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Application of Mixed Reality for Improving Architectural Design Comprehension Effectiveness

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Abstract

Extended Reality (XR) technologies such as AR, VR and MR have influenced many industries, including architecture. Even though they are all capable of creating immersive digital worlds, the only one capable of merging the real world with a holographic 3D model is MR, by letting the user interact intuitively and naturally with the project. In this paper, 42 participants were divided into two groups and analyzed an original architectural renovation design. They assessed the effectiveness of design review using Mixed Reality (MR) versus traditional 2D methods. The results show that MR based design review can effectively communicate 85% of the information to the client versus 70% provided by 2D media. At the same time, it has the potential to enhance the client’s comprehension of the aesthetic characteristics of materials, giving the possibility to replace physical samples during the finishing stage of construction.

Key words: Mixed reality (MR), architectural design review, holograms, sketch up viewer, Microsoft HoloLens, design effectiveness.

1. Introduction

In the last decade, the most common way of representing architectural design ideas has been using traditional 2D orthographic projection drawings (i.e. elevations, sections and floorplans), along with realistic images of digital 3D models called renderings. These renderings were drawn by hand in the past but, due to technological advancements, they are now made digitally in a computer using different software such as Sketchup, Revit, AutoCAD, or ArchiCAD. These tools have given the construction process many benefits like: communication improvement, fluid development of design ideas and problem identification in early stages of the project [1]. Even though these representations have precise measurements and defined materials, they can only be seen through two-dimensional means such as printing or computer screens, which make the process less intuitive.

However, in recent years architectural rendering has received the influence from Extended Reality (XR) technologies. This is a term referring to wearable devices and computer-generated graphics that allow the creation of real-and-virtual environments with which the user can interact [2]. XR includes many types of technologies such as Augmented Reality (AR), Virtual reality (VR) and Mixed Reality (MR). With XR immersive models, it could be possible to address many existing problems in the current design review process which traditionally have inconvenient solutions. For example, design teams in need to produce several physical models to analyze multiple design options for a single project, architects who wish to save time in tedious explanations to non-architect clients about certain project details, contractors who are looking to eliminate the creation of physical mockups when solving design issues in the construction site, or firms wanting to reduce the amount of paper waste they produce while designing a project. MR’s ability to allow the user to see the real world while displaying a holographic 3D model merged with the physical environment [3], gives a more intuitive and natural interaction with architectural design. It can provide just the critical, spatially referenced information, that augments an individual’s knowledge of the environment [4] better than printed rendered images, computer screens and VR headsets produced for the same purpose [5].

The rapid advancement of technology and the potential applications of MR both in the office and the construction site, make it a technology that might revolutionize the way architects and other construction professionals work in the next couple of decades. That is why the researchers decided to explore MR’s possibilities. They designed an experiment based on an original architectural design, in order to determine if the use of Mixed Reality in the architectural design review process is more effective than traditional representation methods for communicating the architect’s proposal during the development stage of design. This will hopefully aid in expanding the existing body of knowledge that relates XR and architecture, give more concrete results on how this relationship can be sustained and possible methods on how XR, specifically MR solutions, can be applied pragmatically in the field or the office. At the same time, this research could also help professionals, who are unsure of whether MR is a good fit for their company, to make a decision that fits their specific needs.

2. Background

2.1. Extended Reality

Extended Reality (XR) refers to all real and virtual combined environments as well as human-machine interactions generated by computer technology and wearables [2]. All these technologies can create immersive digital worlds to various extents, and each offers specific tools that can allow the user to achieve different goals. Hence to discuss about XR, it is necessary to first discuss what is known as the Reality-Virtuality Continuum [6]. In one end, AR happens when the real world is enhanced with digital content. That is like pointing a smartphone's camera to a specific place or object and later getting information about it on top of the displayed image. A recent example of this technology is the "Google Glass" head mounted display (HMD) which provides users with glanceable, voice activated assistance [7]. On the other end, VR happens when the real environment is completely shut out, and a user is immersed by a completely digital environment. One example of this technology is Facebook's Oculus Quest which is already widely used by the videogame industry [8]. In the midpoint of this "flow" stands MR. It refers to a continuum where computer generated content is blended in varying proportion with an individual's view of the real-world scene [4]. Currently the most popular headset in this category is the Microsoft HoloLens. According to Microsoft itself, Mixed Reality is a blend of the physical and digital worlds where humans, computers and the environment can interact.

