Haliç Üniversitesi Fen Bilimleri Dergisi 2024, 7/2: 107-132
DOI: 10.46373/hafebid.1542678

ISSN: 2618-6241
e-ISSN: 2667-5757

Exploring Architectural Tools for Oculus Quest 2

Erdem YILDIRIM[1*]

[1]Department of Architecture, Faculty of Architecture, Dokuz Eylül University, İzmir, Türkiye

Geliş Tarihi: 03.09.2024
Kabul Tarihi: 28.10.2024

***Sorumlu Yazar e mail:** erdem.yildirim@deu.edu.tr

Atıf/Citation: Yıldırım, E., "Exploring Architectural Tools for Oculus Quest 2", Haliç Üniversitesi Fen Bilimleri Dergisi 2024, 7/2: 107-132.

Araştırma Makalesi/ ***Research Article***

Abstract

Virtual Reality (VR) has emerged as a transformative technology in architectural design, providing immersive and interactive experiences that surpass traditional methods. This article explores the diverse applications of VR in architecture, with a particular focus on the Oculus Quest 2 due to its accessibility, dedicated user platform, and specialized software. The study thoroughly examines both stand-alone and computer-connected VR tools and platforms, detailing how they can be utilized in architectural workflows. Stand-alone software such as Gravity Sketch, Arkio, and SketchUp Viewer run directly on the Oculus Quest 2, offering intuitive design and visualization capabilities without the need for a computer. On the other hand, the software requiring computer connectivity like Blender, Rhino, Unity, and Enscape leverage the processing power of a PC to provide advanced features and detailed visualizations through platforms like SteamVR or Meta Quest Link.

The article also provides a comparative analysis of these tools, highlighting their strengths and limitations, focusing on their usability, accessibility, and relevance to architectural practice. Additionally, the integration of VR with Building Information Modeling (BIM) is identified as a significant innovation that enhances collaboration and information synchronization throughout the design and construction process. While the primary focus is on practical applications for architects and designers, the article also briefly touches on the educational implications of VR software, offering insights into how these tools can be used to enable students engage with complex spatial concepts in an intuitive manner.

The findings of this study emphasize VR's critical role in fostering creativity, improving design accuracy, and enhancing the overall architectural workflow. The analysis reveals that tools like Gravity Sketch excel in freeform modeling, while Arkio stands out for its BIM compatibility and cross-platform availability. These insights provide a foundation for future research, development, and innovation, positioning VR as a pioneer technology in the future of architecture.

Keywords: Architecture, Virtual Reality, Oculus Quest 2, 3D Visualization, BIM, Architectural Education

Oculus Quest 2 için Mimari Araçların Keşfi

Öz

Sanal Gerçeklik (VR), mimari tasarımda geleneksel yöntemleri aşan, sürükleyici ve etkileşimli deneyimler sunan dönüştürücü bir teknoloji olarak ortaya çıkmıştır. Bu makale, erişilebilirliği, belirli bir kullanıcı platformuna sahip olması ve özel uygulamaları nedeniyle Oculus Quest 2'ye odaklanarak, VR'ın mimarlıkta çeşitli uygulamalarını incelemektedir. Çalışma, hem bağımsız hem de bilgisayar bağlantılı VR araçlarını ve platformlarını detaylı bir şekilde ele alarak mimari iş akışlarında nasıl kullanılabileceklerini açıklamaktadır. Gravity Sketch, Arkio ve SketchUp Viewer gibi bağımsız uygulamalar, Oculus Quest 2 üzerinde doğrudan çalışarak bilgisayara ihtiyaç duymadan sezgisel tasarım ve görselleştirme yetenekleri sunar. Öte yandan, Blender, Rhino, Unity ve Enscape gibi bilgisayar bağlantısı gerektiren uygulamalar, SteamVR veya Meta Quest Link gibi platformlar aracılığıyla PC'nin işlem gücünden yararlanarak gelişmiş özellikler ve detaylı görselleştirmeler sağlar.

Makale ayrıca bu araçların güçlü ve zayıf yönlerini vurgulayan karşılaştırmalı bir analiz sunarak, kullanılabilirlik, erişilebilirlik ve mimari uygulamalara uygunluklarına odaklanmaktadır. Ayrıca, VR'ın Bina Bilgi Modellemesi (BIM) ile entegrasyonu, tasarım ve inşaat süreci boyunca iş birliğini ve bilgi senkronizasyonunu artıran önemli bir yenilik olarak tanımlanmaktadır. Ana odak, mimarlar ve tasarımcılar için pratik uygulamalar üzerinde olsa da, makale aynı zamanda VR yazılımlarının eğitimsel etkilerine de kısaca değinerek bu araçların karmaşık mekansal kavramlarla sezgisel bir şekilde etkileşim kurmak için nasıl kullanılabileceğine dair içgörüler sunmaktadır.

Bu makale, mimarideki VR yazılımlarının mevcut durumuna kapsamlı bir bakış sunarak, gelecekteki eğilimler ve potansiyel gelişmeler hakkında bilgiler sağlamaktadır. Bulgular, VR'ın yaratıcılığı teşvik etmede, tasarım doğruluğunu artırmada ve genel mimari iş akışını iyileştirmede kritik bir rol oynadığını vurgulamakta ve VR'ı geleceğin mimarisinde temel bir teknoloji olarak konumlandırmaktadır.

Anahtar Kelimeler: Mimarlık, Sanal Gerçeklik, Oculus Quest 2, 3D Görselleştirme, BIM, Mimarlık Eğitimi

1. Introduction

Virtual Reality (VR) has transformed a variety of disciplines, such as architecture, engineering, education, and the humanities. VR, a technology that simulates a three-dimensional environment, provides immersive experiences that have the potential to revolutionize the way we interact with objects and spaces, as well as envision and design them. VR has emerged as a potent tool that surpasses conventional two-dimensional representations from the screens in the context of architectural design and visualization, allowing architects, designers, and students to interact with spatial concepts in a more intuitive manner.

