doodling' in the immersive space.

Keywords: *sketching, virtual reality, prototyping, animation-based sketching, immersive information spaces*

INTRODUCTION

When designing immersive information spaces, understood as the conjunction between a physical presence, and a virtual layer of digital information, traditional design tools, such as scenarios, personas, and mockups, are generally not enough to capture and sufficiently explore the intended user experience of the design proposal (Jerald 2016). This aspect is true both in terms of the feedback loop of the individual designers iterative 'design moves' during exploration (e.g. Schön in Winograd 1996) and in terms of sharing and critiquing the design proposal amongst design peers, because of the abstract nature of the combined virtual and physical design space. In recent years, this problematic area of design has seen an increased attention mainly due to the maturity of Virtual Reality (VR) technologies now being available on consumer and prosumer level, expanding the use cases and portfolio of applied cases for both designing for, and designing through immersive digital spaces. This extends from broadly oriented consumers appliances in entertainment and games (e.g. Pallavicini et al 2017, Rosa et al 2016), to more specialized professional use cases in e.g. surgical training (Huber et al 2017), manufacturing (Seth et al 2010), industrial design (Berg & Vance 2017), and architecture (Portman et al 2015). Despite these recent developments in design applications for VR, there still seems to exist a barrier for how to use it in the early idea stages of design. Traditionally, these stages are defined by various interpretations and manifestations of 'design sketching' (e.g. Verstijnen et al 1998, Goldschmidt 1994, Buxton 2010). In sketching, the ideation is informed by creating rapid, evocative, and non-didactic outputs - as opposed to the definitive nature of prototypes (Buxton 2010). But the perhaps most important aspect of design sketches is their disposable nature - they are plentiful, and created through a fast feedback loop of reflection in and on action (Schön in Winograd 1996), where the ideas should be allowed to perish as fast as they were created. This sketching feedback loop is still a challenge when working with immersive technologies like VR. It could be argued that when applied to display an architectural CAD drawing through an immersive 360 degree perspective (Portman et al 2015), the mere act of viewing a CAD 'sketch' in VR is a natural extension of the sketching feedback loop. However, we argue that this feedback loop could be brought earlier in the design process, to the steps before computational tools like CAD software. This is due to the nature of computerized design tools, which are somewhat already constrained by their own didactic procedures, and thus less 'sketchy' than e.g. the early hand-drawn sketches or physical mockups, made by the designer before having any firm grasp of the design problem at hand.In the study presented in this paper, we set out to explore how 'sketchy' feedback loops could be achieved when exploring immersive design concepts in VR settings - both when designing for VR, and when designing through VR. The paper details the findings from a series of design workshops, exploring various techniques and methods for sketching and prototyping immersive information spaces aimed for VR. Below we briefly introduce the sketching and prototyping approaches we based these studies upon, before introducing the findings from the workshop.

IMMERSIVE SKETCHING AND PROTOTYPING

One emerging approach for bringing hand-drawn sketches into a VR environment is the use of equirectangular coordinate systems (the same format used on a traditional world map). Here, a 360 degree map is flattened and distorted to fit a 2D surface. The quality of these 2D representations are that, if drawn correctly and taking the distorted perspective into consideration, the output image will be non-distorted in a VR environment from a first person point of view. A few examples of equirectangular sketches are shown in Fig 1 as well as a guiding grid made for sketching.

Equirectangular sketches - the pen-and-paper of immersive sketching?

Sketching in a equirectangular coordinate system requires the designer to think of traditional straight lines as curves, and divide the sketching canvas into 'field of views' where the middle of the paper is the front view, and the left, right, top, and bottom corresponds to looking to to the sides as well as up and down. This requires the designer to rethink the dimensional space of the paper, where specific regions are more distorted than others. But in its premise, equirectangular grids is an attempt to transfer the principles inherent to traditional design sketching as a way of doing 'visual thinking (Suwa & Tversky 1997, Goldschmidt 1994, Schön & Wiggins 1992), mimicking the immediate feedback loop of expressing a design move, seeing and reflecting on the depicted, and then make a new design move as a response to how the sketch was 'read'. Equirectangular sketching shares many qualities of pen and paper, but lacks one crucial aspect in regard to the visual thinking

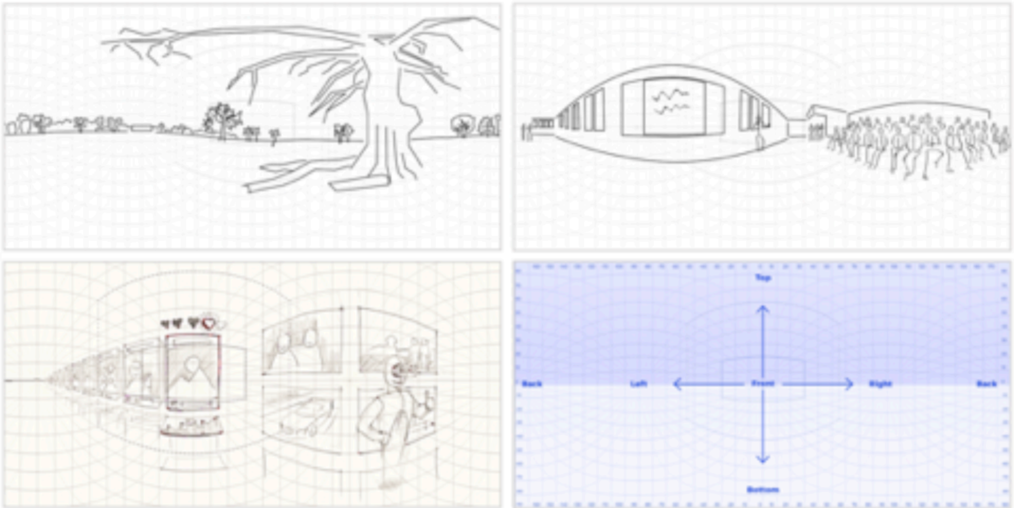

Figure 1
Examples of sketches made in the equirectangular coordinate system, with the our designed guiding grid to the lower right.

of sketching: the immediate feedback loop. While the designer can immediately see the specific strokes and changes made in the equirectangular grid, the impact of the sketching move on the immersive information space depicted is first realised when the paper is copied into a supported viewing platform. This process can be done rather quickly, with only few seconds between scanning the paper and seeing the response digitally in 360 degree. However, this also brings a certain amount of finality to the sketch output being scanned and viewed in 360 degree since the designers has to assess the sketch is now 'ready' to be explored as immersive space, and not just as flat equirectangular representation. This brings the danger of putting too much effort into the sketch, defeating the purpose of sketches being timely, disposable and non-committable (Buxton 2010). As such, the equirectangular sketches are at risk of not being ambiguous enough to "...leave big enough holes for interpretation" (Buxton 2010, 115). The equirectangular sketching approach may thus act as way for the designer to explore their concepts on paper in one prolonged sketching move, before reflecting on the output and letting others experience and critique it through the immersive viewing medium later on.

Temporal sketches as a middle ground

Another potential sketching method for immersive technologies is temporal sketching approaches, such as video sketching (Tikkanen, T., Cabrera, AB. 2008), and animation-based sketching (Vistisen 2016, Tran Luciani & Vistisen 2017). This approach also challenges what can be considered sketching. Regardless of whether the temporal sketch is based on simple stop motion effects or edited motion graphics, the process of making a design move, reflecting upon it, and then making a concurrent move is challenged since the digital medium requires the designer to determine more aspects in their head, before expressing it visually. Temporal sketching mostly lack the immersive viewing, since most video and animation-based sketches tend to be narrative scenarios shown from a linear structured perspective. While it is possible to simulate e.g. a first person VR view through graphic masking overlays, it will still only mimic the immersive 360 degree space, and not enable the designer, or other stakeholders, to assess the immersive aspects in detail, but rather assess the scenario as a whole user journey. However, with recent developments in digital authoring tools, the possibilities to actively create, edit and live-preview changes made to e.g. 360 degree footage and imagery has shown potential to actually enable true digital sketching in a live updated 360 degree preview inside software such as Adobe Premiere and Adobe After Effects. This would blur the lines between temporal sketching, which tends to be linear, and immersive sketching, which needs some degree of user interaction, positions itself along contemporary contributions on using video and animation in sketching (e.g. Vistisen 2016, Löwgren 2004, Fallman, D. & Moussette, 2011). These new emerging uses of the software was thus our state of art in how temporal sketching was applied and introduced in the workshops for this study.

VR sketching - true immersive sketching

The potential to use VR as a sketching/prototyping tool has long been recognized by the literature, but while there have been several studies detailing the development of tools for VR sketching and modelling (e.g Fiorentino, De Amicis, Monno, & Stork, 2002; Schkolne, Pruett, & Schröder, 2001; Jackson & Keefe, 2006; Barrera Machuca, Asente, Lu, Kim, & Stuerzlinger, 2017), there is a lack of literature about the process of sketching through VR and reflection on the use of currently available tools. Using VR tools as sketching media for early design has several potential benefits, such as spatiality, allowing the designer to walk into the sketch, one-to-one proportions, association, using existing objects as references in the environment and formability (Israel, Wiese, Mateescu, Zöllner & Stark, 2009). The immersive experience of VR sketching also allows our bodies to be part of the design process, making it possible to use them as reference and consider ergonomics early in the design process. Moreover, VR interaction allows the designers to use their hands directly in the creation process (Petrov, 2018). A recent study on VR and creativity by Yang et al. (2018) suggests that immersive VR helps to maintain a more stable focus and enables a better state of flow, which results in a greater creativity performance. The study compared the creative output in immersive VR using 'Tilt Brush' and traditional pen-and-paper-sketches. While the participants in the study were only allowed 5 minutes to design their product in respective media, the results suggest that the immersive VR environment stimulated novel ideas and inspired the participants to be free from past ideas. Similarly, Keeley (2018) studied 19 second year students using VR sketching tool 'Tilt Brush' to explore how VR sketching impacts on the designer's ability to produce concepts and communicate them in conceptual design. The post-use questionnaires and focus groups revealed that the students thought that VR sketching improved their creativity and their ability to communicate. The latter was because they could easier analyze their objects in 3D space instead of on a flat paper. They also suggested that VR gave them a better sense of scale, especially with larger products. Moreover, when observing the students, Keeley (2018) noted that the immersive nature of VR sketching allowed the creation of concepts from the user's point-of-view, such as making a sleeping bag by lying down and drawing it from the inside.

DESIGN WORKSHOPS

The design workshops were a core part of a studio-based course in immersive information spaces held at Linköping University. During a period of three months in fall 2018, seminars and design workshops were given with the goal for students to develop proficiency exploring innovative concepts for immersive spaces, like VR. The design workshops were practical learning activities focused on techniques for designing and exploring individual concepts for an immersive space. While all students chose to use VR as their final medium, various types of sketches were produced along the way. Some immersive concepts were explored through 2D sketching tools, which we label 'sketching for VR', while others were being created in the 3D immersive environment, which we label 'sketching through VR'. The design workshops were divided into two parts to introduce tools and techniques to enable sketching for VR and sketching through VR respectively.We, the authors, were facilitators at the workshops and gathered data through observations and field notes. We also collected the students' produced materials such as work-in-progress sketches, final sketches, and their own written reflections. The data was used to examine and analyze the design process of their concept development.We examined the design process of six of the students with explicit consent, all accordingly to the GDPR regulations. They were all second-year students at the same Design master program, but had backgrounds in various different design domains such as graphic design, web design, and product design. Through previous project works within the program they had all been exposed to sketching and prototyping approaches, but they were all novices with regards to VR. This particular course in immersive information spaces focused even more on the explorative aspects, giving the students the opportunity to further develop their sketching mind-set. In the analysis we have arranged the cases into a series of induced themes for which the included case is exemplary of - not necessarily presenting each case in its full extent, but comparing and including different cases under the same theme.

INSIGHTS FROM THE DESIGN WORKSHOPS

In this section we show selected examples from the two workshops highlighting lessons learned about sketching and prototyping when designing immersive information spaces.

From idea to sketch to prototype - a horizontal slice of applied methods

A project concerned with designing a virtual underwater exhibition about historical shipwrecks was an example of a horizontal slice of all introduced methods from the workshops. The student initially sought to convert flat graphics into equirectangular images digitally, but quickly realised an issue of non-panoramic graphics distorting heavily when adjusted to an equirectangular grid. Instead, the student experimented with mocking up an equirectangular landscape of graphics in the grid. Afterwards, the student took the experiment into VR and explored the consequences of the arrangement. An expected next 'sketching move' would have been to make adjustments to the design (a refinement) or make a new version based on the reflection from seeing the sketch in VR (an iteration). However, the student expressed that this sketch was only an experiment which "...enhanced the level of immersion and understanding of how the final VR experience might feel". As such, the equirectangular graphics were not a concept on itself, but rather an 'investigation' of the design space, rather than a conceptual 'explorative' sketch (see Olofsson & Sjölen 2007). This inquiry into the design space is akin to traditional rough doodles exploring the design space, but with little direction towards true ideation of new solutions.

Figure 2
Examples of the immersive sketches and prototypes made of the 'virtual diving cage' concept. The first equirectangular investigation of design space in a VR viewer (left), and the first refined conceptual exploration of the experience of a diving cage (right).

This led the student to actively direct his efforts in using the equirectangular guiding grid as the basis for sketching his new concept idea of a 'virtual diving cage', effectively taking inspiration from the prior sketch, but now with considerations about what the user could experience and interact with the immersive experience. This process took place inside Adobe Premiere, with the possibility to get immediate feedback through live-rendering and the built-in 360 degree viewer, allowing for explorative sketching moves, where the student both refined and made different iterations of the diving cage concept. The student also tried to transfer his sketching process to the VR design applications 'Masterpiece VR' and 'Tilt Brush' to experiment with not just sketching for

VR, but directly through VR. While this provided the benefit of not having to make the mental translation from equirectangular depiction to 360 degree viewer, these tools also presented both some practical and ergonomic challenges for the sketching process. A practical challenge was how these immersive VR applications were "...constrained to one room and as far as we saw, there was no way of creating several scenes and jump between them". This was opposed to the relative freedom of expression experienced with the equirectangular sketches, which were challenging to get an initial grasp upon, but offered more versatility.The student used the VR application 'Storyboard VR', and transcended into trying to make a more refined version of the diving cage concept, coming closer to the look and feel of the concept's visual design and interactions. This tool use was thus more akin to the resolving and specific nature of prototyping, seeking to narrow down choices in the design space rather than diverging towards exploring new directions. Here, the student experienced the benefit of having sketched digitally inside Adobe Premiere earlier, since the digital assets could be transferred directly into 'Storyboard VR' - essentially enabling a transition between sketching and prototyping without turning to a new 'material'. What was obtained was a more true immersive response due to the VR applications ability to provide not just 360 degree orientation, but also parallaxed depth. The details being explored was seen adding a significant progress towards asking specific questions of e.g. how a user should interact when facing a specific part of the experience. The application thus promoted the creation of more detailed assets in traditional 2D design software, and arranging them in VR afterwards. As such, the student did not make gradual sketching loops anymore, but rather specified the details of his design prior to prototyping the exact scene in the software. Some iterations did appear, in regards to how to arrange the pre-produced elements, with new ideas about e.g. the design of graphical overlays on the underwater setup arising from seeing the placement live in the VR environment. This shows that even when prototyping, the need to explore and immersive yourself as designer into the VR design space also fosters 'sketchy' behaviour - even though the assets used are premade outside the VR setting.

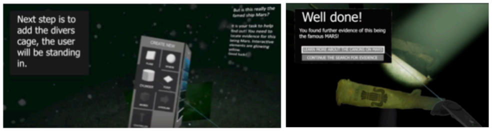

Figure 3
The arrangement of previous designed graphical elements in underwater backdrop in 'Storyboard VR' (left), and an example of the student attempting to design user interfaces and simulate an interaction in the application (right).

However, a significant drawback experienced while using 'Storyboard VR' was that although the experience is immersive, there is no way to add real interactivity. While the application lets the user create more 'scenes' and flip between them like a storyboard, the lack of more elaborate user interactions with e.g. virtual elements was experienced as a barrier to move the prototyping further. This prompted the student to apply temporal video- and animation-based sketching methods. Initially this was introduced as a 'middle ground' between the equirectangular sketching and the VR applications used for prototyping. But in this case, the student needed a more free form to further develop his prototype in terms of exploring the interaction design, but also to think about about the entire scenario of the proposed concept as a whole. The student thus combined graphical elements made for both the equirectangular sketches and 'Storyboard VR' and edited them together in Adobe Premiere, adding masking overlay to simulate the edges of a head-mounted display. Inside this simulated field of view, the student animated a virtual hand interacting with the shipwreck and other items from within the diving cage. Other graphical elements, such as video and text annotations, were gradually added to create a complete concept for the interaction, and the resulting informations shown to the user. Finally the student created an animated video scene from outside the VR environment, showcasing some contextual considerations for what would happen before and after the VR experience itself.

Figure 4
The final temporal sketches made to simulate interactivity from 1st person (left), and the overview of the pre-experience context of the VR application (right).

In this instance, what we thought would be a middle ground turned out to be the last step of the process - adding contextual details and narrative flow to the entire user experience of the proposed immersive concept as a whole. The temporal mediums were limited in terms of enabling true immersive VR exploration, but enabled the combination of many different types of visual materials to simulate the specific features the students lacked the ability to express through VR. Interestingly, almost all projects applying the temporal methods choose to show a bit of the context of use through these techniques, emphasizing the importance of not just thinking of the sketching for the immersion of the concept alone, but also address the 'before' and 'after'. Again, the temporal applications were assessed to have their own limitations, mainly that they had to be 'hacked' to work well for design sketching, and not just for traditional video editing. Furthermore, the static nature of video also left the students with questions still unanswered about the possible use cases which might arise with their concepts - not easily testable without realising full functionality in VR.

Sketching as doodling - building a sketching literacy for a new medium

Doodling in traditional sketching is method of letting the pen go and seeing what happens. Doodling is without goal and intention, but as the designer doodles, at any time there might be a "happy accident" which sparks a direction for more intentional sketching. This doodling mindset can also be used when exploring a concept in a new medium, as experimenting with the tool's capabilities and how it can be used is as much an exploration of the medium as the concept itself. One student experienced a turning moment in the process when she let the VR tool direct her in her concept development, exploring and experimenting with the assets and functionality that were available in the tool instead of trying to force it to do what she had in mind. Another student was initially frustrated with the interaction space limits in VR, describing how she often got lost in the virtual world and ended "bumping into" the edges of the interaction space, seeing the blue grid signifying that a physical barrier is close by. However, when she decided to make use of the limitations, it inspired her to create an interaction concept where she took away the ability to teleport around in the virtual world and used the limited space as a way to convey the powerlessness of not being able to walk away when subjected to the racial injustice in her interaction concept. Thus, exploring the limitations of the software presented new creative constraints of 'being boxed in' which developed the concept even further; exploring the medium and tool became integrated into the sketching loop itself. Both of these examples could be thought of as a conversation with the sketching tool and not just with the sketch. By letting the affordances of the tool guide them, they set themselves up for "accidental discoveries" and used the limitation of the tools as a creative input rather than a hindrance.

Figure 5
Stills from the immersive experience of being subjected to racism. The top left image shows the first scene, a park where police radio sound clips are played in the background. The other three pictures show the second scene, a convenience store where a person is following you and looking at you from behind shelves, with a heartbeat sound playing as the person gets closer.

Throughout the course, we noted that the students struggled to sketch exploratory. Many were focused on communicating a concept that they imagined in their own head and got frustrated that they were not proficient enough to use the tools and techniques in a "sketchy way". One student expressed that she "wasted a day" with the equirectangular grid. Another felt that she could not express what she was imagining in her head and complained that "because I don't know the tool [...] I just do what the tool can make". Because of the difficulties to use the non-idiomatic sketching tools, they felt that they invested so much in each "sketch" that they were not actually making idea sketches, as they were neither disposable, plentiful or quick. Thus, while we have used the term "sketching tool", the insights suggest that the tools do not allow sketching straight "out of the box". They all need to be appropriated to accommodate sketching, especially when the medium is non-idiomatic, such as equirectangular projection, as the sketching tool will most likely also have that character.

Sketching process does not always go from low fidelity to higher fidelity

In most traditional design processes, concept development tends to progress from using low fidelity (lo-fi) tools to create sketches, such as analogue hand-drawn sketches, to higher fidelity (hi-fi) tools to create prototypes, such as physical mockups and digital CAD models. Even though we organized the workshops to mirror this tradition by starting with lo-fi tools before the sessions with hi-fi tools, the students were free to choose what techniques and tools to use for their individual projects. Analyzing the students' design processes after the fact shows that starting with lo-fi before moving on to hi-fi tools and techniques is not always the preferred way when sketching for VR. Some students even found lo-fi tools irrelevant and "useless" for sketching their VR concept and felt the need to immediately experience first-hand the non-idiomatic aspects of VR. "I think the 3D sketching tools were more beneficial [...] because you are able to create and experience this scene by yourself. This I considered as a major learning: it helps immensely to just immerse yourself in the scene you are creating in order to develop it."For some students it made more sense to start sketching with hi-fi tools such as 'Storyboard VR' or 'Tilt Brush' because they are used more like traditional tools that the students already were familiar with, compared to animation-based sketches using lo-fi tools such as an equirectangular sketches and rough animations, which requires a completely different skillset. "While using Storyboard VR was entirely new to me it allowed me to create experiences inside of it with knowledge that I already had."Despite the advantages hi-fi tools seemed to have, it does not make lo-fi tools redundant in the process of sketching for VR. The outcome of using hi-fi tools easily becomes too detailed which could cloud the purpose of sketching. "In my concept video [...] trying two different methods, both of which looked rather sketchy [...] Being able to move assets inside the 3D space sort of like how objects behave in a design program like Illustrator or Photoshop would make for an extremely precise and better workflow." In other words, using hi-fi tools can unfortunately invite someone to get focused on details too early in the explorative process and prohibit a quick and sketchy approach.Another reason why sketching directly through VR may not always be preferred is the risk of cybersickness, i.e. motion sickness felt in VR. While this is a well-known challenge when using VR applications (LaViola 2000), the issue seems to be heavier represented with VR applications that are not just delivering a specific predefined streamlined experience. This might be due to the often quick and unnatural movements and positions needed to e.g. sketch a detail underneath an object made in 'Tilt Brush', which might increase the risk of experiencing cybersickness. The issue of cybersickness was clearly articulated as an issue holding the students back in fully realizing valuable sketching loops through the use of VR applications. Two of the six students experienced major cybersickness in the sense that it actually hindered their work process. One of the students took a pill against seasickness in an attempt to overcome the cybersickness, but unfortunately it did not help. In order to minimize their time spent in VR, the students found alternative ways of preparing assets at a computer, for example by using 'SketchUp' that they could import into a VR-app such as 'Tilt Brush' to test and tweak scale and position. It all comes down to picking the right tool for the task based on the purpose of the sketching activity and the individual's skills and abilities or limitations. As with most design projects some students experienced or noted that it was beneficial to take an iterative approach moving between lo-fi and hi-fi tools, but the fidelity of the tool or produced result does not necessarily reflect whether it is a sketch or a prototype.. "Sketching 2D helped me converging, while sketching 3D helped me diverging again. A reiterative rhythm that I believe would be incredibly interesting to repeat and continue".

REFLECTIONS

This paper has presented our insights into introducing immersive sketching approaches to design students with little prior experience with designing for and in virtual reality. Since the data samples are limited to the two workshops, the insights are tentative in nature and not conclusive. However, they do highlight some interesting aspects about sketching in and for immersive environments that can inform further studies and future works.A major finding might seem obvious: 3D sketching is hard to grasp. The basic ability to understand the 360 dimensionality of the VR environment showed to be the most challenging aspect for the design students. This seems like a paradox, since many of the concepts dealt with spatial aspects, and thus the 3D design space should in theory augment the design process. However, from our analysis we argue that the observed challenge to grasp the immersive design space is due to the fact that immersiveness is not a traditional aspect of sketching, but rather an aspect of much later phases in design, leading to a lacking idioms and conventions for how to actually reflect in and on action about the sketches made both for and through VR. While we observed some instances of what could be interpreted as sketching feedback loops, most of the true sketching happened either in traditional 2D mediums like pen and paper, or through simulating only one perspective of VR at a time through iterative video sketching. Where the sketchy behavior arose in the VR setting was when the tool limitations provoked the design students to reframe their ideas to fit the technical constraints of both the authoring tool as well as the VR technology itself. We argue that this is an effect of the unconventional tools applied - even VR design tools like 'Storyboard VR' and 'Tilt Brush' are not tailored for iterative sketching, but rather for mocking up premade scenes or artistic endeavors. These unfamiliar, non-idiomatic tools make it challenging to achieve the ideal 'reflective conversation' with the material, because of a constant resistance from the design material. Since the students were unfamiliar with the tools, they had to devote a lot of time to each "sketch", which shifted the reflective conversation into an "output monologue". Thus, using non-idiomatic tools for reflective conversation probably requires higher sketching literacy to be able to sustain the "sketchy" mindset. To build sketching literacy for the new medium we found that it was beneficial to explore the tool's capabilities with a "doodling mindset", i.e. to let the affordances of the tool guide in order to have a reflective conversation with the sketching tool. That opened the mind to view unintended outcomes as "happy accidents".Immersive sketching is still in its infancy and many of our findings can potentially be dismissed as 'just being lack of design experience' with both the domain and its tools. However, both the practical issues of enabling non-interrupted sketching loops, and the ergonomics of prolonged sketching through VR without suffering from motion sickness, also points to the need of better tools for early exploration for and through VR. Our attempts with equirectangular and temporal sketching show that different needs, besides the ability to be fully immersed in VR, may arise and that the sketching environment and the literacy required to navigate these will probably need require more than one tool or one approach to fully enable immersive sketches to be done and be valuable early in the design process. Therefore, we end by arguing for the development of more formalized patterns, guideline materials and tools (e.g. equirectangular guiding grids, VR annotation tools etc.) to not just enable immersive sketching, but also enable grasping the immersive design space itself to truly achieve sketching feedback loops for VR in design.

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Mixed Reality and lost heritage:

*Reconstituting the Monastery of Santa Cruz of Coimbra through VR-AR convergence**

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To fulfil the specific purposes of a three-year research project we are working on (to reconstitute the Monastery of Santa Cruz of Coimbra in 3D, and its situation in 1834, before the partial demolitions of the late 19th and early 20th centuries took place) we became interested in the possibilities of fusion between Augmented Reality and Virtual Reality - an interactive experience generated by a computer that takes place inside of a simulated environment. These two emergent development fields gave birth to what was recently coined as Mixed Reality and the environments created can be analogous to the real world or they can be based in imaginary environments. We have two basic aims for this initial research: first to create the tools to provide knowledge and wisdom (knowledge with emotions) around lost heritage. The second aim, profoundly related with the first one, is to create a methodology and software capable to surpass a Turing-type Test for Virtual and Augmented Reality, where the observer could be immersed in an environment where virtual outputs and feedback can be greater or, at least, similar to the real world.

Keywords: *Mixed Reality, Virtual Reality, Augmented Reality, Lost Heritage, Monastery of Santa Cruz of Coimbra*

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THE SANTA CRUZ RESEARCH PROJECT

The Santa Cruz monastery, in Coimbra, of the Canons Regular of St. Augustine, founded in 1131, was one of the major religious houses of Portugal before the religious orders were extinguished, by decree of the new liberal government, in 1834. The following abandonment of the building and its application to the most diverse uses led to the progressive loss of important artistic and architectonic heritage. No-table architectonic features can still be seen today, such as the late-gothic church, the church's chancel (that hosts the tombs of the first two Portuguese Kings), the late gothic cloister and refectory, the renaissance Manga fountain, the mannerist vestry and the baroque sanctuary. However, important parts of the monastery were destroyed during the late 19th and early 20th centuries, such as the monastic façade and entrance cloister (which were substituted by the new Town Hall building of 1876-79), the 110-meter-long renaissance dormitory, the Manga cloister (which surrounded the remaining fountain) and the medieval/baroque bell-tower. This destruction largely affect the overall perception, amongst modern day visitors, of the scale and monumentality of the monastic complex during the later years of its original function.

This is why we thought of setting up a research project that could put together both history of art and history of architecture with the new technologies, particularly in the fields of Virtual and Augmented Reality. Our project proposal was welcomed and selected in a national competition and is now being funded by the Portuguese Research Foundation (*FCT- Fundação para a Ciência e a Tecnologia*, research project code number 30704). The aim of the Santa Cruz research project is to allow for a renewed understanding of the Santa Cruz monastery's erased past through the use of Virtual Reconstructions of its lost architectural heritage that can be perceived through Virtual Reality devices, which will be available for visitors of the modern building and site (personal Smartphones can also be used to download and watch the 3D VR 360 contents on site, matching the architectural remains).

Of course, we will rely on the work, knowledge and expertise of several researchers in several fields, some of them directly connected with the research project, such as archaeologists (Alarcão, 2011), art historians (Dias & Coutinho, 2003; Craveiro, 2011), photography historians (Ramires, 2001) and architects (Lobo, 2006; Couto, 2014) which will account for the physical state of the monastic complex in the mid-19th century, before the main destructive actions took place.In our research project the overlapped geometrical information can assist the existing environment with missed architectural elements that are presented, masking important areas of the existing environment with data from other epoch or context. This new/old information will be faultlessly linked with the real environment in an immersive experience.The primary value of Mixed Reality technologies applied to our research project is that they will bring components of the digital world into a person's perception of the real world, not just as a simple display of data, but through the integration of immersive sensations that are perceived as natural parts of an environment.Main overlaps that we are aiming to build are the elevation of the original cloister surroundings around the remaining Manga fountain (in order to re-insert this magnificent Renaissance architectural piece into its original built environment), the reconstitution of the monastic Renaissance façade beside the remaining church façade, and the insertion of the magnificent human scale sculptural terracotta ensemble of the «Last Supper» (executed by Hodart between 1530 and 1534 and today at the Machado de Castro National Museum) into its original setting, presiding over the monastery's still standing refectory hall.From our work, other developments can be attained in the near future, such as going further back in time, to the original Romanesque church and cloister, which were substituted in the early 16th century by the still standing church and cloister structures.

THE GLOBAL CONTEXT

Cultural and Creative industries are globally recognized, nowadays, as one of the most relevant economic factors of growth and job creation. In Europe particularly, where these industries represent around 5% of the European Union's GDP (Forum D'Avignon & TERA consultants, 2014), it is vital to study and promote the uniqueness of its cultural heritage sites. UNESCO World Heritage sites compromise 40% of global tourism revenues from cultural products related with the local monuments, arts and crafts. The Santa Cruz monastery is not a World Heritage Site in itself but belongs to the Property Area of the University of Coimbra which was recently granted with the UNESCO World Heritage classification in 2013 (url: worldheritage.uc.pt). Approximately 10% of the European Union's GDP comes from International Tourism activities.The rapid arrival of digitization and the associated shift in the way people apprehend reality is forcing the Creative Cultural Industries (OECD designation) to develop new growth strategies to improve this almost trillionaire industry. The CCI's boast €558 billion in value added to national GDP's in 2011 (Forum D'Avignon & TERA consultants, 2014)To accomplish the specific purposes of a Creative Cultural Industries related project, we became interested in the fusion of Virtual Reality and Augmented Reality, two emergent development fields that gave birth to what was coined as Mixed Reality (Milgram & Kishino, 1994).

MIXED REALITY ERA

Contemporary authors/artists such as Maurice Conti and Zenka (Jenny Carden) suggest that we are at the dawn of a new age of human history defined by the way we apprehend knowledge.This last revolution - the Information Age - is connecting us to realities far beyond our natural senses, giving birth to Augmented Reality, characterized by cognitive augmentations anchored in our basic sensory system, providing an interactive experience of a real environment where the elements of reality are nurtured with digital information, across several senses, to empathize certain aspects of reality. Augmented Reality allows computational systems to help us to observe and think, based on the way our nervous system was developed and pre-wired, as well as allowing us to communicate symbolically in several cultural contexts (nature and nurture).To fulfill the specific purposes of the three-year Santa Cruz research project we are working on, we became interested in the possibilities of fusion between Augmented Reality and Virtual Reality - an interactive experience generated by a computer that takes place inside of a simulated environment. These two emergent development fields gave birth to what was recently coined as Mixed Reality (Milgram & Kishino, 1994) and the environments created can be analogous to the real world or they can be based in imaginary environments. Unlike AR or indirect AR, Mixed Reality is not based on the simple superimposition of layers of information to create enriched contents. Mixed reality works mainly with tridimensional maps of the surroundings (figure 1) to interconnect the real and the virtual elements inside a physical paradigm that leads us to a better understanding of the reality or, if we pretend to, can lead us to a better illusion. Nevertheless, other sensory feedback like and auditory and the haptic (as defined by Gibson, 1968) have been also explored.

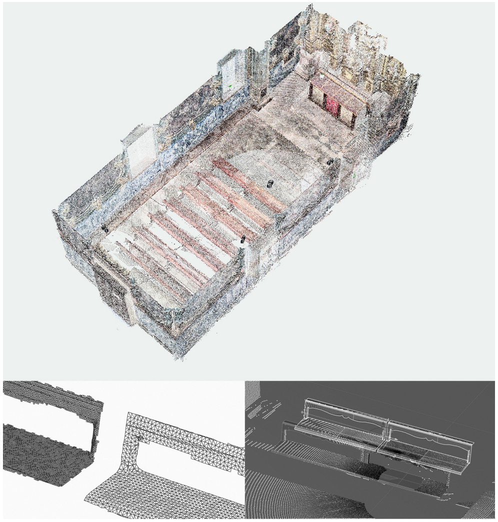

Figure 1
Our first tests were done inside a Jesuit chapel that belongs to Coimbra University Department of Architecture (cloud-point survey). First rehearsals of modelling environments by automatic methods in order to generate 3D faces based on point clouds provided by laser scans: 3D faces of the Jesuit chapel benches.

To enhance the sensory and intellectual experience, our project also combines explicit and tacit knowledge. For instance, the public can read or hear of descriptions of Hodart's «Last Supper», or visit the human scale sculptural figures at the museum room (set in a much larger space, according to a relatively random disposition), but they will also be able to look around and experience the sculptural ensemble in a more correct assemblage and placed in other, more constricted, settings such as the original one was - a small room over the Santa Cruz monastery refectory top wall.

This idea, to make the biblical «Last Supper» experience as real as possible, was in fact attempted by Hodart himself with his original sculptural recreation (figure 2). With the technology and knowledge of his time, and alike the immersive big paints drawn in perspective views during the Renaissance (such as Leonardo's own «Last Supper» at *Santa Maria delle Grazie* monastery in Milan), the intention was there to experience this biblical primordial context with the maximum of fidelity.

ABOUT THE "VR TURING TEST"

In 2016, Renshaw, Sonnenfeld and Meyers proposed at the Human Factors and Ergonomics Society Annual Meeting the ground rules for a future development of a Turing type test for Virtual Reality in order to pursue the objectives of the imitation game created by Alan Turing in 1950 (Renshaw, Sonnenfeld & Meyers, 2016). This challenge, initially focused on aspects related with Artificial Intelligence, also promotes studies of how humans construct a judgment about the veracity and tangibility of their routine observations. Accordingly, a "Virtual Reality Turing Test" is shaped and used as a reference for the accomplishment of created immersive environments.The observers submitted to the "VR Turing Test" are, firstly, the visitors of a prototype display where digital versions of some human scale sculptures of Hodart's «Last Supper» (figure 3) are taken from its actual and well known environment - the museum room previously referred to - and abruptly inserted into other architectural spaces with scarce relation with the actual (or even the original) context.

Figure 2
Human scale figures of the terracotta ensemble of the «Last Supper» by Hodart, of 1530-34, at the Machado de Castro National Museum, Coimbra (Christ, St. Peter and an apostle).

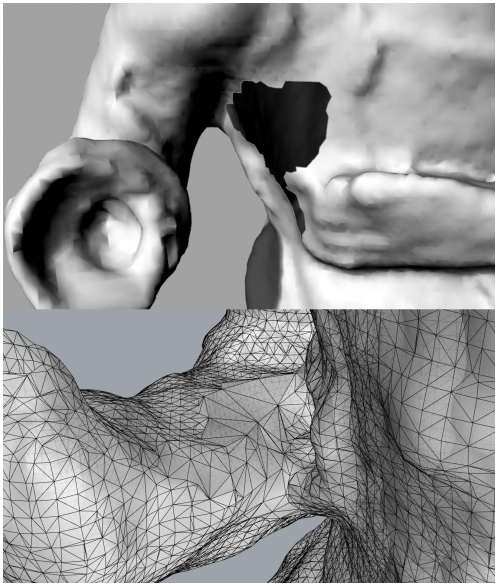

Figure 3
3D face (rendered and wireframe) reconstruction of missed parts of sculptural elements based on edge analysis applied to figures of the «Last Supper» by Hodart.

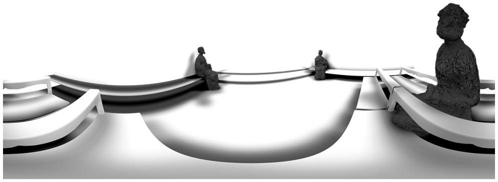

Figure 4
Raw image of the insertion of three «Last Supper» figures into a totally different context. Both the statues and the observer are inserted in the artistic installation.

Figure 5
Part of a raw 360 by 180 degrees 4k stereoscopic image simulating the intercalation of the «Last Supper» sculptures placed between real chapel benches previously 3D scanned and photographed.

In fact, we have essayed placing three central figures of the sculptural ensemble (Christ, the assumed St. Peter, and St. John) in the former Jesuit chapel of the University of Coimbra's Department of Architecture (figures 4 and 5). Reactions from observers could be video-recorded in order to verify the momentarily accomplishment of the "VR Turing Test". Instinct reactions such as surprise or distress, as well as other more complex responses such as the verification of the physicality of the sculptures, could also be verified. A similar experience will be attempted here in Denmark, in a workshop we are organizing for the 7th eCAADe Regional International Symposium, in which we will place some of the «Last Supper» figures at the table of the CREATE building refectory in Aalborg («Dinner at the Table: VR/AR Convergence applied to the 'Last Supper'»).

We are aware that all the efforts made nowadays to implement a real-like environment will be improved by the refinement of techniques and by Moore's law effect (Moore, 1965), which can be observed in several emergent technological fields. All these problems will be solved in a near future by the acceleration of the information processing capacity. The "brute-force" applied to creating anticipated interactions between real and virtual elements, as well as the infamous apparatus needed for the immersive experiments can be, in a matter of time, substituted by disruptive technologies capable to providing direct visual brain encoding, similar to what we already have for sound reading with cochlear implants. Meanwhile, the methodologies applied in this project can be improved in order to persecute the "VR Turing Test" in all the knowledge contents of the Santa Cruz project.