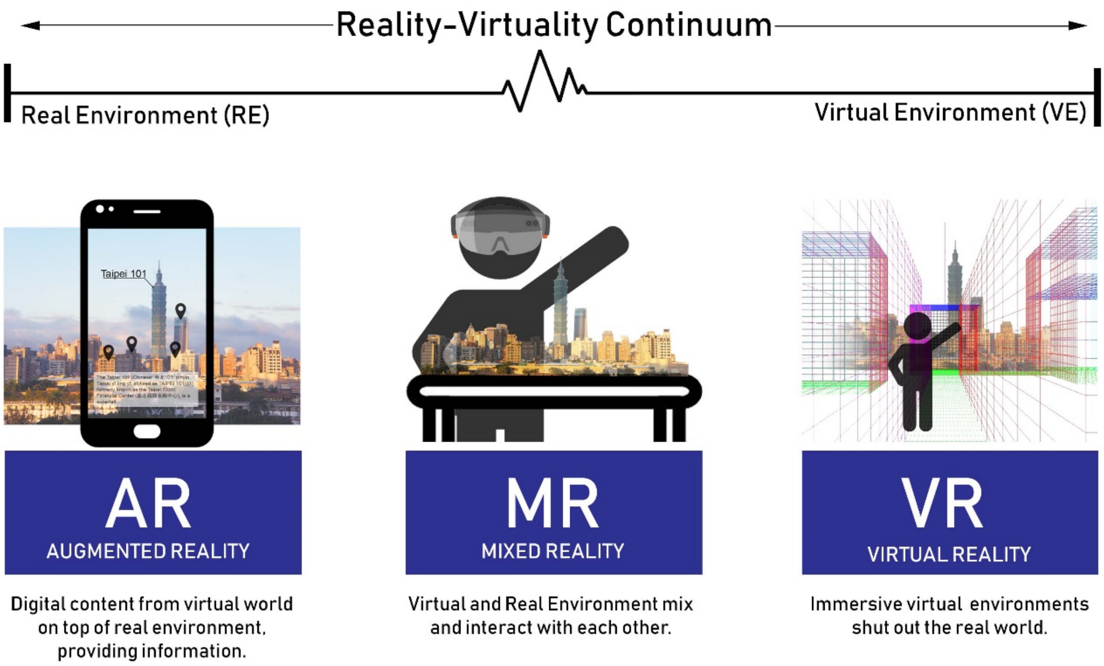

Figure 1 Differences between AR, MR and VR. Reference: [6]

There are no devices today that can provide the user with an experience across the entire spectrum, thus users must first clarify their main goal for using XR and choose a device accordingly [9]. However, XR technology could be useful in the learning process of design [10], since ambiguities in communication could be eliminated, ultimately improving the design review process.

2.2. Review of Related Research with XR

Recent years have witnessed the emergence of a newly created interest for XR. Technologies like VR and AR are now in the forefront of change for many industries including construction, seeing the numbers of XR related research almost double in the 2007-2017 decade [11]. The emergence of robust XR applications has allowed AR and other technologies to enter people’s daily lives and become a major trend for the future due to their portability and ubiquity [12]. These characteristics help improve usability and maintain functionality in the field, such as providing information contained in drawings for comparison with the real situation on site. Recent years have also seen VR and MR headsets become more readily available at varying retail prices. This has given the opportunity for many researchers to explore and evaluate the value and usability of XR for architecture in different areas. A brief summary of related research is presented in hope of expanding the reader’s knowledge on the topic and give a general idea of what has already been done with this technology.

In the year 2006 a group of researchers performed an experiment to evaluate how VR could benefit the design review of courthouses in the United States [13]. This research was used as a pilot project by the government to determine wether VR design review would succeed as a substitute to the current court house review process. The original method involved renting a space with a similar size to the intended courtroom and creating a plywood mock-up model of the design.In that year, VR was still in an early stage, so no head mounted display was used. Instead, to create the immersive enviroment researchers used a system known as CAVE (Computer Assisted Virtual Environment), which used enviornmental projectors directed to the walls of a cube shaped room to create a VR experience. Then, in order to create geometric data for display, Autodesk Revit BIM software was used. Results showed a significant reduction in review time, which went down from 8 hours with the plywood mock-ups, to 3 hours with the CAVE VR. At the same time, since the review team was viewing the model together, they could focus on one issue at a time, and discussions also proved to be more efficient.