The integration of VR into architectural design enables a more thorough comprehension of the human interaction, lighting, materials, and spatial relationships within a designed environment. The design process is further improved by the integration of VR with Building Information Modeling (BIM), which provides a collaborative platform that synchronizes information across various stages of a project, from conceptualization to construction [1].

VR has been implemented in the educational sector to enhance the learning and teaching experiences [2]. It enables students to innovatively recognize good design practices and visualize complex systems. Additionally, VR and AR's potential for research, dissemination, and mediation in the humanities is illustrated by its use in the recreation of historical sites and events [3]. The potential of VR to manage intricate spatial configurations and continuous updates in accordance with new standards and healing techniques is emphasized by its use in complex architectures, such as soundscape design [4].

The Oculus Quest was chosen for this study due to its wireless capabilities, user-friendly interface, and high-resolution display, dedicated app market which make it an ideal platform for architectural design and education. Its economic accessibility, portability and extensive application support provide architects and students with an

accessible and effective VR experience, enhancing the overall usability and integration of VR in architectural workflows.

The architectural design process is a structured sequence of stages that guide the development of a project from initial concept to final construction. VR technology can significantly enhance each of these stages, particularly in the following areas:

In the conceptual design phase, architects brainstorm and develop the basic idea or concept for the project. VR allows for the creation of immersive 3D sketches, enabling designers and stakeholders to explore and refine ideas in a virtual space. This enhances creativity and helps in visualizing the potential of the design early on like physical models but much faster.

Throughout in the whole design process, VR serves as a powerful tool for real-time visualization. It allows architects to create detailed virtual models that can be explored and modified at any stage of the design. This continuous visualization helps in identifying potential issues, making necessary adjustments, and ensuring that the design evolves in line with the project goals.

VR is particularly effective for client presentations and demonstrations. It provides clients with an immersive experience, allowing them to walk through the virtual model of the project. This helps in conveying design concepts more effectively and facilitates better communication and feedback. Clients can experience the space as if it were already built, leading to more informed decision-making.

By integrating VR technology at these critical stages of the architectural design process, architects can enhance visualization, improve collaboration, and streamline workflows. The Oculus Quest 2, with its accessibility and advanced capabilities, serves as an effective tool for implementing VR in these various phases, thereby transforming traditional architectural practices.

2. Literature Review

The history of VR is extensive and multifaceted, encompassing a variety of fields and applications. Schroeder [5] offers a comprehensive account of the evolution of interactive computer graphics, examining the socio-technical influences that have influenced the development of multi-user VR systems. Brooks [6] contemplates the early stages of VR technology, exploring its potential as a novel form of expression. The evolution and diversification of VR applications are further characterized by the integration of VR in various sectors, including air traffic control [7], surgical education [8], or public education [9].

The integration of VR into the architectural design process has garnered substantial attention. Aydın and Aktaş [10] investigate the function of VR-based architectural design education, which encompasses real-time rendering and 3D form-finding. The Eindhoven Perspective by Achten et al. [11] delineates the context and history of VR in architectural education, examining the use of VR in student projects since 1991. Zhang [12] presents a methodology for the integration of VR-BIM into the construction management undergraduate program, addressing obstacles and suggesting potential solutions.

VR's role in architectural visualization is significant, providing enhanced spatial understanding and interactive design environments. Giailorenzo et al. [13] have investigated the potential of VR in intricate architectures, including hospital design. They developed a methodology that integrates BIM models with high-end immersive VR systems. The efficiency of VR in an urban planning context was emphasized by Imottesjo and Kain [14], who investigated the usability of online VR technology for 3D urban planning and design. Lau et al. [15] conducted a cross-sectional study to compare VR visualization with 3D printed heart models in congenital heart disease.

In various contexts, the collaborative and immersive aspects of VR have been investigated. The application of a VR-based workflow in a real project was examined by Zaker and Coloma [16], who

assessed the advanced features of VR software. Walmsley and Kersten [17] detailed the creation of an immersive VR application for the Imperial Cathedral in Königslutter that incorporates 360° panoramic photographs into the virtual environment.

The application of VR in the construction industry has shown significant promise in enhancing various aspects of project management and execution. VR allows for immersive 3D walkthroughs of building designs, providing a more intuitive understanding of spatial relationships and potential challenges within a project. VR can also be used for construction training and education, offering safer and more effective training environments [18,19]. Additionally, VR aids in optimizing site planning and improving quality control and inspection processes by allowing for detailed simulations and real-time adjustments [20].

Numerous studies have illustrated the utilization of VR in the preservation of cultural heritage and historical recreation. Soto-Martín et al. [21] present a method for the reconstruction and restoration of historic buildings and mural paintings through the use of digital models. This approach demonstrates the effectiveness of VR in preserving and presenting historical artifacts and sites. The use of VR in the production process, particularly in complex architectural projects, has shown significant potential. François et al. [22] describe the VESPACE project, which employs VR to recreate 18th-century theater. This project highlights the use of VR for detailed production planning and execution in historical recreations.

In conclusion, the integration of VR technology within these domains not only enhances current practices but also paves the way for future innovations. The ongoing advancements in VR are likely to further revolutionize how we approach education, project management, and preservation efforts. As VR continues to evolve, its potential to transform and improve various aspects of architecture and construction will undoubtedly expand, making it an indispensable tool for professionals in these fields. Future research should continue

to explore and document these developments, ensuring that the full spectrum of VR's capabilities is realized and effectively utilized.

3. Methodology

The methodology employed in this study aims to provide a comprehensive analysis of the applications of virtual reality in architectural modeling and visualization. A thorough literature review was performed to identify relevant studies, articles, and case studies concerning the applications of virtual reality in architectural design, education, construction, historical recreation, technology comparison, collaboration.