MIXED REALITY CONTEMPORARY EDGES

Commercial contemporary VR glasses, and contents provided to them, are normally limited to three degrees of movement (rotation around x, y and z axis). Other can be simulated but are not coherent with the user's movement. Every day, new technologies are being launched into the market. Nevertheless, the majority of hardware and software providers are not evolving in the direction of new interaction capabilities. Interaction tools are still largely in the joystick era and don't give us any particular motivation to explore these rudimentary game-like interfaces.On the other hand, the state of the art technologies in Augmented Reality are based in glasses where low quality 3D digital images are mixed with the real world. In short, 3D computer-generated imagery is superimposed over reality using one or several layers of transparent screens where a digital light field is projected. Despite the accelerated technological advances, there are several limitations in these current tools for Augmented Reality. The limited field of view on which digital images are projected, the image resolution itself and the real-time rendering limitations are some of the contemporary main restrictions to an immersive experience.Ideally, this type of Augmented Reality technologies should map the world, placing virtual objects into reality. For example, walls, floors and tables should be detected to coexist with the digital 3D contents created or translated from other contexts. Both structural and geometrical understanding of reality, as well as some semantic understanding of the way in which we interpret reality is needed to produce the immersive effect.

TECHNOLOGICAL DETAILS OF OUR RESEARCH

Like Eduard T. Hall mentioned in his book The Hidden Dimension (Hall, 1966), there are several different ways which our brain uses to interpret the space that surrounds us. In our research project we are focused in the following aspects of space interpretation:

- Dropped shadows (coherence and hierarchy);
- Illumination (intensity and colour);
- Focal distance (the focal point can be part of the story telling technic like we are used to practice in photography or cinema. The elements that we want the observer to be focused on are the ones we will, literally, focus on at the final cut);
- Parallax (slicing several spherical views and remaking them through a programmed process);
- Fog or atmosphere density;
- Interaction between the sound heard in real space and the introduced sound environment (eco and noise reduction);
- Coherent sound directions (binaural).

Instead of leaving to the glasses the effort of reading the 3D environment in real time, our methodolgy is being tuned to a state of the art technology, where 3D laser scanning and 360º images are combined to provide both stereo images and 3D vector information. These techniques and technologies give us the opportunity to make several geometrical and image refinements that can be given to the final observer as a high quality stereoscopic 360º immersive experience. To create 360º parallax environments, firstly we have to take several Ultra High Definition (UHD) spherical photos according to the directions and spots where we want to intensify the observer's experience of immersive parallax perspectives. Secondly, all the photos are subjected to a programmed process where each spherical photo is combined/remixed with other several photos in order to obtain parallax views keeping, at the same time, the notion of continuity between the several sliced pieces needed to obtain the parallax effect. Another process that is made in parallel is the 3D laser scanning of the spaces where we want to introduce new information. In this case, the raw scan is processed with Artificial Intelligence (A.I.) in order to rationalize geometries presented in the point cloud. In the great majority of the architectural cases, human hand is needed in order to reduce drastically the quantity of information presented after a A.I. shape rationalization. After the geometrical validation of the 3D faces, UHD renders are done based on the spots and lens used to photograph the 4K 360º parallax environments. Finally, both environments are creatively mixed in video.

RESEARCH PROJECT SITUATION POINT

At the moment, in our research project, we are developing two main VR-AR convergences which will be able to be experienced by future visitors to the Monastery of Santa Cruz and to its surrounding area. The first we have already partially unveiled and has to do with the reinsertion of the terracotta "Last Supper" ensemble in its original setting - a former elevated space that existed on the top wall of the monastic refectory. Although the late-gothic refectory still stands, the space where the “Last Super” was originally placed has been destroyed and the Renaissance opening, through which the composition could be seen, has been walled. We have already surveyed, with cloud-point technology, the eleven figures of Christ and the Apostles, one torso and one head that are kept and exhibited at the Machado de Castro National Museum, in Coimbra.

Figure 6
Cloud-point surveys of the Santa Cruz Monastery refectory.

With the help or art historians and specialists in Renaissance perspective, and by working upon the 3D models, we will try to reconstitute their original disposition, since no photographs remain of the time before the sculptures were taken away from the monastery, in the mid-19th century. In this way we will have to reconstitute the classical opening, the space behind it and the scene itself by means of a virtual 3D model, which will then be associated and mixed with a 360º parallax photomontage environment of the refectory hall or with raw scan optimizations of cloud-point surveys of the same space (figure 6). The terracotta sculptural ensemble can then be perceived as belonging to its original place through the use of *Oculus-Go* or VR headsets for current use smartphones.

A second exercise, almost opposite to the first we have just described, will be to recreate in 3D and through the visualization of old photographs, the built structures that surrounded the Renaissance Manga fountain *tempietto* and thus constituted the Manga cloister. These surrounding structures have been totally destroyed since the late 19th century and the remaining fountain *tempietto* is set today in the middle of a public urban garden with direct physical and visual access from the street (figure 7).In this way a fountain *tempietto* that was idealized for a quiet and contemplative enclosure is now exposed to the hustle of city life, a situation which totally alters both the architect’s and the patron’s original intention.

Figure 7
Photograph of the Manga cloister and baroque bell-tower, Santa Cruz Monastery, Coimbra, cª 1880, and Manga fountain /tempietto/ today.

Hence, we are now developing a 3D model of all surrounding structures which also include the baroque bell-tower (demolished in 1935) which could be seen from inside the cloister towards the North. We will then merge the 3D model of the surroundings with a raw scan optimization of a cloud-point survey of this outstanding architectural piece (figure 8) or with 360º parallax photomontage of the existing fountain *tempietto* (figure 9).

A third convergence we are also considering to develop, in the near future, will be the "substitution" of the actual Town Hall, built in 1876-79, by the 16th century monastic façade that stood beside the imposing late-gothic monastic church of Santa Cruz. On the opposite side of the monastic church we will also proceed with the replacement of the actual façade of the Santa Cruz Café by the former elevation of the parochial church of St. John. The former elevations can be tracked down in a 1796 drawing and in mid-19th century well-known photographs (Ramires, 2001; Dias & Coutinho, 2003).

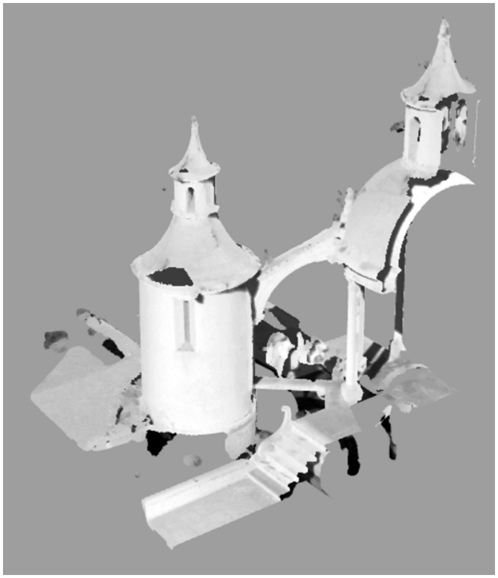

Figure 8
Raw scan optimization of cloud-point survey and automatic 3d modelation: sector of the Manga fountain tempietto.

CONCLUSION

Concluding, there are two basic aims of this initial research: first to create the tools to provide knowledge and wisdom (knowledge with emotions) around lost heritage. The second aim, profoundly related with the first one, is to create a methodology and software capable to surpass a Turing-type Test for Virtual and Augmented Reality, where the observer could be immersed in an environment where virtual outputs and feedback can be greater or, at least, similar to the real world.

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Figure 9
3D model of the former Manga cloister and bell tower with photomontage of the existing fountain /tempietto/ in the center.

Improving Visual Design Perception by an Integrated Mixed Reality Environment for Performative Architecture

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Expressive design visualization is critical for the architectural designers` visual perception of 3D architectural models. Virtual environments, especially mixed reality (MR), have the potential to enhance designers' design perception and spatial understanding. In performance-based design, building simulations and quantitative analysis of performance predictions are integral to the design process. Specifically, daylighting simulation is considered as a crucial operation through the design development and remains a complex topic to be understood. However, daylighting simulations can be understood more effectively visually rather than numerically. The gap between quantitative analysis and design can be bridged by 3D geometry visualization through immersive technologies. The focus of this study is to present an MR visualization tool integrated with daylighting simulations that aims to improve performance-based architectural design processes. The tool intends to overcome the current problems in the existing architectural visualization methods by facilitating the visualization of the building geometry, the information on building components (building information model data) by simulation results. The tool was evaluated through its use by architecture students during a 2,5-day design workshop. In this paper, an MR based architectural tool is presented and its performance on architects` design perception and model interaction is examined. The results indicate that the tool can support effective visualizations that can enhance designers' understanding of complex daylighting simulations with improved visual perception. The user evaluation of the tool regarding usability and presence was presented in our previous studies (Akin et al., 2018; Ergün et al., 2019).

Keywords: *visual perception, mixed reality, building information modelling, performative simulations, daylighting*

INTRODUCTION

The concept of space and the three dimensionality of design artefacts are critical in architecture. The conventional means of digital design have been limited to computer aided design (CAD) tools that model architectural geometries in non-immersive computer displays. However, 2D drawings or 3D models visualized on a 2D screen may fall short in providing complete awareness of space (Mobach, 2010). Albeit these tools are referred as 3D models, they require the architect's mental 3D reconstruction of the design artefacts from a 2D screen. This cognitive transformation has been a limitation for design and hinders total spatial perception (Safin et al., 2005). Recently, there is a shift in architectural design from conventional computer aided design (CAD) tools towards intelligent Building Information Modelling (BIM) platforms (Arayici et al., 2011). BIM is a 3D object-oriented parametric design environment that consists of smart elements, which represent designated building components with associated semantic and topologic data (Nicolle et al., 2011). BIM offers opportunities and tools for planning, designing, constructing, analysing and managing buildings to design professionals (Eastman et al., 2011). In addition to its other contributions in various design stages, BIM is also identified as the key solution for performance-based architectural design with its integrated simulation tools (Natephra et al., 2016). Simulation-based design is particularly effective during the early phases of design. Early performative decisions have the utmost impact on the overall performance of a building. Building performance simulation tools are systematically used in the design of high-performance buildings to predict, assess and to verify building performance (Galasiu et al., 2006). Simulation tools can give designers the ability to improve performance across a range of relevant criteria, including daylighting illumination (Barbato et al., 2014).

Spatial daylighting performance, which evaluates the useful daylight reaches to building interiors, is an important architectural concept. It examines the benefits which originate from natural daylighting such as improved health, visual comfort and energy conservation. Moreover, according to the studies, lighting is responsible for 40-70% of the total electricity consumption in buildings (Ashe et al., 2010; Dietterich, 2000). The efficient and correct use of natural lighting can prevent unnecessary energy consumption, and thus improve sustainability. However, daylighting is hard to predict, as its simulation results generally consist of a vast amount of quantitative data. The evaluation of this quantitative data requires sufficient expertise on the field. Increased perceptive visualization of BIM models and the simulation results are significant for architectural design for the reduction of project errors, costs and delivery time. Even though the BIM models are three-dimensional, simulation results, especially daylighting results, are generally represented in either raw text, table and graph format or in passive 2D visualizations inside the models. This creates a weak association between simulations and the architectural geometry. These problems challenge the architects' comprehension of the simulation results and interfere with the performance of sustainable architectural productions (Natephra et al., 2016).

Immersive environments (IEs) have a huge potential for architectural design as they offer realistic and dynamic design representations. IEs in architecture offer functionalities for architects to walk through, make spatial estimations and control the 3D environment reciprocally (Dam et al., 2000), and present novel opportunities for architects to study visual perception of architectural simulations (Scarfe et al., 2015). IEs have proven to improve design processes by increasing designers' engagement with the 'problem-space' and 'solution-space' that leads towards artefact maturity (Rahimian et al., 2011). Multiple scales of the design model, which allow the simultaneous considerations of details in different levels and the spatial perception in distinct scales for architects, can be facilitated. In addition, as Dam et al. (2000) stated, IEs can also hold a great potential for coping with vast amounts of data, such as simulation results.

Immersive technologies such as mixed reality (MR) are based on the integration of the real and virtual worlds where both physical and digital objects can co-exist and interact simultaneously. Even though MR environments do not offer complete immersion, Kellogg et al. (2008) point out that as long as the users perceive virtual objects as close to physical reality, it can create an immersion as well. Since MR is a relatively new tool, there is a limited research work on its potentials for architectural design focusing on visual perception. Therefore, there is a need for an integrated MR tool that offers interactive architectural visualization. The user evaluation of the tool regarding usability, technology acceptance and presence was presented in our previous studies (Akin et al., 2018; Ergun et al., 2019). In this paper, an MR based architectural tool, HoloArch 1.0, is presented and its performance on architects' design perception and model interaction is examined.

2 RELATED WORK

2.1 Building Information Modelling and IEs

The transitional change towards smart BIM platforms in the industry facilitated the extension of its capabilities to address the needs of architects over rapidly developing technologies. One of the implemented technologies from the recent years is the interactive IEs. There is a growing demand in the integration of IEs. There is a growing demand in the integration of BIM and IEs. This research field was addressed previously in terms of design review (Ikeda et al., 2011), design feedback (Heydarian et al., 2014) education (Fonseca et al., 2016) and construction (Sampaio et al., 2018). The integration of IEs in architectural visualization is not new, as many previous studies exist with different IE types (augmented, mixed, virtual) with various appliances. Clevenger et al. (2015) developed a BIM-supported tool to understand the roles of 3D visualization in safety training in construction. Williams et al. (2014) developed a tool for mobile MR environments in order to examine facility management in healthcare facilities. Meza et al. (2014) focused on the use of BIM information for augmented reality (AR) for scheduling.

The application of IEs to BIM created a new field in the growing software industry. Apart from the academic research, there are a number of software tools focusing on the integration of BIM and IEs. An MR tool named BIM Holoview [1], visualizes 3D BIM models as holograms. The users can overlap their models with the existing buildings to see hidden elements such as ducting and plumbing systems. Another tool named Autodesk Revit Live [2] offers interactive visualization of the BIM models in VR. The users can scale and move models and measure distances interactively. However, both of the mentioned tools do not focus on performative simulation visualizations.

2.2 Performance Simulations and IEs

The visualization of performative simulation results in IEs is a rather unaddressed field in the literature. However, several academic studies addressed the potential of the performative simulation visualization. For instance, Natephra et al. (2016) presented a VR tool, which allows users to export their BIM models to be imported into VR. Users can simulate the artificial and natural lighting on the platform and decide which type of luminaires they can use. However, the tool was not compatible with MR environments. Similarly, Schiavoni et al. (2015) studied the immersive visualization of the daylighting conditions in a virtual underground city. However, the visualization of the simulation results was limited to overlapped 2D images within a 3D environment. Araujo et al. (2014) presented a lighting simulation tool for VR, where they focused on the lighting design of artificial fixtures in large interior/exterior ceremonial places. Furthermore, Fukuda et al. (2015) presented an integrated design tool that visualizes CFD simulation results inside the building geometry by coupling concepts such as AR, VR, BIM and computational fluid dynamics (CFD). Bahar et al. (2015) developed an MR based tool for the visualization of the thermal building simulations. The system uses multiple visualization methods for simulation results such as colored translucent cubes and particles. However, similar to

Fukuda et al. and Araujo et al., Bahar et al. did not include the visualization of the daylighting simulations into their studies. Apart from the academic studies, Enscape [3], a real time rendering plug-in for Revit, simulates the artificial and natural lighting effects on the building models. The visualized simulation results are supported with a legend which indicates the extreme lux values in the model. However, the system was not developed to be used for MR environments.

According to the literature review, there is a lack of integrated immersive tools in support of performative architectural design visualization in MR environments. In this regard, we present a tool, HoloArch, that allows the designers to review architectural design models and simulation results interactively (Akin et al., 2018; Ergün et al., 2019). HoloArch integrates various concepts from different design fields such as daylighting simulations, BIM and immersive technologies (Figure 1). HoloArch aims to expand current capabilities of the BIM tools and to use multiple modes of visualization techniques to improve the visual perception of designers.

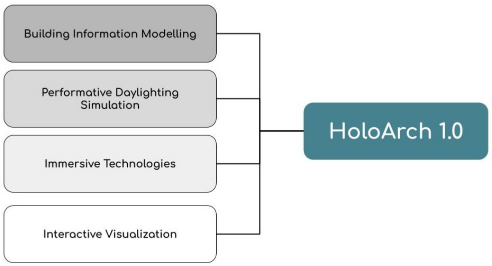

Figure 1
The topics involved during the development of the proposed tool.

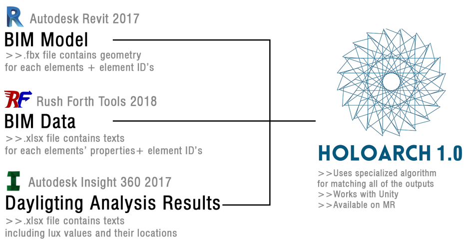

Figure 2
The workflow of the tool.

3 THE PROPOSED TOOL FOR IMMERSIVE PERFORMANCE BASED DESIGN: HOLOARCH

The limited research work on the immersive visualization of the performative and architectural simulations in the literature calls for a method for the seamless integration of BIM models and the relevant data for MR, and of their visualization of the performative simulations results. A game development engine, Unity [4], was used in the development of HoloArch. HoloArch is targeted particularly for Microsoft HoloLens [5]. HoloLens, a mixed-reality head mounted computer, has in-built sensors that are responsive to the user gestures. The users can control the environment by gazing, pinching, tapping or custom predefined gestures. In addition, the BIM tool was selected as Autodesk Revit [6]. The following sections summarize the main workflow of the tool.

3.1 The proposed workflow for HoloArch

3.1.1 Transfer Method for 3D Architectural Geometry: Autodesk Revit to Unity. HoloArch supports a unidirectional workflow between Unity and Revit. One of the aims of the study was the integration of the semantic data (BIM data) and the 3D geometry (BIM model) in the MR environment. For data integration between two different platforms, a common file format was selected as FBX (Filmbox). This file format contains both the 3D geometry of the architectural model and its building components' unique Element IDs. FBX format can be exported directly from Revit's interface.

3.1.2 Transfer Method for BIM Data: Autodesk Revit to Unity. The advantage of the BIM tools relies on their storage capabilities that enable archiving vast amounts of data related to building components. The stored data can be used both during the design process and throughout the project's life cycle. A plug-in for Autodesk Revit, RushForth Tools [7], can export selected parameters of the building model into an Excel file. For this study, the daylighting relevant parameters of the elements are determined and exported with their unique IDs (identical to the IDs in the FBX file). HoloArch can automatically match the BIM data on an Excel file and the BIM geometry in the FBX file by means of these element IDs.

3.1.3 Transfer Method for Simulation Data: Autodesk Revit to Unity. Autodesk Insight [8], a plug-in for Revit, conducts daylighting and lighting illumination analyses, and visualizes the results in 2D as an overlay to the plan layout. Autodesk Insight is able to export the quantitative daylighting illumination data underlying the 2D analysis visualization. In these raw data files, each simulation grids' location (x, y, z) and their calculated daylighting illumination values (in Lux) are provided. Currently, HoloArch visualizes two simulations results per single run: Morning and afternoon. HoloArch takes the raw data and visualizes each simulation points as extruded bars. The bars change color and height according to the values. HoloArch uses color codes ranging from red to blue for the extreme ends of the illumination scale. While red represents the over lit areas, blue shows the areas where daylighting is insufficient. Finally, all exported data from the different platforms are integrated into Unity, and HoloArch can be experienced on the MR environment.

3.2 Supported Actions
The tool's interface supports designers in visualizing the daylighting illumination simulation results (Figure 3). HoloArch's supported actions can be classified as following:

Visualize.
- 3D daylighting representation according to the selected time (Morning and afternoon)
- Selecting BIM data of the selected element
- Shadow visualization according to the selected analysis type and site location

Navigate.
- Rotating and scaling the building
- Moving the model to any desired location in physical reality
- UI placement to different locations

Interact.
- Moving and rotating objects including trees, shading devices, furniture systems
- Moving building elements including windows, walls and doors
- UI placement to different locations
- Selection of the individual elements or the whole model

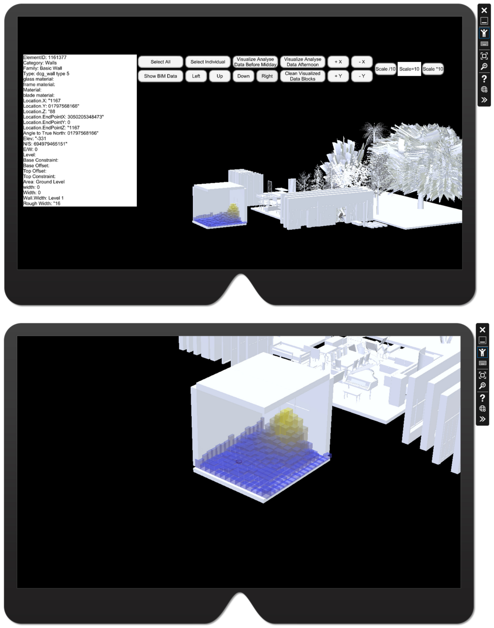

Figure 3
The daylighting visualization and the user interface with basic sample project on Hyper-V.

4 THE WORKSHOP AND EVALUATION
The need for performance based immersive design tools that support performative design development, review and design interaction were previously identified. HoloArch was developed for the MR environment to address these needs. However, MR is a relatively new field and the previous studies on the matter are limited in architecture related fields. An MR tool, HoloArch, can be a solution for increasing visual perception, which plays a significant role

Figure 4
The photos of the participants while they were experiencing HoloArch using Microsoft HoloLens.

in architects' design decisions. For the validation of the tool for the users' visual perception and interaction, a 2.5-day workshop was organized. The workshop was a part of the Design Computation Summer School 2018 [9], organized by the Design Computation Group of the Faculty of Architecture, University of Lisbon, under the title "Immersive and Responsive: Performative Architectural Design in Mixed Reality." Figure 4 shows the participant's photos while they were using HoloArch with HoloLens.

The first 1.5 days were dedicated to lectures and hands-on exercises on sustainable design, daylighting, BIM and MR. Software tutorials were given for Autodesk FormIt [10], Autodesk Revit and Insight 360. Students were divided into two groups, and were asked to design a home office building in two different cities: Cairo and Reykjavik. Each city presents various challenging daylighting conditions due to the different solar illumination they receive. Students initialized the design process by creating mass options on Autodesk FormIt and by selecting one alternative among their mass models. The selected design alternatives were detailed, and daylighting simulations were performed in Autodesk Revit and Insight. The design outputs including the building geometry, BIM data and the simulation results were transferred to HoloArch. Finally, all participants experienced their design in MR by visualizing, exploring and interacting with their building designs using HoloLens on HoloArch.

For evaluation, questionnaires with 5 level Likert Scale (1= Strongly disagree, 2= Disagree, 3= Neither agree nor disagree, 4= Agree, 5= Strongly agree) with optional comment fields are adopted. The neutral level in the questionnaire was determined as 3.0 out of 5.0. A descriptive analysis tool, IBM SPSS [11], was used to calculate the mean and the standard deviation values. 36 questions were designed by modifying the common VR questionnaires. The questionnaire was grouped into two sections: 1) Architectural issues regarding the design perception, model interaction and 2) Standard VR evaluation questions regarding tool usability (Broke, 1996) and presence (Witmer et al., 1998). The results of this second part have been presented in two previous studies (Akın et al., 2018; Ergün et al., 2019). The model interaction and design perception (12 questions), the participants' previous skills and experiences on the workshop topics (three questions) and the user comments are presented and discussed in this paper.

5 RESULTS AND DISCUSSION

This paper examines the tool from the architectural point of view in terms of design perception and the model interaction. To support questionnaire results, user comments were also included in this section. Table 1 presents the results obtained from the participants.

Table 1
The questions and results of the questionnaires.

7 Questions	**Interaction in MR**	**MEAN**	**STD. DEV.**
	My interaction with the environment and the objects felt natural.	3.22	±0.78
	The visual aspects of the environment helped me to feel involved.	3.67	±1.24
	My sense of objects in the environment was compelling.	3.56	±0.95
	My experiences in the immersive environment was consistent with my real world experiences.	3.56	±0.49
	I was able to examine objects closely.	4.00	±0.94
	I felt involved in the immersive environment because the model interaction was responsive.	4.22	±0.78
	I lost track of time while I was interacting within the immersive environment.	4.11	±0.73
	Overall Success	**3.76**	**±0.33**
5 Questions	**Design Perception**	**MEAN**	**STD. DEV.**
	My perception of the building geometry was successful.	3.33	1.25
	My exploration was successful.	4.00	0.94
	I found the visualization of the BIM data successful.	3.56	1.34
	The visualization of the daylighting results was successful.	3.89	0.99
	I could associate the building design with the simulation results.	3.67	1.05
	Overall Success	**3.69**	**±0.23**
3 Questions	**Skills and Experiences**	**MEAN**	**STD. DEV.**
	What was previous skills with Revit?	1.67	1.05
	What was previous experience with daylighting simulations?	3.33	0.94
	What was previous experience with immersive environments?	3.00	1.25
	Overall Success	**2.67**	**±0.72**

According to Pertaub et al. (2002), IEs are proven to improve the awareness of 3D models by increasing visual perception. The overall results for design perception section were obtained as: mean value (MV) of 3.69/5.0 with 1.12 standard deviation (STD DEV). Since the neutral level for the questionnaire was 3.0/5.0, it can be deduced that the findings verify the claims of Pertaub et al. (2002). This result implies that design perception of the environment was satisfactory. HoloArch allows users to see their designs in multiple scales with the aid of the MR appliance and the holograms which let them act as they do in the physical reality. One participant stated that while experiencing HoloArch, she had difficulties from time to time in distinguishing the physical and virtual spaces as the boundaries were blurred between the two realms. Another participant noted that MR gave her the opportunity to become fully aware of what was happening around herself as she could perceive both the physical and virtual environment simultaneously.

However, when the section questions are examined separately, the perception of the building geometry received lower scores compared with the other questions in the section, with MV of 3.33/5.0 with the highest STD DEV. A possible reason is identified as the physical qualities of the room that the workshop was conducted. Since the workshop was performed during day time, exposure to daylighting could have affected the visibility of the holograms. One participant added that she finds it difficult to perceive visual holograms due to their high translucency. Therefore, it is possible to suggest that dark rooms could offer a more suitable environment to experiment with the MR environments in order to eliminate translucency problems. Another reason for this problem could be the visual conflict between the real objects and the holograms. Another issue addressed by the participants was related with understanding the 1:1 scale in MR. HoloLens has limited field of vision. When users opt for bigger scales, the model geometry cannot fit in the boundaries of the display. This problem might have hindered the visual perception of the complete geometry. In this regard, one participant said that she had recurring problems about the field of view and it affected her comprehension of the model.

The absence of the materials in the model is identified as a potential challenge against visual perception. This was a conscious decision of the development team, due to the anticipated difficulties on the combined visualization of colorful daylighting simulations and materials. A visual overlap could lead to a visual overload for the users. Therefore, the material textures were eliminated to be able to visually highlight the simulation results. Positively, this distinction between the model and analyses led to positive comments in the daylighting visualization section of the questionnaire that is scored as 3.89/5.0.

As widely mentioned in the existing literature (Natephra et al., 2016; Bahar et al., 2015), 3D visualization offers better understanding of complex simulation results. In our case, similar results could be inferred. HoloArch's daylighting visualization capabilities were evaluated as the most prominent feature by a participant. In addition, the association of simulation results with the building geometry was found successful, with the MV of 3.67/5.0. The color-coding representing the level of the daylighting was appreciated by one of the participants as it offered instant identification of the problematic areas in the building. These comments imply that HoloArch's visualization methods are found easy to process. In contrast, a participant pointed out the lack of simultaneous simulation updates while the objects -such as trees or shading elements- in front of the façade openings are being moved. In the current version of HoloArch, daylighting analyses are conducted on Revit and this process is only unidirectional. Further studies on the simultaneous bidirectional workflow are needed to better understand how geometry editing affects the daylighting simulations. On the other hand, the visualization of the BIM data was found satisfactory according to the users. However, the results were lower than the predictions of the authors with MV score of 3.56/5.0 with STD DEV of 1.34. Even though the results were higher than the neutral level, improvements on the visualization of BIM data are required. For this purpose, a hierarchical categorization can be implemented for receiving higher results in the further testing of HoloArch.

The overall results for the interaction section were MV of 3.76/5.0 with STD DEV of 0.33. The results were satisfactory for the model interaction in MR. In HoloArch, users can explore their models by walking around and by getting closer to them. Users can select the objects that they want to move and relocate them in order to improve their daylighting design. One participant stated that using HoloArch with HoloLens gave her the opportunity to see the outside actions, therefore she did not bump into physical objects. On the other hand, even though the overall score was acceptable; some participants commented on the limitations related with the motion tracking and the gesture recognition during both testing and evaluation sections. In addition, the interaction method was not found natural enough as it had the lowest score among the other results in the section. According to Parsons et al. (2014), IEs allow new ways to understand and to interact with architectural models, and thus present novel expanding field for architectural design thinking. Since MR is a relatively new technology and its use is not familiar to many architects, participants might find it difficult to control the environment with their gestures. On the other hand, the results for the skills and experiences section were MV of 2.67/5.0 with STD DEV of 1.08 . The results regarding the low level of relevant experience (i.e. on Revit or daylighting simulations) might be another possible problem, which hinders the effective use of the developed tool. However, the overall results show that participants were still able to understand the aim of the tool.

In conclusion, the results of the questionnaire and the user comments verify the potentials of the tool. In particular, the tool's visualization capabilities were found more successful than the Revit environment in terms of visual perception, navigation through the model and the visualization of integrated simulation data as seen in the overall results illustrated in Table 1. Even though the participants faced several problems, the overall results were higher than the neutral level. This might be related to the participants' initial enthusiasm of experimenting with a new technology, HoloLens. They showed a higher level of curiosity and engagement to the technology. Therefore, it is possible to claim that they might omit some of the limitations related with the HoloLens.

6 CONCLUSION

It has been argued that immersive technologies, particularly MR, can support architectural design processes and augment the perception of the complex daylighting simulation results. In this paper, we present an integrated visualization tool, which aims to support the visual perception of both the architectural models and the daylighting simulations using HoloLens. The system was tested with 9 participants in a 2,5-day workshop. The results of the evaluation indicated that MR-based performative visualizations have the potential to improve visual perception and the interaction of the designers with their designs for them to give better performative design decisions in architectural daylighting design.

According to user feedback, HoloArch has the potential in terms of daylighting analysis visualization, model interaction, increased visual perception. In contrast, HoloArch has limitations in terms of BIM data visualization and absence of simultaneous daylighting analysis update. The number of participants at the workshop was limited due to the course capacity. Moreover, the allocated time for the workshop, which was 2.5 days, was insufficient to fully experiment with HoloArch considering the tool's complexity and the heavy workload of the workshop. This study has given rise to new research questions in need of further investigation. The feedback obtained from the participants was supportive for the further development and improvement of the system.

7 ACKNOWLEDGEMENTS

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Context-Aware Image Acquisition Approaches for Renovation Building Process Using AR and Linked Data

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This paper discusses the development of a prototype that deals with the photo documentation of buildings in need of renovation and incorporates the documentation process into the BIM methodology. To achieve this, technologies such as Augmented Reality for localization and navigation within buildings, and Linked Data for connecting data sets with a BIM model, are used. The aim of this work is to establish a direct link from a photo taken in a building to an IFC model, and vice versa, and to improve the process of the documentation of buildings.

Keywords: *Augmented Reality, Linked Data, Image acquisition, Building documentation, BIM*

INTRODUCTION

While the Building Information Modelling (BIM) method has already proven its value in the field of new buildings, there are still many challenges regarding renovation work in combination with BIM that the construction industry needs to address. One of the reasons for this are many small- to medium-sized enterprises (SME), highly specialized stakeholders, who have not yet participated in the latest developments of the industry. Furthermore, the obstacles to get in touch with BIM are quite high, as the software is often not affordable for small companies, and employees need to receive special training. A number of researcher initiatives are currently addressing the topic of making BIM easy to use and are trying to find out how these companies can be integrated into the process by minimizing the obstacles in terms of time and costs. (Beetz et al., 2016)

The objective of this paper is related to this effort and focuses on taking images of an existing building for documentation purposes. This is one of the first tasks planners are carrying out when they enter the building site. Over the entire construction cycle, the photographic documentation remains a continuous process. Moreover, nowadays it is common for planners to use their mobile phones for this task and to synchronize the photos on a local filesystem, or sometimes even with a cloud storage. Although many offices attempt to bring order into their processes, it often leads to large, cluttered collections of images in which it is difficult to quickly find a specific image. Another issue with this technique is that these images do not carry any additional information. Neither is it convenient to add information such as comments or status messages, nor to know the exact position in the building where the photo was taken. An automatic connection between the acquired images and an IFC model is the aim of this work.

Rather than an isolated solution that only solves the problem described above, a working method is proposed that can be combined with other developments in the construction sector. Images are created with a mobile phone and uploaded to a database. Additional data sets, which are generated from the sensors of the mobile device or added manually by the user, are stored on a graph database. A connection to an IFC model should be enabled and an integration into a Linked Data based building model, as proposed in (Beetz et al., 2005), can be established. With this connection it is possible for the user to make requests to components and to see whether and which pictures of the respective component had been taken. Implementing this concept into a spatial database it is also possible to display all images in the building that are within a certain radius around a chosen position.

Since the connection with the IFC model takes place later in the process, the work focuses on the steps immediately before and after the creation of the building geometry. The actual phase of modelling the building is not part of the observation of this work. For all subsequent steps, it is important not to create completely new solutions, but to use the resources that already exist and are being used in the industry today.

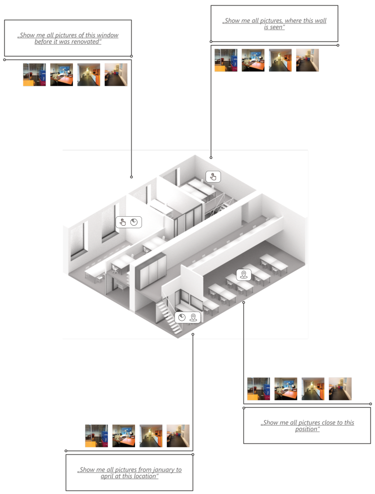

Figure 1
Abstract representation which illustrates the queries to a 3D model with attached images

RELATED WORK

Working on this prototype, several kinds of related topics were identified, that have been part of the research and everyday life of planners. The following paragraphs discuss these and show how we intend to build on them.

Mobile Navigation

The first topics is navigation with apps for mobile devices. Using various tracking methods, they can find out where the user is currently located and synchronize the location with a digital map. This is used in consumer applications such as Google Maps and OpenStreetMap on the one hand and is also the subject of research such as in the field of geosciences on others. (Fukuda and Tian Zhang, 2012) However, this works focus lies on the area of indoor navigation apps, since tracking inside buildings is still a greater obstacle than outside buildings. Nowadays these are used, for example, in airports and shopping centres to improve customers orientation within these large complexes. (Boysen et al., 2014)

Construction site management tools

Another topic deals mainly with the management of the construction site itself. Various applications have been developed for this purpose with whom a planner can create notes, annotations and comments on the status of the construction on site. This is often supplemented with a function to take photos and to attach them on a plan by manual input. These applications should enable the user to keep a better overview of the progress of the construction site and generally improve the construction process. An example is BIM 360 by Autodesk, which provides some of these functionalities. Another application for controlling the construction site is GAMMA AR , which overlays a building with an IFC 3D model and thus offers the user a visual option to quickly identify and note error sources. These errors can be recorded directly on site and transmitted to the project participants using the BIM Collaboration Format (BCF).

BIM Collaboration Format

For this work, the BCF format itself is a source of inspiration, since it is responsible for creating and exchanging issues with the BIM model between project partners and between different software applications. These issues are stored in a zip file, which in return consists of several XML files. Within these XML files, the issues are located in the model, using a camera position and rotation at the location where the issue was created, and are linked to the model components using the globally unique identifiers of the IFC schema. (Beetz et al., 2018) Today, to a large extent this format is used in connection with collision checks of models authored by various trades. However, it also has application on physical construction sites, as for example in the case of GAMMA AR. In addition to the exchange format, a bcfAPI is currently being developed which is intended to replace the non-automated manual sending of these files and allows the data to be stored directly on a server as well as being distributed from there. [1] Since the BCF method is already widely used in industry, its structure serves as a model for the development of data organisation in this project. Since the data should be stored as neutrally as possible, it is also conceivable to generate BCFs from it.

Cultural Heritage Documentation

In the field of archiving cultural buildings, development can be observed that refers to problems like those described in this paper. The MonArch project at the university of Passau is developing a system that gathers all data of a building and places them in a spatial context by allowing documents, images etc. to be attached to components. Using drag and drop operations, the user can generate the connection between building elements and documents. For example, a photo can simply be dragged onto a window to create a link between these objects. The generated relationships create a much clearer organizational framework that is easy to use with the ability to handle very specific search queries. (Freitag and Stenzer, 2017)

The work presented in this paper aims at a similar approach, but initially focuses on the creation of simple images that are automatically linked to an IFC model with as much additional data as possible, thus creating an integration into the BIM methodology.

METHODOLOGY

This paper proposes an easy to use mobile application for taking pictures on a construction site, based on the technology of Google ARCore . Images taken with this app are enriched with information, provided by the various sensors which are built into regular mobile phones. These sensors, combined with the latest technology in augmented reality, can be used to detect the accurate position inside a building. In addition, an IFC Viewer is used, which allows the data generated with the app to be downloaded and viewed. The Unreal Engine is used both for the development of the app and for the interaction of the created images with an IFC model. Nevertheless, it serves only as an exchangeable tool. Similar results can also be achieved with other software such as Unity and Android Studio . To view IFCs, theoretically any available BIM software which can be extended with own plugins can be used. The following paragraphs explain the individual technical and methodological components on which this work is based.

Positioning

To position and track inside a building, the research of recent years provides several methods to achieve this goal. Three promising technologies are considered for the scope of this work.

The first option is to track the mobile device based on satellite positioning such as the Global Positioning System (GPS), as seen in (Hii Jun Chung et al., 2009). While this type of tracking provides good results for outdoor use, it is not optimal for indoor tracking. The satellite signal inside buildings is often not strong enough and thus acceptable accuracy cannot be achieved. (Stojanović and Stojanović, 2014)

Another method, which is often used for indoor tracking applications nowadays, is a positioning via triangulation using radio technologies like WLAN and Bluetooth. (Stojanović and Stojanović, 2014) Although this technique allows a very reliable localization within houses, it is not suitable for our specific use case, because it is accompanied by an increased preparation of the construction site. This would, at a time when the actual construction work on the building has not yet begun and only a first documentation of the existing building is being taken up, contradict the principle of "easy to use" and "easy to access".