In 2018 researchers from the Georgia Institute of Technology carried out an experiment to analyze the user interface and human factors involved in immersive VR platforms for design review [14]. They developed an experiment were participants had to identify elements in a VR model (number of doors, shape of windows, column location, etc.) and then answer a question which evaulated their overall comprehension of the space. For this research the Oculus Rift DK2 headset and Autodesk Revit were used to create the VR display and geometric data respectively; the sample size was of 5 participants, all of them being professionals in the architecture or engineering fields. The results showed immersive VR was able to provide users with excellent cognitive performance. They reported that VR immersive simulations can leverage spatial perception and improve design comprehension as opposed to traditional media.

On the same year, a group of researchers used the Microsoft Hololens to enhance user experience in House Selling [15]. The team used Unity software to create their geometric data and import it to the HMD. Their experiment had a random sample of 12 people, and consisted of two groups divided according to the media to be used (Hololens or 2D). Users would explore a 3D model or 2D plans, and then answer a questionnaire about what they saw and provide feedback; their times were also recorded. They concluded that potential clients could be influenced by models that help them to quickly and clearly understand and familiarise themselves with the design. They also reported that participants who used the Hololens could intuitively understand the designer’s ideas and save time during the process of information exchange, with lower error rates compared to the users of 2D. They also mention that MR technology has potential for the future house selling market, as consumers show higher purchasing inclination when they can quickly understand the information being presented.

In 2019, a researcher from the University of Applied Sciences Upper Austria developed a research to analyze the potential of VR on engineering design review. [16] He used an HTC Vive HMD and Unity with Autodesk 3DS Max for preparing the VR display and geometric data respectively. 16 participants with different working backgrounds were asked to review and find faults in the 3D model of two power units. The goal was to compare the effectiveness of VR supported design review versus conventional approaches with CAD software support (2D). Participants were divided in teams, were one person would use the HMD and the rest would look at the model through a TV screen; then the team did another review with an alternative 2D method. Then a questionnaire was used to assess how many “flaws” participants could find inside the VR model. The results show that VR-supported design review allows users to see more faults in a 3D engineering model than CAD software-based design review approaches, due to its more intuitive way of looking at a 3D object.

Finally, a group of researchers carried out a study which finalized in 2019, where 13 design review meetings were analyzed over the course of 28 months, focusing on projects inside the campus of a large university [17]. They recorded every design meeting and used software to extract the data. Results show that VR models describe details more concretely, and viewers are able to understand better as they can simulate their workflow during occupation and operation, making it easier to identify mistakes. They also mention that VR is good for conveying a correct perception of size, scale, volume and depth of a space more accurately, and that it benefits design comprehension when dealing with irregular, complex and curved shapes.

The related research presented above might lead to the conclusion that XR techonology will dramatically improve design comprehension. However, recent research also asserts that technologies like VR should be treated with equal importance to 2D drawings and BIM (Building Information Modelling, like Autodesk Revit). Adducing that VR should complement the shortcomings of traditional media (like drawings), and not completely replace them [17].

2.3. The Architectural Review Process and Design Change

The design review process is a very important part of the lifecycle of a construction project, since it is present in almost all of its phases. Changes in a construction project are inevitable [18], and when they happen change orders appear. These are formal documents that notify changes in the design [19], and for many authors [18, 20-22], architectural design related problems are a main source for the creation of change orders. They agree that the lack of communication fluidity caused by variations during construction can lead a project to incur in cost overruns, delays in completion times, as well as causing rework and legal claims and disputes [20]. Hence, good communication during design review is very important to improve the effectiveness of handling changes in a project.

Design review depends on communication, and the range of people that are consulted for it is always extensive [24-25]. During the process, participants must view many graphics at the same time, and verbal critiques are usually supported by simple sketches [21].Nevertheless, in 2D drawings, spatial conflicts among different specialties must be addressed by “skilled” users who rely on their own human perception to understand drawings, in order to avoid changes and rework [22]. The problem is that these representations are abstract and fragmented: Abstract because drawings of building components are represented through lines and symbols, and fragmented because relevant information is distributed in different drawing sheets [17]. That means reviewers must go through many drawings scattered around different pages just to get a clear picture of the design. Sometimes, even if the person looking at the plans is a skilled worker in the architecture field, questions about the design will always arise during the first inspection.

The researchers of this paper have construction working experience in Honduras and Taiwan. Working in two places which are intrinsically different sheds some interesting light onto how similar the problems that architects face can be, and give theoretical value to the exploration of ways to use available technology to make design review more efficient. While working on-site for a Honduran consulting company and then in-office for a Taiwanese architecture firm, many challenges related to design review were identified. Most of them during the construction phase of the building and the preliminary stage of design review.