A comparative analysis was performed to evaluate the characteristics, usability, integration with other tools, and specific applications in architectural design of different VR modeling and visualization applications. This analysis was guided by prior research comparing VR with alternative technologies [23] and examining the collaborative and immersive dimensions of VR [24].

The VR applications were classified into three primary categories according to their operational prerequisites and intended users: standalone applications, applications necessitating computer connectivity, and entry-level applications. Standalone applications operate directly on the Oculus Quest 2 without requiring a computer, encompassing both visualization and design tools. Applications necessitating computer connectivity generally function via plugins and platforms such as SteamVR or Meta Quest Link, encompassing both visualization and design tools. Entry-level applications are accessible tools designed for pre-architectural education at the secondary school level or for non-professional users.

Each application was assessed according to its capacity to import and export diverse file formats, essential for interoperability and integration into current architectural workflows. This encompassed formats including OBJ, FBX, SKP, and others. The potential influence

of VR tools on architectural education was evaluated, emphasizing their capacity to improve pedagogical methods, spatial comprehension, and student involvement. This entailed assessing the accessibility, usability, and pertinence of VR tools in educational environments.

The results from the literature review, comparative analysis, categorization, and evaluations were integrated to present a thorough overview of the present status of VR applications in architecture. This synthesis emphasized the advantages, drawbacks, and prospective future developments of VR technology in the domain.

4. Examination of Applications

This section is segmented into three parts to thoroughly examine the diverse applications of virtual reality in architecture utilizing the Oculus Quest 2. The Oculus Quest 2's distinctive advantage over platforms such as the HTC Vive is its capability to function autonomously without requiring a computer. This independent functionality is utilized by various applications, which will be examined in the initial section. The subsequent section will concentrate on techniques necessitating computer connectivity, usually via plugins and platforms such as SteamVR or Meta Quest Link. The third section will address entry-level applications appropriate for pre-architectural education at the secondary school level or for non-professional users.

This section is segmented into three parts to thoroughly examine the diverse applications of virtual reality in architecture utilizing the Oculus Quest 2. The Oculus Quest 2's distinct advantage over platforms such as the HTC Vive is its capacity for standalone operation without reliance on a computer. This independent functionality is utilized by various applications, which will be examined in the initial section. The subsequent section will concentrate on techniques necessitating computer connectivity, generally via plugins and platforms such as SteamVR or Meta Quest Link. The third section will address

entry-level applications appropriate for pre-architectural education at the secondary school level or for non-professional users.

4.1 Standalone Applications

Standalone applications operate directly on the Oculus Quest 2, eliminating the necessity for a computer, thereby enhancing accessibility and convenience for professional and educational applications in the studio. These applications utilize the Oculus Quest 2's features to deliver immersive experiences without requiring supplementary hardware makes them more accessible in many situations.

4.1.1 Independent Visualization Applications

Standalone visualization applications are specifically intended for the observation and interaction with 3D models within a virtual setting. These applications utilize the Oculus Quest 2's functionalities to deliver immersive experiences independently of a computer. They are especially beneficial for client presentations, design evaluations, and virtual tours, providing intricate visualizations that improve comprehension of architectural projects. Although these applications emphasize visualization, they also incorporate fundamental interaction features that enable users to navigate and examine the models more intuitively.

Resolve is a robust virtual reality application intended for immersive visualization. It enables architects and designers to investigate 3D models within a completely immersive environment, offering an authentic perception of scale and space. Resolve facilitates the exportation of annotations in BCF (BIM Collaboration Format) and XML formats, thereby ensuring compatibility with other applications such as Revizto and Navisworks.

AutodeskXR provides an extensive array of tools for visualizing architectural designs in virtual reality. This standalone application

allows users to engage with intricate 3D models and environments, thereby improving comprehension of complex architectural projects (Figure 1). AutodeskXR facilitates the importation of models from Revit and other Autodesk applications, generally utilizing formats such as FBX, DWG, and DWF.

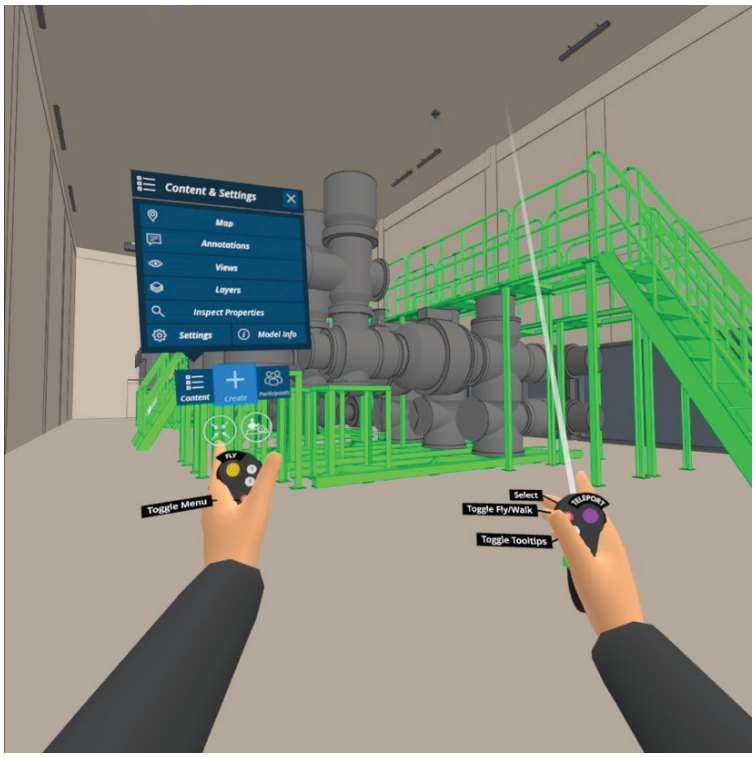

Figure 1. AutodeskXR's interface.