For the prototype, the motion tracking of ARCore is used which is based on concurrent odometry and mapping, also called COM. [2] In cooperation with the orientation and positioning sensors of the mobile device and the help of ARCore found feature points in the environment, the mobile phone is enabled to understand the space around itself and to place virtual objects in it, which are displayed firmly anchored in the real space. [3] Although the tracking is still in constant development and is sometimes struggling with dropouts, it achieves a very good accuracy and runs quite reliable in reasonable lighting conditions. The disadvantage of this tracking method, however, is that the positioning has no relation to a geographical coordinate system and the starting point in virtual space depends on an initial position, which is always (0|0|0) in the virtual world. This origin point is dependent on an as-built plan, more precisely with the centre (0|0) of the plan, which is loaded into the app as the basis for the respective building. To calibrate a session, a user as to pick a starting point on a map. [4] Before the calibration is finished, the height in relation to the ground needs to be determined. This step is necessary because otherwise we would be at altitude 0 with our current calibration. Currently, the initial height is fixed at 112 cm. For there on, all values for the location and the rotation are interpolated from the thus defined origin. After the adjustment is done the user can walk around the building while the phone keeps tracking the position. Every time a new session is started, the application needs to be recalibrated. During the session, the AR Toolkit is able to use feature points [3] for recalibrating if the tracking is lost, but as of now, the software is not able to save this information for another session. [5] The accuracy of the tracking achieved with this method depends on the correct positioning of the user. However, if the user does the positioning in the plan well, a higher accuracy can be achieved than with the other two variants mentioned. (Stojanović and Stojanović, 2014)

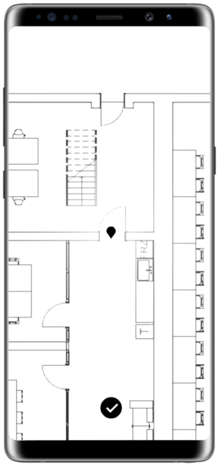

Figure 2
The start position can be determined by clicking on the corresponding position in the map.

Data gathering

During a session, when creating the photos, different types of data are collected, which are both created by user and generated by the mobile phone's internal sensors. With the collected data, the aim is to enable a connection with an IFC model and at the same time to generate useful information for planners and viewers that are directly related to the image. This is in direct contrast to current working methods, where images are often created with a digital device, but information is written down in analogue form. This data is only linked in the photographer's mind and cannot be understood well by other people. In order to create a link between the two elements, the previously described tracking comes into play. When taking a photo, a digital clone of the camera is created at the position where the mobile phone is located, and it is enriched with various information. In addition, each object is assigned to a special project, which can be defined at the beginning of a session. Each clone is also assigned a random 32-digit character sequence, which represents a unique identifier in the further course of the project. Data such as compass direction and time are read from the phone's sensors, while comments, tags and status indicators can be entered directly by the user. Generally, this data can be divided into two categories. On the one hand, we have the data such as the position and rotation of the camera, which are essential for the functionality of this workflow and on the other hand there is the user-generated optional input, which should give the planner some useful tools. Finally, the generated data can be divided into two types: binary and text-based. The images in this case are the binary data, while all other information can be described with simple strings and numbers.

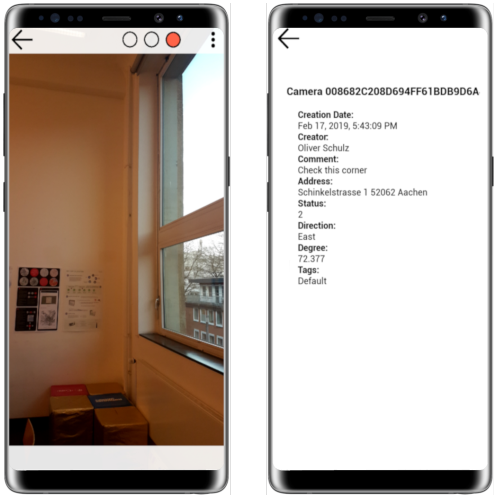

Figure 3
Preview of the image with its status (left side) and all associated parameters (right side)

Data processing

The collected data associated with each camera object must be uploaded from the local device to a database to make it available to other project participants and to link it to the corresponding IFC model. A dual system is used for this task, which is intended to provide a maximum degree of flexibility. While the camera's metadata is uploaded to a graph database, all images are stored on a cloud as they are already used in many offices (e.g. Google Drive, Dropbox, OneDrive etc.). This dual system was chosen because it allows the user to build on existing structures and allows easy and independent access to their images. Down- and uploading of the data is handled via HTTP- Requests. The decision was made against a relational database, because the graph database can better handle a dynamic extension of the data. In addition, we aim to be able to link it to existing research that deals with the possibilities of mapping IFCs in graph databases as described in (Beetz et al., 2005). A close interdependence of these projects is intended to be established with this step.

Furthermore, all query results that are generated when uploading to the graph database are uploaded to the cloud as JSON files. This is to ensure that all collected information will not be lost after the database has been switched off or purged and thus remains preserved. Since the cloud itself is synchronized on local computers, no further backup system is foreseen for the time being.

User Interface

Since the simplicity of use is in focus, the structure of the user interface plays an important role in the creation of the application. Although it must not be overloaded with functionalities, it must fulfil the conditions mentioned above. A role model for this prototype is the camera application, which is available on all regular mobile phones and can be operated by most users. By orienting the research on this structure and its functionality, the intention is to prevent a user from becoming lost in the app. The software will be started normally from the start screen of the phone and the user will be taken to the main menu where it is possible to choose a project and to start the AR session. Once the session has been executed, a new screen will appear where the user will be asked to synchronise on a digital map with his current position in the building. From that moment on, the handling should not differ much from a normal camera app. As soon as several photos have been created, they can be viewed in a gallery and uploaded to the storages.

Synchronization with a BIM model

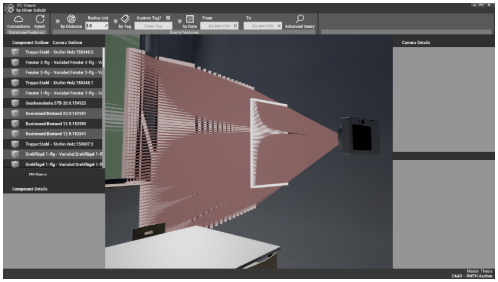

Figure 4
Ray-cast performed in the IFC Viewer. The white dots in the middle represent the 20x20 pixel tiles of the image at a 1-meter distance from the camera. A beam is sent through each of these tiles and it is examined where it hits.

The last step in this process is to link the generated images with a model. For reasons of simplicity, the software Unreal Engine 4 was used, as it was with the creation of the app. Although the Unreal Engine traditionally has no connection to the BIM workflow, for this work it was provided with an IFC add-on, based on the open source project "IfcOpenShell" , which makes it possible to use the engine as an IFC viewer. Nonetheless, the software used here is only a proxy for other BIM applications, since the following steps can be covered equally satisfactorily by them. For the following steps the model's origin needs to be synchronized with the origin of the images, created with the application. To achieve this, we either align the position of the model with the plan from the application or we use the plan as an underlay during the creation of the model, so that the origin is the same from the beginning. Now all camera information can be downloaded from the web storage. The location- and rotation-values of the placed cameras are matched with the ones saved in the database, so the perspective of our newly created camera and the captured image we took with the mobile phone should be nearly equal. Downloading the information from the graph store is done the same way the data was uploaded from the app.

By using HTTP requests, we first query the database for every distinct camera ID and then save them to a list. Now we start a second query with this list, where we ask the server to return all the stored data for every item in the list. For each ID a camera is generated in the viewport and linked with all its information. After a camera has been placed, it performs a ray-cast in the direction of view, which searches for all components in the camera's field of sight and saves them in another list. The ray-cast fires an infinite line for every 20x20 pixel tile. Because the ray-cast probably hits each object several times, each component is added as a unique item to a list, which is then pushed back into the database. In addition to the first list, we create a second one in which all IDs of the hit objects are stored in the order in which they were hit. The first object hit by the ray-cast therefore has the index 0 in our list. This array now makes it possible to assign all 20 x 20 pixels tiles on an image to a specific IFC component. With this step, the link between the image documentation and the IFC model is established and each image can be assigned to all components that can be seen on it and the other way around.

```
Hit Components =    {
                      0cNd9$6G906ACzh2dBNgTu   :  0
                      0FQL28A_r1lhOxT4d_BEFM   :  1
                      188nErZwD48uddol0PtTy9   :  2
                      1zMXMGg3H1MOhxQ9qjUS4B   :  3
}
```

$$
\text{Pixel Matrix} = \begin{bmatrix}
1 & 1 & 1 & 2 & 0 & 0 \\
1 & 1 & 1 & 2 & 0 & 0 \\
1 & 1 & 1 & 2 & 0 & 0 \\
1 & 1 & 1 & 2 & 0 & 0 \\
1 & 1 & 1 & 2 & 0 & 0 \\
1 & 1 & 1 & 2 & 0 & 0 \\
1 & 1 & 1 & 2 & 2 & 2 \\
3 & 3 & 3 & 2 & 2 & 2 \\
3 & 3 & 3 & 3 & 2 & 2 \\
3 & 3 & 3 & 3 & 2 & 2 \\
3 & 3 & 3 & 3 & 3 & 2 \\
3 & 3 & 3 & 3 & 3 & 2 \\
3 & 3 & 3 & 3 & 3 & 3
\end{bmatrix}
$$

Figure 5
Schematic representation of the functionality of the ray-cast. Each component is assigned an index. The corresponding index is then inserted in the matrix depending on which object the pixel is portraying.

RESULTS

The result of this project is a workflow consisting of a mobile phone application and an IFC model viewer based on the Unreal Engine, which are both connected with two data storages. It can be watched in a video. [6] Together they enabled a two-dimensional photo to be linked to a three-dimensional IFC model. An outcome of this linking of information is the ability to enrich images with more semantic information and cross link the image to the components seen on it, and vice versa.

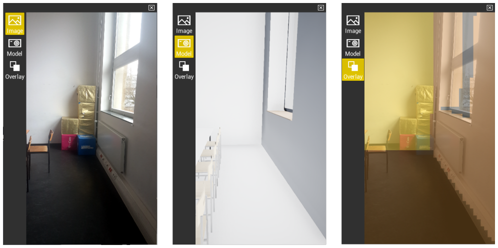

Figure 6
The two different view modes and the overlay that can be placed over both variants

The application

With the application, it was possible to walk through the building and take the photos. The mobile device is tracked with the AR technology and its position inside the building is synchronized on a virtual minimap. Other small tools like displaying a compass, adding tags and defining status alerts could also be handled via the app. While walking through the example building, we noticed that there were still a lot of disturbances that could diminish the tracking during a session, or even make it completely unusable. This was especially the case in poor lighting conditions. Also, sensors like the directional sensor (compass) were not always working as expected and occasionally showed wrong results. The manual setting of the position, at the beginning of the app, provided a mixed result in the accuracy of the tracking, which could range from a few centimetres to about half a meter. On the other hand, the rotation of the camera usually delivered very reliable values. In general, the tracking accuracy exceeded expectations. The upload of the images to the database worked without any problems and could even continue after a crash, which seldomly occurred.

The web storages

The two databases used created the connecting element between the two components that can be utilized by the users. The cloud database was used to receive all binary data and to represent a kind of web interface, which could be used completely independent from both platforms to browse through the images. The graph database received all raw data generated from the app and the viewer. With an integrated development environment (IDE), the data could be retrieved completely without other tools. Unfortunately, these only appeared in long lists that were not particularly easy to read. The fact that both technologies could be controlled with the REST API made it possible to bundle all download and upload processes and handle them using the same fundamentals. Thus, there was no need to develop two completely independent methods.

The IFC viewer

In the IFC Viewer the cameras were loaded into the model by the click of a button. With a ray-cast operation, the model was searched for all components seen by the camera. Since the ray-cast was created in relation to the pixel density of the image, this caused a performance issue with the engine, which was solved by reducing the scan to every 20 x 20 pixel-tile of the image. In a sperate window the original image and the digital twin could be compared and overlaid with the pixel values of the ray-cast. It was possible to click anywhere in the image to highlight the corresponding component in the viewer. The other way around, the viewer allowed to select components that showed the user which pictures they were displayed on. The first attempts still included pieces of furniture when querying the view, but this was removed in later implementations, as these are non-static objects whose position varies too often in reality in comparison to the 3D model. A further obstacle was represented by components which, such as windows, were partly made of transparent material. These prevented the ray-cast from passing through them. Although this was in accor-

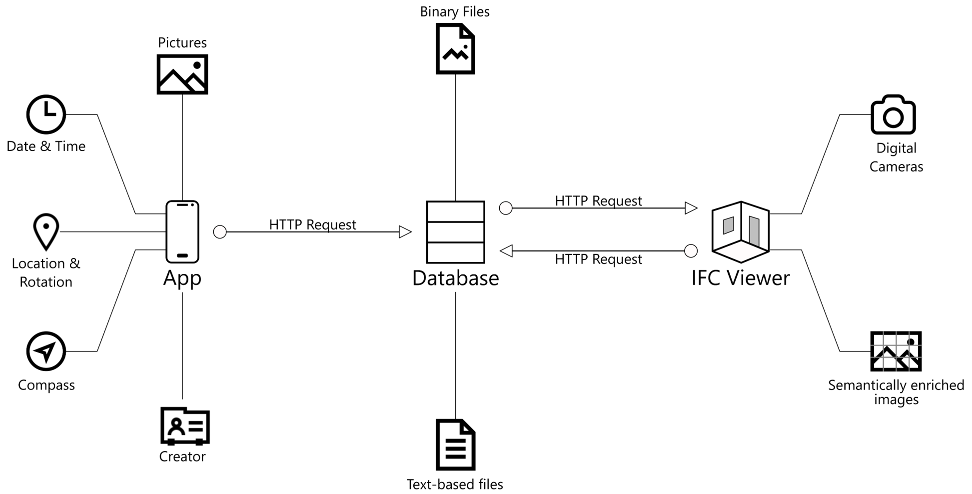

Figure 7
Overview of the three cornerstones of the project. The database is the linking element in the middle and is responsible for communication.

dance to the nature of the function, it caused the paradox that the camera itself could look through these parts and see other components, but the raycast ignored them completely, because it made no difference between the materials it encountered.

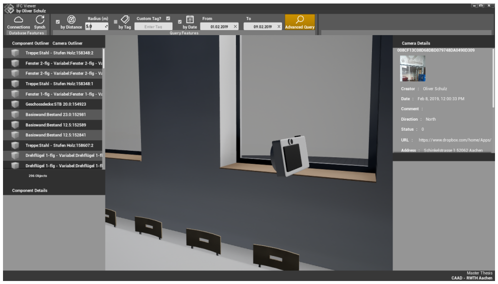

Figure 8
Screenshot from the IFC Viewer. In the middle a camera can be seen which was generated with the mobile application.

DISCUSSION

In comparison to current workflows, which are used for the documentation of buildings, this paper shows a promising new way to integrate this process into the BIM method without the need of being a BIM expert. In addition, no new technologies need to be developed for this and existing solutions were utilized. However, it is noticeable that some problems still must be addressed. The described tracking within buildings is a key component for the success of this method. Although it does not require perfect accuracy to be useful, total breakdowns and major tracking losses must be reduced to a minimum to ensure user acceptance. A further problem is the manual calibration of the user, which has repeatedly caused problems with accuracy. Although this was sufficient for the prototype, it showed that a more reliable method of calibration is needed. However, a look at other projects shows that solutions have already been developed that can be built on. For example, it would be possible to perform a triangulation with the help of the plan and the AR technology of the mobile device, with which a more precise position could be determined. A corresponding solution can be found in the GAMMA AR project. To do this, it would be necessary to select a line on the map and place it in the real building at the right location. Another possibility would be the use of markers that require positioning at a previously defined location.

This is probably a very simple method for calibrating the app quickly, but on the other hand it would require more time for preparation because all spots have to be set in advance and marked in the app. The limits of the possibilities of this prototype could also be clearly seen in the development. ARCore's tracking technology has proven its worth and very often provided reliable tracking results, but it turned out that not every building is suitable for this type of recording. The moment a building has too little contrast or its rooms are very dark, tracking quickly reaches its limits. Very narrow rooms can also make it difficult to use the app satisfactorily. A type of building that would certainly cause many issues could be small church towers. But since the AR tracking technologies have made great progress in recent years, future iterations might already reduce these problems. Furthermore, parts of the application could still be used in such buildings despite these problems, as small tools such as the compass- or tag-functionality could already provide added value for the users.

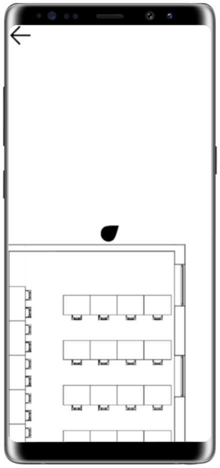

Figure 9
Occasionally, the application lost its tracking. This caused the tracking to be temporarily kicked out of the building.

The IFC viewer gives a preview of how a building information model can be used as a data container for old and heritage buildings. Although initial developments in this direction can already be seen in projects like (Freitag and Stenzer, 2017), a partial automation of this process was achieved in this project in cooperation with the mobile application. The connections that the viewer creates between the images and the components are still very rudimentary in time. Further improvements to this could create even more complex queries to the model and allow manual input of images that were created without this app. Even an approximate mouse positioning of a camera could provide added value. The ray-cast, which should be based on the pixel density of the image, has proven to be very performance-intensive. At a relatively low resolution of 720 x 1280 pixels, it performed almost one million operations per image. The computing load was reduced by hitting only every 20 to 20 pixels with a ray-cast. Although the result has become somewhat less accurate, it allows a larger number of images to be retrieved simultaneously as part of the prototype. Since it is now possible to determine exactly which pixel of an image shows which component by means of these ray-casts, we can create further advanced solutions based on this technique.

Distributing data from a mobile phone via a dual system has proven its worth. The cloud structure for the images can be easily integrated into office structures and is already available in some cases. The graph database is therefore only responsible for the raw data. Since the information is not stored directly in a specific data format, it is also possible to generate it and combine the project with other formats. For example, almost all data required to generate BCFs are already stored in the database and can be distributed to project partners.

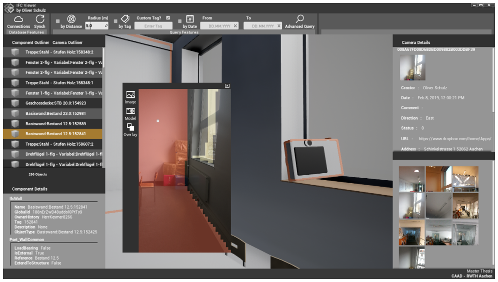

Figure 10
An image of a camera displayed in the Viewer. The colored dots on top of the image are the individual components that the camera sees.

CONCLUSION

This paper explored the possibilities of linking images to a virtual building model. It shows that current developments in the field of commercial mobile phones are sufficient enough to track the position in most buildings. Moreover, it is possible to generate additional data such as directions, air pressure etc. from the device and to attach them directly to an image. The collected data was loaded on a database, or in the case of the pictures on a cloud, and thus made available for further applications. A possible implementation of this data was demonstrated by loading it into a 3D model and enriching it with further information. The symbiosis of these two worlds - the real world represented by the images and the virtual world represented by the IFC model - provides promising results from which further research can be imagined.

By using Linked Data this project can be integrated into a larger context. The prototype described here is considered as a building block for further research in the context of the H2020 BIM4Ren project that is addressing SME-specific processes and interoperability challenges for the renovation of residential buildings. With the help of the ray-cast, which we executed in the project, it is now possible to provide IFC Models with the exact positions of damages to the building substance and to insert them into the geometry. Furthermore, it is possible to use the images as a kind of decals and map them directly onto the 3D objects. This could further enhance the connection between the 3D model and the real building.

Ultimately, a long-term goal is to create a public memory that accompanies the building throughout its life cycle, and beyond. Knowledge about the building could be preserved over different phases and accessed by a simple click in a BIM application. In the future it could be avoided to organize tedious searches for certain images in clusters of subfolders. By simply entering the position, a date or the name of a component, the corresponding images could be delivered. Vice versa it would be possible to only click on the image at the specific position and be led directly to the corresponding component. There would be no need to speculate about where an image was taken.

Although this paper focuses mainly on the area of building renovation and architectural heritage, the results are largely applicable to the area of constructing new buildings.

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The use of virtual reality in exploring non-linear interpretations of literary architecture: an initial methodology

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This paper focuses on the multiple interpretations of literary architecture, using Virtual Reality (VR) that bridges the reader's immaterial graphic fragments in their mind and the immersive virtual environment. Rather than an adaptation or aesthetic re-creation from a piece of text to its interpretation, this paper aims to investigate how to keep interpretation from an endless "sliding of meaning" (Eco 1990, p.151) and create a set of criteria by which the interpretation can be critically assessed. Furthermore, different groups of the readers (e.g. those who have or do not have an architectural background) will have the chance to experience the visualised interpretation by means of interaction between users and interface in VR and give their response and feedback respectively, which will reveal how the reader's interpretation influence the original text. This paper introduces a number of potential literary works as case studies and a preliminary plan of imagining the text in a virtual environment, the mode of interaction and the collection of feedback. However, as an initial proposal of research methodology in an early-stage PhD programme, it is still to be tested and refined in future work.

Keywords: *Multi-interpretation, Virtual reality, Literary architecture*

INTRODUCTION

In Borge's *The Garden of Forking Paths*, the Chinese scholar Ts'ui Pen left these last words and his mysterious novel to his descendants: "I leave to the various futures (not to all) my garden of forking paths" (Borges 2000, p.51). The protagonist finally deciphered this phrase that implies a non-linear narration. The storytelling does not attempt to confront the reader with several alternatives where they choose one and eliminate others, and instead, Borges (ibid., p.51) aims for the reader to choose "all of them simultaneously". If this novel does exist, how can a reader experience all the endings of the story? This inexistent novel suggests a piece of text that is open to being interpreted according to different readers' comprehension. Rorty (1982, p.151) stated that the interpreter "beats the text into a shape which will serve his own purpose". For example, in every reader's mind, the images of the cities in Italo Calvino's *Invisible Cities* are different; it is difficult to decide which interpretation is the one in the author's mind. However, the author advocates the readers' rights: "a book is a space which the reader must enter, wander round, maybe lose his way in, and eventually find an exit, or perhaps even several exits" (Calvino 1983, p.38). Although Ryan (2001, p.120) mentioned that the text could imprint "quasi-photographic sharpness" on the readers' mind, these images are usually incomplete. From the point of view of the readers who have an architectural background, the fictional architecture has the potential to be interpreted to a complete visualisation, and the utilisation of Virtual Reality (VR) develops these interpretations to a multi-sensory version which can be experienced by the users. Because of the diversity of the readers' understandings, they might imagine the fictional architecture as various styles, shapes and materials. However, even if the text indicates unlimited interpretations, it still disproves that "interpretation has no public criteria" (Eco 1990, p.144). Therefore, this paper, as a part of an early-stage PhD programme situated in between theory and practice, raises the questions of how to translate the multiple interpretations of fictional architecture to VR and to what extent can these interpretations be critically assessed based on a set of criteria? Is there a mode of interaction between the users and the computer, which can represent different interpretations simultaneously in VR? Furthermore, what factor influences the readers to produce different interpretations and how can a text be influenced by its interpreters? This paper proposes a methodology to begin investigating the multi-interpretations of literary architecture in VR, which will be the implement as the next stage of PhD research.

VR AS A TOOL OF STORYTELLING

Virtual reality has been used to represent the architectural design concept in the way that the users can immerse in a full-scale digital model. The immersion can be enhanced by virtue of the entity's characteristic such as texture, glossiness and other details (it does not necessarily have to be photorealistic). Furthermore, VR and game developing application have the potential to translate the ambiguity of the text in a variety of different directions, according to the individual readers' interpretations of the text. In collaboration with the detailed full-scale model and the translation of the ambiguous quality of the text, the immersion of the Virtual Environment (VE) may be further magnified. Char Davies' *Osmose* creates a virtual zero-gravity world in which the users can freely wander around. The text as overlapping images cause illusion to the users as though they are entering several worlds simultaneously, which are penetrating to each other, and the boundaries have dissolved, "suggesting meaning rather than explicitly illustrating," and "evoking a range of associations and interpretations in the mind of the viewer" (Davies and Harrison 1996, p.1). The spatial immersion of the users is continuously maintained in Davies' aesthetic work by producing the participants the feeling of "presence" (Witmer and Singer 1998, p.225). According to Ryan's assertion, the spatial immersion also occurs in reading activity and depends on "the coincidental resonance of the text with the reader's personal memories" (Ryan 2001, p.121), implying that the immersion becomes diverse due to the readers' various empirical experience.

Regarding the text as historical urban context, VR has been enabled the ability to visualise the hidden stories of a city, even when some of them are parallel. Webb and Brown (2011) explore how to enhance the current understanding of the lost or unbuilt works of architecture by using digital techniques based on the surviving literature or fragmented images. Kartalou's paper (2016) indicates that digital technology can be used to reveal the hidden intangible elements of cultural heritage, allowing people to experience a "more complete image of cultural heritage". Moloney et al. (2017) developed two immersive virtual reality (*iVR*) applications to visualise different versions of unbuilt architecture, along with other relevant information such as drawings, photo, paintings, and narrations of text for the "historical interpretation of unbuilt architectural drawings". This research provides a range of methodologies along with the utilisation of VR and architectural representation, which is also the essential toolkit of this research.

Non-linear storytelling allows the readers to experience the narration in **forking paths** as opposed to telling a story without providing options to the readers, and it can be enhanced through an immersive VR. The story in the open-world RPG (role-playing game) *The Witcher 3: The Wild Hunt* develops by the players' choice at every decision point, and the players will not know what the consequence to the characters until the ending of the game. As a result, they could watch their favourite characters die or experience the perfect ending. What makes it unique is that the characters and stories become completed and convincing because of the "morally ambiguous areas and decisions to be made that highlight what makes our world so complex" (Welsh 2016). A cinematic interactive game (using real actors) *Late Shift* provides more than 180 irreversible options to the players, and which lead to more than seven endings. The essence of this form of storytelling is creating a **decision tree** by which every player can choose at a series of decision points and approach to one of the multiple endings. In another video game, *Dark Souls*, the fictional world is created in a non-linear way - all the maps and architecture are connected; hence the players can choose any entry to take an unknown adventure. According to Brown's research video (2018), although the game has a general sequence of the acts, most of the players tend to choose a random and more hazardous route - even though they might spend hours on finding a way in the chaotic labyrinth and fighting the enemies, it is the unique quality of this game. Besides, the storytelling in *Dark Souls* is so obscure that the players can only trace the evidence of the hidden story by finding the specific items. However, for the map is an open labyrinth, the order of emergence of these items lead to various interpretations of the story.

These precedents generate the background into the potential of this research to extend the methodology of interpreting the historical architecture from existing documents to the interpretation of fictional architecture. Game making involves the creation of the VE and the relationship among the VE, the UI and the storytelling, which is instructive to my research. VR shows its potential to be a valid tool that re-visualise unbuilt architecture. Moreover, Davies and Moloney's work both introduce multisensory experience, creating an immersive virtual environment which is the crucial characteristic of VR. On that account, this research aims to explore how to interpret the fictional architectural space to an immersive VR version using digital techniques, and how can multiple interpretations be made simultaneously. According to Moloney's study, different interpretations of the historic architecture are created digitally in an application made in Unity3D, along with a user interface (UI). Therefore, the users can choose viewpoints, watch different versions of the building and learn about the history and context of the project by user input (2017, p.716-720). As such, this research will develop this methodology after collecting various interpretations from the participants who have an architectural background (students, architects, and so forth) in separated elements as a preliminary library (this will be discussed in the next section). In the form of a Unity3D application, the following stage is to build digital virtual models and the ambient environment as a translation from the collected data, and the VE will immerse the participants to let them experience own and other interpreters' versions of the fictional architectural space in this application. The UI will help the users not only to control and navigate in the VE but also to acquire multiple information about the literary work. This is followed by the response and feedback from the participants about to what extent does the VR experience correspond to their unshaped interpretations, and the application will be refined according to the feedback, see figure 1.

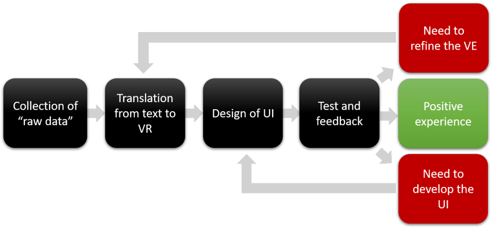

Figure 1
The process of producing the interpretation from text to VR.

FROM TEXT TO INTERPRETATIONS

Whereas the difficulty of interpreting literary works, especially regarding the ambiguous description, which is that the author's intention usually stays out of control or unknown to the readers. Thus, the interpretations can easily "lead to the acceptance of a never-ending drift or sliding of meaning" (Eco 1990, p.151), if there is no limit of the interpretation.

It is true that the unbuilt or lost architectural space in the text always encourages the reader to imagine the details of the place as a vessel for the plots, for instance, the Aedificium in Eco's *The Name of the Rose*, Minas Tirith in Tolkien's *The Lord of the Rings*, Hogwarts in *Harry Potter*, and Chang'an as a capital city of Tang dynasty in traditional Chinese poetry. The details of the architectural space in the adaption from text to film or other visual media have amazed us with metaphoric visual details: the endless staircase as an interpretation of the labyrinthine library in the Aedificium, the first magnificent portrait of Minas Tirith in Gandalf's view, and the flyby upon Hogwarts' castle in the valley, and so on. In the case of re-creating the library in *The Name of the Rose*, the labyrinthine layout in the original text were reinterpreted to an endless staircase that was inspired by Piranesi's etching. The reason for this modification was not only a representation of the filmmakers' understandings of the novel but also a solution for dealing with the technical issues (Werder 2012). However, can they ever be more accurate than every reader's imagination?

Accordingly, several significant literary works will be selected as case studies, which are Eco's *The Name of the Rose*, Calvino's *Invisible Cities*, and a piece of traditional Chinese poetry, *Meeting Li Kuei-nien in the Southland*. Each case will focus on the research questions from different angles and contribute particular benefits to the research.

The library in The Name of the Rose

Umberto Eco's *The Name of the Rose* portraits a clear image of the fictional monastery which locates in the mountains in medieval Italy. The main characters - William and Adso - investigate a series of murder cases and Eco designed a library as a labyrinth in which William and Adso got lost when they first entered. Eco has described the experience of their loss in detail including the route of their exploration, the architectural details, the inscriptions, and Adso's mental activities (Eco 2014, p.179-188). This research will capture this section as a piece of the original text, providing the participants (architectural students) with a series of spatial experiences. As mentioned previously, the first stage before digital model making is collecting a range of interpretations from the participants in analogue or digital form. In this case, the research aims to create a framework by which the participants will interpret the text regarding the details of the architectural space. For example, after reading the text, the participant will be asked to present their interpretation on a detailed questionnaire regarding the tangible (dimensions, material, artefacts, and so forth) and intangible elements (atmosphere, sound, light, weather and so on), see figure 2. According to Witmer and Singer's study (1998, p.225), they designed a set of questionnaires to "measure presence in VEs" and to "evaluate relationships among reported presence and other research variables". Al-Attili and Coyne (2004, p.280) also used questionnaires to canvass the relationships between "the scale of the body", "the scale of the environment" and "the scale of the body compared to the scale of the environment". Thus, based on the previous studies using the questionnaire as an analytical tool, the interpretations can be collected and categorised on the same level; furthermore, the questionnaire will cover the following stages to inquire how the participant can get involved in modelling the VE and the assessment of their experience in VR.

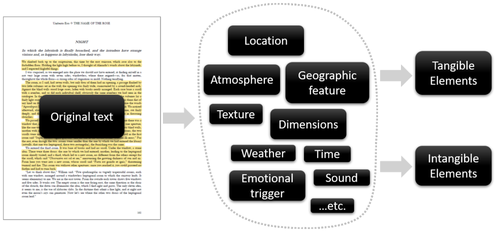

Figure 2
Collecting tangible and intangible interpretations of the participants.

Assuming interpretation has a limitation, Eco had described that the interaction between the text, the author and the reader produces the complex activity of interpretation, which involves “the cultural conventions that that language has produced and the very history of the previous interpretations”. Therefore, if a reader wants to interpret a piece of text, he or she must value the “cultural and linguistic background” (Eco 1990, p.183-184). Consequently, relevant information about the cultural background of the text such as the author’s intention, which could help the interpreters to create the border of their semantic interpretation.

Translation

As the participants are those who have an architectural background, they are eligible for translating their thoughts of the tangible elements into concrete forms such as digital models and sketches. However, this is after defining the specific groups of participants. For example, first- and second-year students are encouraged to interpret by hand drawing, participants who are architects or Masters students will translate their thoughts directly into digital models. The interpretations as digital models are to be inserted into a whole model of the monastery (based on Eco’s drawing) which leaves an empty part for the interpreter’s model to fit in, see figure 3. Thus, the interpreters’ interpretations are limited in the same space with a set of fixed dimensions. The completed digital model will finally be imported to Unity3D to generate a further VE. As for the analogue interpretations (sketches), 3D drawing in Photoshop is a potential medium to translate 2D drawings into a panoramic version, see figure 4. Jurabaev’s work (2017) shows the possibility of this creative tool to apply to my research. In the panoramic mode in Photoshop, the user can rotate to a view to working on; then the 2D drawing can be completed on a new plain layer. Finally, the plain layer will be merged down with the 3D drawing layer and will be projected onto the panorama.

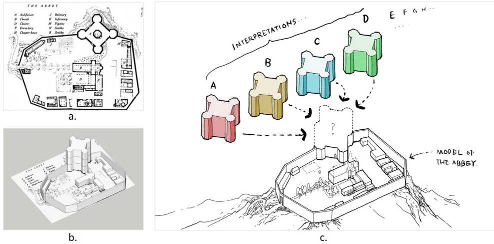

Figure 3
a. The layout of the monastery drawn by Eco, copied from the title page of The Name of the Rose; b. The preliminary digital model of the monastery based on Eco’s drawing, created by the author using SketchUp; c. This sketch shows that participants’ interpretations as digital models can be fitted into the whole model, drawn by the author using Procreate on iPad.

CONCLUSION

Because the research is in the early stage, the previous methodology needs to be tested in the future and thereby be refined or reconsidered, and the research questions could be refined and narrow down. For example, the case study of *The Name of the Rose* will continue transferring the participants’ analogue or digital interpretations into Unity3D, along with the other intangible elements (atmosphere, light, sound and so forth) and the UI system to create the immersive VR application. In which the study will test to what extent can the participants’ interpretations be proved in the following text, which is the key criteria to evaluate the interpretation (Eco 1990, p.181). The novel has described more intelligible speculation of the plan of the library through William and Adso’s conversation (2014, p.225-226). Eco also categorised this labyrinthine library as a ”mannerist labyrinth” in which the readers need an ”Ariadne’s-thread to keep from getting lost” (1984, p.57). By comparing the interpretation from the ”model reader” and the one from the ”empirical reader” (Eco 1990, p.180), this case study will reveal the relationship among the text, the author and the reader, showing what factor influences the readers' interpretations and how can the text be influenced by its interpreters. Regarding the other two cases, *Invisible Cities* implies an open text that refers to numerous uncontrollable factors, influencing the readers' interpretation. It requires a more flexible frame in which the interpreters can work on the similar level; the case of the Chinese poetry aims to investigate if a piece of text was translated into several languages, how do the interpreters respond to this situation?

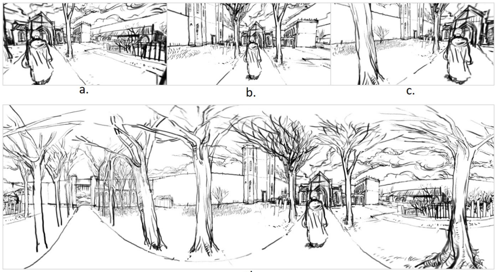

Figure 4
A panorama drawing showing the spatial cognition in the monastery in The Name of the Rose based on the reader's interpretation; a,b,c. Rotation of the viewpoint in 3D drawing mode; d. The projection of the panorama. Drawn by the author using Photoshop.

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The effect of biomechanical symmetry on presence and simulator sickness in a virtual reality application controlled by a VR bike

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This paper investigates whether a projected body and bike following biomechanical symmetry principles can increase presence in a virtual reality (VR) game. The VirZOOM bike was used as a controller and a game was designed for players to have a virtual body sitting on a bike, pedalling in sync with their real body. The game was evaluated with 35 participants, measuring results with the Presence and Kennedy Simulator Sickness Questionnaires. In addition, reaction time was measured for every game. Our analysis concluded that the way biomechanical symmetry was implemented didn't affect simulator sickness, presence, or reaction time.

Keywords: *Biomechanical symmetry, Presence, Motion sickness, VirZOOM bike, Virtual environment, Virtual reality*

INTRODUCTION

One of the fastest growing technology industries is virtual reality (VR) [4]. However, VR technology has a number of significant shortcomings related to the user experience, affecting the quality of interaction with the virtual environment. While interacting with the virtual environment. While interacting with the environment, the user can experience effects such as eye strain, disorientation, headaches, and motion sickness [1]. Furthermore, moving around in virtual environments (VEs) is posing an interaction design challenge, where walking has proven to be especially difficult to emulate (Souman et al. 2011; [3]), as it induces motion sickness in players. The VirZOOM bike is an exercise bike equipped with sensors enabling it to be used as a VR controller, utilizing biking as an alternative form of locomotion in the VE [2]. The above mentioned shortcomings were the motivation for exploring the topics of presence, immersion, and motion sickness, as well as locomotion control with the VirZOOM bike technology and how these are affected by the application of biomechanical symmetry in such a context.

In section Related work we provide an overview of related work, investigating the current terminology and methods used in relevant studies. The proposed implementation is described in section Implementation. Section Results describes the evaluation and results, and section Discussion presents a brief discussion and the main conclusions of this paper.

RELATED WORK

Sensory Conflict Theory

The vestibular system is a sensory complex that provides information regarding one's orientation in space, balance, and is involved in coordinating their movements. It is located in the inner ear and it performs its functions by collecting information about the head's acceleration, position, and orientation.

The conflict between the vestibular and vision system's perception is the most widely accepted theory describing simulator sickness (Jerald 2015). Simulator sickness is caused by visual motion alone, while physically induced motion sickness is caused by physical movement. The former can be alleviated by closing the eyes, this is not the case with physically induced motion sickness. The reason for this is that simulator sickness occurs based on visual stimulation that does not match with what the body feels. (Jerald 2015).