3D Vista VR is a multifaceted application for the creation and observation of virtual tours. It enables architects to showcase their designs interactively, offering clients a virtual tour of the project (Figure 2). 3D Vista VR facilitates the importation of image formats including JPG, PNG, BMP, TIFF, and GIF, and enables the exportation of virtual tours in web-compatible formats as well as standalone executable files (EXE for PC and tar.bz2 for Mac).

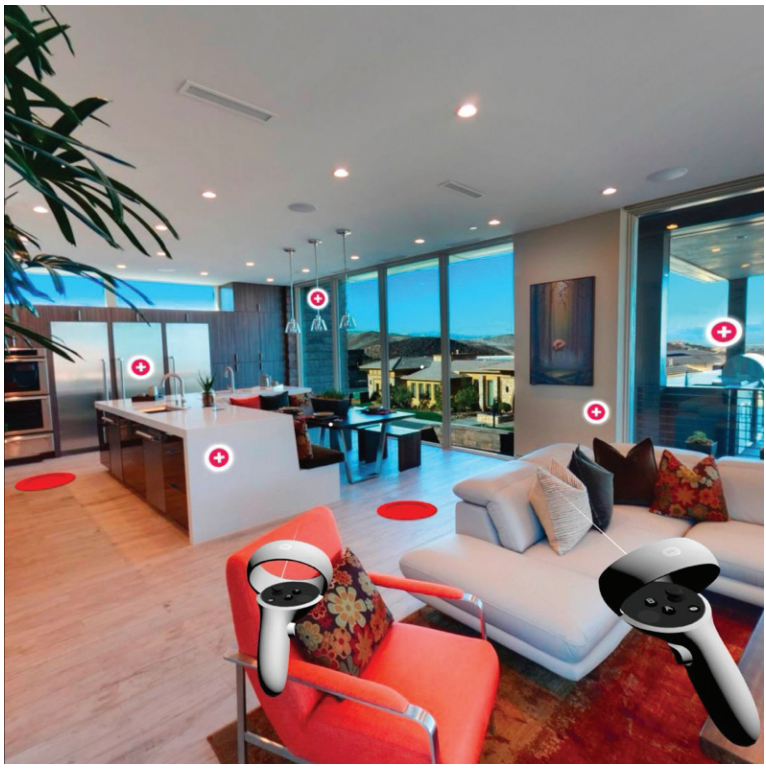

Figure 2. 3D Vista VR's interface.

4.1.2 Standalone Design Applications

Standalone design applications transcend basic visualization by allowing users to create, alter, and engage with 3D models directly within the VR environment. These applications are specifically designed for the Oculus Quest 2, offering a seamless and immersive design experience independent of a computer. They facilitate various design activities, including sketching, modeling, and collaborative on site or online design sessions, rendering them suitable for both professional architects and students. Although visualization is essential to these applications, their main emphasis is on enhancing the design process via intuitive and interactive tools.

Gravity Sketch is a virtual reality design tool enabling users to construct three-dimensional models within a virtual setting. It facilitates intuitive sketching and modeling, rendering it an invaluable instrument mainly for industial designers and architects to conceptualize and refine their freeform designs in real-time. Gravity Sketch facilitates the importation of models in OBJ and FBX formats, and the exportation of models in OBJ, FBX, and IGES formats. Gravity Sketch excels in creating curvilinear forms, making it popular in automotive and industrial design for its ability to model complex, freeform shapes. This same capability is valuable in architecture, where it allows architects to explore innovative, fluid designs. By enabling real-time adjustments and immersive visualization, Gravity Sketch enhances the architectural design process, fostering creativity and precision in developing unique, high-quality projects. Additionally, it offers Rhinoceros T-spline-like modification of surfaces, providing architects with advanced tools for refining and perfecting their designs (Figure 3).

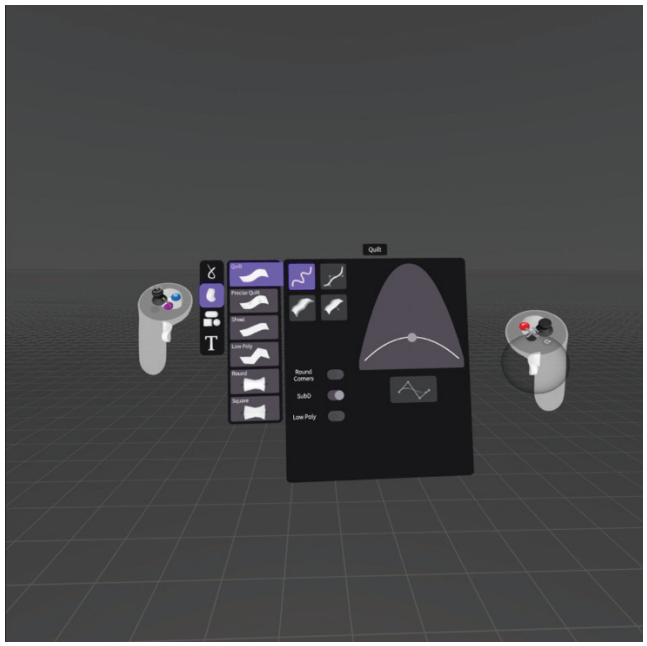

Figure 3. Gravity Sketch's freeform surface interface.

Arkio is a collaborative design application that allows users to sketch, model, and create in virtual reality. Arkio, as an independent application on Oculus Quest 2, is ideally suited for architectural design courses and professional applications, fostering creativity and collaboration in design processes (Figure 4). Arkio facilitates the importation of models in OBJ and FBX formats, as well as the exportation of models in the same formats. The most important feature of Arkio is its execution in most of the operating systems like Windows, OSX, Android and IOS.

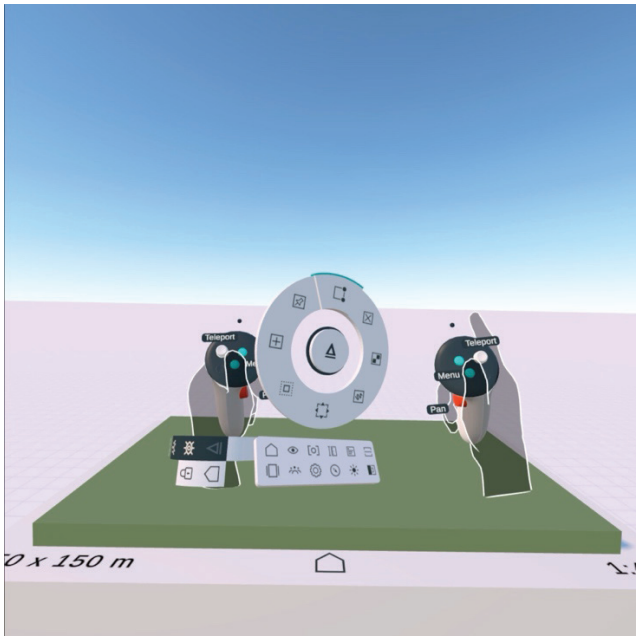

Figure 4. Arkio's interface.

Shapes XR is intended for the creation and presentation of immersive 3D models. It enables architects to visualize their designs in virtual reality, offering an interactive method for spatial planning and design with vast amount of assets (Figure 5). This independent application is especially beneficial for initial design and concept formulation my enabling custom animations in VR. Shapes XR

facilitates the importation of models in prevalent 3D formats, including OBJ and FBX, and the exportation of models in OBJ and FBX formats.

Figure 5. ShapeXR's asset library.

SketchUp Viewer: SketchUp Viewer is a virtual reality extension of the popular 3D modeling software SketchUp. It allows users to display and modify 3D models in virtual reality directly on the Oculus Quest 2, offering an immersive experience for both designers and clients. This independent application improves the visualization and evaluation process in architectural projects (Figure 6). SketchUp Viewer facilitates the importation of models in the SKP format, which is native to SketchUp.

Figure 6. SketchUp Viever's interface.

4.2 Applications Requiring Computer Connectivity

4.2.1 Visualization Applications

Applications for visualization in this category are chiefly employed for the examination and interaction with 3D models within a detailed and immersive setting. These applications typically necessitate the processing of models on a computer, which are subsequently streamed to the Oculus Quest 2 through SteamVR or Meta Quest Link. This configuration facilitates intricate and comprehensive visualizations, which are crucial for professional architectural presentations and design evaluations.

Rhinoceros - Simlab: Rhinoceros, often referred to as Rhino, is a potent 3D modeling software that, in conjunction with Simlab, offers

advanced VR visualization functionalities. Simlab accommodates a diverse array of import and export formats, such as 3D PDF, FBX, OBJ, STL, among others. This adaptability enables architects to utilize diverse file formats and effortlessly incorporate their models into virtual reality settings. The integration of Rhino and Simlab improves spatial comprehension and client presentations through the provision of intricate and interactive visualizations.

Enscape is a real-time rendering and virtual reality plugin that integrates effortlessly with widely used architectural design software, including SketchUp, Revit, ArchiCAD, and Rhino. Enscape facilitates export in formats such as EXE standalone files, Web Standalone, and multiple image formats (PNG, JPG, EXR, TGA). This facilitates superior visualizations and immersive walkthroughs, rendering it an indispensable instrument for design evaluations and client presentations in 2D. Enscape's capability to export VR scenes as standalone executables is especially advantageous for disseminating interactive experiences without necessitating supplementary software.

Unreal Engine and Twinmotion provide sophisticated real-time rendering and virtual reality functionalities. Twinmotion accommodates import formats like FBX, C4D, OBJ, and SKP, and export formats such as EXE standalone files and Datasmith files for Unreal Engine 3. This formidable pair enables architects to produce intricate and interactive visualizations. The models are processed on a computer and subsequently experienced in virtual reality via the Oculus Quest 2, facilitating a realistic and immersive design review process. The integration with Datasmith guarantees the precise transfer of all geometry, materials, and lighting configurations to Unreal Engine for additional refinement.

4.2.2 Design Applications

Applications in this category allow users to create, modify, and engage with 3D models within a virtual environment. These applications

generally necessitate a computer to manage the processing power essential for intricate design tasks, with the VR experience enabled via SteamVR or Meta Quest Link. This configuration facilitates more intricate and engaging design processes, rendering these tools indispensable for professional architects and designers.

MindeskVR is a virtual reality design tool that integrates with widely used CAD software, including Rhino and SolidWorks. It accommodates import formats such as Rhino (.3dm), SolidWorks (.sldprt, .sldasm), and export formats including FBX and OBJ4. MindeskVR enables architects to construct and alter 3D models instantaneously within a virtual setting. The processing occurs on a computer, with the VR experience transmitted to the Oculus Quest 2, facilitating a seamless and immersive design workflow. The live-link functionality guarantees that modifications executed in the CAD software are immediately manifested in the VR environment.

Unity and Pixyz together provide a robust platform for developing interactive 3D content and virtual reality applications. Pixyz accommodates a diverse array of import formats, such as CATIA, NX, SolidWorks, STEP, IGES, FBX, OBJ, among others. Export formats encompass FBX, OBJ, glTF, and USDZ6. This configuration enables architects to design and visualize their projects within an immersive virtual reality environment. The computer manages the processing, while the Oculus Quest 2 enables the VR experience. Pixyz's capability to manage intricate CAD models and enhance them for real-time rendering in Unity renders it an indispensable instrument for comprehensive and interactive architectural design.

4.3. Entry Level Applications

Entry-level applications are crafted to be intuitive and accessible, rendering them appropriate for pre-architectural education at the secondary school level or for non-professional users. These applications offer a streamlined introduction to virtual reality and

architectural design, enabling users to investigate fundamental concepts and cultivate essential skills. Although they may lack the sophisticated functionalities of professional tools, they are beneficial for educational purposes and for novices in the field of architecture.