The most commonly used method for measuring simulator sickness is the Kennedy Simulator Sickness Questionnaire (SSQ). SSQ gives researchers 4 scores: the total sickness score, a score of oculomotor, a score for disorientation, and a score for nausea. The method is highly subjective and relies on the ability of the participants to identify symptoms within themselves (Jerald 2015).

The correlation between simulator sickness and the feeling of presence is: when the feeling of presence is lowered, the symptoms of simulator sickness are more severe (Jerald 2015). Furthermore, immersion has a correlation to presence as follows: if the immersion increases, so does the presence. Different studies show that presence can be increased by employing biomechanical symmetry (Jerald 2015). Lastly, attention is also a factor that influences the presence in a virtual environment (Witmer and Singer 1998). Reaction time has been used as a measure of attention and engagement (Breuker et al. 2005). Therefore, it can be argued that an objective way to measure presence could be the time it takes the user to react to a certain task. It can also be hypothesized that there is a correlation between the reaction time of the user and their feeling of presence.

Presence

Witmer and Singer (1998) define presence as a subjective experience where the person is physically situated in the real world but is engaged in another environment. Held and Durlach (1992) define presence in VR as an "experience", where one cannot detach from the real experience appearing simultaneously with the virtual one. They state that while wearing a HMD to engage in VR, the world around the user does not disappear, it can be heard, smelled, and felt. An accepted tool for measuring presence is the Presence Questionnaire (PQ), which allows a subjective evaluation. There are no official methods used to quantify presence. Lastly, the ability to direct attention from the real world to the VR one also plays a role in being present in a VE (Witmer and Singer 1998).

Biomechanical symmetry

Biomechanical symmetry refers to the phenomenon of physical body movements in VE being in harmony with corresponding real-world movements. It is one of the main concepts of interaction fidelity, which can be defined as "the degree to which physical actions used for a virtual task correspond to the physical actions used in the equivalent real-world task" (Jerald 2015). Regarding VR, the term refers to replicating the user's real movements in the virtual world. To give an example, walking on an omnidirectional treadmill is more biomechanically symmetric to how we walk in the real world than e.g. using a joystick to move. Users feeling their virtual body performing a task in the VE as if they were performing the task in the real world can give a high sense of presence. (Jerald 2015)

IMPLEMENTATION

Since there are already some preexisting games [2] for the VirZOOM bike, quick and dirty tests were conducted to analyse them. After the participants played the games, they were asked to complete the

Kennedy Simulator Sickness and the Presence Questionnaires.In the tested games there was no virtual representation of the player, which means that if the user looked at themselves, there was nothing representing their physical presence. To address this gap a virtual body was modelled for our solution.

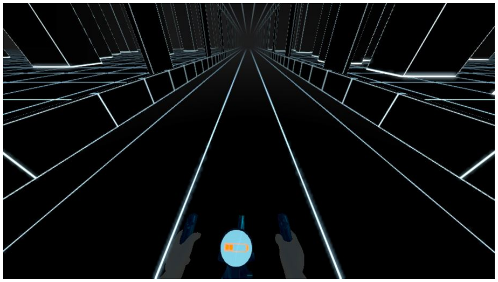

Figure 1
A screenshot from the created game with a body projection.

The solution developed for this project is an endless runner style game, where players bike through a virtual world that is slowly dissolving behind them, and where there are three parallel lanes (see figure 1). Players have a virtual body and can move between the lanes by tilting their head or leaning right or left. Along the lanes, there were positive and negative pick-ups, which would either give the player more time to escape the dissolving world, or deduct it.

EVALUATION AND RESULTS

Design

The study used a repeated-measures design, as the test subjects participated in both conditions of the experiment. The predictor variable was Body Projection, as the users would play the same game with and without the body projection. Three outcome variables were observed: level of presence, reaction time, and simulator sickness score.

Participants

There were 35 people who took part in each condition of the test. From them 27 were male and 7 female. The users were between 20 and 31 years old. The average age of the participants was 23,3 years. The participants were all at least moderately experienced with VR.

Apparatus

To conduct the test, the following tools were used. A VirZOOM bike for in-game locomotion, and an HTC Vive head mounted display. The data for Presence and Simulator Sickness was gathered with the help of the SSQ and a modified PQ which did not include questions pertaining to audio and haptic feedback. Two versions of the prototype were utilised for the evaluation. One version included the biomechanically symmetric body projection, and the other did not. The data for the reaction time of the participants was collected by measuring the time between the point when the user has to change the lane (in-game) and the time it takes to execute that action.

Procedure

The facilitator helped the participants put on the HTC Vive headset, and guided them on how to use the VirZoom Bike. Furthermore, the participants were introduced to the objectives of the game, and then the game was started. As soon as the user began pedalling, a stopwatch was started. Each of the participants were asked to play each version of the game for 120 seconds and after each game, they were asked to fill out the The Kennedy Simulator Sickness Questionnaire (Kennedy et al. 1993), as well as the Presence Questionnaire (Witmer and Singer 1998). Since the game was designed to have three lanes, the user was prevented from moving farther outside to explore the world. In addition, they did not have time to examine it, since they had to move away from the disintegrating world. The users were asked to preform an avoidance action as soon as they observed a negative pickup in their lane. Reaction times, from the time the pick-up was spawned in the game until when the player started to change the lane, were measured and saved throughout each test. Categorical data was collected through the questionnaires and used to estimate the severity of simulator sickness and the level of presence.

Results

The results of the Levene's test showed that the data sets were homogenic. The results from the Shapiro-Wilk test showed that the data from the reaction time measurements, as well as the data from the presence questionnaire, was normally distributed. Based on these findings, a dependent Two Sample t-test was used for the reaction time and presence questionnaire scores. For the simulator sickness questionnaire scores a Wilcoxon rank-sum test was conducted. The results showed that the reaction time of the participants was not significantly different between the two conditions ($p > 0,05$) with less than small effect size of $r = 0.116$. Where the mean of the reaction time with body projection data was $M = 0.5778057$ and the mean for the reaction time without body projection data was $M = 0.5719771$.

Furthermore, the results from the presence questionnaire t-test showed that the level of presence experienced by the participants did not differ significantly between the game with body projection and the one without it. The effect size was calculated to be $r = 0.159$ which showed small effect size. The mean for the Presence results without the body projection was $M = 65.74286$ and the mean of the results with it was $M = 66.97143$.

The results from the Wilcoxon rank-sum test conducted on the Simulator Sickness data again confirmed that there is no significant difference between the means of the two conditions based on a probability value of $p > 0.05$. Moreover, the mean of the data gathered for the test with the body projection was $M = 197.0189$ and for the test without it $M = 221.0596$. The results from the Pearson test for linear correlation showed that there is no positive or negative linear correlation between the measured reaction times and presence scores, as well as reaction times and simulator sickness scores regardless of the body projection.

DISCUSSION

The aim of this project was to investigate if applying biomechanical symmetry to a virtual body in a virtual environment will affect the level of simulator sickness and presence.

The evaluation showed, that the difference between the means of the scores for presence and simulator sickness were not significant. However, there are a number of areas that need to be further developed or investigated in order to more reliably measure the effect of biomechanical symmetry in VR.

One of the elements not implemented perfectly was the biomechanical symmetry itself. While playing the game, it could sometimes occur that the movement of the legs would go slightly out of sync with the real movement. This could be caused by latency from the bike's data transfer of RPM values, or possibly because the program did not change the animation speed fast enough based on the data it received.

Moreover, some of the users did not notice the virtual body during the evaluation. Most of them asked, at the end of the test, what the difference was between the two games they played.

There are a number of things that could address raising awareness of the virtual body. Reflective floors or other mirrored surfaces allowing the users to notice the body could be implemented. In addition, the game only implemented moving legs, the rest of the body was static. By animating the torso and hands to reflect the users' movements, they could take notice of the biomechanical symmetry. Furthermore, the only element drawing attention to their hands and body was the dial placed on the handlebars.

Lastly, the methods used in the quick and dirty tests and the methods used in the evaluation were different. For the evaluation, questions that were deemed irrelevant were removed from the Presence questionnaire, and we had a larger number of participants. By designing the two tests to use the same presence questionnaire and number of participants, the preexisting games could be compared with the designed solution in terms of simulator sickness and presence.

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Establishing daylight studies inside architectural scale models with 360° panoramas viewed in VR

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The benefits of studying daylight behavior with physical scale models is well established. Scale models are widely used as design tools from the early conceptual design phase to the final presentation, in order to inform and communicate spatial experience and atmosphere created by daylight. Photographing the interior of daylight illuminated scale models takes special considerations concerning camera size and the construction of the scale model. The point of view is often through a window or other openings in the model for practical reasons, and an experience of being in the space is difficult to achieve.Capturing 360° panoramas from scale model interiors enables a novel experience of the model space in 1:1 viewed in Virtual Reality. Establishing a correct eye-height is mandatory for the precise perception of scale, whereas model construction materials seems to be of minor significance. In this paper, a study done through an explorative and observative research describes the practical findings of capturing 360° panoramas inside daylight illuminated scale models. The purpose is to create a guide for students to use 360° panoramic photographing and the various display possibilities to enhance the conceptual design phase as well as representing the results.

Keywords: *VR, Scale model, Daylight, 360° panorama*

INTRODUCTION AND BACKGROUND

Architectural scale models for daylight studies

"Models are an excellent way to experiment with materials, their translucency or transparency, and the reflections and refractions they produce. The models that we built are full of different properties of light. This is something you can never achieve in computer renderings" (Steven Holl, 2017). In spite of today's digital simulation possibilities, physical scale models are still an essential design tool to study and communicate the experience and atmospheric effects of daylight in spaces of architecture (Guzowsky 2018). Models suitable for daylight studies should be made in materials, which block the light with no light leaks to disturb the light effects studied, also the size of the model should be suitable for photographing with a camera (Egan et al. 2002). Building the model requires attention to material qualities in connection to light and how these qualities changes the visual perception of the space according to the changes of daylight. Steven Holl states, that physical models offer a good way to increase students' awareness of light and materials and thus the haptic quality of architecture (Schoof 2017).

The concept, and use of architectural models is rooted in a strong tradition for resemblance, translation and determination (Bertram 2012). The daylight illuminated model can take as many forms and purposes as any architectural model, what distinguishes these kind of models is their ability to support the design with daylight. There will be questions of resemblance according to the reflecting and transmitting light qualities of materials, translation of ideas and concepts as well of determination in the form of intentions, strategy and making of the models.

Photographing daylight illuminated scale models

Establishing the daylight condition of the scale model to be studied, the model can either be positioned outside under the real sky or in a room with an artificial sky, which simulate overcast and clear sky conditions (Egan et. al 2002). In natural daylight, the model is illuminated by the present dynamic daylight condition. The artificial sky and sun in combination, creates a specific and stable daylight condition to work with. An important feature of the daylight illuminated scale model is for a photographic devise to get access to the interior of the model in order to document the daylight effects and/or use the captured interior for architectural representation. A hole of approx. 5 cm between the exterior and the interior of the model allow access by a camera with interchangeable lens, see figure1a.

The endoscope, originally a medical instrument, became increasingly widespread in model photography from the mid 1960'ies, as it allowed for realistic spatial simulation (Sachsse 2012). The long thin lens, attached to a camera with an adapter, allows eye-height photo shoots inside even small-scale models, see figure1c.

The smartphone camera has proved to be a quick and handy solution to capture the illuminated interior of a scale model; it has a small lens like the endoscope - but circumference like a compact camera, which does not always allow for access to the interior of the model, see figure1b.

The default display possibilities of the captured views on screens or in print are all in 2D. The photographic technology of the 360° camera captures panoramic views and allows for a 3D experience, see figure 1d. Photo shoots with a 360° camera inside a scale model thus allow for a panoramic view inside the daylight illuminated scale model.

Virtual Reality and Scale

360° panorama renderings or spherical photos either captured by fisheye-lens cameras or stitched together from regular perspective photos can provide great immersion and a 1:1 bodily experience when viewed in a VR headset. The fact that the camera Point Of View (POV) acts as eye height in VR, determines the perceived scale of the scene or environment to be 1:1 no matter the original or real-world scale, if the established eye height in VR matches the user's real-world eye height (Leyrer et al., 2015). Amber Garage [5] uses the perception of scale according to eye-height to alter the viewer size in The City VR Experience, enabling a giant view or mouse view of

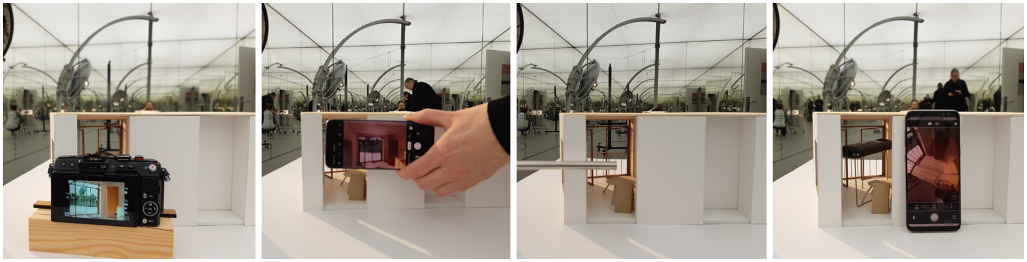

Figure 1
Capturing interior views with compact camera (a), smartphone camera (b), compact camera with endoscope (c) and with Theta V (d).

the 3D city map.

In this research, the viewer size is based on an average human height with a corresponding eye height of 160 cm. The perception of scale in the architectural scale models viewed in VR, on the other hand is changed by establishing a scaled POV in the 360° panorama corresponding to the chosen eye-height. When experienced in VR the 360° photographic panoramas of scale models are perceived as built in scale 1:1.

Virtual Reality and daylight

Spatial phenomena like distribution of light in space is more precisely explained and perceived with the bodily experience in VR than with traditional architectural 2D representations. Good results have been achieved with students using smart phone VR as representational medium for visualising and visually evaluating architectural lighting concepts using rendered 360° panoramas (Kreutzberg, 2018). Studies of the influence of light on the atmosphere of a space (Stokkermans et al., 2017) and perception of daylight in VR, indicate a high level of perceptual accuracy, showing no significant differences between the real and virtual environments on the studied evaluations (Chamilothori et al., 2018). A comparative experiment of subjective perceived visual qualities and ambience of daylight in 360° photographic panoramas viewed in VR, compared to the perceived visual qualities and ambience of the real world site, showed a rather uniform perception of daylight brightness (Kreutzberg et al., 2019). The ability to capture light distribution with photographic precision combined with a 360° panoramic VR display enhances and expands the use of illuminated scale models for daylight studies.

METHODOLOGY

In this research, experimental 360° photographing and video capture inside daylight illuminated architectural models of different scales and construction materials were performed. The aim was to test the usability of a 360° camera (Ricoh Theta V [6]) in relation to daylight studies and to be able to provide a best practice guide for architecture students.

The interior of scale models in 1:10, 1:20, 1:50 and 1:100 were test-photographed in the daylight laboratory of the KADK:LAB. The daylight laboratory provides a mirror box style artificial sky and a movable artificial sun (Christensen, 1976). The daylight conditions of the test-photo shoots were overcast sky and a number of sun path positions, typically explored by the students.

Technical equipment and the investigation of establishing correct eye-height, Point of View, camera settings and post- production are described underneath as well as a test of various display formats. The display modes of the panorama output were tested and evaluated with students.

Technical equipment

The size of the model space in combination with the camera size determine the possibility of capturing a 360° panorama at the correct eye-height. For these experiments a Ricoh Theta V one-click camera was chosen, because of its small dimensions, its high quality photographic output, its ability to be remotely controlled and its consumer friendly prizing.

The Ricoh Theta V camera dimensions are: 45.2 mm (W) × 130.6 mm (H) × 22.9 mm (17.9 mm excluding lens section) (D).

The camera has a fixed f-stop 2.0 and an ISO sensitivity range from 64 to 3200 for still images and shutter speed from 1/25000 to 60 seconds. White balance mode can be set to Auto, various pre-sets or by Colour temperature (2500 to 10000 Kelvin). A Wi-Fi connected smart phone controls all camera settings. The communication distance between the smart phone and camera is 10m. However, this varies depending on the usage environment. Auto focus from 10 cm to ∞.

Referring to previous exposure testing with a Ricoh Theta S camera [1] in a 1:1 daylight studio in varying weather conditions (Kreutzberg et al. 2019), an ISO 64 setting with Auto Shutter was chosen to minimize image grain. White balance was set to AUTO in the experiments, but could be set by Colour temperature to calibrate with on-site measurements.

Several smart phone makes were used as camera control devices as well as displays; Samsung Galaxy S8 [4], Samsung Galaxy A6 [3], and iPhone 6 [2].

Homido V2 [9] was chosen as Head Mounted Display (HMD) because of its high lens quality and wide 103° Field of View, as well as its adjustable Inter Pupillary Distance (IPD) and adjustable lens-screen distance.

Establishing correct eye-height.

In initial testing with a conceptual 1:20 sketch model, the camera was placed on the floor through a hole made in the elevated model to achieve correct eye-height, see figure 2.

Figure 2
Camera placed on floor through hole in elevated model to achieve correct eye height.

Figure 3
Camera stands

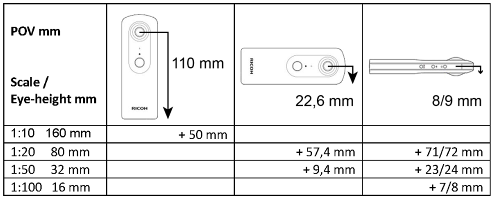

Figure 4
Camera-stand heights in mm for camera in upright, rolled and rolled/pitched positions.

To test a less model destructive setup, the camera was rotated to a horizontal pose (roll) to lower the lens centre and was placed on a simple stand. Some postproduction was anticipated to rotate the resulting 360° spherical panorama back into alignment, but using the native Theta app for viewing automatically realigned the horizon. The Theta V camera has a built in gyroscope with zenith correction and this function automatically adjusts the vertical direction of the image when viewed in a capable app.

Testing the rolled cameras ability to establish correct eye-height in a 1:100 volume model resulted in a perceived eye height in scale 1:1 of approximately 2200 mm, and correcting this into a percieved eye-height of 1600 mm would require some carving in the bottom plate of the model to lower the camera 6 mm. The solution was to also rotate the camera in its length axis (pitch) and block it up 7 mm.

The initial test shootings of the above-mentioned scale models led to the design of a set of support stands for the Theta V 360° camera to achieve a perceived eye height of 1600 mm in VR, see figure 3.

For scale 1:10 models a concave 3D printed support stand for the camera in upright position was designed. For scale 1:20 and 1:50 models minimalistic asymmetric support stands in bend wire for the cameras in rolled/pitched positions were designed as well as for scale 1:20 models for the camera in rolled position (the latter being rather unstable). For scale 1:50 models a row of staples was used as stand for the camera in rolled position. For scale 1:100 models the asymmetric support stand for the camera in rolled/pitched position was cut in cardboard, see figure 4.

Point of View

When establishing the POV with a 360° camera, it is not only a matter of framing the picture as in traditional photography, but also the possibility to establish several desired sight lines within the same panorama. The ability to look around freely in a 360 panoramic space may invite for a POV in the centre of the space. A more informative POV might be along axis's of connecting spaces. For presentation or sharing purposes, placing the POV in a corner of the interior can create a comfortable overview without having to rotate the head and body too much. The size of the model space of course influences the possibilities of an "ideal" POV, since the camera and its elevation stand need to fit into the interior space to accommodate 360° photography.

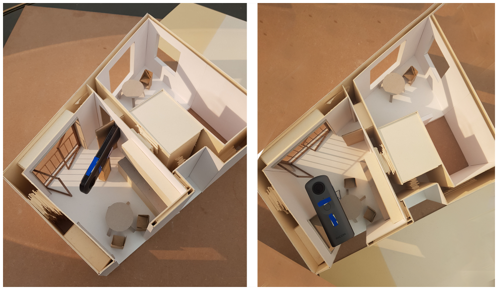

Figure 5
Rolled camera placed in direct sunlight casting shadows (left), rolled and pitched camera placed in shade (right).

When capturing 360° panoramas with direct sun illumination, the camera should preferably be placed in the shade to avoid shadow casting unless the investigation is concerning glare, see figure 5.

Stitching
The Ricoh Theta V camera automatically stitches the 180° images from the two fisheye lenses. The visibility of the camera house itself is erased by blending surrounding pixels. The quality of the automatic stitching is influenced by distance to the lenses and contrast and pattern along the stitching rim. The joints between the images captured by the two lenses will be skewed in images of subjects within 40 cm of the lens, which usually is the case with scale models.

Figure 6
No stitching errors in 1:50 model with camera rolled (left). Visible stitching errors at window sills with camera pitched and rolled (right).

It is advisable to avoid parallel pattern or geometry contrast along the stitching rim. The stitching rim of approximately 18 mm equals 90 cm in 1:50 models, blurring everything within the height of 115 cm to 205 cm (+- 45 cm from the POV) that is not clearly extended perpendicular to the rim on either side, see figure 6.

Diagonal lines in geometry or from shadows along the rim are skewed as well.

Display Modes
The power of 360° panoramas is their ability to display on screens with embedded navigational interaction when viewed in a dedicated app. The native Theta app (IOS & Android) provides instant feedback with a live view from a Wi-Fi-connected smart phone or tablet with gyroscope. It proved very useful when testing POVs to minimise stitching errors. As soon as the panorama is captured multiple views are available. VR view (Single lens), VR view (twin lens) and Standard screen.

VR view (Single lens) displays a portion of the panorama perceived to be in scale 1:1 in the direction the device is pointing. Rotating and reorienting the device, displays other parts of the panorama. VR view (Single lens) display turned out to be very useful for collaboration, enabling more people to observe daylight in scale models at the same time, especially when displayed on a large tablet.

VR view (twin lens) also displays a portion of the panorama in the direction the device is pointing, but on a split screen. Mounting the smart phone on a head mounted display (HMD) enables viewers to experience a 1:1 bodily perception of the captured space and its daylight illumination.

Standard screen display rotates the view with touch gestures. On a computer screen mouse or arrows rotate the panorama view. With the dedicated Ricoh Theta desktop app Auto rotate is also a feature.

Post production
Theta 360° panoramas can be viewed in many apps, but not all of them can read the embedded Exif data with information on Pinch (Tilt), Roll and Rotation of the camera to display a straight horizon.The RICOH THETA basic app [7] can straighten the horizon and at

the same time inject inter changeable meta data XMP (Extensible Metadata Platform) [8] into the panoramas, enabling other apps to display the panoramas correct, see figures 7 (top) and (middle).

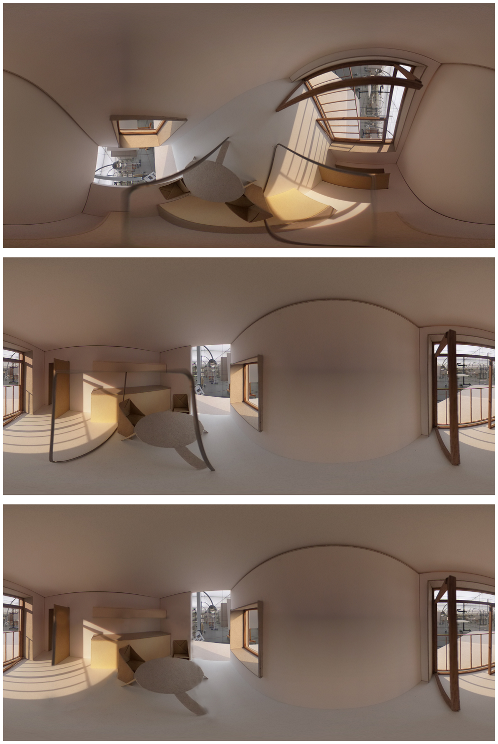

Figure 7
Original 360° panorama output from camera pitched and rolled (top). Write with top/bottom correction, JPEG data with XMP (middle). Elevation stand removed in edit (bottom).

For retouching the camera stand Photoshop's 3D spherical panorama editing features were used. After editing in Photoshop, the panorama was once more run through the RICOH THETA basic app for meta data injection, see figure 7 (bottom).

The models - scales and materials
The models investigated were of different scales and constructed in various materials and with different emphasis on finish. It was observed how the model constructions and different surface materials and finishes were experienced when scaled in VR.

The 1:10 demonstration model (of a daylight studio) was very detailed and with smooth surfaces of similar colours and reflective qualities as in the real 1:1 space it represented. Not surprisingly, it was hard to distinguish between the captured VR images of the 1:10 interior and the reference interior in 1:1.

Chairs of folded paper and a table and kitchen unit in cardboard made up the essential interior in the 1:20 housing model. Window and door framings were made of coloured balsa wood. The paper and cardboard materials were easily recognizable in the 1:1 VR view as well as the balsa wood, although the material structure was scaled. The space itself was rather roughly assembled from unpainted cardboard, revealing gaps at junctions (no light leaks though) exaggerated in VR view. The sense of proper 1:1 scale in VR and believable light distribution was established with well-known objects; windows, doors, chairs, table and kitchen desk in correct proportions and sizes regardless of scaled materials.

Several 1:50 models were investigated, some of them with rooms too small to place the camera properly, others with larger rooms but having issues with a blurred stitching area, see figure 6. The 1:50 models were the most difficult ones to correctly place the 360 camera in.

The 1:100 volume model explored was cut in white polystyrene, and surfaces did not correspond to the Copenhagen inner courtyard it represented. In the 1:1 VR view, the rough surface of the polystyrene appeared large and abstract with prominent shadows in the surface structure; still the impression of the sunlight distribution inside the inner space of the courtyard was perceivable and appeared reliable.

FINDINGS
The photographic testing showed, that it is possible to capture panoramic views inside physical scale models, and that this technique makes a valuable tool to observe and evaluate on experience and atmosphere created by daylight in the interior of the models in addition to the photographic techniques

already known and used. Since the camera tested has a near focus limit of 10 cm and a twin lens capture system, preconditions in the form of establishing the right eye height, POV and stitching must be considered. The camera tested needs certain conditions to perform well; the interior space should be large enough to contain the camera, a device, which position the camera in correct position to achieve the right eye height is needed, and cautiousness to stitching issues must be done. The materials of the scale models do not distort the spatial and bodily experience, when observed in 1:1, still considerations should be taken to the light reflective and transmitting qualities of the materials, like in any daylight illuminated model.

Using the Ricoh Theta V camera to create 360° panoramic views, the daylight distribution and the atmosphere of a space illuminated by daylight can be experienced in 1:1 in very early conceptual models as well as in finalized presentation models. More people thanks to the various display modes can observe iterative changes of the scale model or changes of daylight immediately.

Further studies

The experiments and testing done make it possible to make a best practice guide of how to make the right pre-conditions to capture interiors with a 360° camera inside daylight illuminated scale models. There are plenty possibilities for further studies: Sharing VR views across distances. Co-existence between the physical VR experience and digital simulation of daylight. Transferring the representation of material qualities in physical scale models to visualizations. Glare studies inside daylight illuminated models. 360° video capture of diurnal and yearly sunlight. Refining the design of elevation stands: 1:10 - 3D printed stand should not be concave but slimmed to vertical with embedded weight ballast for stabilization. Stitching error at bottom would be minimized. 1:50 Test I-beam. Painting metal wire stands matte white might work as camouflage.

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A Study of Perceived Spatial Depth in Relation to Brightness Level Evaluated by VR

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The topic of visual illusion has been studied extensively in the field of psychology, documented by a vast amount of literature, though an equivalent amount of interest is absent in the study of the topic from an architectural perspective in modern days. (Suppes 1991) The application of visual illusions in building design remains to be a viva voce traditional wisdom rather than a scientifically backed theory. The contribution of this paper is the formulation of a scientific method to express the hypothetical relationship of subjective spatial perception and its lighting condition, despite the presence of imperfect induction. A simple superimposition method of mapping the resulting color map to existing architectural drawings is also proposed to enable easy understanding the lighting ``performance'' of a space, and can be utilized as a design tool for further computational analytics.

Keywords: *Visual Illusion, Psychology of Perception, Virtual Reality*

1. INTRODUCTION

Visual illusions have long been an integrated part of the architecture and its theoretical formulation can be traced back to as early as the writing of Vitruvius, and application observed in the design of the Parthenon where the inward-leaning Doric columns and drooping pedestal deceive the eyes into believing the structure as a perfect and pure geometry. Detailed drawings in the book describing optical corrections for visual perception had established a mathematical theory of proportion, the guidelines of which have since been applied empirically, by architects and designers to the geometric design of building elements. In the entrance gallery of Palazzo Spada designed by Baroque architect Francesco Borromini, the diminishing columns and rising floor strategically create an optical illusion of a much deeper space; in St. Peter's Square, the flanking colonnades divert subtly to adjust for the perspective distortion. The topic of visual illusion has been studied extensively in the field of psychology, documented by a vast amount of literature, though an equivalent amount of interest is absent in the study of the topic from an architectural perspective in modern days. (Suppes 1991) The application of visual illusions in building design remains to be a viva voce traditional wisdom rather than a scientifically backed theory.

2. BACKGROUND

In contemporary urban interior spaces, especially in Asian cities where the population density is high, the scarcity of floor area has led to an interest in property developers and designers to remediate the undesirable effect of visual confinement posed by cramped physical spaces. Small interior space is often associated with claustrophobia that causes anxiety to the inhabitants. Limited physical intervention can be devised due to restrictions in the building's structural composition. In practice, there are trivial methods in the choice of finishing materials (e.g., mirrors) of the enclosing walls to create an illusion of a more expansive space that has moderate effectiveness. Lighting condition is one of the few elements that the designer has a relatively high degree of control through artificial lighting fixtures. This paper studies the possibility and feasibility of manipulating lighting configurations to visually relieve the strain of small interior spaces for maximized comfortability.

3. OBJECTIVES

There are two folds to the objectives of this paper. The first is to propose a practical method to expand the visually perceived size of a space through manipulation in the ambient lighting level and distribution configuration for use in interior design projects. The method is to be complemented by an attempt to investigate whether there is a correlation between the lighting condition, visual expansiveness, and the position of the participant's view point in a space.

The second objective is to establish a scientific method in the estimation and visualization of the posited visual illusion induced by the lighting configuration through experiments, conducted with participants answering prescribed questions while being immersed in a virtual reality (VR) environment created by a head-mounted display (HMD) device. The visualized result can be seamlessly incorporated into architectural drawings, or superimposed into augmented / mixed reality (AR/MR) environments.

Based on the scientific approaches to describe spatial expansiveness with the techniques of Isovist (Heiler, 1967), and sight-depth (Kitagawa, 1999), this experiment attempts to supplement these tools with a more cognition-oriented approach. In the conventional process of architectural design, the designer assumes the hypothetical formality of the extent of a space, which, however, is rarely validated with a scientific setup. In addition, the illuminance in a certain space changes constantly with the surrounding environmental condition, thus, computer-simulated environments in VR systems are more reliable and consistent for cognition experiments, yielding a more accurate estimation of the value of coefficient. Another issue is the design of a method to quantify the perceived impression of brightness level in a certain space. One of the most objective indicators of brightness is illuminance (lux), recommended by JIS (Japanese Industrial Standard) and the Illuminating Engineering Society of North America (IESNA) for architectural description of a space (2010, JISC), (2007, ASHRAE/IESNA). However, this indicator does not always accurately reflect the realistic perception of brightness (Panasonic, 2010), as the illuminance value is usually only derived from the calculated value of the surface points of a horizontal plane.

4. PRECEDENTS IN SPATIAL EXPANSIVENESS ANALYSIS AND THE USE OF VIRTUAL REALITY

The method of topological view analysis in built environment spaces originates from the UCL Space Syntax Laboratory (Hillier, et.al 1984), leading to the development of a succession of geospatial analysis softwares, including the UCL Depthmap 10 (Pinelo and Turner 2010). The method was used to assess the "visual accessibility" of a space, represented by point isovists, referring to area polygons that is visually accessible from a location along with measurements of which. The juxtaposition of analytical values taken from multiple viewpoints on the same visualization graph, usually in the form of a heat map, offers quantified hints to understanding the visitor's experience of visual expansiveness of the space. (Lee et.al, 2019). The resulting visibility graph can further be used to inform agent-based analyses, predicting the movement patterns of pedestrians and vehicles.

In the recent twenty years, VR technology has seen increasing application in clinical psychology experiments (Wilson, et al 2015) for its advantages in economical affordability and capacity in reproducing almost unlimited ecologically valid stimulus in a tightly controlled virtual environment. Rizzo et al. referred to VR as "the ultimate Skinner box", where the parameters of a visual stimulus can be precisely and rapidly manipulated. Extensive research has been conducted to study the level of presence, or how "real" the participant perceives the virtual environment to be. High-fidelity, immersive VR systems are found to be able to elicit intensive emotional responses from participants (Sutcliffe, et al 2005) that are closely related to that of real-life situations (Kwon, et al 2013).

In study of Hanaoka et al., the spatial expansiveness of a virtual interior environment perceived visually by the participants was studied in a series of cognition experiments using HMD VR/AR systems (Hanaoka, et al 2018). The visual perception of the size of the environment is influenced by the presence of obstacles in the line of sight, and the distance between the observer, obstacle, and the enclosing walls. The study also points out that the depth cues of motion parallax, ambient illumination level and object material could also potentially influence the perceived impression of the space.

5. PROBLEM STATEMENT

- There are existing literatures describing the methodology of quantifying the visual accessibility of a space with topological analyses, though there is a lack of understanding on the cognition aspect of spatial perception.
- There have been experiments studying the overall ambient lighting level of a space, but whether the formation of lighting distribution influences the perception of space remains unclear.

6. HYPOTHESIS

The lighting configuration of a space, that is the floor being lit unevenly in different formation patterns which is often the case in interior design projects, would impact the perceived expansiveness of an enclosed space.

Figure 1
Image Sketch of this experiment

7. RESEARCH QUESTIONS

1. Measurement of the perceived expansiveness of a space is to be represented by the estimated distance between the observer and the opposing enclosure wall in a rectangular space. If the estimation of the value of this distance shows influence from the lighting condition of the space, it may be deduced that the perceived overall size of the space is also affected, producing a visual illusion that the space is perceived to be bigger or smaller than its actual size.

2. The configuration of the light source locations above and the lit area pattern that it creates on the floor, would have implications on the above visual illusion. Should the assumption be valid, the exact correlation between the locations of light source or lit area, the relative position of the observer and the

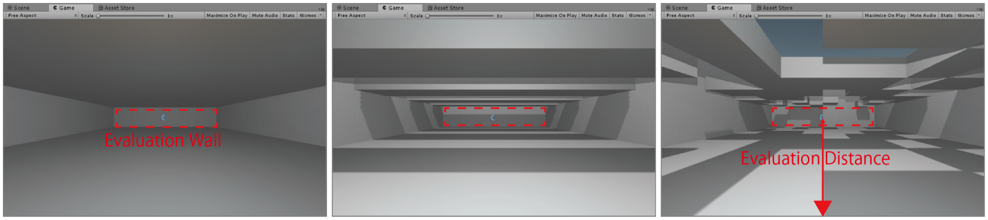

Figure 2
The VR Preview

The floor is exposed by the simulated light from eternal far upwards. The geometry of roof changes randomly by clicking button by examiner, examinee answers the distance named 'Evaluation Distance' between examinee' s view point and 'Evaluation Wall' . These oral answers are recorded by examiner thus described Excel by numbers.

estimated measure should be examined.

8. METHOD AND TOOLS TO EXAMINE

In the setup of the VR-based experiment, the participant observes a vacant room measuring 10 meters in depth and width, with the ceiling rising 3 meters from the floor. (Fig.2)

The ceiling plane of the room is divided by a 10 x 10 grid, into square cells each measuring 1 meter on the sides. Visibility of each cell is switched off randomly, with the chance independent from the resulting overall pattern. Therefore, there is a variance in the ceiling coverage area in the sequence of experiment rounds as the configuration resets every time. From a theoretical statistics point of view, the average percentage of the coverage area should be approaching 50% as the number of experiment rounds increases. The floor plane is lit by the simulated light source from above masked by the ceiling plane while the brightness level stays consistent across the lit cells throughout the experiment rounds.

The participant "stands" at the center of one of the floor perimeters, the height of the viewpoint is fixed at 1600 mm above the floor, while the participant is asked to sit on a chair in reality. The participant can move his or her head around to see space in 360 degrees, but cannot move or walk around. He or she is asked to look around the space before answering the prescribed question. A participant typically spends approximately 10 seconds in observation.

The experiment proceeds with the participant providing numerical estimation of the "Evaluation Distance", referring to the distance between the participant's view point and the rear "Evaluation Wall". The participant's verbal answer is recorded by the examiner, and the configuration of the ceiling plane cells is randomly redistributed at the beginning of each questioning round, for a total of 30 times for one participant. There were 5 participants involved in the experiment.

The sheer amount of environmental and geometrical data posed difficulties in the communication between the HMD softwares for environmental analysis, CAD, and visualization purposes, where the bottleneck is caused by bandwidth limitations of wireless protocol consisting of input and output data. The number of software simultaneous commands in sequence impedes the system flow. Limiting the number of digital working platforms would reduce the performance cost for correspondence between different softwares, concentrating the computation power for software-wise internal processing. In this system setup, only Rhinoceros and its plug-in, Fologram(refer from fologram.com), are used.

9. DATA

The second part of this experiment calculates the correlation coefficient between the brightness level of each divided floor cell and the evaluation distance. All evaluated answers obtained from participants are combined and analyzed as a whole.

The following table summarizes the experiment. The results of 150 rounds of experiment are respectively recorded in 150 rows. The columns corre-

Figure 3
Data Sample in Excel

	b75	b76	b77	b78	b79	b80	b81	b82	b83	b84	b85	b86	b87	b88	b89	b90	b91	b92	b93	b94	b95	b96	b97	b98	b99	Eval
0	0	0	0	1	1	1	0	1	0	1	0	0	0	0	1	0	0	1	1	0	0	0	0	0	0	8
0	0	1	0	0	0	0	1	1	0	1	1	1	1	1	1	0	1	0	1	1	1	0	1	0	0	7.5
1	1	1	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	1	1	1	0	1	1	0	9
0	0	0	1	1	0	1	1	1	1	0	1	1	1	1	1	0	1	0	1	1	1	0	1	1	0	8
1	0	0	1	0	0	1	1	0	1	1	0	1	0	0	1	1	0	1	0	1	0	0	0	1	1	7.5
0	1	0	0	1	0	1	0	0	0	0	1	0	1	1	0	0	1	0	0	1	1	1	1	0	0	7.5
1	0	1	0	1	1	1	1	0	1	0	0	0	0	1	0	1	1	0	1	0	1	0	0	1	1	6.8

sponds to the 100 floor cells, each storing a binary value that represents the visibility of the overhead ceiling cell (0 for invisible and 1 for visible). An extra final column documents the answer given by the participant for the evaluation distance in meters. Correlation coefficient of the values of each cell against the perceived distance is calculated, then mapped and visualized in the following figure.