Open Brush is an open-source virtual reality painting application that originated from Google's Tilt Brush. It enables users to generate 3D artwork within a virtual environment, serving as an exceptional instrument for examining spatial concepts and artistic expression. Open Brush facilitates the import and export of models in formats like OBJ and GLB, allowing users to share their creations with various 3D applications.

Home Design 3D VR is an intuitive application enabling users to design and visualize residential layouts within a virtual setting. It is especially appropriate for novices and enthusiasts seeking to explore interior design and spatial arrangement. The application facilitates the importation of models in formats such as OBJ and the exportation of designs in both 2D and 3D formats, thereby simplifying project sharing and further development.

These introductory applications offer an accessible entry point to virtual reality and architectural design, assisting users in developing confidence and foundational skills prior to advancing to more sophisticated tools. They are optimal for educational contexts and for individuals seeking to investigate the fundamentals of architectural design in a virtual setting.

5. Results

The examination and comparative evaluation of various VR tools in architectural design, visualization, and education have uncovered a dynamic and intricate landscape. The primary insights, implications, challenges, and opportunities that result from this analysis are synthesized in this section.

5.1 Functionality and Features

Insights into the capabilities, strengths, and weaknesses of various VR tools in architectural design and visualization are gained through the comparative evaluation of features and functionality. This section compares and evaluates the features and functionality of professional 3D modeling tools, architectural visualization tools, educational and entry-level tools, and open-source and customizable tools. The selection of a tool is contingent upon the specific requirements, objectives, and contexts, which can range from professional 3D modeling and architectural visualization to educational engagement and open-source customization. The ongoing development of these tools [25], in conjunction with the increasing integration of VR technology [26], presents exciting opportunities for further innovation and exploration in the field of architecture and beyond.

5.2 Accessibility and Usability

The effectiveness and adoption of VR tools in architectural practice, education, and visualization are significantly influenced by their usability and accessibility. This section evaluates and contrasts the accessibility and usability of a variety of VR tools, taking into account factors such as user-friendliness, learning curve, customization, collaboration, and integration with other tools [27]. The comparative assessment of accessibility and usability reveals a wide variety of VR tools, each of which is tailored to the unique requirements, levels of expertise, and applications of its users. Professional tools may provide advanced capabilities; however, they may also necessitate more rigorous training. In contrast, educational and entry-level tools emphasize accessibility and user-friendliness. Open-source and customizable tools provide adaptability; however, they may necessitate particular technical abilities.

5.3 Relevance to Architectural Education

The integration of VR tools in architectural education has emerged as a transformative approach to the teaching and learning of design principles, spatial understanding, collaboration, and creativity. This section evaluates the potential of a variety of VR tools to improve pedagogical practices and student engagement in architectural education. The multifaceted landscape of VR tools is revealed through the comparative evaluation of features and functionality, usability and accessibility, and relevance to architectural education. Each tool is tailored to meet the specific requirements of various educational contexts, expertise levels, and needs, and offers a variety of applications and capabilities [28]. The incorporation of VR into architectural education offers thrilling prospects for exploration, collaboration, and innovation [29–31].

When selecting a tool, it is crucial to ensure that the features, usability, accessibility, and relevance are in accordance with the desired outcomes, user expertise, and educational objectives. Further advancements in the accessibility to opportunities in education, and beyond are anticipated as a result of the ongoing evolution of VR technology and the increasing interest in immersive experiences in various education disciplines [32,33].

5.4 Summary of Applications

The following table provides a summary of the various applications available for Oculus Quest 2, including their categories and supported import/export formats:

Table 1. Overview of VR Applications for Oculus Quest 2 in Architectural Design.

App Name	Category	Import Formats	Export Formats	Operating Systems
Resolve	Standalone Visualization Apps	-	BCF, XML	Oculus Quest 2
AutodeskXR	Standalone Visualization Apps	FBX, DWG, DWF	-	Oculus Quest 2
3D Vista VR	Standalone Visualization Apps	JPG, PNG, BMP, TIFF, GIF	EXE (PC), tar.bz2 (Mac)	Oculus Quest 2, Windows, Mac
Gravity Sketch	Standalone Design Apps	OBJ, FBX	OBJ, FBX, IGES	Oculus Quest 2, Windows, Mac
Arkio	Standalone Design Apps	OBJ, FBX	OBJ, FBX	Oculus Quest 2, Windows, Mac, iOS, Android
Shapes XR	Standalone Design Apps	OBJ, FBX	OBJ, FBX	Oculus Quest 2
SketchUp Viewer	Standalone Design Apps	SKP	-	Oculus Quest 2, Windows, Mac
Rhinoceros - Simlab	Visualization Apps Requiring Computer Connectivity	3D PDF, FBX, OBJ, STL	-	Windows, Mac
Enscape	Visualization Apps Requiring Computer Connectivity	-	-	Windows
Unreal Engine	Visualization Apps Requiring Computer Connectivity	FBX, C4D, OBJ, SKP	EXE standalone files, Datasmith files	Windows, Mac
MindeskVR	Design Apps Requiring Computer Connectivity	.3dm, .sldprt, .sldasm	FBX, OBJ	Windows
Unity - Pixyz	Design Apps Requiring Computer Connectivity	CATIA, NX, SolidWorks, STEP, IGES, FBX, OBJ	FBX, OBJ, glTF, USDZ	Windows, Mac
Open Brush	Entry Level Apps	OBJ, GLB	-	Oculus Quest 2
Home Design 3D VR	Entry Level Apps	OBJ	-	Oculus Quest 2, Windows, Mac, iOS, Android

6. Discussion

The analysis and comparative assessment of various VR tools in architectural design, visualization, and education have revealed a complex and evolving landscape. This discussion synthesizes the primary insights, implications, challenges, and opportunities derived from the analysis.

Gravity Sketch excels in freeform modeling, facilitating intuitive sketching and real-time iteration. This tool is especially beneficial for architects requiring rapid conceptualization and refinement of their designs within a virtual setting. Conversely, Arkio demonstrates superior BIM compatibility and is accessible on all operating systems, rendering it a versatile instrument for collaborative design and educational applications. Arkio's integration with BIM improves collaboration and information synchronization during the design and construction phases, facilitating a seamless workflow for architects and designers.

The capacity to enhance pedagogical methods, spatial comprehension, and student involvement is apparent in the significance of VR tools within architectural education. New tools offer accessible and user-friendly platforms for instructing design principles, fostering collaboration, and enhancing creativity [11,34]. The incorporation of virtual reality in architectural education enhances experiential learning, thus closing the divide between theory and practice. Applications such as Gravity Sketch and Arkio provide distinct benefits in educational environments, with Gravity Sketch facilitating tactile, imaginative exploration and Arkio enhancing collaborative, BIM-integrated learning experiences.

Ongoing advancements and opportunities are expected as VR technology evolves, alongside a growing interest and investment. The exploration of new tools, methodologies, and applications may yield novel insights and innovations in architectural design, visualization, and education. Collaborations between industry and academia,

interdisciplinary involvement, and joint research could significantly augment the potential and influence of virtual reality in architecture.

7. Conclusion

This analysis has examined a wide range of solutions, including architectural visualization platforms, professional 3D modeling tools, educational and entry-level applications, and open-source and customizable options. The incorporation of VR into architectural practice is a substantial advancement in innovation, as it improves communication, collaboration, creativity, and spatial comprehension. The way architects and designers interact with their work has been revolutionized by the emergence of powerful platforms for real-time rendering and immersive experiences.

A versatile and adaptable toolkit for a variety of needs and contexts is provided by the diversity of VR tools, which exhibit varying levels of complexity, usability, and accessibility. Although there are obstacles and constraints, the ongoing development of technology and the increasing popularity of immersive experiences indicate that there will be additional advancements and opportunities.

This analysis contributes to a more comprehensive understanding of the potential and function of VR in the field of architecture. It provides a foundation for the exploration, innovation, and collaboration of architects, designers, educators, students, and researchers, thereby influencing the future of architectural practice and education. The implications and insights that result from this investigation are not limited to the field of architecture; they are also compatible with more general themes such as educational transformation, technological innovation, and interdisciplinary collaboration. They encourage further research, development, and reflection, thereby contributing to the ongoing dialogue and discovery in the dynamic and ever-evolving field of VR.

References

[1] Rocha, L. S.; Krassmann, A. L.; Notare, M. R.; Vidotto, K. N. S.: BIM associated with virtual and augmented reality resources in an educational context: a systematic literature review. Interactive Learning Environments, , 1–14 (2024). http://doi:10.1080/10494820.2024.2350647.

[2] Alvarado, R. G.; Maver, T.: Virtual Reality in Architectural Education: Defining Possibilities. ACADIA Quarterly, **18**, 97–99 (1999).

[3] Zoellner, M.; Keil, J.; Drevensek, T.; Wuest, H.: Cultural heritage layers: Integrating historic media in augmented reality. In *VSMM 2009 - Proceedings of the 15th International Conference on Virtual Systems and Multimedia*; IEEE, (2009); pp. 193–196.

[4] Rudi, J.: Designing Soundscapes for Presence in Virtual Reality Exhibitions: A Study of Visitor Experiences. Visitor Studies, **24**, 121–136 (2021). http://doi:10.1080/10645578.2021.1907151.

[5] Schroeder, R.: Networked Worlds: Social Aspects of Multi-User Virtual Reality Technology. Sociological Research Online, **2**, 89–99 (1997).

[6] Brooks, F. P.: What's Real About Virtual Reality? In *Proceedings IEEE Virtual Reality*; Houston, (1999); p. Cat. No. 99CB36316.

[7] Akselsson, R. ; Källqvist, C. ; Bednarek, V. ; Cepciansky, M. ; Trollås, A. ; Davies, R. ; Eriksson, J. ; Olsson, R. ;; Johansson, G.: Virtual Reality in Air Traffic Control. In *Proceedings of the IEA 2000/HFES 2000 Congress*; APA: San Diego, (2000); Vol. 6, pp. 273–275.

[8] Klasen, J. R. S.; Thatcher, G. P.; Bleedorn, J. A.; Soukup, J. W.: Virtual surgical planning and 3D printing: Methodology and applications in veterinary oromaxillofacial surgery. Frontiers in Veterinary Science, **9** (2022). http://doi:10.3389/FVETS.2022.971318/FULL.

[9] Kamińska, D.; Sapiński, T.; Wiak, S.; Tikk, T.; Haamer, R. E.; Avots, E.; Helmi, A.; Ozcinar, C.; Anbarjafari, G.: Virtual reality and its applications in education: Survey. Information (Switzerland), **10**, 1–20 (2019). http://doi:10.3390/info10100318.

[10] Aydin, S.; Aktaş, B.: Developing an Integrated VR Infrastructure in Architectural Design Education. Frontiers in Robotics and AI, **7** (2020). http://doi:10.3389/frobt.2020.495468.

[11] Achten, H.; Vries, B. DE; Jessurun, A.: DDDOOLZ A Virtual Reality Sketch Tool for Early Design. In *CAADRIA 2000: Proceedings of the Fifth Conference on Computer Aided Architectural Design*; Singapore, (2000); pp. 451–460.

[12] Zhang, B.: Research on visual design method and application of architecture based on BIM + VR. In *IOP Conference Series: Materials Science and Engineering*; (2020); Vol. 750, p. 012110.

[13] Giailorenzo, V.; Banerjee, P.; Conroy, L.; Franke, J.: Application of Virtual Reality in Hospital Facilities Design. Virtual Reality, **4**, 223–234 (1999).