The correlation factor demonstrates the magnitude of visual illusion created. A positive correlation factor means the space is perceived to be bigger (or extending further) than the actual dimension with a higher brightness level in the corresponding floor cell, and vice versa, a negative correlation factor means the space appears to be smaller when the floor cell receives less illumination.

Blue areas denote cells with a positive factor. They tend to concentrate in central part of the room, with a few patches scattered towards the left side at the back (opposing perimeter edge), and on the right side towards the participant's edge.

Red areas shows an opposite correlation. They are primarily distributed towards the closer left and further right side of the participant (purple dotted area), with a tendency to elude areas adjacent to the walls, absent completely from the participant's edge and the opposing perimeter edge (blue dotted area).

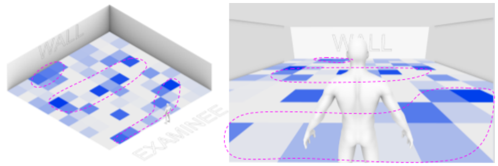

Figure 4
Positive Coefficient Area in the Experiment

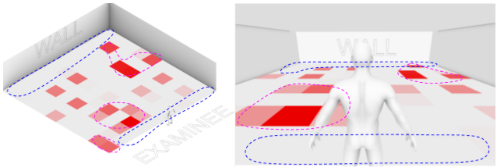

Figure 5
Negative Coefficient Area in the Experiment

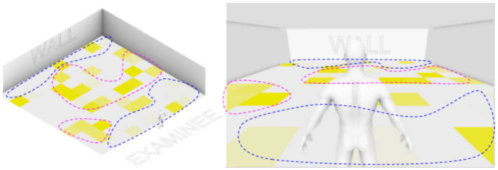

Figure 6
No Coefficient Area in Experiment

The yellow area shows cells that no correlation has been observed, meaning the cell's brightness level does not affect the perception of spatial size. The brighter yellow cells are found in the center of the room (purple dotted area), avoiding also from the participant's edge and the opposing perimeter edge (blue dot areas).

10. CONCLUSION

Based on the results from the experiment, the following points are concluded:

1. There are more areas with a positive correlation coefficient than negative ones, meaning in general, a space would appear to be bigger when the floor is lit brighter.

2. The immediate area in front of participant, or observer, and the opposing edge of the space does not affect the result.

3. Asymmetrical result: The left area to the viewpoint of the participant has a greater impact on the effect of visual illusion in both positive and negative coefficients.

Aspects to be improved in future work:

4. All participants evaluated the depth of space to be less than 10 meters in almost all scenarios. Underestimating depth in VR environments is a known common problem and its relation with the physical reality needs to be explored and calibrated for the result to be applied in real world.

5. The perception of "Evaluation Distance" depends solely on the participant's subjective judgement, either a larger population of participants should be needed to reach a generalizable induction, or the individual results should first be adjusted with weights.

6. The analytical result is dealt with in a non-hierarchical way, individual difference has not been taken into account statistically.

7. There is a theoretical discrepancy between rendered stimuli displayed on the HMD screen and the actual illuminated space which is consisted of more complicated materials with the additional lighting phenomenons of diffusion, speculation, reflection and refraction.

The problem stated in point 3 might have been caused by a randomly generated biased emergence of patterns. To eliminate such unintentional bias, the ceiling should be randomized with a controlling criteria.

11. PROSPECTS & CONTRIBUTION

The contribution of this paper is the formulation of a scientific method to express the hypothetical relationship of subjective spatial perception and its lighting condition, despite the presence of imperfect induction. A simple superimposition method of mapping the resulting color map to existing architectural drawings is also proposed to enable easy understanding the lighting "performance" of a space, and can be utilized as a design tool for further computational analytics.

The findings of this paper contributes to providing quantitative insights to the design of lighting condition for interior spaces. By applying these results to a design layout for lighting instruments, one can maximize the volume of the space perceived by its users.

In order to achieve more precise simulation, properties of the lighting source has to be improved and calibrated to better represent the real lighting equipment. For example, the shadow would be less intense and blurred in real condition in the real world. Also, adding people and furniture to the space will offer a more realistic perception and precise experimental setup for the research. This can lead to a research of finding a combination of best lighting configuration and partition layout within the limited space.

Another improvement can be to have multiple intensity of the light. In this case, it can search for the best combination of lighting layout and intensity within the given amount of energy consumption. It would clarify whether having several strong lighting instruments is better than uniformly placed soft and less intense lighting effects or not.

As a future development, the evaluation method can be improved by using a 3D gaze point estimation. This research relied on the evaluation by verbally asking the examinee how much distance they think is between them and the wall. This part can be quantified better if eye tracking system is employed to estimate the gaze point of the examinee in 3D dimensional space.

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The use of VR technologies to enhance methods for lighting design practice

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Contemporary architecture, engineering and construction practices primarily use virtual reality (VR) either as a means for communication between the different disciplines, co-design, or as a presentation medium, that gives to clients a human-scale experience of a project. This situation also applies to the field of lighting design, creating a situation where the only area of the lighting design process not influenced by VR, is the area of the design itself. Ideally, lighting is designed within the context of a physical space, allowing a more accurate rendition and perception of how light influences its surroundings and the ability to convey the effects of spatial lighting similar to how humans would perceive them. However, such an approach to visually representing light in the earlier stages of the design is not currently possible. This paper presents a description of the development and testing of an immersive VR tool for the development of lighting design at a 1:1 scale in a real-time virtual environment (VE). While the project's results are limited due to its proof-of-concept development stage, the responses from the participants indicate that the tool is advantageous in the design development as well as the design communication phases. The VR tool described allowed for more design iterations and experiments, better perception of spatial lighting effects, better representation of lighting at a 1:1 scale from a human perceptual perspective, and allows the lighting designer an opportunity to become an actor in the space rather than an observer behind a screen.

Keywords: *Virtual reality, Lighting Design, Design Process, Design Tool*

INTRODUCTION

Contemporary architecture, engineering and construction practices primarily use virtual reality (VR) either as a means for communication between the different disciplines, co-design, or as a presentation medium, that gives to clients a human-scale experience of a project. This situation also applies to the field of lighting design, creating a situation where the only area of the lighting design process not influenced by VR, is the area of the design itself. Ideally, lighting is designed within the context of a physical space, allowing a more accurate rendition and perception of how light influences its surroundings and the ability to convey the effects of spatial lighting similar to how humans would perceive them. However, such an approach to visually representing light in the earlier stages of the design is not currently possible. The authors have therefore attempted to develop such a tool.

To establish a set of criteria for a virtual reality system aiming at improving the process of designing with light for architectural spaces, the paper looks at how the current lighting design process is composed and how the process is applied in a practical framework. A theory of lighting design process proposed by Hansen and Mullins (2014) builds on a multidisciplinary foundation that combines the research fields of architecture, anthropology, lighting engineering and media technology. Other studies, which have previously explored the use of VR systems as a tool for the design phase in architecture, although the diversity of the systems investigated is scarce, have largely found that the feedback provided by a VR system in regards to the spatial qualities of a design is unmatched by other design tools. A study by Angulo and de Velasco (2014) tested the use of VR to support students in the design of architectural spaces. They found that VR allowed the students to obtain aesthetic impressions of special design, and to test different design combinations of objects, while evaluating and validating the spatial geometrical relationships their designs conveyed. The feedback from such evaluation was shown to inform and promote changes in the design phase. Related findings regarding continuous feedback have also been previously shown (Achten & Turksma 1999; Smeltzer et al., 1994). Continuous feedback facilitates the evaluation of designs in 3D much faster than conventional methods (Achten & Turksma 1999) and with the added ability of real-time interaction to perform modifications to the design, enables the evaluation of design variations in a short time frame (Smeltzer et al., 1994), thereby increasing the productivity of the design process and allowing for more design iterations. Similarly, the ability to keep the height of the user in the VE at an eye height consistent with the user in the real world, together with using reference objects in the scene, enables the avoidance of the ambiguous or incorrect perception of scale in a VE (Kreutzberg, 2014; Tamke, 2005). These and other studies thus stress the importance of keeping the character in the VE at human height, as well as how intuitive navigation increases the level of immersion for the user (Kreutzberg, 2014; Angulo, A & de Velasco, 2014; Tamke, 2005). Studies also suggest that a VR design tool needs naturalistic elements in the interface (Dokonal et al., 2016), which can be achieved by using analogies from the real world combined with different functionalities and options within VR (Smeltzer et al., 1994). Studies have also stressed the importance and need for materials as well as shadows (Angulo, A & de Velasco, 2014; Coroado et al., 2015) since it helps with understanding complicated spaces and aids in the definition of volumes in the VE (Kreutzberg, 2014).

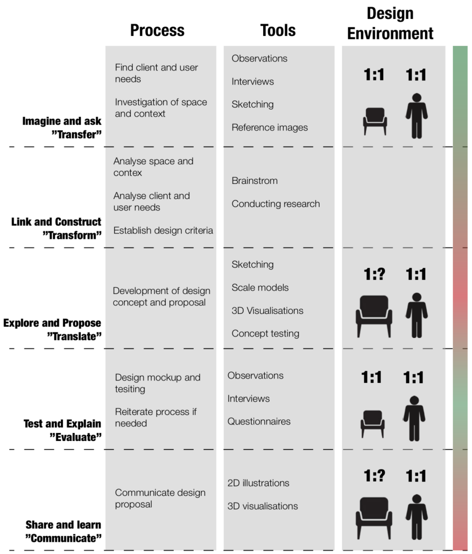

Figure 1
Process model of the example project.

The author has set out to develop a VR tool for application in lighting design with a departure point in these previous studies, with a particular emphasis on its use in design development (see Figure 1). The hypothesis is that the VR tool will improve upon the conventional process of today's lighting design practice. The author has furthermore defined three design criteria for its successful development: 1) Functionality, i.e. what the user is able to do with the tool; 2) Usability and interaction, i.e. how the user is able to interact with the tool; and lastly 3) Visual feedback, i.e. what the user is presented with visually.

METHOD

The development of the VR tool entailed the study of various game engines before deciding on Unity. Unity comes integrated with middleware for computing global illuminations (GI) called Enlighten. Enlighten directs the computing of indirect illumination and can achieve speeds that are considered close to real-time. For Enlighten to do so, it solves an approximation to the rendering equation for GI that assumes finite elements and a diffuse transport of light, thereby eliminating many variables in the GI equation to achieve real-time computational speed. This method for computing lighting (also known as Radiosity), though it does not offer physically accurate indirect illumination, gives an approximation at a fraction of the cost compared to other methods, thus making a VR lighting design tool feasible. At the time of development of this VR tool (early April 2018) there existed no method for calculating lighting in Unreal Engine 4, which was equivalent to Enlighten in Unity, whilst offering the same level of support and documentation from the developer, thus making Unity the more appropriate choice.

The VR lighting design tool in its current state of development offers the user the functionalities for selecting and instantiating different light fixtures from the projects asset folder, through the use of the "project" workspace. The lighting fixtures in the VE can then be moved into the required positions using the transformation gizmo. The translation of lighting fixtures is done through the use of EditorVR, an experimental asset package launched by Unity with an open API, as a tool for designers and creators to build VE's while being inside the VE itself. A custom tool enables access to the selected lights' properties, which makes it possible to change certain properties depending on the manufacturers' specification for that particular lighting fixture such as the lights color temperature, angular spread and lumen output. The VR lighting design tool takes full advantage of the benefits of VR by keeping the user immersed throughout the design process and ensures that the feedback in regards to both interaction and the visuals are real time.

After development, the initial hypothesis was tested through the collection and statistical analysis of data. Primarily, the collection of qualitative data was chosen to investigate if the VR tool improves upon the process of designing with light, how it does so, and what value the VR tool brings to the design process. The tests also collected quantitative usability data, which will be used to inform the future development of the VR lighting design tool. Since the tool is designed to be used in the lighting design process, the test participants were all lighting designers and the tool was tested in a design context similar to the one it has been designed to improve. The tests were thus structured as a scenario based usability test, where the participants were given an identical set of tasks to complete, using the VR tool's functionalities. Subsequently, interviews were conducted to collect responses on whether the VR tool brought any added value and benefit to the process of lighting design. The responses from the interview were analyzed using interpretive content analysis to find general themes in the participants' responses.

The test was conducted over a period of 5 days, from the 23rd to 27th of April near the Aalborg University campus in Copenhagen. For the hardware, An Oculus Rift with motion controllers and tracking sensors was used for the test, allowing the participants a tracking area of roughly 2 x 2m for navigating in the VE. The Oculus Rift guardian system was used to map out the tracking area and set up boundaries for the participant in the VE, in order to indicate if the participant was moving close to or outside the tracking area. The test was conducted on 18 participants (10 female, 8 male) between the age of 22 to 32 with 50% being between 24 and 25. All test participants were students from the Masters' program of lighting design from Aalborg University Copenhagen. The pre-test interview revealed that all participants had prior experiences with VR and were familiar with using 3D software in their lighting design process.

An interpretive content analysis was conducted on the responses from the post-test interview following the approach of emerging coding as described by Lazar, Feng, & Hocheiser (2017). The approach of emerging coding is based on the notion of grounded theory and is appropriate when theory and research literature on a subject is limited, which is true for the use of VR in the lighting design field.

RESULTS

The results from the interpretive content analysis indicate that the VR tool was believed applicable in both the design development process and the design communication process. For the purpose of design communication, participants wanted to use the VR tool to present walk-throughs of a space and to allow clients to take control of the VR tool with the ability to manipulate the light and the VE. Using VR to make walk-throughs of a space is no new feat within the AEC industry, but allowing for more interactivity in such process is an interesting topic that could be investigating further. How much control should be allowed to the client is unclear, but some participants believed that the client should only have the possibility to change properties in the VE that would be available after the implementation of the lighting design in the real world.

P11 (Q9) - "But for the client to use, it should be more simple, they should only be allowed to walk around, and not to change fixture properties, except in the real world if the fixtures come with some kind of user input".

Participants also mention that the VR tool could be used to mediate a discussion between the client and the designer (P18). Some participants believed that by allowing the client to use the tool, that it would be easier for them to experience different things (P9) and help them create a connection to the space (P18). Whether there would be more evidence to back up these claims is uncertain but it would be interesting to investigate further, to explore new ways for presenting lighting designs to clients and other parties.

Regarding the VR tools' applicability for design development, the responses showed a wide range of applications with the most frequent response being for the purposes of design experimentation. That this particular area (of design exploration) was the most frequent answer comes as no surprise, since the VR tool was presented to the participants as a tool for use following the initial concept development phase (see Figure 1), where in the authors' view it is most likely that some experimentation for the development of a concept will occur. Nevertheless, the responses are still considered reliable since a closer look suggests that a level of reflection took place before the participants answered the questions. From an analysis of the responses, it can be seen that some participants did not merely respond with a simple application for the VR tool but rather elaborated on their response, like participant 12:

P12 (Q6) - "It gave a nice overview of what the fixture would look like and gave a quick idea of how the lighting would look in the space".

Some participants also reflected on their use of the VR tool, comparing it to their previous experiences with lighting design development, like participants 2, 12 and 14.

P2 (Q8) - "it can sometimes be difficult to get a dimensional understanding of the room and what different fixtures would do to it, that is a thing that can be difficult to evaluate on a screen the effects of a light in the space, that was better here".

P12 (Q5) - "It is hard to sketch light, and here is it a better tool for sketching lighting".

P14 (Q8) - "sometimes when you go from sketching to Dialux it can be difficult to know what you get, this can be a good approximation".

When asked about what values, if any, the participant could see the tool bringing to their lighting design process, it seemed as though the benefits they had experienced would accommodate the problematic areas discovered in this project's analysis. The responses derived from the post-test interviews outline the values that VR in general would bring the lighting design process. These benefits include that VR can give the user a representation of light and space in 1:1 scale and from a human perspective, whilst giving a better understanding and impression of what differences lighting design can effect in spatial volumes. The VR tool was also believed to facilitate a better understanding, as well as save time, when communicating designs and to speed up the process of design development. By expediting the design development process more time could be used for testing different design possibilities, and thus more design iterations could be made, asserting more confidence in the design proposal.

The values highlighted above indicate that a VR tool could be able to overcome the problems regarding human spatial perception in the design development process imposed by the use of conventional design tools, thus adding value and improving the contemporary lighting design process. Though it is unclear how reliable the results are, due to the limitations imposed by how they were gathered, on who they were gathered and how they were analyzed, the results can at this stage can be considered to give a preliminary indication of the inherent values of a VR tool for the lighting design process, confirming previous studies relating to VR in architectural design.

With any new tool, it may be expected that some uncertainties and reservations about the tool will arise. In the case of this VR tool the reservations have especially been concerned with the amount of creativity the VR tool affords the user and what sort of context the VR tool can be used for.

The uncertainty of whether the VR tool would limit the users creativity has to be considered a major issue, since the VR tool is meant to be used for the design development, which is inherently a creative process. The concern about creativity is not a prominently featured area in the content analysis and the responses are either rather vague, P6 (Q12) - *"There could be some more playfulness with the creative aspects the user would be limited"*, or concern the lack of functionalities, like the responses from participant 11,12 and 13.

P11 (Q10) - "No, the program at its current stage would limit the user, so all the things above would need to be changed then it would be a tool that would be useful".

P12 (Q8) - "because you have total freedom when sketching. Do to the limited functionality it limited the capabilities for creativity".

P13 (Q8) - "It does, but the features are not complete and it does not have everything so it is limited creatively and not every fixture on the marked is available".

The functionalities that give ground to the concern for limiting design creativity are for participant 13 the variety of available fixtures that can be manipulated in the VE. Participant 11, when saying "all the things above", refers to difficulties with the controls. However, the variety and range of fixtures will expand with the further development of the VR tool whereas responses from other participant indicate that difficulties with the controls will diminish with continued use of the VR tool. As for the response from participant 12, it seams as though they are making a comparison of the creative aspects between sketching and the VR tool which indicates that the person might have misunderstood the intent of the VR tool. The VR tool is not meant to replace any conventional tool, and thus not designed to match any inherent functionalities from tools like sketching, but rather serve as a complimentary tool to the design development process. Since this response is the only one of its kind regarding this prospect of creativity, it has not been considered as representing a general view among the participant subjects.

Some concerns were expressed that questioned whether the VR tool would applicable in design contexts other than the relatively simple spatial environment tested in this project. While the initial goal for this VR tool was to improve the contemporary lighting design process, the tool ideally should be applicable in any lighting design context. Further testing in other virtual environments would however have to be conducted to establish this with any certainty.

The responses from the participants indicate that the VR tool in its current stage would not be applicable to develop designs for larger spaces. This is due to the uncomfortable ways of navigating the VE (P11) and because it is believed the VR tool would lose its immersive feeling if the space was much larger (P9).

P9 (Q10) - "If the project was a simple room and there was a bigger selection of fixtures then yes, if the room was much bigger the tool would use its immersive feeling".

P11 (Q6) - "When the room is so small you do not really need to walk around, but if the room was bigger navigation could become a problem".

The capabilities of VR is not believed to be a limiting factor when it comes to generalizing the applicability of this VR tool. The dimensions and scales of objects follow a 1:1 relationship with the real world and give a sense of dimensionality to a space unmatched by any other conventional design tool. As expressed by participant 8 - *"you can get something that is closer to reality compared to what other tools can give you at the moment"*. The VR tool builds on the same principles and one can thus assume that if the issues with the navigation were resolved, that the applicability of the VR tool could be extended to other project contexts.

CONCLUSION

While the project's results are limited due to its proof-of-concept development stage, the responses from the participants indicate that the tool is advantageous in the design development as well as the design communication phases. Results indicate that the VR tool can speed up the process of design experimentation allowing for more design iterations and experiments; that they could perceive spatial lighting effects better than with conventional design tools; and that the tool allowed a better representation of the space and lighting at a 1:1 scale from a human perceptual perspective giving the lighting designer an opportunity to become an actor in the space rather than an observer behind a screen.

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Integrating Digital Reality into architectural education

Virtual Urban Environment Design and Real-Time Simulated Behaviors

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This paper proposes an educational approach for learning architecture based on prototype digital reality experiences tailored to students` needs. We use a combination of tools and methods from different disciplines, such architecturology and game design. The hypothesis is tested on architecture students from the course 'Architectural Design 9: Urban Design` at the National Technical University of Athens, fall semester, 2018-2019.We propose using the application 'Behavior Interactive Interface` (BII) for Unity 3D with preset behaviors of virtual actors, in order to evaluate the effectiveness of the students' urban design proposals. This tool can be directly utilized for the self-improvement of the architectural designing skills of the students. The integration of such a method facilitates cognitive interactions through real-time immersive visualization during the process of learning. We expect to provide students the necessary new assets for their future professional life in a compact theoretical and practical educational package.

Keywords: *behavior interface, interactive, education, scale, integrated method, design*

INTRODUCTION

Immersive and virtual reality environments present nowadays a growing interest for researchers, designers, psychologists, programmers, neuroscientists, artists and architects as a result of the established visual production and communication of different aspects of modern culture. This essay targets architecture's students and their perception of the concept of scale and its transformations in virtual immersive and multiuser environments. To be able to provide methodologies to students, we apply to the epistemological field of phenomenology in architecture, perception and game design. The merge of these disciplines can provide dynamic 3D representations of architectural models in a real-time multiuser interface.

The context of this paper constitutes the basis of an ongoing PhD research carried out in collaboration between the School of Architecture of Paris La Villette (ENSAPLV) and the Architecture Department of the National Technical University of Athens (NTUA).

In the context for this doctoral research we present a pilot-framework of educational workflow in architecture. As a starting point, we launch a questionnaire and has been answered by 97 students and young professionals of architecture, with medium age 26 years old.

79.2% of participants replied affirmatively to the question: *Sometimes during the design, I encountered difficulties in conceiving the space on different architectural scales (1:2000, 1:500, etc.) and make the transition between them*. This result indicates that more than half of the architecture's students are in need of new methodological approaches concerning teaching architectural work and representation.

There is still a huge demand by students in architecture to integrate crossdisciplinary studies concerning virtual and mixed reality methods into their university studies. We aim to develop educational methods of approaching architectural interactive design that include the creation of an ephemeral interactive immersive experience in real-time, combined with notions of dimensions and perception.

The followings, game design, phenomenology of perception and architecture, present the different points that underlie the research.

Scientific Anchoring

A thorough research and collaboration with other disciplines as game design, neuroscience and art is necessary for the architects in education, in order to highlight the implication of interaction with different scales during the architectural concept phase.

Our didactic proposal expects to elicit the emerging cultural cognitions, biases and *perspective illusions* and lets the student express herself or himself. In parallel, our didactic proposal provides students the methodology through a tailor-made tool to assist and evaluate architectural conception.

"In a sense, perspective transforms psychophysiological space into mathematical space" (Panofsky,1997). It rebuilds missing parts "between front and back, right and left, between bodies and intervening space ("empty" space), so that the sum of all the parts of space and all its contents are absorbed into a single *quantum continuum*" (Panofsky,1997).

Toward Interaction

The urban virtual environment escapes its static nature by dematerialization, as well as its locational coordinates and geographical constraints in terms of representational reconstitution. In the same time, the First-Person Perspective view lets the user immerse into a virtual ephemeral identity. Several philosophers consider the space more as a "spontaneous event rather than a static and neutral scenery" (Champion, 2019). The conception of space consists a dynamic process of cognitive activity for designers with studies in architecture that can be observed and evaluated in virtual reality environments.

We are going to evaluate our experiment by a "mise en scene" of importing simulated behaviors in the virtual environment.

Phenomenological object of Architecture

The object of architecture as a geometric space (physical or digital) is different than the field of tools that architects use traditionally to teach and learn architecture (drawings and physical models). Philip Boudon (Boudon, 1991) and his team differentiated in the past the object of speech and the field of speech (Lecourtois, 2011). In our case the object of that speech is defined as the virtual static 3D object environment able to receive the virtual presence of the user. This object, seen as result of conception, is considered different from the physical real-object in terms of scale, perception and understanding.

Understanding the designing transition from one scale to another is made with difficulty by students and professionals in architecture, especially in terms of understanding the sizes of territories and parts of the city.

The theoretical model proposed as *Applied Architecturology* provides a solid ground that allows observation and evaluation of the object of architecture independently of the different styles of architecture (Lecourtois, 2011).

In *Questions of perception, Phenomenology of Architecture*, architect Steven Holl describes the task of architecture as the concrete example that enables a *continuum of culture*. The purpose of architecture is to shelter us, to become our home that provides us an identity and this identity is "embodied in architecture as an existential metaphor, as body and being" (Holl,2006). Therefore, interactions of users and their architectural surroundings is a core aspect of our experiment.

In the context of our experiment, the scale of global coexists in permanence with the scale of local, in different levels of perception. Although cognitively this is possible, the representation of a map in 1:1 scale is considered impossible. Applying the concept of scale is needed for the cognitive process of a "reduction of" or "augment to" the perception of space. The phenomenological approach to modern digital tools by architects, arises the question of concepts of place and emplacement in relation to the phenomenon of globalisation (Champion,2019).

Phenomenological object of Perception

In order to understand the perception of student's cognition, we created a targeted questionnaire. In the questionnaire, we showed to the 97 participants the multistable image as presented in Figure 1, asking them to define what they see among several options. Although the objective interpretation of this image is that of a 2D sketch, *73,2%* of the participants claimed they see a cube (see Figure 2, Circular diagram). Multistable perception theory of neuroscience is questioning perception according to body-mind relation, cognitive biases, optical illusions as perceptual phenomena in which there are many unpredictable subjective changes, confirming the phrase that "true reality exists independently of perception" (Pillai, 2013).

In an analogy of the city scale, urban territories as parts of the city are constantly exposed, represented and transformed by international digital media, cinema, video games; thus, these urban territories are often interpreted subjectively by means of communication and interaction concerning distance and presence.

Modern day social networks accompanied with daily use of the mobile phone and perpetual connection on the Internet, create the sense of direct access to information. For example, the asset of easy accessibility and instant gratification is an asset that increases city's performance, as transforms the perception of the scales of a city. The cognitive interaction between the user and the application, similar to the "interaction between observer and environment", leads to cognitive maps (Lynch,1990).

The new perception of digital cartography gives the notion of *distance* a *virtual materiality*. The geometrical space, augmented by the virtual material, enables virtual identities, behaviors or flows.

Henceforth, the geometrical space of architecture *[...] "as a cognitive activity of thought of future space"* (Lecourtois, 2011) can put in evidence notions of *distance* and *presence* concerning the conception of architecture. Here, the concept of *scale* takes a temporal notion and needs dimensions of presence to exist. Time's and distance's perception changes into the application of virtual environment.

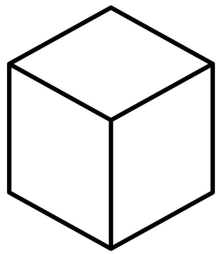


Figure 1
Multistable image.

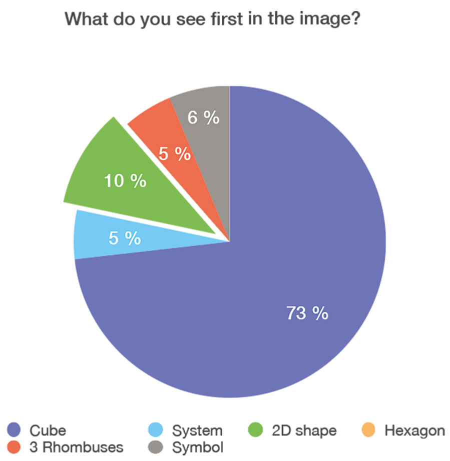


Figure 2
Circular diagram. Significant Statistical Result , test for one proportion, hypothesis value 0,05. Only 10 % of the participants answered that they see a 2d shape.

Phenomenological object of Gamespace

Game design and the industry of video games (Sim City, GTA, Minecraft, Cities Skylines) augment the sense of presence in virtual environments. Games propose realities and world building by giving dimensions to them. The concept of space in video games is marked by ambiguity (Garandel, 2012). In one hand, it can be considered as space "lived", as space that is perceived by the senses (Garandel, 2012). While, on the other hand, gamespace can be described as a "rational" space, where the ensemble of elements that exist inside, develop at least one relation among them (Garandel, 2012). It is the observer that perceives partially the space by the senses in a subjective way (lived), while it is not the space that is perceived as an ensemble (rational space) in an objective way. Pascal Garandel in his essay, *A phenomenological approach in the space of video games*, proposes the *geometrical space* as one possible space that combines and articulates these notions, sensorial and conceptual.

Similarly, architectural space is "[...]considered as space of thought rather than the space itself" (Lecourtois, 2011); computer games can be considered places of interaction rather than places themselves. We identify that there is a common ground, this of geometrical space and its interactions, between architecture and game design.

The large-scale methodological approach of traditional teaching in architecture has few integrated methods that include interaction and design through multiple senses. Does a "gamification" of architectural conception reveal content about cognitive operations? How do young architects conceive and build reality?

Several tools based on game design can assist the architectural education, providing a know-how to the students that permits them to observe and evaluate their models. The field of game design enables interactions into the 3d virtual environment as geometrical space. Therefore, game design as discipline of design, allows the emergence of new aspects of educational approaches for architects, since "[...] in experimental forms of urban planning it is hard to oversee all the actual situations that may occur in advance" (Tan, 2017).

Furthermore, the profession of the architect has undergone a fundamental mutation in the last twenty years which has been based much on the widely used media in the world of work as a computer game. CAD (Computer Aided Design) offers important advantages to architects in terms of speed of design production, schematics, synthesis images and even videos. Despite the increase in architectural designs and drawings, architect Rem Koolhaas, when interviewed, commented on a difficulty in architects communicating their ideas and implied the weakness of architects to interpret each cultural phenomenon that is based on its own system of values. That means that the perception of concepts as scale, dimension, cannot always be explained to students simply by exhaustive production of drawings. As a learning tool, immersive visualisation of conception, can help the student to measure 'quality' understanding of those concepts by in a relation to dimensions.

Design patterns in architectural conception provide no verbal indications in the buildings, no sound or wind. In the context of this article, game design allows design patterns to become a primary aspect of achieving an effective architectural urban solution.

The understanding of the notion of the pattern design helps students to familiarize with the notion of scale, mapping examples of actors' behavior and their dynamic interfaces. In pattern design, we can discover the hierarchy of an architectural urban project. It reveals the complexity of prototyping and the key for this form of analysis is to set two criterions (Rodwin,1981):

1. Identify form qualities significant to the scale of the territory of implementation. These qualities can be controlled by scale.
2. The interactions of behavior must concern the physical form of the environment or the distribution of activities or functions as two separate things.

Therefore, we visualise the urban characteristics of the selected area for implementation and set functions to objects as behaviors with control conditions of *distance*, *collision* and *time*.

By influencing the object behavior by size, hierarchy, function, speed, the patterns of influence become strategic linkages for the interactions within and between objects that interact. The aim of the pattern design is to generate events manifested by forms of interaction.

In a game environment, the urban environment must be created in a way that the user (player/student of architecture) is working *with* it and it does not become an obstacle for further exploration of the virtual environment. This allows the user to instantly recognize the *navigational pattern* (Larsen, 2006) and explore the environment fluidly.

Similarly to, how the designers of games try to prototype a space or scales of the space and the strive to prototype it in an interactive form (Tottem, 2014), to integrate this experiment with students of the Departement of Architecture of NTUA.

Hypothesis

By applying means of immersion to the concept of scale, we use visual interactive representations to evaluate the efficiency of urban design proposals and to verify the implementation of complexes' buildings into the urban tissue.

Transforming the virtual environment into a rapidly visitable and habitable place, is a way to augment learning capacity and self-evaluation for students of the activity of conception.

The hypothesis is tested via a methodology of integration based on principles from game design field and architectural education.

METHODOLOGY

The traditional educational method of architectural work's conception involves the creation of small, 2-4, student groups working in collaboration. In the form of an atelier, students exercise architectural design, while teachers, in an open space, discuss the student's urban design proposals, which in our case are to implement complexes of housing buildings into the Athens city's fabric.

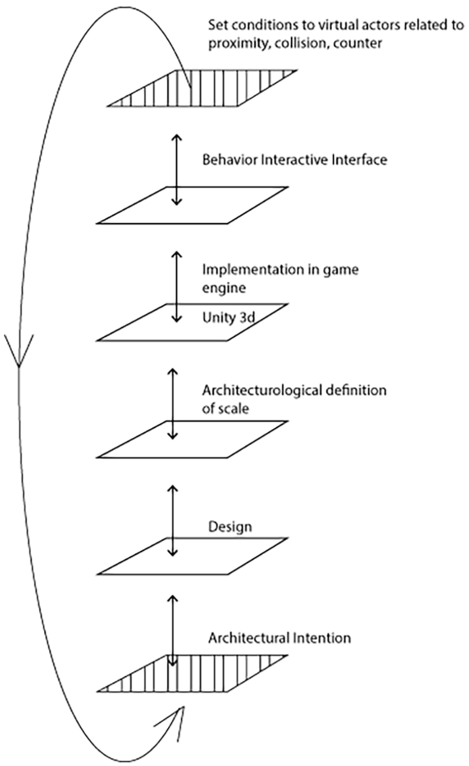
This educational method is an open process, since students of each group can even participate during the correction of other groups. Dialogue and collaboration are the key foundation of the teaching method, as it includes presence and interactivity of both teachers and students.

Our experiment was conducted for this research during the teaching work for the course *Architectural Design 9: Urban Design* under the subject *"Social Housing"* at NTUA, with the help of the students during the fall semester.

The methodology to test this hypothesis can be represented as a layering logic for learning process (see Figure 3).

Specifically, the hypothesis is tested, through the prototyping of an experimental application.

We launch an application to visualize in immersive mode the dimensions of the site of implementation, to give measures to conditions and make observations, in a dynamic virtual environment. Finally, the experiment includes the use of a 3D dynamic system interface for behaviors to help understand the concept of scale.



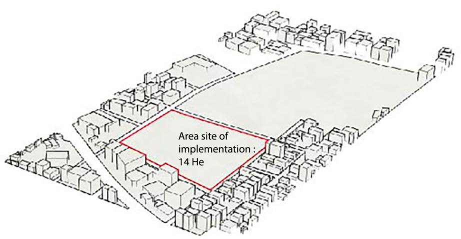


Figure 3
Educational Integration. Layering logic for learning process.

Figure 4
Case study. Site of implementation, Athens, Greece.

Case study in architecture

The urban design proposals are spawned by the exercise of the semester that requires the creation of 180-200 residencies, for 600-700 habitants by designing and integrating new neighborhoods within the urban environment. In an area of 14,000 square meters, in Philadelphia, Attica (see Figure 4), the student groups analyze the urban territory and propose an intervention strategy based on land use (commerce, houses, industry, etc.), heights of surrounding buildings, roads' wideness and the natural and artificial landmarks.

The study starts with applying scales of 1:2000 and 1:1000, with either drawings or physical models. Afterwards, the scales in which the exercise is analyzed concerns the investigation at the urban environment (in 1:2000 and 1:1000), the volumetric integration of the building in the urban fabric in 1:500 (see Figure 5), the landscape design in 1:200 and the scale of the residencies in 1:100 scale. Overall the exercise runs through design reading and understanding, from 4 to 5 scales or more (spectrum of scales from 1:2000 - 1:100).

The theme given by the professors, simulated in the virtual environment can be easily explorable, a 1.4-hectare land (or 14.000 m2), surface big enough to be considered as a surface of "playing the city" and create interactions.

The decision making of design is collaborative work where the goal is to reconstruct the tissue of the city by the implementation of houses, respecting several cultural and functional rules. It is a cognitive activity of high-level complexity.The three factors of collaboration, participation and immersion during the conception add to this complexity.

Architecturological Scale	Pertinence	Dimension	Reference
Geometric scale	Persistent of the cubic geometric layout	Maintain a cubic form measure, Resistance at deformation	Cube, Rigidity

Table 1
Applied Architecturology fot the students's proposal.

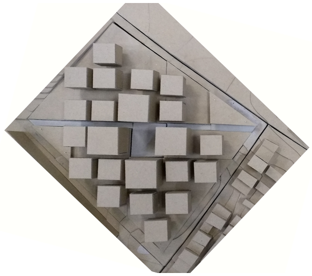


Figure 5
Case of study, Student’s proposal physical model in scale 1:500.

Framework description

The framework of the experiment presents an educational digital example demo named ”Visit the unbuild”. It is based on the 3d environment students’ proposal and suggests the implementation to it of a *meaningful interaction*. The scientific team developed the open source plug-in Behavior Interactive Interface (BII) for virtual actors inside the framework of the European Project Virtual Artistic Laboratory: @postasis, with Paris 8 University, 2018-2020. For our demo we apply the beta version of the BII to generate interactions.

Figure 6
Behavior Interactive Interface (BII).

Characteristics of the Interface

The user of BII can change in real-time the different views of representation, Top, Axonometric, First Person Controller and Observer, while on play.

Next, the user can set *movement* (random, forward, on map) to the actors (3d objects). Finally, to generate behaviors, we set *functions to actors* (spawn, destroy, follow, increase, etc.) by controlling conditions related to *proximity*, *collision* and *counter time* of the actor (see Figure 6). By setting behaviors to actors, the user can easily *populate* any virtual environment and create interactions among actors.

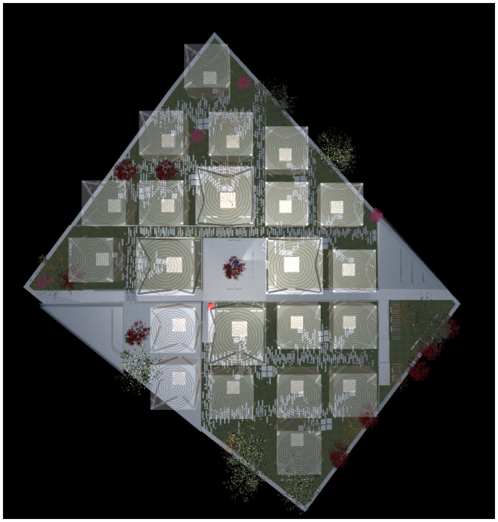


Figure 7
Merged Scales detailing representation. Buildings and ground detailing.

Define scale for experiment

Favorable scale of urban buildings’ implementation for the demo is 1:500 scale, concerning the level of abstraction. For the level of abstraction about the ground floor (landscape), we choose 1:200 scale as it appears in Figure 7.

At the 1:500 scale stage, students evaluate their measures and integrate 180-200 apartments and public uses in the site. Guided by architectural elements of conception as the movement of pedestrian-car, private-public uses and intermediate spaces, the students implement their buildings according to the study plot.

Emphasis is placed on the entrances and exits of buildings, the difference between the axis and the grid, the scale of the road, the relationship between the roads' width and the buildings, the natural lighting of the apartments, the orientation, the possibility of volatility of the construction and also, the materials that the students choose to propose for use.

We determine the 3d model of the virtual environment as a merge of two scales, in terms of detailing. The reveal of buildings' detailing is in 1:500 and the detailing of the ground is in 1:200 scale. Finally, this is the virtual environment that we set to apply later the *Behavior Interactive Interface* (BII).

Preparation of implementation interface

For this process of demo's development, we use the software Unity 3D as game engine, where we import the package BII. This process contains:

- The implementation of low polygon environment in Unity 3D
- Setting Metrics
- The definition of the navigation surface
- Setting behavior

The experiment test aims cognitive operations for understanding dimensions and their correspondence to real dimensions.

Define Navigation Mesh

This part of integrated methodology refers to the definition of the terrain of movement and interaction, the *Navigation Mesh*, as a rigid surface. In our case, this mesh represents the 14he real site of implementation in Attica.

Our surface must be one single mesh, as one 3d object.

The Navigation Mesh represents the *terrain of play* and it is a part of the 3d virtual environment. It is where the virtual actors can interact and the place of behaviors' simulation (see Figure 8).

Set Metrics

In order to create a perception of time and distance into the virtual environment, we set a point of reference with homocentric circles of 10m radius difference each (see Figure 8), so as to obtain perception of distance in the virtual environment, in a visual way.

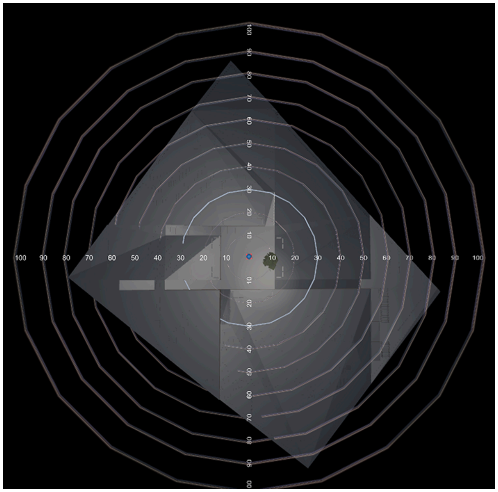


Figure 8
Define Navigation Mesh as one object and Set Metrics as a tool of reference.

Set actor's movement

The student as a user defines a constant movement to actors (directional, random, on path, target object, collide, etc.) as common condition. For this experiment we use the *random direction* for actors.

Set Conditions to virtual actors

The Navigation Mesh is the terrain to create specific functions for the virtual actors or virtual habitants. There are several functions for actors that we can experiment: look actor, look away actor, spawn actor, increase scale, decrease scale, increase speed, decrease speed, destroy actor, copy direction and copy opposite direction. These functions are controlled based on proximity, collision, and counter time of the actor.

For our experiment we use only the spawn actor function. The spawn actor function multiplies the actor based on time and distance. This function permits to generate actors, then, populate and fill the Navigation Mesh, as shown in Figures 9 and 10.

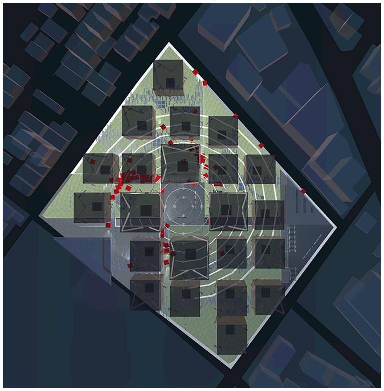


Figure 9
Spawn Function with Conditions related to time and distance.

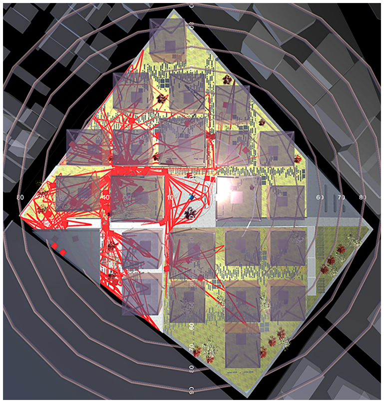


Figure 10
Observe actors' movement in the virtual environment.

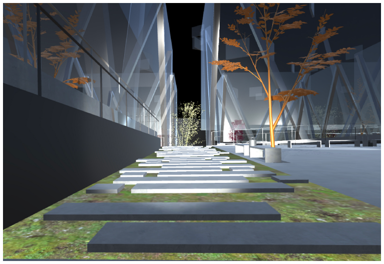


Figure 11
First Person Perspective view

Results

The participants when interviewed mentioned that BII interface is not as intuitive as expected, but it reminds the logic of other 3D software for architects as Rhino et Grasshopper. Though, the experience permitted them a detached opinion about their conception in real-time. They realized that dimensions represented by 3D software in general (including BII) are slightly distorted, especially in terms of perspective. The impression from First Person Perspective was that dimensions were "smaller" from what they had conceived (see Figure 11). Afterwards, during the Spawn Actor example exercise, they reconsidered some of the dimensions applied to their model such as the paths' width and entrance's height.

Discussion

This demo application is approached as an interactive architecturologic model, that means that it is not [...] "a model in design neither a model for designing" (Lecourtois, 2011). It is suggested as a knowledge model on activity of design and a tool of self-evaluation in virtual environment.

It creates a reality of place to instant visualisation with the notion of "inhabiting the unbuilt". Moreover, by "inhabiting the unbuild" and by simulating vivid representations of reality, apprehension of the latter is enhanced on a cognitive level.

Furthermore, the first person view (see Figure) from the inhabitants perspective, allows students to extend their own point of view, allowing them to transcend their own cognitive or preconceived notions of their creation. In addition, design patterns allow the students to extend their understanding to different scales of their urban designs.

Interaction with dynamic objects that simulates actors' behavior in the virtual environment, permits researchers and students to observe actual situations that may occur at the urban planning, for example in cases of emergency and to evaluate urban environment's proposals. This experiment provides an additional perspective and method of feedback to the student's urban design proposals, supplementing traditional education.

CONCLUSION

In this phase of the experiment the conclusions are theoretical. The application of digital tools does allow presence into the environment, and helps cognitive operations improving understanding of the concept of scale in the urban environment.

The association of architecture with game design principles facilitates the comprehension of notions related to scale and is beneficial for architects' skills based on initial feedback. To play with models and different scales, "[...] by applying sciences of artificial is a way of questioning architecture" (Lecourtois, 2011).

Playing, as an architectural conception, is an individual conceived cognitive activity (Lecourtois, 2011); and game design notions can offer this conception, the new extended means to "qualify" reality. (Lecourtois, 2011).

The application of *Fundamentals of Architecturology* (Lecourtois, 2011) in video games and precisely the concept of scale, by defining criterions based on interaction and immersion in virtual environments do emerge as a new architectural methodology. By defining a scale or a combination of scales, our proposal integrates the possibility of designing (conceiving) the architectural environment as an interactive one. The environment is able to receive visualized interactions or behaviors that also reveal information about architectural dimensioning.

Next steps

We aim to further progress our experiment and to evaluate the effectiveness of digital tools in the students' education, by measuring the adaptations of their design made as result of interacting with our tool.

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Figure 12

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The Effect of Immersive Virtual Reality on Perception of Topological Relations in Architectural Design Education

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The study aims to examine the perception of topological relations of spaces through comparing immersive virtual reality environment (IVR) and 3D modeling environment. In addition, the effect of color in the perception of topological relations are also investigated. A couple of experiment setups were created in order to compare IVR and 3D modeling environments with eleven participants that are graduate architecture students. After the experiments were completed, a survey was conducted. The responses of the survey were evaluated together with the experiment outcomes. In light of the results, it is observed that perception of space and its topological relations have no major differences in the IVR and the 3D modeling environments. It is said that the IVR environment helps users to enhance their productivity and to gain new perspectives by creating a sense of presence during the design process in the digital environment. It can be suggested that VR technology has great potential in educational environments, especially architecture design studios to contribute to the design process and design education.

Keywords: *Virtual Reality, Topological Relations, Architectural Design Education, Google Blocks*

INTRODUCTION

Information and communication technologies are developing and renewing day by day. With these developments, technology has found itself an important place in the field of education. Traditional tools such as pencil, paper and technological tools like 3D modeling software are used in order to express design ideas. The common feature of these tools is that they represent 3D models on a 2D plane. In addition, new mediums such as virtual reality (VR) are begun to be used in the design process and design education. Virtual reality can be described as "a computer-generated environment that offers a viewer a convincing illusion and a sensation of being inside an artificial world that exists only in the computer" (Castronovo, 2013, p.23). It is possible to create an immersive experience with virtual reality technology. Accordingly, immersive virtual reality can be defined as an interaction with virtual utopias or environments through the sense of presence unlike analog images or simulations (Grau, 2003).

The study aims to examine the perception of topological relations of spaces through comparing immersive virtual reality environment (IVR) and 3D modeling environment. In addition, the effect of color in the perception of topological relations was also investigated. A couple of experiment setups were created in order to compare IVR and 3D modeling environments with eleven participants. After the experiments were completed, a survey was conducted. The results of the survey were evaluated together with the experiment outcomes.

HTC Vive and Oculus Rift Headsets were used to create IVR environment during the design experiments. Two headsets are consist of two controllers, one headset and two base stations. Also, the design of these two controllers is different. Hence, two mediums were evaluated with the survey according to their ease of use and to investigate their effect on the behavior of the participants during VR experience.

RELATED WORKS

In architecture, it is difficult to test the designs to be produced in the real scale. Design ideas can be represented by sketches, scale models or 3D models. Although these expression methods are an effective way of evaluating, they do not allow individuals to interact directly with the design. In addition, VR technology offers an effective, interactive and realistic experience. Although VR technology is initially used only as a presentation tool, it can be used in the initial phase of design. In this way, it is possible to evaluate design ideas in a more interactive way from the beginning of the design process. In this respect, technology and architectural design can collaborate to enhance the architectural design process (Achten et al., 1999).

There are studies suggesting the use of IVR environment in the early phase of architectural design education, as a trigger for the development of students' spatial skills and perceptions. In a study by Schnabel and Kvan (2001), how designers have shared their design ideas with the other designers is examined by comparing virtual media and traditional paper items. It is said that it is important for students to use virtual environments that will contribute to 3D thinking in the initial phase of design.

The study conducted by Pandey et al. (2015) proposes a learning platform, which aims to increase the spatial ability of the students in architectural design education. It is said that the use of IVR environment as a tool in education will improve the students' ability to perceive space and accordingly, their learning motivations and creativity will increase.

Research by Schnabel and Kvan (2003) compares the perception of topological relations of the students through 2D, 3D environments and IVR environments. In this study, a cube consisting of different, colored parts is designed. Students are asked to examine the cube in three different environments. After the investigation, the students are asked to recreate the cube they studied. As a result, it is observed that the students who worked in a 2D environment created the cube successfully. However, even after recreating the cube, it is seen that the students did not fully understand the relations of the parts of the cube. Even though the students who worked in the VR and IVR environments incorrectly positioned the cube parts while recreating the composition, it is observed that they understood the relations between the parts better and more comprehensively. It is stated that the IVR environment provides instant information to the user that it is not possible with a computer or in 2D environments.

Another research by Schnabel (2003) says that architectural spaces can be understood better in the IVR environment than the 2D environments or the layout view. Also, it is said that the perception of spatial relations is relatively higher in the IVR environment than the 3D modeling environment.

A study conducted by Abdelhameed (2013) suggests that structure and architectural space can be designed together effectively with the use of IVR. Accordingly, an experiment is conducted with architecture students who made the transition between modeling and VR software while designing a building. It is said that the use of VR technology in education increases the creativity of architecture students, helps them to understand and comprehend better the topological relations between spaces, and the 3D forms. Also, Paes et al. (2017) state that the perception of space in the immersive environment is stronger than the traditional 3D environment.

According to Angulo (2015), the IVR environment provides an alternative way to perceive spaces. The students stated that after the experiments, they understand better the topological relations of architectural spaces in the IVR environment compared to traditional design environment. The study predicts that the use of IVR in education may alter the teaching method of design studios.

George et al. (2017) suggest that using IVR in the design studio encourages students to develop different thinking methods and to design in a more flexible way. In addition, it is suggested that IVR environments will play an important role in the design process in the future.

Chang (2017) argues that size, depth and the scale of architectural spaces are comprehended better in the IVR environment compared to the computer-aided design environment. It is mentioned that it is easier to perceive topological relations in the IVR environment.

DESIGN EXPERIMENTS

In this study, two different topics are discussed. Firstly, the effect of color in the perception of topological relation is questioned with an experiment. This experiment conducted with eight participants. Secondly, with another experiment, IVR and 3D modeling environments are compared in terms of establishment of topological relations and the creation of design alternatives. Moreover, a survey was conducted following Experiment 2 to understand the effects of the tools and methods that participants used on their production process during the experiment. This experiment was conducted with eleven participants.

Participants for both experiments were selected from volunteer graduate architecture students enrolled in Architectural Design Computing program to ensure there are not extreme differences in their level of knowledge and skill. All the participants are already experienced with 3D modeling software. However, the majority of the participants were unfamiliar with virtual reality. Thus, a design exercise was conducted with the participants in order to reduce and ideally eliminate their unfamiliarity with the virtual environment before the experiments (Figure 1).

Figure 1
Some of the participants while they are using headsets.

Two different headsets are used in the experiments: HTC Vive and Oculus Rift. Headsets are used to create an experience in the immersive environment. HTC Vive and Oculus Rift consist of two controllers, one headset and two base stations. These two headsets are similar in terms of their way of use but slightly different in terms of technology. HTC Vive base stations are hanged diagonally to track the user's head and hand movements using Bluetooth technology. Oculus Rift sensors located two sides of the PC to track user's head and hand movements using infrared technology. HTC Vive presents 360° tracking of users in the play area. However, Oculus Rift presents 180° tracking of users in the play area with two sensors. Tracking angle of Oculus Rift can be enhanced to 360° with an additional third sensor.

Google Blocks is an application that allows 3D modeling in the VR environment. It can be said that characteristics and modeling logic of Google Blocks are similar to common 3D modeling software such as 3d Studio Max or Blender. Specific geometric forms can be selected and 3D shapes can be manipulated by various operations like extrude, divide and so on. Low poly models and drawings can be made by selecting primitive geometric shapes and colors. The software allows users to design and examine the 3D model in different scales and move around the 3D modeling space like sculpting. Blocks enables exporting the models in various formats, allowing further work outside of the VR environment. Because of these features, Google Blocks is chosen to be used in the design exercises and experiments.

Before the exercise, general training on how to find their direction, move and use the headset and controllers in the IVR environment were provided to the participants. After the training, Google Blocks application was introduced to the participants. An exercise about the interface of the Google Blocks software was performed to increase students' familiarity with the IVR environment and to enable them to use the application rapidly and with ease.

The participants were asked to create an abstract form by using the operations in the software for the design exercise to gain expertise on the interface of the Google Blocks (Figure 2). Each participant has used the headsets for 20 to 25 minutes. During the exercise, participants frequently asked questions about how to use the interface or controls. These questions were answered during the exercise.

Figure 2
Models created by the participants during exercise using Google Blocks.

It is observed that most of the participants are got used to the software after 5 to 10 minutes. However, some participants faced some problems getting used to the interface. In the exercise, two headsets were used: Oculus Rift and HTC Vive. Although the software work in the same way in the IVR environment, the trigger, and buttons of the controllers are different. The difference between the headsets was explained to the participants.

Experiment 1: The color factor on the perception of topological relations

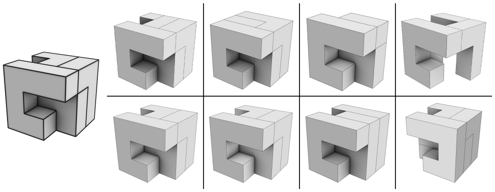
In the first experiment, the effect of color on the perception of topological relations is investigated. The experiment was conducted with eight participants.

Method. For the experiment, two similar 3D models were created, one is colored and the other one is monochrome. Each model comprises of five different geometric forms with different topological relations consist of cube-shaped pieces. For colored model, five different colors are assigned to the five different geometric forms. For the monochrome model edges of five different geometric forms are represented by thick dark colored lines. The participants were asked to examine each model individually in the IVR environment for 5 minutes. Then, they were asked to remember the topological relations of the geometric forms. Then, they were asked to reproduce the model by using cube-shaped pieces in the 3D modeling environment in 10 minutes.

3D models created by participants were evaluated according to two criteria. First criteria concerns about if the topological relations were constructed correctly or incorrectly. The other criteria aim to examine if participants reproduce the geometric forms correctly or incorrectly. Improper placement and misplacement of the geometric forms were defined as the incorrect construction of topological relations. Incorrect or incomplete modeling of one or more of the geometric forms by using cube-shaped pieces was defined as incorrect reproduction.

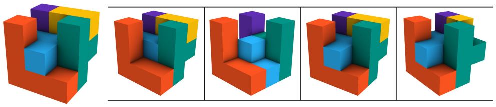
Results. In the monochrome model, it is found that all participants were misplaced at least one of the five different geometric forms while recreating topological relations. Also, it was seen that some of the geometric forms were incomplete (Figure 3).

Figure 3
Monochrome model. Left: Given cube model. Right: Recreations of the cube by the participants.



In the colored model, it is observed that four participants correctly reproduced the colored geometric forms and the topological relations, and four participants made some mistakes. Two of the four participants constructed the topological relations correctly; however, they reproduced the geometric forms with minor mistakes. Minor mistake represents reproducing geometric form one-cube piece missing. The other two participants created the topological relations incorrectly (Figure 4).

Figure 4
Colored model. Left: Given cube model. Right: Recreations of the cube by the participants.



In this respect, it is seen that participants distinguished the colored model better as a whole and perceived the topological relations better than the monochrome model. It can be said that color has an important role in the perception of topological relations and in the differentiation of part-whole relations.

Experiment 2: Creating design alternatives

In the second experiment, IVR and 3D modeling environments are compared through constructing topological relations and creating design alternatives. It is investigated in which environment the participants were more productive in terms of quantity and variety of the creations, and in which environment the participants perceived topological relations better during the creation process. Additionally, the effect of experiencing different scales together during their design tasks has been investigated.

Method. Participants were asked to work in Google Blocks to design using HTC Vive and Oculus Rift headsets for IVR environment. For the 3D modeling environment, participants were told to work with the modeling software that they are the most comfortable and efficient with, such as Rhinoceros, 3d Studio Max, and Blender.

For this experiment, the participants were asked to create functional compositions using basic and colored cube-units for an exhibition space in line with the given requirement list. As a requirement list, an exhibition hall of ten cube-units, a semi-open exhibition area with four cube-units, an office with two cube-units, a foyer with two cube-units, a storage room with one cube-unit and a WC with one cube-unit were given.

Functions were represented with different colors in order to distinguish them. The exhibition hall was expected to be the violet, semi-open exhibition was lilac, the foyer was yellow, the office was green, the storage room was orange and the WC was blue (Table 1). A set of rules about the relations between the functions were given. The foyer must be connected to the exhibition hall, office and WC and, the exhibition area must be connected to the storage room.

It was stated that the exhibition area could be designed as multi-story. In order to create a space two or more story high, the participants were told to use transparent cubes to represent that height and, the transparent cubes would not be counted as a cube-unit. In order to create a second floor or more, participants were asked to put the cube-units on top of each other.

Table 1
Requirement list for the exhibition area.

Function	Cube-unit	Color
Exhibition Hall	10	Violet
Semi-open Exhibition Hall	4	Lilac
Foyer	2	Yellow
Office	2	Green
Storage Room	1	Orange
WC	1	Blue

The experiment was carried out separately in the IVR and 3D modeling environments in 15 to 20 minutes. During the given time span, participants were asked to produce as many alternatives as possible. At the end of the experiment, the design alternatives created by the participants in two environments were examined by comparing them among each other. It is seen that result vary in quantity and variety of alternatives.

A survey was prepared that contains ten questions with three sections following the experiment. Questions are determined by examining the survey questions from Schnabel and Kvan (2003), Abdelhameed (2013), Angulo (2015), Heyderian (2015), Pandey (2015), Janßen (2016) and Vaziri (2017). The survey sections are consists of perception, presence and, differences of HTC Vive and Oculus Rift Virtual Headsets. Results were also compared by answers obtained from the survey.

Results. Created design alternatives differ from each other in the IVR environment. It is observed that some participants were produced more than one alternative, while some participants were produced only one alternative. It is seen that compositions are mostly created as a single or double story. Four participants have added a third elevation, in contrast to the other students. It is observed that the elements such as courtyard, canopy and terrace are used as design enrichment features. Totally, seven participants used courtyards, nine participants used canopies, and four participants used terraces. In total, twenty-five design alternatives are produced in the IVR environment (Figure 5).

In addition, it is observed that during the experiment in the IVR environment, participants created their design alternatives faster and asked less question about controllers compared to the modeling exercise. Hence, it can be said that design exercise has a positive effect. However, it is observed that it is not sufficient enough and some participants could not have full control over the interface. It can be deduced that a longer training process is a necessity.

The alternatives created in the 3D modeling environment were examined among each other as well. It is seen that models are mostly created as two-story, similar to IVR environment. Two participants have added a third floor. In addition, similar to the IVR environment, elements such as courtyard, canopy and terrace were detected in the design alternatives. Five participants used courtyards, four participants used canopies, and six participants used terraces. In total, forty design alternatives were created in the 3D modeling environment (Figure 6).

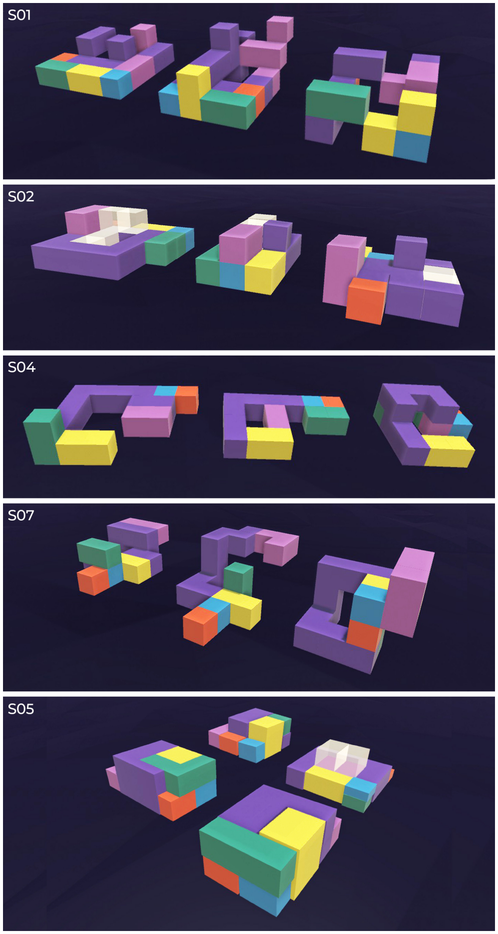


Figure 5
Some of the design alternatives created by participants using Google Blocks in IVR environment.

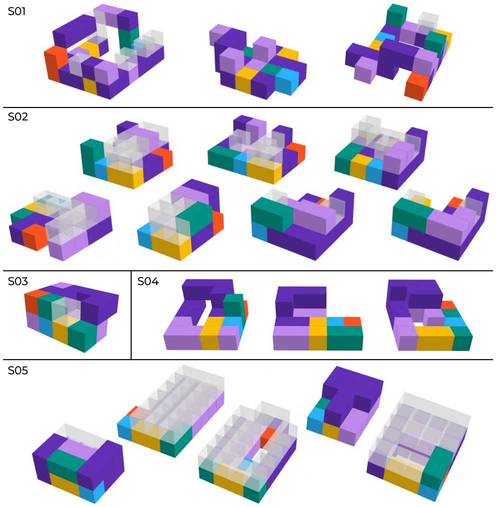


Figure 6
Some of the design alternatives created by participants in 3D modeling environment.

Experiment outcomes were evaluated together for each participant. The alternative compositions created in IVR and 3D modeling environments differ from each other in a few ways. The quantity of the alternatives produced in the 3D modeling environment is higher than the ones in the IVR environment. However, it is seen that the alternative compositions created in the 3D modeling environment contain similar topological relations. On the other hand, it is seen that the number of variety of compositions created in the IVR environment is higher than the ones in the 3D modeling environment. Thus, it can be deduced that the alternative compositions produced in the IVR environment had a higher variety in terms of topological relations.

It is possible to explain the similarities between alternative compositions with different reasons. Firstly, it is possible to copy and paste the geometries much faster and in a more practical way in the 3D modeling environment. In the IVR environment, copy-paste process cannot be performed as practically as in the 3D modeling software. In the 3D modeling software, the selection is usually made by box selection with a mouse. However, box selection is not an option in Google Blocks. This means that each model part must be selected individually for copying. Therefore, it can be said that the IVR environment is not practical enough for using this operation.

Besides, copying can have both positive and negative aspects. The quick and practical process of copying and pasting can be considered positive for creating rapid and large number of alternative compositions. Creating a different alternative by making small changes in the copied model had increased the quantity of design alternatives in the 3D environment. However, it can be said that the design alternatives and the topological relations between the functions resemble each other as a result of copy-paste operation in the 3D modeling environment. In this respect, the variety of created topological relations were less than the IVR environment. On the other hand, in the IVR environment, since the whole model cannot be practically copied, it is seen that participants are created the design alternatives by rethinking the design compositions and the topological relations (Figure 7).

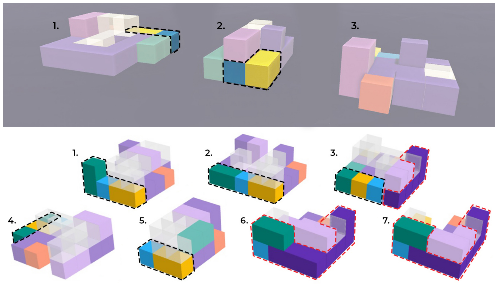


Figure 7
Resemlences of the design alternatives created by one of the participants (Top: IVR environment, Bottom: 3D modeling environment).

Secondly, the sense of presence in the IVR environment may be the reason for the different results obtained from the experiments. Users are surrounded by a digital modeling space while they are in the IVR environment. This allows users to create anything in anywhere within the environment. It can be said that users are in the design itself. The sense of presence is also supported by the ability to examine and experience designs from different scales and perspectives. Users can observe the design in real size or alter the design while walking in it. It is observed that the number of features to enrich the design alternatives were higher in the IVR environment than the 3D modeling environment. It can be deduced that sense of presence in the IVR, provided participants different point of views, which led participants to be more productive during the creation process. In addition, another reason why the variety of topological relations are higher in the IVR environment can be explained with the sense of presence. Participants tend to use different scales and perspectives more frequently while designing in the IVR environment than the 3D modeling environment. It is observed that participants mostly produced their compositions in a fixed and a wider perspective rather than experiencing the compositions in human scale or eye-level perspectives in the 3D environment.

When the responses of the survey were examined, all of the participants stated that they felt presence in the IVR environment, while only two of them stated that they felt presence in the 3D modeling environment. These results support the findings of the experiment about the productions of topological relations. Furthermore, it is asked that if they used different scales during the design process. These responses support the result of the experiment about the tendency of the participants to use different scales and perspectives in the IVR environment. In the survey, it is asked how participants rate their level of perception of the given model as a whole. Two participants answered very well, seven answered well and two answered medium to the question for the IVR environment. Six participants answered very well, three answered well and three answered medium for the 3D environment (Figure 8).

In the survey, it is asked how participants rate their level of perception of the given model as a whole. Two participants responded very well, seven responded well and two responded medium to the question for the IVR environment. Six participants responded very well, three responded well and three responded medium for the 3D environment (Figure 8). It can be assumed that there are no major differences between these two environments. It can be said that 3D modeling environment is more advantageous than the IVR environment when it is important to perceive the model as a whole or to understand the design from a wider perspective.

In addition to experiments, differences between the headsets were investigated. It can be said that HTC Vive is more useful compared to Oculus Rift because of the 360° tracking system. On the other hand, most of the participants stated that Oculus Rift controllers are more comfortable and easy to use compared to HTC Vive (Figure 9).

CONCLUSION AND DISCUSSION

It is observed that the IVR environment has potential in architectural design education. Experiments showed that designing in IVR enhances students' productivity and provides students different point of views to experience and improve their designs. Results can indicate that IVR has potential to be used as a design tool in architectural education rather than just viewing completed projects.

Experiment results and survey responses are in contradiction with each other. Experiment results showed that participants produced more topological relations than the 3D modeling environment. However, participants said that they perceived topological relations better in the 3D modeling environment. These contradictions show that further researches are needed with the increment of the number of participants in order to obtain certain results.

All an all, it can be concluded that the contribution of VR technology to educational environments, especially in architectural design studios, will contribute design process and design education in terms of adding different perspectives to students, developing 3D thinking, adding the sense of presence in designing process. Since the design is an everchanging and self-renewing area, using current media and new technologies in education is very important in carrying the design into the future.

APPENDIX

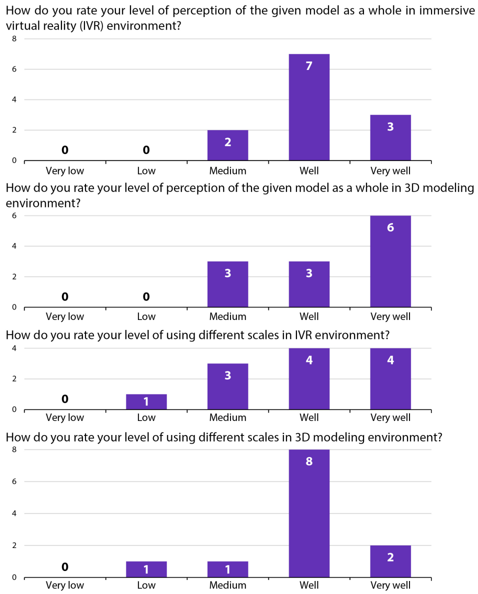


Figure 8
Survey questions about perception and using different scales together.

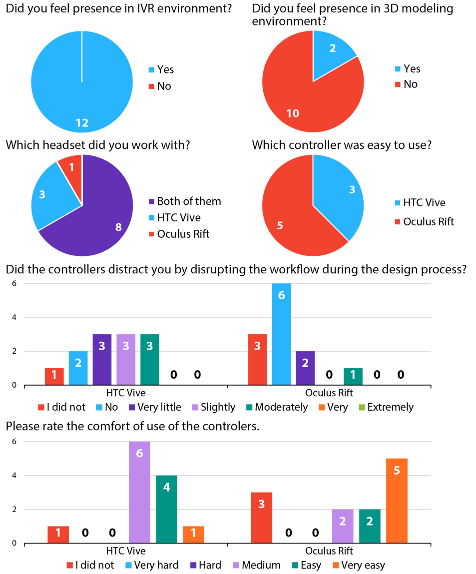


Figure 9
Survey questions about presence and the differences of the controllers.

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VRiC: Virtual Reality in Construction

Proposal of a Virtual Reality Based Learning Environment for Building Construction Systems

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In the scope of the study, a virtual learning environment (VLE) is proposed in order to benefit from the potentials of the virtual reality (VR) technology in the context of construction education for architecture students. A vast number of studies show that learning environments, where a strong relation is established between students and the information have positive effect on learners. Accordingly, learning enivronments should encouraged students to learn by exploration in a participatory way. In contrast, learning environments related to construction education are mostly lack of such features. Learning environments where students are not able to have an active interaction with the information is insufficient and ineffective for the construction education. In this context, it is deduced that establishment of a learning environment where users examine building components by various interactions may enhance students learning process. Accordingly, a learning environment is proposed, titled Virtual Reality in Construction (VRiC), where learner can explore architectural buildings, its components and its materials with an immersive experience. Various user interfaces and user interactions are created in order to compose interactions between the users and the architectural elements.

Keywords: *Virtual Reality, Architectural Education, Construction Education, Virtual Learning Environments, Unreal Engine, Oculus Rift*

INTRODUCTION

Emerging technologies are rapidly altering the relationship between individuals and information. Today's learners are more inclined to learn with visual media tools that are used in a participatory and interactive manner. This situation leads to a shift from face-to-face, didactic learning to self-learning and learning with gamification. Therefore, the establishment of an integrated structure of educational environments with different interactive visualization techniques is playing an important role in the learning context. An in-depth examination of the potential implications of new technologies in architectural education is a requirement. It is argued that virtual learning environment model is an important tool in terms of adapting architectural education to new paradigm shift.

The aim of the study is to question and reconsider architectural education and the learning environments by using potentials of the virtual learning environments (VLE) and virtual reality (VR) technology. For this purpose, a VLE is proposed in the context of construction education for architecture students. Building construction courses have a crucial place in architectural curricula. Examination of the building components, materials, structural systems, investigation on the construction techniques and technologies are the main interests of the construction courses. There are inadequacies on the creation of interactive learning environment where students can examine closely building components and materials by touching, experiencing and experimenting. Traditional learning spaces like classes, lecture halls and so on do not allow the detailed analysis of systems such as structure, facade, insulation, which are the most basic parts of architectural buildings. In addition, it is often impossible to examine their structural sections and their system details in 1:1 scale and on their own context. Furthermore, one of the most important advantages of VR environments is that it is possible to experience and learn in a way that is difficult to experience and dangerous in controllable and safe environment through interactions.

In the context of construction education, several number of studies show that most of the architecture and engineering schools have lecturer centric learning environments. According to the same studies, such learning style which is not learner centered is ineffective and inefficient in terms of structural knowledge learning (Goedert et al., 2011; Kubicki and Boton, 2011; Clevenger et al., 2012). It is not possible to create a participatory educational environment with the traditional lecture methods (Kubicki and Boton, 2011). In addition, narrator-centered learning environments are not suitable for describing complex systems such as building components and their relations (Clevenger et al., 2012). The reason is the lack of adequate interactions between students and information. It is possible to effect students' level of learning positively by establishing an active interaction between student and the information (Chau, 2007; Felder and Silverman, 1988; Li and Liu, 2004; Nirmalakhandan et al., 2007).

On the other hand, there are multiple reasons of building construction courses have inadequate to create interactive learning environment. According to Park et al. (2015) field trips are the only way for students to practice the building construction related subjects. Sampaio and Martins (2014) emphasized that organizing and having necessary permissions for safe construction site field trips are frequently encountered challenges difficult to achieve. According to Farrow and McCabe (2012), the difficulties of programming the organization required for a field trip, visiting a construction site and ensuring the safety of the student are the major challenges schools and teachers encounter. Vergara et al. (2016) argue that in laboratory studies it is very difficult to create environments where all students equally participate. It is difficult to create a flexible experience environment in construction laboratories for students. It is hard to use laboratory environment where structural information subjects are examined in an efficient and effective way due to crowded classes or student groups. Irizarry et al. (2012) also argues that it is not possible to create an interactive learning environment due to the inadequacies of laboratories.

In this context, this study focuses on the creation of an active learning environment, where students reach information with various interactions, might contribute to the learning of building construction related subjects. With the help of VR technologies, it is possible to create easily accessible and safe virtual environments where encourage active learning.

VIRTUAL LEARNING ENVIRONMENTS IN CONSTRUCTION EDUCATION

It is possible to find various studies on virtual education environments related to the building construction courses. In a study conducted by Alvarado et al. (2001) a virtual reality environment is proposed where students can examine a timber structure in

1:1 scale. Did et al. (2014) proposed a digital learning tool that aims to recreate "steel sculpture". Steel sculpture erected by American Institute of Steel Construction on various campuses is a compact physical representation of various steel elements and connections that are frequently used in building constructions. According to Sampaio et al. (2010), use of interactive 3D models during education may help students to avoid from passive learning behavior. Furthermore, a learning tool is proposed which allows learning fundamentals of steel bridges by exploration and examination in 3D environment.

Behzadan and Kamat (2013) argued that there are deficiencies of participation and interaction in civil engineering students learning environments. According to their declaration, construction courses are mostly lecture based and lack of using visual media. In this context, Behzadan and Kamat proposed an innovative learning tools includes remote videotaping and ultra-wide ban locationing. Another study conducted by Irizarry et al. (2012) a learning environment was proposed which aims to introduce concrete building elements with the use of 3D BIM models. Their motivation is derived from the enhancing students' information repository on building elements.

Furthermore, in a research, which uses BIM models to establish a virtual learning environment by Billie et al. (2014), game engines are used to create interactivity. In this research, it is aimed to create a realistic virtual environment where it is possible to examine building and its information layers in an interactive way. According to Park et al. (2015) for students it is not possible gain enough information and experience with the traditional education methods about subjects that are complex and instable such as building and construction sites. They argued that even there are few studies in literature that aims to enhance construction education with the use of novel technologies, proposed environments do not have enough detail and the interaction established are limited.

VRIC: VIRTUAL REALITY IN CONSTRUCTION

Virtual Reality in Construction (VRiC) is a virtual reality based application developed for learning and teaching fundamentals of construction in architectural education. Proposed framework covers generation of 3D architectural structural elements, building materials, and their details in 3D environment, creation of an explorative virtual space, which includes generated 3D models, and manipulation and examination of models in VR environment with an immersive experience. VRiC aims to provide students an interactive and explorative learning environment. The explorative learning processes involve examination and deconstruction of a predefined 3D building model, its structural and material components. In that sense, a 3D digital building model and its inner relations can be considered as an interactive exploration space. Accordingly, it is aimed to encourage students to explore the building by interact with its components with the sense of presence. The interaction with the components of 3D digital building model in VRiC allows users to filter information (layer-based interaction), examine an architectural element (material/layer/connection detail) in its context, and deal with being-in-the-space experience. Hence, it is possible to establish an interactive immersive learning environment where students can freely and safely explore a construction virtually which is hard to establish in real world. It is possible to observe architectural components, materials and their relations on their own context in 1:1 scale.

In this study, a framework for an interactive learning environment based on virtual reality is proposed and this framework is examined in the context of a user scenario. The user interface, interaction module and technological infrastructure as components of the proposed framework are described in relation with the user scenario.

Scenario for User Experience Setup

The user scenario includes the 3D detailed model of a living unit designed with 250 cubic meters of reinforced concrete construction system. Accordingly an experience setup was established which includes a detailed 3D model of a concrete building (Figure 1).