[14] Imottesjo, H.; Kain, J. H.: The Urban CoCreation Lab—An Integrated Platform for Remote and Simultaneous Collaborative Urban Planning and Design through Web-Based Desktop 3D Modeling, Head-Mounted Virtual Reality and Mobile Augmented Reality: Prototyping a Minimum Viable Product and Developing Specifications for a Minimum Marketable Product. Applied Sciences (Switzerland), **12**, 1–28 (2022). http://doi:10.3390/app12020797.

[15] Lau, I.; Gupta, A.; Sun, Z.: Clinical value of virtual reality versus 3d printing in congenital heart disease. Biomolecules, **11** (2021). http://doi:10.3390/biom11060884.

[16] Zaker, R.; Coloma, E.: Virtual reality-integrated workflow in BIM-enabled projects collaboration and design review: a case study. Visualization in Engineering, **6** (2018). http://doi:10.1186/s40327-018-0065-6.

[17] Walmsley, A. P.; Kersten, T. P.: The imperial cathedral in Königslutter (Germany) as an immersive experience in virtual reality with integrated 360° panoramic photography. Applied Sciences (Switzerland), **10** (2020). http://doi:10.3390/app10041517.

[18] Whyte, J.: Innovation and users: Virtual reality in the construction sector. Construction Management and Economics, **21**, 565–572 (2003). http://doi:10.1080/0144619032000113690.

[19] Li, X.; Yi, W.; Chi, H. L.; Wang, X.; Chan, A. P. C.: A critical review of virtual and augmented reality (VR/AR) applications in construction safety. Automation in Construction, **86**, 150–162 (2018). http://doi:10.1016/j.autcon.2017.11.003.

[20] Davila Delgado, J. M.; Oyedele, L.; Demian, P.; Beach, T.: A research agenda for augmented and virtual reality in architecture, engineering and construction. Advanced Engineering Informatics, **45** (2020). http://doi:10.1016/j.aei.2020.101122.

[21] Soto-Martin, O.; Fuentes-Porto, A.; Martin-Gutierrez, J.: A digital reconstruction of a historical building and virtual reintegration of mural paintings to create an interactive and immersive experience in virtual reality. Applied Sciences (Switzerland), **10** (2020). http://doi:10.3390/app10020597.

[22] François, P.; Leichman, J.; Laroche, F.; Rubellin, F.: Virtual reality as a versatile tool for research, dissemination and mediation in the humanities. Virtual Archaeology Review, **12**, 2021 (2021). http://doi:10.4995/var.2021.14880ï.

[23] Paes, D.; Arantes, E.; Irizarry, J.: Immersive environment for improving the understanding of architectural 3D models: Comparing user spatial perception between immersive and traditional virtual reality systems. Automation in Construction, **84**, 292–303 (2017). http://doi:10.1016/j.autcon.2017.09.016.

[24] Ehab, A.; Burnett, G.; Heath, T.: Enhancing Public Engagement in Architectural Design: A Comparative Analysis of Advanced Virtual Reality Approaches in Building Information Modeling and Gamification Techniques. Buildings, **13** (2023). http://doi:10.3390/buildings13051262.

[25] Hajirasouli, A.; Banihashemi, S.; Sanders, P.; Rahimian, F.: BIM-enabled virtual reality (VR)-based pedagogical framework in architectural design studios. Smart and Sustainable Built Environment, (2023). http://doi:10.1108/SASBE-07-2022-0149.

[26] Zoleykani, M. J.; Abbasianjahromi, H.; Banihashemi, S.; Tabadkani, S. A.; Hajirasouli, A.: Extended reality (XR) technologies in the construction safety: systematic review and analysis. Construction Innovation, **24**, 1137–1164 (2024). http://doi:10.1108/CI-05-2022-0131.

[27] Zhang, Q.; Wang, K.; Zhou, S.: Application and practice of vr virtual education platform in improving the quality and ability of college students. IEEE Access, **8**, 162830–162837 (2020). http://doi:10.1109/ACCESS.2020.3019262.

[28] Bartosh, A.; Anzalone, P.: Experimental Applications of Virtual Reality in Design Education. In *ACADIA proceedings*; Austin, (2019); pp. 458–467.

[29] Ibrahim, A.; Al-Rababah, A. I.; Bani Baker, Q.: Integrating virtual reality technology into architecture education: the case of architectural history courses. Open House International, **46**, 498–509 (2021). http://doi:10.1108/OHI-12-2020-0190.

[30] Rauf, H. L.; Shareef, S. S.; Othman, N. N.: Innovation in Architecture Education: Collaborative Learning Method Through Virtual Reality. Journal of Higher Education Theory and Practice, **21**, 33–40 (2021). http://doi:10.33423/jhetp.v21i16.4909.

[31] Rodriguez, C.; Hudson, R.; Niblock, C.: Collaborative learning in architectural education: Benefits of combining conventional studio, virtual design studio and live projects. British Journal of Educational Technology, **49**, 337–353 (2018). http://doi:10.1111/bjet.12535.

[32] Kumar, K. L.; Owston, R.: Evaluating e-learning accessibility by automated and student-centered methods. Educational Technology Research and Development, **64**, 263–283 (2016). http://doi:10.1007/s11423-015-9413-6.

[33] Nersesian, E.; Spryszynski, A.; Thompson, U.; Lee, M.: Encompassing english language learners in virtual reality. In *Proceedings - 2018 IEEE International Conference on Artificial Intelligence and Virtual Reality, AIVR 2018*; Institute of Electrical and Electronics Engineers Inc.: Taichung, (2018); pp. 200–203.

[34] Kamath, R. S.; Dongale, T. D.; Kamat, R. K.: Development of Virtual Reality Tool for Creative Learning in Architectural Education. Int. J. Qual. Assur. Eng. Technol. Educ., **2**, 16–24 (2012).