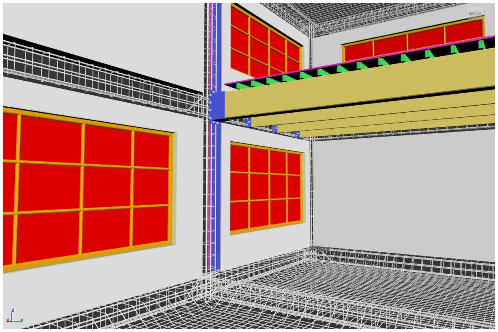

Figure 1
Interactable elements and materials of the building model.

Components, materials and structure systems were planned and model in relation the concrete construction systems. One of the reason of why examination of a concrete building was determined as the scenario for user experience setup is that they are majority of today's construction stock. Therefore, it is possible to argue that it is important to enhance students' visual repository on concrete building systems. Another reason is concrete building components are enclosed systems. It is not possible to understand their inner relations after a construction is completed. Their structural properties are the result of reinforcements installed inside of beams and columns. It is possible to examine reinforcements only during the construction phase of a building or in structure laboratories. It is not possible to observe them in an active building while they are in their own context. For this reason, it is argued that it is highly possible to benefit from the potentials of the VR technology in proposed scenario. Thus, the concrete building is a suitable scenario for the study. Addition to concrete elements, there are also steel and wood components are used in proposed environment. The reason is giving generic information on integration of different materials in concrete buildings.

Architectural elements and materials that can be observed and can be interacted in VRiC are shown below:

- Concrete columns and beams,
- Curtain walls,
- Concrete floor,
- Timber beams,
- Steel joints,
- Windows and doors.

In consideration to created building model will have educational purposes, it is a necessity to prepare the model in accordance with the accurate construction properties. It is important to create elements, materials, their relations and dimensions accurately. Concordantly, Ching, 2014 and Neufert, 2012 are used as reference during the establishment of 3D building model. In addition, Masonry Detailing Series established by International Masonry Institute was also used during this period [1].

Building model, which will be explored in VRiC was prepared in 3D Studio Max 2018. It is planned to give realistic appearance to the environment in order to be able to have immersive experience. Lighting, textures and various objects are added for enhancing the sense of presence (Figure 2).

Figure 2
Building model in virtual reality environment.

There was a need to transform the 3D model into an interactive environment where will be experience in VR. Also, there was a need for establishment of the various interface and interactions in order to interact with the building elements and be able to explore them (Figure 3). Thus, within the process of creating user interface and the user interactions Unreal Engine 4.20 was used. Moreover, Oculus Rift Headset was used with the aim of to experience created immersive VR environment.

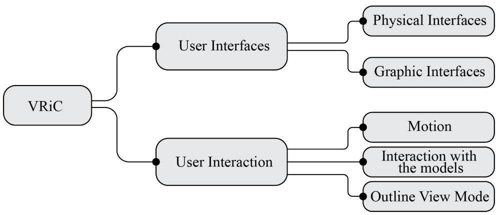

Figure 3
Elements of the VRiC.

User Interfaces

Two different kind of user interfaces are used in VRiC environment. These are physical interfaces and digital interfaces. Physical interfaces represent the physical tools or hardware, which are used to interact with the virtual environment. Graphical interfaces stand for visual elements used in VR environment whose able users to interact.

Physical Interfaces. Oculus Rift motion controllers and various gestures are used as physical interfaces. During the creation of the VR environment in Unreal engine, buttons on the motion controller were assigned for different functions (Figure 4). These functions are teleport, choose, grab, wireframe mod and x-ray mod that will be explained briefly in the user interactions section. Gestures are the body movement, which will be performed by the users. Gestures are limited by technological efficiency of the Oculus Rift. There are limited numbers of gestures possible to assign for the interactions. Pointing, touching and walking are the gestures, which are established in VRiC.

Graphic Interfaces. An option menu was designed to activate various interactions with the building components. It is possible to define option menu as a catalogue, which shows the each material layer on the chosen element. Each layer of the activated architectural element is represented with an image on the menu. It is possible to choose and explore the materials by using options menu. For example, in the proposed environment when the curtain wall is chosen, an option menu will appears which shows the interior finish, plaster, rough plaster, aerated concrete blocks, insulation, plaster and exterior finish layers respectively (Figure 5).

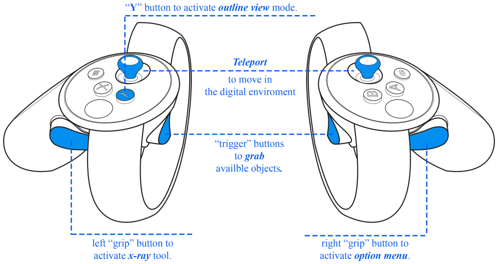

Figure 4
Oculus controllers.

Figure 5
Option menu.

User Interaction

There are three different types of interaction established in the proposed VLE. These are movement, interaction with the architectural elements and the outline view mode. Movement interaction describes how user will move in virtual environment. Interaction with the architectural elements describes the interaction, which defines how users explore and investigate the components, materials and their relations in VR environment. Outline view mode stands for the interaction established in order to create novel experience in same environment by chancing the appearance of the environments.

Motion. There are two types of movement is found in VRiC. These are physical movement and digital movement. Physical movement represents the transferring user's physical location into the digital environment. With the help of this transfer, it is possible to walk in the VRiC virtually while walking in the physical world. The other option is digital movement.

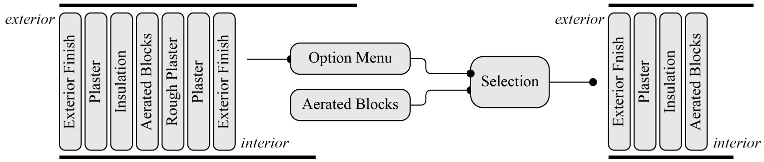

Figure 6
Principles of the option menu.

Users may push the teleport button on the motion controller while pointing the place where they want to go (Figure 7). After this action, users find their selves at the virtual location pointed. This enables the movement of the users in the virtual environment without need for any physical action.

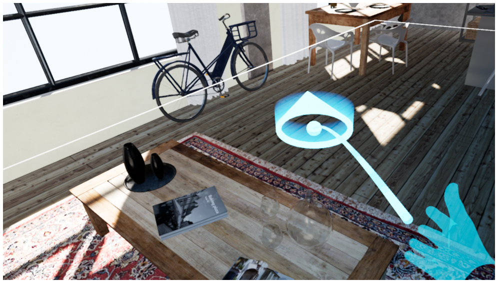

Figure 7
Teleport action which enables users to move in the building model.

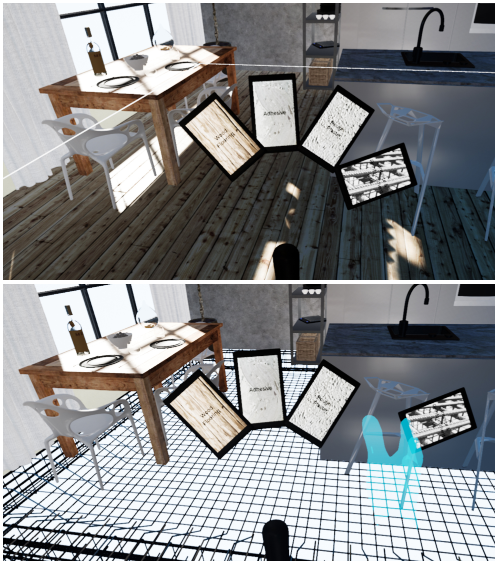

Figure 8
Interaction with the material layers.

Interaction with the architectural elements. It is possible to interact with architectural elements by using option menu. Process of the interactions can be summarized with three steps. First, users may activate the building component by pointing gesture and pushing grip button on the right controller in VR environment. After the activation of the element, option menu will be appeared in front of the users. Users may grab the menu, change its location and close it by pressing the same button. Secondly, users may choose the layer they want to explore by using touch gesture. They may virtually touch one of the catalogue cards on the menu. Finally, the chosen layer will be appeared on the architectural element. This interaction may help users to investigate the architectural elements and its materials in detail (Figure 6, 8).

Another interaction established between users and the building model is the x-ray tool. X-ray tool is responsible for the examination of the sections of the elements. It is aimed to let users to make local explorations on the components while observing their material layers as a whole. X-ray tool may appear in front of the user by pressing left grip button. X-ray tool is a ring shaped object, which opens holes on the surfaces. After users activate the tool, they may grab it and bring it closer to the element, which they want to investigate. Then, a hole occurs on the element. By looking through this hole user may observe all the overlapping materials on the element (Figure 9).

Another advantage of the x-ray tool is that it allows users to make exploration on the local places where components are intersected. It is possible to examine how different materials behave or observe their application configurations on the locations they are intersected.

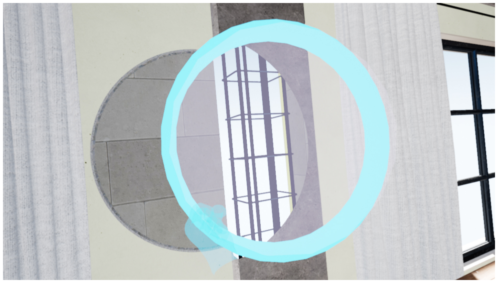

Figure 9
X-ray tool.

Outline View Mode. In the proposed VLE users are able to walk and observe a building with realistic materials, shade and lightings. Addition to realistic view of the model, it is aimed to enhance learning experience by implementing different view modes such as outline mode (Figure 10).

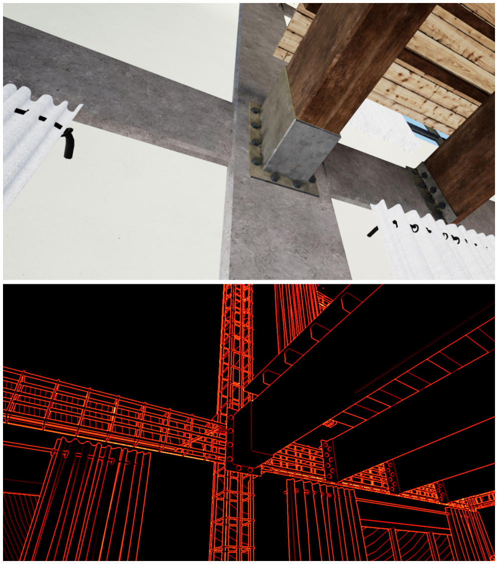

Figure 10
Outline view mode.

Main objective of the establishment of the outline view mode is to simulate appearance of the technical drawings in 3D immersive VR environment. User may activate or deactivate the outline view mode by pressing the "Y" button on the left controller. When the outline view mode activated realistic appearance of the model disappears. Instead, the entire environment becomes black except the outline of the objects that appear in red lines. Thus, user may feel their selves like walking in a technical drawing. It is possible to have novel experiences during exploration with the help of outline view mode. It is possible to operate all the interactions previously described as well in outline view mode.

CONCLUSION AND DISCUSSION

In the scope of the study, a VLE named VRiC: Virtual Reality in Construction is proposed. The aim of the proposed VLE is to investigate the potentials of VR technology in learning construction in architectural education. It is assumed that the establishment of a learning environment that allows active interaction would have a positive effect on the students learning. In the proposed VLE, students can learn by discoveries, experiments and experiences. While students walk inside a building, they will have the opportunity to examine the building elements and its materials. In the explained scenario, learners can explore a concrete building, its components and materials while they sense presence in the modeled environment. Therefore, students are able to explore architectural buildings in a new way, which is not possible in the physical world. The relation between the object of learning and learning is dependent on the users' actions in the presented framework. This provides learning in a non-linear way rather than a lecture based linear/sequential learning. Accordingly, it is concluded that within the proposed framework, it is possible to establish a construction education learning environment where is interactive, participatory and encouraging for learning by discoveries.

In future studies, it is planned to develop more flexible interface by adding real-time user interaction module including different components, materials and details. With the help of a graphical interface, which will be implemented, users may upload their own models to the application in order to have real time interaction with their own creations.

In addition, experiments based on user experience should be conducted to evaluate effects of proposed VLE on architecture students. It is also possible to evaluate VRiC in a construction course during a semester. During this period, it is possible to conduct various user tests, surveys and observations. Thus, success of VRiC can be evaluated in the context of creating an interactive learning environment and its effect on the students learning level.

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An Empirical Inquiry into the Affective Qualities of Virtual Spatial Enclosures in Head Mounted Display driven VR Systems

The Logic at Work behind the Magic of Space

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This research is an inquiry into the correlations between specific formal parameters of virtual spatial enclosures in HMD driven VR systems, and corresponding emotional responses in subjects . The experiments comprised of three sets of formal parameters - size of openings, enclosure volume, and length:width ratio. The emotional attributes tested were Valence and Arousal. Immersive virtual environments depicting enclosures with changing values of these parameters were presented to 50 subjects through a head mounted VR gear. Responses were recorded in the form of affective appraisals using a scaling system based on the Self Assessment Manikin, and were plotted on the Circumplex Model of Affect. The results revealed that the parameter of Arousal strongly correlated with the illumination levels (wall:window ratio) within an enclosure, and did not correlate independently with any other parameter. Peak Valence values corresponded to a wall/window ratio of .03 an enclosure volume of 70 cu.m and a length:width range between 1:1 and 1:1.5. The golden ratio was not rated favorably. Differences in volume between very large enclosures were not perceptible. The appraisal of spaces was also found to be consistently affected by preceding spaces.

Keywords: *spatial enclosures, formal attributes, affective qualities, emotional response, virtual reality, head mounted display*

Spatial enclosures are well known to have a great degree of emotional impact on the individuals inhabiting them. Different spaces affect us in different ways, and elicit a wide variety of emotional and perceptual responses. Some make us feel happy and positive, while others arouse feelings of discomfort or come across as depressing. Small rooms have a different effect on us as compared to very large halls, while dark spaces spark different emotional responses as compared to very bright enclosures.

The affective qualities of specific attributes of enclosures lie within the realm of spatial 'experience', and have long been regarded in the field of architecture as 'intangible' aspects that cannot easily be objectively measured. While the field of environmental psychology has developed multiple models for the objective measurement of affective states, these models have only recently begun to be applied to the realm of spatial enclosures. The basic hypothesis driving such lines of research is that specific attributes of the form of enclosures, such as shape, size, configuration etc. have empirically testable correlations with one's spatial experience and affective response within that space. There has still not been a great deal of focused empirical research on the exact nature of such correlations. For example, while we know that very small enclosures make us feel uncomfortable, we do not know clearly 'how' small an enclosure elicits 'how' uncomfortable a response. Architects usually still rely heavily on their own intuitions while drawing up a design that keeps these experiential aspects in mind, and it is often considered an acquired skill for a designer to deal with these qualities. A study directed specifically towards the effect of specific spatial parameters on emotional response has the potential to open up very valuable lines of enquiry into the correlations between the physical and the emotional realms in spatial enclosures. It will also help to generate a body of empirical data that will provide architects with strong rational grounding for design decisions pertaining to spatial experience, and has the potential to yield mathematical and computational models in the future.

Over the past few decades, the development of immersive, responsive and interactive virtual representations of space, which are capable of generating simulations that can approximate the sensory inputs provided by a real space, has immense potential to develop into a valuable tool for such lines of empirical research. While VR systems in various stages of development have been applied in a few similar studies in the past (Franz et al. 2003) (Shemesh et al. 2015), it is the rapid development in the field of VR in recent years, and the widespread commercial production of head mounted display (HMD) devices that have made the use of such systems for architectural research readily accessible.

EMOTIONAL IMPACT OF SPATIAL ENCLOSURES

There are an incalculable number of factors that determine the way one perceives a space. The way a person 'feels' in a space is also often considered to be a very subjective affair that is dependent on one's own constitution, character, upbringing, and prior experiences. However, the fact that specific attributes of a space do have an impact on one's emotional experience cannot be denied.

Bitner and Schachter identified three primary categories of attributes that influence the experience of individuals inhabiting it, namely:

(i) Formal attributes, (ii) Signs, symbols and artifacts, and (iii) Ambient conditions (Bitner 1992)

This body of research has restricted itself to the first category. In the context of architecture and space, we may describe 'form' as both the 'internal structure and external outline and the principle that gives unity to the whole' (Ching 1996). To put it simply, form refers to both the internal and external attributes of an object or body. The formal attributes are intrinsic, and the primary characteristics that give it a definition. There are a number of primary attributes of form, namely *shape, size, color, texture, position, orientation and visual inertia* (Ching 1996). These pertain solely to the structure that defines the enclosure, and thus encompass all architectural elements and configurations.

Theories and structures of emotion

A number of theories have been proposed to explain the structure of human emotion. One school of thought opines that there are a number of specific and discrete human emotions (Basic Emotion Theories/Discrete Theories). These maintain that there are sets of very basic and discrete human emotions, such as *Joy, Disgust, Surprise, Fear, Anger* and *Distress* (Ekman 1984), which cannot be broken down into simpler parts. These emotions lie within separate domains and are discrete in nature.

More recent schools of thought opine that there is no set of distinct and discrete emotions. All emotions can rather be mapped on dimensional scales such as the circumplex model. The circumplex model consists of a three dimensional emotion-space with Valence (Pleasure-Displeasure) on the x axis and Arousal (Activation-Deactivation) on the y-axis (Russell 2003). (Figure 1) The z-axis of Dominance is also often used. According to this Dimensional Theory, a wide range of possible human emotions can be defined with respect to these dimensions. For example, the quadrant formed between Activation and Pleasure gives us the emotions of Excitement and Elation, while the quadrant formed between Deactivation and Displeasure gives us the emotions of Tiredness and Sadness.

Recording emotional response

In order to systematically study the effects of specific spatial parameters on emotional state, it becomes necessary to adopt an effective framework for objectively recording emotional response.

One approach towards this focuses on recording the physiological and biological responses that accompany emotional response, thus relying on external indicators. These techniques include analysis of visible indicators such as facial expression, or biological indicators such as Electro Dermal Activity (EDA), Skin temperature (SKT), and Electrocardiography (ECG) (Kim et al 2004). Data from biological indicators alone however are not enough to situate a subject's emotional response on the spectrum of human emotions as described by the circumplex model. A variety of emotions may result in very similar sympathetic and parasympathetic responses, and will thus be largely indistinguishable through the analysis of biological parameters alone. Secondly spatial enclosures are environmental stimuli, and are thus expected to induce emotions that are less intense as compared to those induced by more active stimuli such as a threat (fear) or aggression (anger). Variations in the values of the biological indicators thus may not be significant enough to undertake fruitful analyses.

This study thus adopts a second approach, which relies on one's own verbal assessment of his or her emotional response to any given stimulus (known as an 'affective appraisal/report'). The Semantic Differential (Osgood 1952) offers a set of bipolar adjectives (such as good-bad, hot-cold, tense-relaxed etc.) that each serves as rating scales. Bradley and Lang in 1994 developed a language independent scaling method for recording appraisals known as the Self Assessment Manikin, which is now regularly employed in experiments for measuring a range of emotional stimuli. In this method, the two dimensions of human emotion (Valence and Arousal) are represented as pictorial scales (Bradley and Lang 1994). The third dimension of dominance is often omitted because of lack of unanimity regarding its legitimacy as a dimension, and the difficulty of subjects to relate to the scale.

Virtual display systems

Rapid development in virtual interactive display systems has yielded valuable tools for empirical research in the field of space perception. Recent developments in virtual environment simulations include Head Mounted Displays fitted with audio output and a gyroscope. The stereoscopic visual output is done through and inbuilt OLED display and a pair of convex lenses. The gyroscope and accelerometer senses head position and orientation and changes the display scene accordingly. Scene refresh rate is typically 90 Hz. A number of manufacturers such as Oculus and Sony have in recent years introduced a range of wearable HMDs. Scene inputs can be static in the form of 180x360 spherical images, or dynamic such as 3D models adapted for VR display using a display engine. The field of view ranges typically between 100 and 120 degrees with a display resolution of up to 1200p (Mazuryk et al. 2010).

EXPERIMENT METHODOLOGY

Framework for affective appraisal

Since the experiments dealt with absolute emotions aroused within occupants of spatial enclosures, it was necessary to rely upon an existing model of human emotional response and operate within its framework. The circumplex model of affect was chosen for this purpose (Russell and Pratt 1980) (Figure 1).

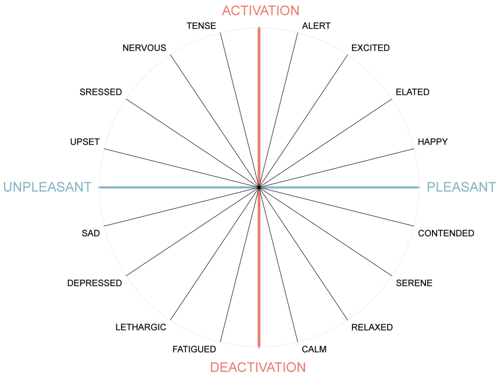

Figure 1
The Circumplex model used for experimentation

The scaling system used for objective recording one's emotional response was derived from Russell's use of the Semantic Differential for unidimensional scaling. It relied on affective appraisals, that is, a subject's own interpretation of his or her affective state. For each spatial variant that was to be tested, subjects' perceived emotional response on the two dimensions of Valence (Pleasant - Unpleasant) and Activation - Deactivation were noted. To do this, the Self Assessment Manikin (SAM) (Bradley and Lang 1994) was employed. The visual scales for Valence and Arousal corresponded to a bipolar scale ranging from -4 to +4. Subjects were asked to respond to each of the spatial configurations being tested by rating the space on each of the two SAM scales. Their responses were then converted into numeric values and plotted on the circumplex model.

Selected spatial parameters for experimentation

There were three sets of parametrically varied spaces that were selected for this stage of experimentation. The spatial parameters chosen were:

(i)Area of Opening (wall area / window area ratio), (ii) Enclosure Volume, and (iii) Enclosure Proportion.

Each of the sets comprised of 6 instances varied according to the parameter being studied. The set varied by size of opening included enclosures with uniformly increasing dimensions of window. Instance 1 thus corresponded to the smallest window, allowing least light to enter, while Instance 6 corresponded to the largest window and thus the brightest enclosure. It may be noted that the area of opening directly defined another parameter, which is the daylight factor (DF), which is described through the following relation:

$$A(glaz) = \frac{DF \cdot 2A_t \cdot (1 - R_{mean})}{T_{vis} \cdot \theta} \qquad (1)$$

where DF: Targeted daylight factor in %; A(t): Total area of all interior surfaces; A(glaz): Total glazing area; R(mean): Mean surface reflectance; T(vis): Glazing Transmittance; Θ: Sky angle in degrees; (Brotas and Wilson 2007)

Now since A(total) remains constant for the experiment, all values except DF and A(glazing) are constant. Thus we find that DF is actually directly proportional to A(glazing). In other words, as area of opening increases, the daylight factor also increases proportionately. (Table 1) Thus the correlations that were to be tested between area of opening and affective response could also be described as a function of the correlations between DF and affective response.

Table 1
Instances varied by Area of Opening (Aglazing)

Instance	1	2	3_{datum}	4	5	6
$A_{glaz.}$ (sq.m)	.28	.88	1.8	3.04	4.6	6.49
$w_{win}xh_{win}$(m)	.6x.48	.84x.6	1.2x1.5	1.56x1.95	1.92x2.4	2.28x2.85
$A_{glazing}/A_{total}$	.003	.009	.017	.03	.045	.063

The second set comprised of enclosures where the cardinal dimensions (length, width and height) all increase uniformly, thus increasing the enclosed vol-

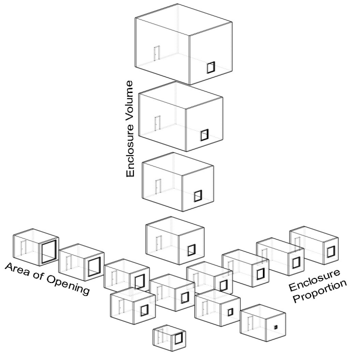

Figure 2
Parameter sets used in preliminary experimentation phase. Area of Opening, Enclosure Volume and Enclosure Proportion

ume. All other parameters including window size remained the same. Again, from the definition of DF, we see that since A(glazing) is constant, DF becomes inversely proportional to A(total). Thus, as volume increased, so did A(total). , thus proportionately decreasing DF. (Table 2) The effect of volume on affective response could thus be purely due to increase in volume, or due to the decrease in DF. To overcome this apparent confusion, a control experiment was conducted, where A(glazing) increased proportionate to the increase in volume, thus keeping DF constant.

Table 2
Instances varied by Enclosure Volume

Instance	1	2_{datum}	3	4	5	6
Vol. (cu.m)	24.01	70	153.8	286.75	480.19	745.46
LxWxH (m)	2.8x3.5x 2.45	4x5x3.5	5.2x6.5 x4.55	6.4x8x5.6	7.6x9.5x 6.65	8.8x11x7. 7
$A_{glazing}/A_{total}$	.036	.017	.01	.007	.005	.004

The set varied by proportion included enclosures of fixed floor area (20sq.m) where the length/width ratio varies uniformly from 1:1 to 1:2.25, thus changing the geometry of the space from a square to varying configurations of rectangles. (Table 3)

Table 3
Instances varied by Enclosure Proportion

Instance	1	2_{datum}	3	4	5	6
L:W	1:1	1:1.25	1:1.5	1:1.75	1:2	1:2.25
LxWxH(m)	4.47x4.4 7x3.5	4x5x3. 5	3.7x5.5 x3.5	3.38x5.91 x3.5	3.16x6.3 2x3.5	2.98x6.7x 3.5
Area (sq.m)	20	20	20	20	20	20

There were thus a total of 18 spaces (6 instances in 3 sets), apart from the control experiment, that were used for the experiments. There was one space - the datum (4mx5mx3.5m enclosure with a 1mx1.2m window opening) - that was common in all three sets. This space played an important role in the order in which the instances were displayed to subjects. Figure 2 shows the 18 parametrically varied enclosure sets.

Generating immersive virtual environments

Each of these enclosures was generated using Rhinoceros and Grasshopper3D and rendered using VRay for SketchUp. The images spherical renders of field of view (FOV) 360˚ and resolution 4000x2000 pixels. (Figure 3) Render time for each scene was roughly 30 minutes. All the scenes were rendered with the camera stationed at eye level (1500mm) above the geometric center of the spaces. This allowed the subject to look around and experience the whole space uniformly. AFulldrive VR engine adapted these spherical renders for 360˚ display through the VR gear.

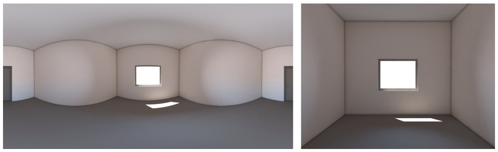

Figure 3
Spherical renders of virtual spaces – FOV 360˚ used in the experiments (left) and FOV 45˚ (right)

Gear

The VR gear comprised of a Head Mounted Device (HMD) comprising of two units - the VR Viewer and the Display Unit. Being a Google Cardboard based setup, the display unit was an android driven mobile device (Lenovo Vibe K5 Note) with a diagonal display dimension of 5.5 inches and a display resolution of 1080 pixels. The head movements of the subject were tracked using the inbuilt gyroscope and the corresponding display was projected. This unit was fitted inside the VR Viewer, which was a Procus One unit with biconvex lenses of focal length 14mm. The interpupillary distance and distance between the display surface and lenses could both be adjusted by the subjects through knob provided on the VR unit.

The setup
The experiment comprised of the subject wearing the HMD. The display that was being shown to the subject at any point of time was streamed live to a laptop (MacBook Pro 8.1) via a steaming engine (Mirror Beta). The immersive spatial environments were displayed through a VR engine (Fulldrive). The observer was seated beside the subject and noted down the SAM Valence and Activation ratings manually.

Sampling
The experiments comprised of a sample of (N = 50) subjects. The control experiment focused towards daylight factor and volume had a sample of (N = 10) subjects. All subjects for all experiments were post-graduate students of CEPT University, Ahmedabad, within the age group 23 - 33, with a bachelor's degree in Architecture.

Experiment Process
The subject was briefed about the experiment process. They were introduced to the two scales of Valence and Arousal, and the rating mechanism (SAM) that they were to employ while giving their responses, and were also given a broad idea of the parameter sets (Opening, Volume and Proportion) that were being studied.

They were then were asked to wear the HMD in a standing position, to ensure coherent interpretation of eye level and freedom of basic movement. and adjust the knobs to ensure that a clear and focused environment was achieved.

The subjects were shown each of the instances for each parameter set. They were given between 15 - 30 seconds to explore each space, and were then asked to rate the space on the SAM scale. The observer translated the SAM rating to a numeric value (between -4 to +4) and recorded it on a data sheet. Qualitative keywords/observations etc were also noted by the observer.

The sample size of 50 was broken into two smaller samples of 25 each. Subjects from the first sample were shown the instances of each parameter set in sequential order i.e. starting from Instance 1 and ending at Instance 6. The order of the three sets themselves was randomized. Subjects from the second sample were shown the instances of each set in random order, but in each case, starting from the datum space(4mx5mx3.5m enclosure with a 1mx1.2m window opening). Thus, the first scene they saw in each set was the same. This was done to ensure perceptual coherence across sets.

RESULTS
Figures 4, 5 and 6 summarize the data obtained from the three sets of experiments.

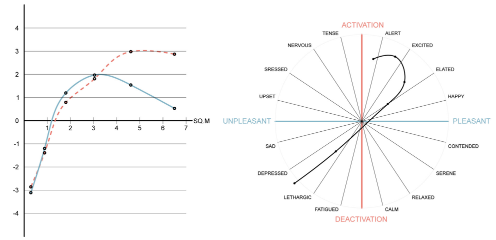

Figure 4
Valence(solid) and Activation(dashed) vs Area of Opening (left) and shift in affective state as plotted on circumplex (right)

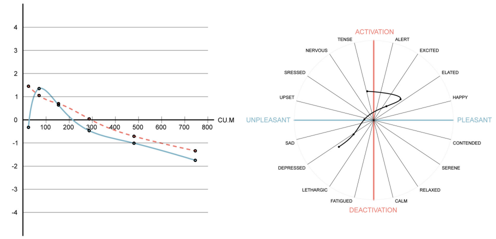

Figure 5
Valence(solid) and Activation(dashed) vs Enclosure Volume (left) and shift in affective state as plotted on circumplex (right)

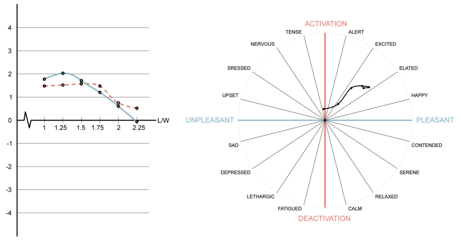

Figure 6
Valence(solid) and Activation(dashed) vs Enclosure Proportion(L/W) (left) and shift in affective state as plotted on circumplex (right)

ANALYSIS AND DISCUSSION

Effect of Sequence

For both sets of subjects (scenes shown in sequence and in random), the nature of the curves for valence and activation were very similar for all three parameter sets, and lay within a very small range of values. (Figure 7), (Figure 8).

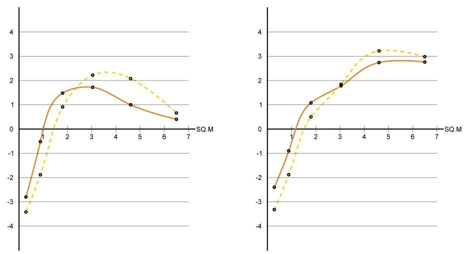

Figure 7
Area of Opening: Ordered(solid) and Random(dashed) sets for Valence (left) and Activation (right)

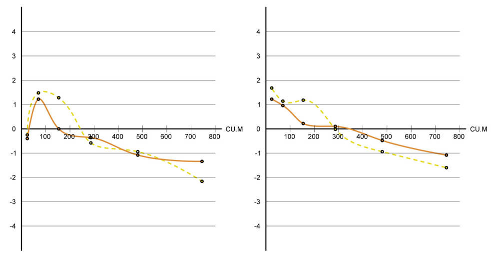

Figure 8
Enclosure Volume: Ordered(solid) and Random(dashed) sets for Valence (left) and Activation (right)

There was, however, a very important point of difference. For both valence and activation, the amplitude (maximum and minimum values) of curves was consistently larger for subjects who were shown scenes in random. This pattern was consistent for all curves for the Opening Size and Enclosure Volume set. (Figure 7), (Figure 8)

This consistent variation in amplitude revealed that the SAM ratings that one would associate to a certain space would be exaggerated if that space followed a contrasting space. For example, a room appeared much brighter to the subject if it was shown immediately after a contrasting dark room and vice versa. This exaggeration of sensory perception was diminished if the spaces were shown in order, i.e. if the bright room followed a room that was marginally less bright. This phenomenon was reflected in both the emotional parameters of valence and activation. In the set where the spaces were shown on random, each space was far more likely to be followed by a contrasting space - something that was never a case in the ordered set.

This inference may be extended to physical spaces too. The entry sequence into a space may well be an important factor in the way we respond emotionally to that space. For example, a large hall may appear larger if entered through a small volume and vice versa.

Peak values of Valence

Peak valence values correspond to architectural configurations where subjects gave the highest ratings on the 'Pleasant - Unpleasant' scale. These configurations thus had the highest degree of 'positive-ness' associated with them.

Size of Opening

Figure 7 shows that for both the random as well as the ordered sets, subjects rated Instance 4 (3.04 SQM of opening) highest on the valence scale. As per the relation between Area of Opening and Daylight Factor as discussed earlier, this space corresponded to (Aglazing/Atotal) ratio of 0.03. It was still not clear how area of opening affects emotional state independent of levels of illumination. It was established beyond doubt through a control experiment conducted for the volume set (discussed later) that the primary factor behind change in emotional state was not area of opening as an independent entity, but rather the Daylight Factor levels as a function of area of opening.

Enclosure Volume

As we see from Figure 8 the valence curve peaks at a volume of 70 cu.m, which corresponds to a spatial configuration of dimension 4mx5mx3.5m. This was consistent for both ordered and random sets. It is worth noting that this space is in fact the datum space that was common to all the parameter sets. It is also of importance that such a space was of very human scale i.e. of dimensions and proportions commonly found in low occupancy domestic spaces such as bedrooms, studies, etc. This finding may empirically set a volume range that constitutes 'human scale', that is an ideal size of enclosure where occupants feel most pleasant.

Figure 8 also shows that for both the ordered as well as the randomized sets, after reaching peak value, the valence curve descends very gradually. However, the corresponding increase in volume is considerable. It may be noted that while there is a very rapid increase in valence between the 24 - 70 cu.m range, the post peak fall in valence is much more gradual, such as in the (300 - 700 cu.m range). Thus subjects recorded a gradual decrease in valence even when there was a rapid increase in volume.

It is evident from this observation that subjects were more sensitive to changes in volume in enclosures that were of a volume comparable to human scale, whereas the perception of volume decreased drastically as enclosures became very large and were no longer comparable to human scale. This explains the gradually decreasing slope of the descending valence graph. This inference may be directly utilized in design of spaces. Creating very large spaces to instil feelings of wonder and awe may not be effective beyond a certain volume range, and only result in wastage of resources.

It is also evident from the rendered images. (Figure 9) The changes in volume for the two spaces corresponding to Instance 1&2 are instantly perceptible. However, the difference in volume between Instance 5&6 is not easily perceptible, making the spaces look almost identical. It will be interesting to note that the absolute change in volume between Instances 5&6 is much greater then the difference between Instance 1&2.

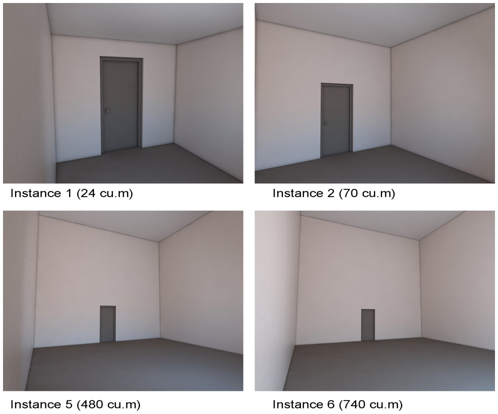

Figure 9
Difference in perceived change in volume in renders for Instance 1&2 (Top) and 5&6 (Bottom). Note how the bottom set appears identical despite having a much larger change in absolute volume

ENCLOSURE PROPORTION

As opposed to the other parameter sets, enclosure proportion did not display a valence peak around a small value range. Figure 6 shows, that even though Instance 2 (length/width = 1.25) corresponded to the maximum value of rated valence, Instance 1 and Instance 3 displayed very similar and high valence values. Thus within the proportion range 1:1 - 1:1.5, rated valence was consistently high. However, there was a sharp drop in the valence curve after 1:1.5. This was clearly evident in the ordered set.

While this tells us that subjects felt most 'positive' within the 1:1 - 1:1.5 proportion range, it also gives us an interesting counter argument to the classical concept of the 'golden ratio' (1:1.61). The data reveals that this ratio was not rated favourably for spaces in plan, where the ratio is not directly visually perceptible. In other words, while the golden ratio may be a very strong 'visual attribute', it may not possess any absolute properties of being perceived independent of the visual realm (such as in elevation).

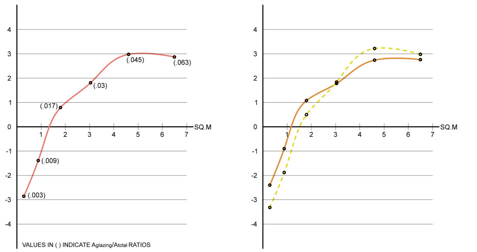

Figure 10
Activation vs Area of Opening: Note the stagnation in slope after Instance 5 for both Ordered(solid) and Random(dashed) sets (right)

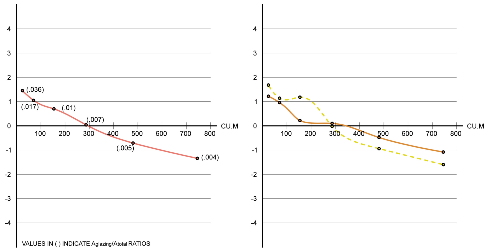

Figure 11
Activation vs Enclosure Volume for combined (left) and Ordered(solid) and Random (dashed) sets (left).

The emotional parameter of Arousal and Daylight Factor

A study of the Arousal curves of all the parameter sets yields a wide range of very important inferences. A look at Figure 10 tells us that arousal strongly correlates with the area of opening and thus daylight factor. The coefficient of correlation was (r = 0.90). This was consistent for both the ordered and the random sets (r =0.89 and r = 0.91 respectively). For both the sets, rise activation appears to stagnate towards the end (the variant corresponding to the greatest area of opening has an activation value roughly the same as its preceding variant). This reveals that our sensitivity to changes in illumination levels appears to fall significantly for very high range of illumination values.

In the case of enclosure volume, however, rated activation fell consistently with increase in volume, for both data sets (Figure 11) (r = -0.98). This may mean two things. The first possibility is that activation may actually be inversely related to enclosure volume. This would mean that subjects consistently felt less aroused as the enclosure became larger and larger. The second possibility is that the fall in activation was not due to increase in volume, but actually due to the drop in daylight factor. Since the area of opening was kept constant for all the variants of room volumes, the A(glazing) / A(total) ratio decreased with increasing volume. This may have been the reason for the steady drop in rated arousal. The coefficient of correlation of arousal with A(glazing) / A(total) was high (r = 0.81)

A control experiment was conducted to understand these findings. The experiment was conducted in a smaller sample set of (N=10) subjects. The six spaces used in the volume set remained the same, except that the window opening area was made to increase proportionate to the increase in volume, thus keeping maintaining a constant A(glazing) / A(total) ratio. The valence and activation values were recorded for each of the instances using the same methodology and process as the other experiments. The graphs below (Figure 12) show the Valence and Activation curves derived from the control experiment as compared to the primary experiments.

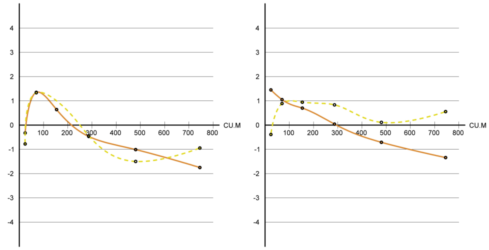

Figure 12
Valence (left) and Activation (right) vs Enclosure volume for Primary(solid) and Control(dashed) Experiments

What was evident from the results of the control experiment was the fact that the nature of the activation curve in the volume set was driven by the level of illumination in the spaces, and not independently by the increase in volume. While the main volume set shows a uniform drop in activation with the increase in volume, the arousal levels in the control experiment (where illumination remained constant) did not correlate with volume (r = 0.06) The Valence parameter behaved in a roughly similar manner for both the primary and the control experiments. (Figure 12)

The strong correlation of the emotional parameter of activation with Aglazing/Atotal in an enclosure gives us valuable insights into the way we respond emotionally to spaces. Activation (or arousal) is a major component of the circumplex model of emotion. From the activation graphs of the three parameter sets, we see that there is little affect of enclosure volume an enclosure proportion on activation, independent of the parameter of illumination. We also know that valence peaks and then drops with increase in illumination.

CONCLUSION

The broad aim of this research was to provide architects with a body of empirically tested scientific knowledge pertaining to specific correlations between specific formal attributes of virtual enclosures and spatial experience in occupants. The inferences derived from this study has the potential to be drawn upon by architects to inform their own design decisions, rather than relying upon intuition alone. More importantly, it is hoped that this work provides direction to future research in this field. There are an infinite number of formal and experiential parameters, and the natural relationships between them are still largely unknown. The HMD driven methodology adopted in this study has the potential to be drawn upon, refined, and applied in similar focused experiments, possibly giving rise to computational models for emotional response in space. This line of inquiry is an attempt to quantify the so-called 'intangible', and to uncover the logic at work behind the magic of space.

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The Neurological Impact of Perception of Architectural Space in Virtual Reality

Virtual Reality with Building Information Modelling and EEG

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The paper will present the preliminary findings from a pilot study that uses a virtual reality feedback collection methodology with building information modelling in combination with a neurological headset. All test subjects were fitted with both the Emotiv Insight and Oculus Rift Head Mounted Display and took a virtual tour through a 3D model. The matching of the test subjects' location in the model, field of view, the task, and the neurological activity, shows a possibility to link an architectural experience to specific emotional responses. This pilot study allows us to evaluate the methodology, frame and content in order to undertake a larger study using a more precise selection and delimitation. The results from this pilot study are hence focusing on addressing the framework for such a study to find out what sort of neurological data can be retrieved, and if the combination with virtual reality could be made useful. We find that there is a consistency in the data retrieved on the individual level. Even though the sample size in this pilot study does not allow concluding definite coherence, we find that the method, with modifications, could be useful to investigate the link between perception and architecture.

Keywords: *virtual reality, representation, perception, tradition, neurology*

INTRODUCTION

Through experiments with virtual reality, our research discusses the possibilities of representation models in architecture. We have performed a series of experiments using virtual reality in combination with other digital technologies such as 3d BIM modelling and eye tracking. We have been comparing how people experience architectural space using eye tracking technology in combination with qualitative questionnaires (Hermund et al. 2016, 2017, 2018). In our research, the next steps will be to combine our body of research with neurological feedback from the easy to use Emotiv Insight 5 channel EEG technology. Our research project is called VSR - virtual scenario responder [1], and we are currently working on a VR response system for the construction field that can be used in the design process, for modification and for validation of an architectural project, including user involvement. We want to connect the system to a wide range of different applications in new construction and restoration. There are many possibilities, and the required focus requires input from many different fields. An important part of the concept is a systematization of a question matrix and the subsequent studies of data. This matrix is created in collaboration between involved parties in construction and with psychologists focusing on cognitive processes, behavior and neurology.

We are currently working with an architectural case close to the city of Vejle in Denmark under the motto "Fitness for Everyone" which is a new section of the sports facility Gaarslevhallen, where accessibility is one of the important issues [2]. We use this case study to test how we can manage a VR workflow that will allow user feedback to be collected through our VSR system, without interfering unnecessary in the users' experience of the architectural atmosphere.

Previous research suggests that virtual reality can simulate a physical scenario to a degree where human behaviour shows correspondences, and is closer related to reality than for instance the experience of the space communicated through plan and section drawings, as traditionally used in architecture. If the technology is used correctly, a representation of architectural projects through virtual reality can significantly improve the usability of digital architectural building information models. (Hermund et al. 2018). Other pilot studies have been working with VR in combination with pupil dilation, as a means of capturing the behavioural aspect of perception (Moleta et al. 2018)

We believe that a virtual environment, through interacting with the environment in the model, can generate immersiveness (Steuer 1992), understood as the sensation of actually being present in an architectural space, even while one knows that this feeling is an illusion created by a digital model (Slater et al. 2009).

Our brains are combining input from different areas to create an experience (Mallgrave 2010). This does not inevitably means that we need photorealistic models to imagine an architectural space. The difficulty is to find a level of detail in the 3D model sufficient to convey the feeling of immersion - the sense of being present in the architecture. In assessing where a digital virtual reality representation can deliver a realistic, but still imaginative model for an architectural vision, we believe that the feedback generated from studies with the neurology headsets, can assist in deciding what elements to include in the modelling methodology. A recent neurology study comparing learning in VR to conventional media (flat 2D screen computers systems) shows that VR increases both sense of immersion and the risk of creating an increase in processing demands on working memory, which can lead to a decrease in knowledge acquisition. (Makransky et al. 2019). While the immersion is fundamental in the field of architecture, the cognitive overload should of course be avoided. This is also part of the reason to why we insist on removing unnecessary details from our test model, in order to reduce background noise.

EXPERIMENT SETUP

The pilot study consists of hardware, software, and methodology enabling a preliminary study of how to apply equipment and what methods to use.

Equipment and model

In this preliminary study, the test subjects were equipped with an Emotiv Insight 5 channel EEG technology brainwave recorder and an Oculus Rift HMD. The case study used is a digital 3D model of the architectural extension to the sports facility Gaarslevhallen, near the city of Vejle in Denmark, presented in 1:1 scale in VR. The test model has been modelled in Autodesk Revit as a sketch 3D digital model with minimum use of textures in order to eliminate as much background noise as possible.

Method

Test subjects whom did not respond with sufficient electric signal to the brain scanner were screened out before the test. We had twelve test subjects, but fur-

Figure 1
The tutorial room with start point is location A where the test subject can move around and watch some chairs. There are doors between the sections. Section is C where a scale model of the test case building is on display and from where the test subjects are teleported to begin the test.

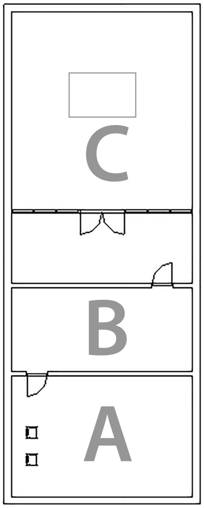
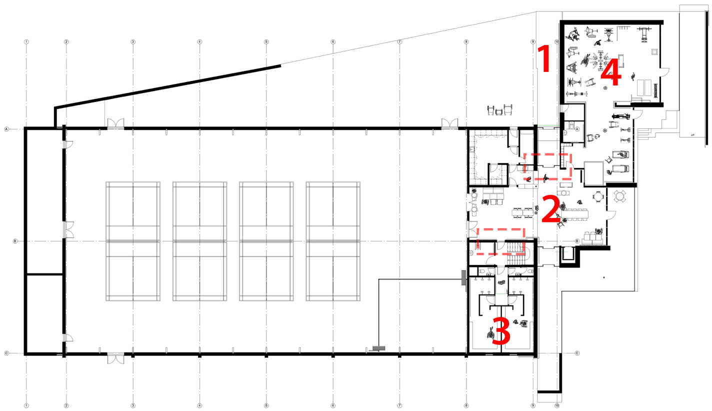


Figure 2
The sports facility Gaarslevhallen with the entry point (1), the foyer (2), the changing room (3), and the fitness room (4).



ther screening out three test subjects (one case of severe motion sickness, and two cases of previous knowledge of the system and the 3D model) left us with eight usable test subjects. Six test subjects were students of architecture and two were architects and educators. One test subject was female and the rest was male. The test subjects were presented with a short brief explaining the outline of the pilot study. Before the real test, we had designed a tutorial VR room where the test subjects could practice moving around and interact eg. with opening doors and using a laser pointer tool. At the beginning of the tutorial room we included the recording of the compulsory individual neurological baseline where the test subject relaxed for fifteen seconds with open eyes and fifteen seconds with closed eyes. (Figure 1).

Figure 3
The level of detail in the “dummy” people is kept at low poly to emphasize the sketchy model in an attempt to avoid distracting the test subjects.

When the test subjects felt reasonably comfortable with the VR controls, going through the tutorial, they could point at a scale model of the case building, and were subsequently teleported to the start point of the 1:1 case building (location 1). Here they received a second brief, explaining where they should go in the model. In order to get a comparable data set, it was necessary to set up a location based task for the test subjects. There were four sequential locations that they should traverse: Outside the building (location 1), through the open foyer (location 2), to the changing room (location 3), to the fitness room (location 4), and finally back outside again (location 1). (Figure 2). The test subjects were told that they could interact with the “dummy people” in the model asking for directions, and real life staff from the research group would answer for the dummy people (Figure 3). The relatively free task was designed like this in order to simulate a possible close to normal use of the fitness facility without steering the test subjects more than necessary. Some guidance, however, seemed necessary in order to being able to analyse the data subsequently. Not every test subject follow the same route, but there are a significant overlap, that can be used to spot potential trends in the behaviour. We also wanted to have as much different data in the pilot study, simply to be able to select from a broader collection of potentially interesting trends.

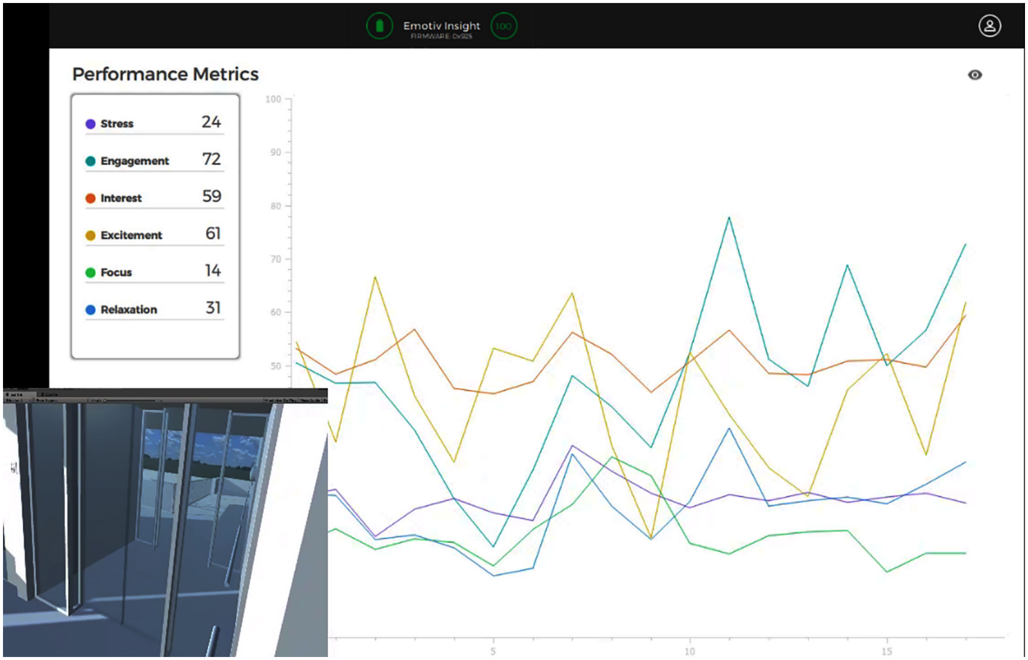
Performance metrics diagrams

In order to collect data from the study, we screencaptured the live feed from the test subjects experience in VR while simultaneously capturing the feed from the Insight brain scanner (Figure 4). The full metrics diagrams were subsequently marked with the same entry points from A to I, to be used in the analysis. The markings are: A - starting point (location 1), B - entering the open foyer (location 2), C - entering the narrow hallway, D - entering changing room (location 3), E - leaving changing room, F - reentering foyer, G - Enter fitness room (location 4), H - leaving fitness, I - leaving foyer to go outside again (location 1) (see also Figure XX in the analysis chapter).

THE EMOTIV INSIGHT READINGS

The output from the Emotiv Insight is from the EEG signal transformed into graphs providing metrics showing six different areas. Since we are architects and not EEG analysts, it makes more sense in this context to use this output. Analysis of the raw EEG data is outside the scope for this study, but could be applied for future research, if undertaken be neuroscientists. We have chosen to focus more on Excitement, Interest and Engagement. These are relatively precise when measured with the Insight. A precision of about 70% for Interest to over 85% for Excitement, and Engagement a little less, when measured against standardised tests and other biosignals in Emotive’s

Figure 4
The screen capture with live feed from the test subjects experience in VR and simultaneously showing the feed from the Insight brain scanner.



lab [3].

Emotiv labs describe these three performance metrics as follows:

Excitement (EXC) is an awareness or feeling of physiological arousal with a positive value. It is characterized by activation in the sympathetic nervous system, which results in a range of physiological responses including pupil dilation, eye widening, sweat gland stimulation, heart rate and muscle tension increases, blood diversion, and digestive inhibition. In general, the greater the increase in physiological arousal the greater the output score for the detection. The Excitement detection is tuned to provide output scores that reflect short-term changes in excitement over time periods as short as several seconds.

Interest (VAL) is the degree of attraction or aversion to the current stimuli, environment or activity and is commonly referred to as Valence. Low interest scores indicate a strong aversion to the task, high interest indicates a strong affinity with the task while mid-range scores indicate you neither like nor dislike the activity.

Engagement (ENG) is experienced as alertness and the conscious direction of attention towards task-relevant stimuli. It measures the level of immersion in the moment and is a mixture of attention and concentration and contrasts with boredom. Engagement is characterized by increased physiological arousal and beta waves along with attenuated alpha waves. The greater the attention, focus and workload, the greater the output score reported by the detection [4].

The Emotiv Insight also uses the EEG signals to measure Stress, Focus, and Relaxation. While we have kept these graphs on the performance metrics sheets (Performance metrics for pilot study [5]) we decided to focus our analysis on the above mentioned more precise criteria for reasons of clarity and simplicity in this pilot study.

Figure 5
Attempt to shield the brain scanner from electrical interference with a tin foil cap.

Figure 6
Shielding the LEDs on the VR HMD proved insignificant result in comparison to shortening to distance between the brainscanner's wireless transmitter and receiver.

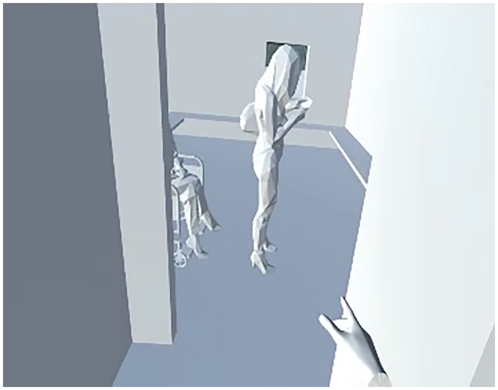


Figure 7
Female characters in the male changing room provided some measurable neuro feedback from some of the test subjects.

POTENTIAL SOURCES OF ERROR

Several circumstances, both technical and physiological, proved to inflict the quality of the outcome of this study. The technical issues were mostly related to interference between the two independent system worn on the head and face, namely the signal from the Insight's electrodes on the scalp and the wireless connections from the leds of the Oculus Rift HMD. We tried both to cover the Insight with tin foil (Figure 5) and covering the LEDs of the HMD (Figure 6) but eventually found those countermeasures were insignificant in comparison to moving the wireless receiver of the Insight within close range (<2m) of the device. A more material factor that also influence the use of the Insight brain scanner is the amount and type of hair on the head of the test subjects. A very dense type of hair proved more difficult to facilitate the electric signal to the electrodes. This being said, we did also encounter some test subjects with very short hair and no connection, or almost no connection, to the brain scanner. Evidently, these test subjects cannot be used in the study. We had one case of motion sickness in relation to the HMD VR experience, which concluded the test before usable data could be collected.

The door sign symbols of the changing rooms had been confused due to updates of the 3D models. That meant that all male test subjects encountered two female dummy characters in the male changing room (Figure 7) and the female test subject was met by a male dummy in a wheelchair. This conceivably caused a nonintentional impact on that particular part of the test.

While the number of test subjects is not sufficient to provide a meaningful quantitative data set, we will focus on a qualitative analysis of the consistency of individual test subjects, and must constrain ourselves to some very cautious general considerations until more samples from more test subjects have been gathered in a larger study.

ANALYSIS

A first glance at the metrics of the eight test subjects does not reveal a very generous amount of neurological correspondence between them. This perhaps indicates that the results of the experiences of the architecture are very dependent on the individual, or that they are different in nature. We are well aware that the sample size consisting of eight test subject cannot be used as a quantitative data set. We will in the analysis focus on the consistency in the individual cases and successively only very cautious, and with many reservations, convey our assumptions of a preliminary comparative analysis. As a delimitation, we will focus on the metrics for Excitement, Interest and Engagement.

The test subjects are numbered (2, 3, 4, 6, 7, 9, 10) due the screen outs of the missing numbers.

In the following sample analysis, the capital letter corresponds to the markings on the metric diagrams mentioned in the experiment setup. Find higher resolution metrics diagrams online (Performance metrics for pilot study [5]).

Test Subject 2

An analysis of test subject 2 (Figure 8) show a general high Interest throughout the test. The Interest rise from the beginning (A) when receiving the instructions and remain high until the subject reaches a dead end in the basement (between E and F) and the Interest drops. At the same time though, the Excitement rises drastically when the subject finds a window from the dead end to the outside.

Towards the end of the test (between G and H), there is a similar rise in both Engagement and Excitement with a drop in Interest, when the subject engage in lifting weights in the fitness room. High readings of Engagement corresponds fine to the interactivity of opening doors (C), using stairs for the first time (E), getting lost and finding back again (E) and, in this case, trying to lift weights (G).

Test subject 3

The most striking reading is observed on the Excitement graph that has a some rather distinguishable fluctuations. When the test subject enters the foyer and begin to look around (B) the Excitement rises very high (from around 15 % to 65 %). This is at the time where the test subject discovers the right door and thus where to go next. When the test subject enters the narrow hallway (C), the Excitement lowers again. When entering the changing room (D) the Excitement rises gradually until the test subject reenters the foyer (F). In the foyer itself, the Excitement rises again and peaks again when exploring he fitness room (G) and when concluding the test (I). This indicates a test subject who are excited to explore on his own, but also a possible link to the architectural perception of the space. The large foyer with lots of light and spacious qualities seems more exciting than the narrow hallway with only doors. Engagement also corresponds to the activity of opening doors, though on moderate scale. Interest remains mid-range and very steady throughout the test.

Test subject 4

In this test, the test subject seems to be very engaged with Engagement readings from 70-90% through most of the test. The Interest is mid-range and steady. The Excitement graph is not very high but peaking at the beginning while looking around and receiving the brief (A) and again in the changing room and when leaving this (D-E). The final peak is when the test is over (I). It is interesting that the Engagement graph seems to mirror the Excitement graph. When the Excitement rise, the Engagement drops. The highest peak of the Excitement is when the test subject momentarily gets lost in the shower. This test subject was very fast, almost as if playing a game that she needed to win. This could explain the very high level of engagement.

Test subject 5

While many fluctuations can be seen in this metrics graph, the Interest graph is the most stable (around 45-60%) through the test. A high level of Engagement and Excitement while receiving the brief (A) drops upon entering the foyer (B). Excitement rises again in the foyer, and Engagement peaks when find-

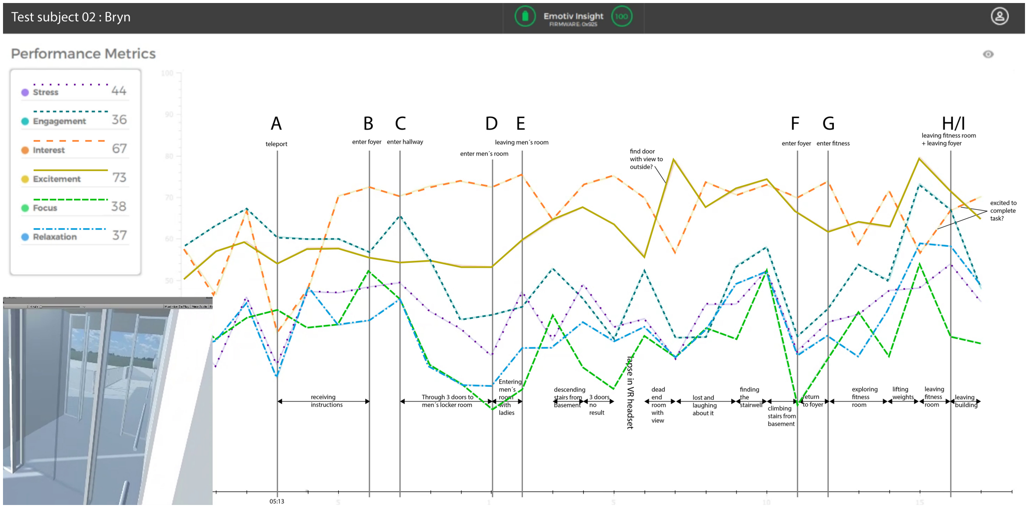


Figure 8
Performance metrics for test subject 2 showing graphs with markings corresponding to specific entry- and exit-points for all the test subjects.

ing and opening the door the narrow hallway (C). In the hallway they both drops. Opening the first set of doors corresponds to a rise in Engagement (C). The Excitement rises inside the changing room (D) until re-entering the foyer (F). In the foyer (between F and G) it peaks while the test subject is exploring and searching for the direction.

Test subject 6

Another example of a relatively high Engagement level, with two significant drops, throughout the test. While Interest is quite stable mid-range all the way, Excitement is low and peaks three times through the test. First peak is upon entering the foyer (B) and the next is in the changing room and leaving this (D, E, F), and the last is upon entering the fitness room (G). Again (as with test subject 4) we can observe a certain mirror effect between Engagement and Excitement, almost as if the mutually excluded on another. The two most radical drops of Engagement are when encountering a locked door (between C and D) and when turning all around confused about the way (between F and G). Both these drops of Engagement are synchronic with a slight rise both Excitement, but also Interest. A locked door seems slightly more interesting than the rest.

Test subject 7

The Interest graph is very stable at mid-range throughout the test. The Excitement graph peaks above mid-range twice in the test. The first peak appears at the beginning when the test subject is looking around and receiving the brief (between A and B) and the second time is in the narrow hallway just before entering the changing room (before D). We also observe a slight rise in excitement while exploring the fitness room (between G and H). A mirror effect between Engagement and Excitement can be traced almost consistently through the test.

Test subject 9

Again, we observe a stable mid-range Interest graph, slightly rising through the test. This test subject has a above mid-range Excitement graph around 65% in average. The Excitement graph is peaking while exploring (between A, B and C), entering doors (C, D, E, F), and when this test subject (male) purposefully entered the women's changing room, finding a dummy male in a wheelchair (due to the mistakenly replaced signage on the doors). In this case we do not observe a definitive mirroring between Engagement and Excitement as they on some occasions seem aligned instead of mirrored. Towards the end of the test there is a traceable, but not strong, mirror effect.

Test subject 10

In general, this test subject's metrics graphs are fluctuating with low drops and high rises on both sides of the mid-range for Engagement and Excitement. The Interest graph is relatively stable, fluctuating slightly below the mid-range. After receiving the brief (A) and beginning to explore on his own, the Excitement graph rises from low to above mid-range. It drops sharply around entering the foyer (B) and then rises (from B to C) to a high peak when entering the changing room (D). The Excitement detection remains above midrange for the rest of the test, dropping slightly when Engagement rises when re-entering foyer (F) and entering fitness room (G). A high peak of Excitement occurs (between F and G) when the test subject on his own accord explores the main sports arena, which is not specifically part of the test. At the exact same period a mirror effect on the Engagement can be observed. At the time the test subject enter the hallway (C), it seems like the Excitement and Engagement are shifting phases like a mirroring effect.

Preliminary comparison

As explained in the analysis introduction, a full comparison of the neurological feedback from the different test subjects makes little sense in this pilot study, when the data are from such a relatively scarce sample size. What is observed in this chapter is therefore mainly assumptions of potential correlations, which can only be qualified in a larger study.

One thing that seems to be correlating in this study, is that the Interest graph remains the most stable for all test subjects. It is also placed in the mid-range area for all test subjects, which indicate that they neither like nor dislike the activity. Another observation is the mirror effect of the Engagement and Excitement in some of the test subject metrics. This is not consistent, but an analysis on a larger sample size could probably be worthwhile in order to see in which cases one can be said to exclude the other.

In relation to the spatial quality of the architecture and its different appearances, e.g. in respectively the large open foyer and the narrow hallway with doors and stairs, it seems too early to say anything conclusive. A cautious estimation of the eight test subjects, in relation to the overall excitement in these two different spaces indicates that only three out of eight feels more excitement in the foyer than in the hallway. In six of the eight cases, we observe a rise in the Excitement when the test subjects enter the changing rooms. Likewise, we observe that six of the eight test subjects feel a drop in excitement once they exit (I) and the test is finished.

The exploration factor in relation to the Excitement is also something that could be a general tendency. When the test subjects are exploring freely, they tend to have a rise in the Excitement graph. This could be an entry point to investigate in a larger sample-size study. That there does not seem to be a clear pattern directly corresponding to the spatial qualities of moving through foyer and into the narrow hall, could simply indicate that the perception of architecture is a highly individual experience. Again, this cannot be investigated from this sample size. We will constrain ourselves to the observation that even though we can observe consistency within the individual test subjects performance metrics, no pattern can yet be discerned in relation to a general perception of the architectural qualities.

CONCLUSION

While we cannot conclude a precise terminology for the experience of architecture in a neurological perspective, we can conclude on the results of the methodology with the purpose of setting up a larger scale experiment with EEG and virtual reality in the field of architecture. The results from the neurological readings are no more or no less than what we expected from this preliminary study. It would have been intriguing if we could detect general correlations between the test subjects, but we did not expect that at this early stage. From the very broad nature of this study, we can extract and streamline the elements that proved to yield results in the individual cases.

The use of interaction, i.e. engaging in opening doors, shows engagement in the test subjects' behaviour. A virtual reality scenario incorporating such elements of interaction that cannot be provided to the same extent using traditional plan and section drawings or even non-immersive 2D and 3D, would be worthwhile to compare to more traditional architectural walkthrough animations in a neurological setting.

It is probably also necessary to focus a larger scale investigation on fewer architectural means. A more clear framework in the 3D model, e.g. limited to a transition from a small space to a larger space, from near darkness to a fully lit space, could perhaps be enough to gather data eliminating potential sources of error right from the beginning. In this case we will design a 3D model "in the lab" which will be more precise in the study than a real world 3D model.

From this preliminary study we can conclude that further studies with expertise from the field of architecture, neurology, and technology are required to generate more knowledge about the specific application of neurology in architectural perception. It seems to be a difficult but at the same time promising path towards a better understanding of the perception of architectural space that can eventually lead to a higher quality of architecture.

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Realistic Real Time Simulation of Room Acoustics using Virtual Reality with Auralization

Development and Initial Testing

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This paper describes the development and initial testing of a Virtual Reality with Auralization system. To facilitate a realistic auralization, sound sources were recorded in an anechoic room and inserted into a test scenario. The scenario was presented to test persons in order to evaluate the realism of the system, and provide feed-back ahead of further development.

Keywords: *Virtual Reality, Auralization, System Development*

INTRODUCTION

Evaluation of the acoustic quality of a room is in most cases based on exact and precise calculations of specific positions in a room. Realistic real time simulation of room acoustics in Virtual Reality (VR), also known as auralization, is another usable tool for evaluation, allowing comparison of multiple design options set against each other.

VR with real time auralization can act as a supplement to detailed acoustic calculations made by acoustic engineers. This method provides the ability to listen to how an acoustic design solution sounds (Kleiner, Mendel; Dalenbäck, Bengt-Inge; Svensson, 1993; Savioja and Svensson, 2015), and base design decisions on experiencing the acoustic perception of a room, in addition to the quantitative results from calculations.

In this paper we use the definition of Auralization formulated by (Schröder, 2011) as: Analogous to visualization... the generation of aural stimuli that correspond to the current sound propagation throughout the simulated scene".

VR in the building industry has previously primarily focused on the visual aspects of the tool, allowing immersion and interactivity, better perceptual experiences and communication leading to better decision making (Niu and Leicht, 2016; Roupé, Johansson and Tallgren, 2016).

Even though VR is used for many types analysis and evaluation of the indoor environment on design projects, the building industry nevertheless rarely include auralization to evaluate the acoustic qualities of rooms or buildings (Vorländer, 2008; Pelzer et al., 2014). The acoustic indoor environment is however just as important for the user experience of a room or building, as the thermal, atmospheric and visual indoor environment.

VR can act as a mean for communication between users and designers (Sørensen and Svidt, 2017) and additionally function in the same way as real life mock-ups, however without the same special and financial expenses involved (Zou, Li and Cao, 2017).

The acoustic design is especially influential in open office environments as unwanted sounds, often described as noise, is suggested to cause interruption, irritation and lowered performance for people perceiving it (Roelofsen, 2008; Seddigh et al., 2015). Sound disturbance is however not necessarily based on a particular sound or the magnitude of a sound, but how the sound is perceived (Roelofsen, 2008). Accordingly, some sounds might appear more annoying in real time than what calculations of the acoustic design might indicate. Realistic auralization in room acoustics is challenging, as a result of the sensitive perception of sound people have (Vorländer et al., 2015).

We designed a VR with Auralization system allowing realistic perception of sound, focusing not only on the acoustic calculations, but also on the realism of the auralization, to facilitate a better foundation for decision making with respect to the acoustic design, allowing for a realistic perception of sound within the virtual environment.

Informal user experience tests using scenarios inserted into the system with real time auralization were performed. The scenario was supplied with realistic sounds from typical one family housing units and educational buildings, allowing testing of the system's realism. Testing additionally allowed us to attain new information about the system and its capabilities ahead of further system development.

METHODOLOGY

To test the VR with Auralization system, anechoic-recorded sounds were inserted into a 94 m2 lecture room test scenario in VR. Sound sources were placed in the scenario using the Epiito Software and AM3D auralization software, based on the Unity Game Engine.

The VR setup for testing included the Oculus Rift CV1 head mounted display (HMD) for the visual part and Seenheiser PC 363 D headphones for playing the sounds during the real time auralization.

The VR with auralization was then examined by multiple persons, with the intention of evaluating the realism of the recorded sounds, the placement of the sound sources, and the realism of the perception possible in the system.

The acoustic quality of the test scenario was based on manual adjustment of the sound levels of the sources. The reverberation was adjusted by a choice of absorption coefficients based on the actual materials in the room and knowledge of the reverberation time.

Empiric data collection

Empiric data were collected based on the contextual design methodology as described by (Beyer and Holtzblatt, 1997) using contextual inquiry, to both ask questions to the test persons, and observe the test persons during their interactions with the system.

Recording setup and entities

Even though sound is perceived differently from person to person, the sounds used for auralization in evaluation of room acoustics, the quality of recordings need a known calibrated recording chain without influence of reverberation from surroundings.

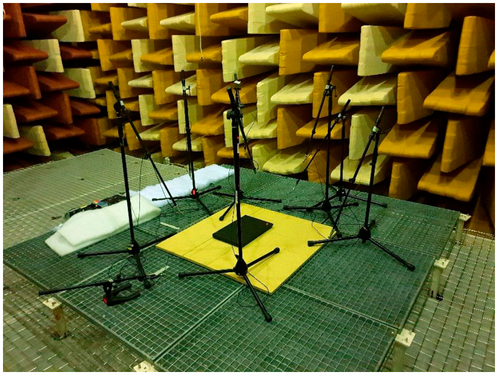

Figure 1
Recording of sound from a laptop in an anechoic room. A square wooden board was placed under the laptop to ensure realism of the recording.

As part of this study, sounds were recorded in an anechoic room at the Department of Electronic Systems at Aalborg University. The anechoic room has sound absorbing wedges assuring a reflection free environment down to approximately 65Hz.

8 G.R.A.S. 40AZ microphones with preamplifier type 26CC were placed around the entity being recorded. In this paper, an entity refers to the thing or process being recorded. The sound was recorded through an RME Micstasy sound card (44.1 kHz 24 bit) using a multi-track recording software on a PC.

Microphones were placed with a distance of 500 mm from the entity being recorded, placed in a sporadic grid constellation as shown in figure 1.

The entities being recorded were selected based on analysis of common household appliances and electronic equipment in typical one family housing units and educational buildings. The scope was thusly limited, to ensure usability of the auralization with VR, in new design and renovation of typical family houses and educational buildings.

System testing

The system was tested using informal experience tests, involving both software and method developers and end users of the VR with Auralization system.

Test persons were instructed to walk around in the scenario and listen to the sounds of the various sound sources placed in the room, as shown i figure 2. The test persons were also instructed to consider the sound transition of the multiple sound sources placed in the scenario.

The sounds played in the scenario were:

- Speech.
- Sound from electronic equipment.
- Sound from construction work through an open window.
- Sound from neighbouring room through an open door.

All sound sources were placed in a fixed position on a specific surface in the scenario.

The testing of the scenario was conducted in the exact room the scenario was based on, at Aalborg University. To make the scenario as realistic as possible it was furnished in the same way as the real room. This was done to allow the test persons to easily compare the experience of the VR scenario to the real room.

FINDINGS

- The overall reactions by the test persons were that the perception of sound through the VR with Auralization system was realistic, and gave a keen understanding of the acoustic qualities of the scenario.
- The ability to interact with the virtual environment allowing the test persons to relocate furniture in the scenario, was a distraction for some of the test persons, who seemed to occasionally focus more on the capabilities of virtual reality than the auralization.
- As some of the test persons were not accustomed to the use of VR, the controlling of the avatar made some of the test persons give up moving around in the scenario, which limited their feedback with respect to the realism of the sound sources.
- The sound source of a neighbouring room, was placed on the open door. When passing through the door all sounds were muted, which was commented by a couple of test persons, as a limitation to the realism of the system.
- As the sound sources in the scenario had a fixed placement, some of the test persons experienced a lowered realism of the sounds movement in the room, as the sound perception was only altered in volume when moving around, and not how the sound was reflected from surfaces.

DISCUSSION

As the use of Virtual Reality (VR) has seen increased use in recent years for various types of design and construction evaluation, including acoustic evaluation, using auralization to the wide portfolio of VR-uses therefore seems logical. Even though full real

Figure 2
Test persons navigating around the test scenario.

life representation of the visual aspects in VR is not a necessity (Pitt et al., 2005), this is not the case when it comes to acoustic design evaluation using VR with auralization.

To be effective as a decision tool for acoustic design, a high degree of realism is imminent. This means the perception made possible by the system must sound realistically.

Virtual Reality is often used as an interactive design platform (Svidt and Sørensen, 2012; Petrova et al., 2017; Rasmussen, Gade and Jensen, 2017) with communication during use occurring either in real life, by people speaking to each other, or through a headset using internet technology to connect with people also using VR in another location.

When using VR with Auralization, with communication in either real life or through communication technology, it can be difficult to control the sound levels.

The sound levels however needs to be controllable in a way that ensures that communication and interaction with other system users sound realistic. This means that sound arising from communication by users, must be played and controlled, without affecting the sounds played in VR. This issue was not addressed in the user experience test. A solution addressing the problem would however optimize usage and realism of the system, when more than one person needs to communication whilst using the system.

The ability to listen to solutions allows designers to make informed design decisions, but also communicate design choices to clients and design project participants in a more tangible manner than looking at drawings, 3D models, graphs or calculations.

LIMITATIONS OF THE STUDY

- The absorption coefficients of the system were adjusted according to actual materials in the room as well as the measured reverberation time, however, the auralization software only allowed for specification of one overall absorption coefficient per surface. So frequency dependencies of the reverberation time in the real room would not necessarily be recreated in VR.
- Only stakeholders of the system development were involved in testing, allowing an obvious bias in evaluating the system as more realistic and usable than people without a bias might have.
- Only one test scenario was used, limiting the range of generalizability of the study.
- In the current study, no quantitative methods were used to document the informal user experience test, all conclusion are therefore based on qualitative evaluations.

CONCLUSION

This paper investigated the possibilities of realistic sound recordings and the use of such in Virtual Reality (VR) with auralization, supplementing acoustic calculations with the ability to listen to design options in a realistic real life manner, before a room or building is constructed.

Informal user experience tests of the sounds made it possible to evaluate the use and realism of the system. It additionally made it possible to see how VR with auralization can potentially supplement the acoustic design evaluation used in the design industry.

Promising results were captured during the tests, through contextual inquiry, as all test persons rated the system as realistic. Improvements however needs to be made to the VR with Auralization system with respect to placement and movement of sound sources and transition of sound between rooms or scenarios.

FUTURE WORK

To ensure a reliable perceptual experience for users of the Virtual Reality (VR) with auralization system, further research must be done in respect to placement of sound sources in VR.

To make the system available on a larger scale, calibration of listening devices is necessary to ensure accurate playing of the recorded sounds in both headphones and through speakers, in order for the perceptual experiences to be realistic. Such calibration device must therefore be developed as part of future development of the system.

Unbiased tests of the system is needed in order to evaluate the system, its use, and its usability with respect to the design industry in general.

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