First, in the case of the consulting company, the appearance of change orders during construction can cause many parts of a building to be redesigned or modified. These changes then have to be explained and clarified to the contractors and in certain cases directly to site workers. When this happens 2D workshop drawings are usually taken to the site, and the team attempts to clarify how the new modifications would look like on the intended space. Other times, for example when building a hand railing, physical mockups need to be produced to make sure the activity will be carried out according to the specification requirements. In these cases, the ability to see a design placed on site, in 3D and full scale would make those situations smoother in terms of explanation and visual aid for all the parties involved.

In the case of an architecture firm, when developing the preliminary design for a client, the team has to come up with multiple design options that later need to be transferred to a computer based 3D model, a physical model, or both, in order to showcase the design to the stakeholders. During this process, firms usually produce large amounts of paper waste for reviewing design options and also spend many hours cutting cardboard or other materials to create a model that will be used for one meeting and then will probably be thrown away. Under both scenarios, long, sometimes tedious explanations are needed to ensure every participant in the review meetings understands the different parts of the design, because 2D drawings are not always capable of offering enough information, for people from different fields who oversee the construction, to fully understand a design or modification. Under this light, XR technology can aid to improve this issue, since as previous research shows, its use is more intuitive and contributes to the effectiveness of this process by allowing users to observe all the relationships of a particular design simultaneously, and engages the users by reducing the effort needed to understand a proposal [17].

2.4. Choosing the XR: VR, AR or MR?

In the last decade, XR became more readily available at affordable prices, giving individual users the chance to start exploring the possibilities that the related devices could offer for different fields. By the year 2015, smart glasses or head-mounted displays (HMD) had already gained traction as next generation mainstream devices [23], and in 2016, many VR and MR HMD were released to the market. The HTC Vive (VR), Oculus Rift (VR) and the Microsoft HoloLens (MR) are some of the most prominent examples. All of these HMD's were capable of rendering immersive 3D environments, each with its own specific way of interacting with the real-world. During that time, the use of plastic handheld controllers along with a tethered HMD device was the best way to interact with a digital environment, which was completely shut out from the real-world. However, the HoloLens innovated the user-3D model interactions by offering the possibility to mix the virtual and the real worlds through its MR (mixed reality) technology [3, 29]. The device was untethered, and was capable to realistically integrate 3D information into a user's perception of the real-world, which no other commercially available technology could offer [5].

By the year 2019, many other companies had created untethered, or standalone head mounted displays, predominantly for VR. Through an analysis of the manufacturer's websites, only three might be comparable to the HoloLens, due to a function Oculus HMD developers call "Passthrough". This function is generally advertised as a safety measure for defining a "walking area" where the headset will be used. It allows a VR HMD to temporarily step outside of VR and see a real-time view of the world around the user through the use of integrated grayscale cameras on the device [24]. According to the information gathered at the beginning of the year 2020, the devices that included this function were: The Oculus Quest, the HTC Vive Focus, and Lenovo Mirage Solo. All of these headsets allow users to see the outside world, however the functions they offer to interact with it are very limited. Moreover, even though some HMD's like the Oculus Quest include a hand tracking function [8], VR technologies still highly rely on the use of handheld plastic controllers in order to move through the space, even while using the "passthrough" function.

In contrast, the HoloLens uses hand gestures and eye tracking to control its interface. Its holographic display also allows the user to remain in the "real world" while still looking at the 3D model and not lose his sense of location. The HoloLens also works without cables or other attached devices, has stereo sound and a Holographic Processing Unit CPU that allows people to instantly manipulate data [15]. It has color display, gaze tracking, two simple control gesture inputs, 4 microphones, and spatial sound and voice support [25]. In a way, it resembles the use of a smartphone because the user requires no prior training to interact with the 3D model, and basically becomes a small, wearable computer capable of generating high resolution, spatially located 3D content in real time. This absence of prior required training means the designer can load a 3D model beforehand and the clients only need to put on the HMD and walk around instinctively. The Hololens could allow the users to interact with 3D models as if they were "real" physical models placed on a table, or walk around a 3D holographic space placed on site. It also becomes really useful in the construction site, where being aware of one's surroundings is crucial to avoid potential hazards. Therefore the characteristics of the HoloLens make it a suitable option for architectural design review, which is why it was the chosen headmounted display for carrying out this research.

2.5. Environmental Perception and Recognition

The perceptual aspect of design is complicated and non-obvious, when the designer gives out a message, the receptor tries to decode its meaning, based on what he knows and is capable of understanding [26] For this reason, concretely defining the process of how people look and understand their environment, both virtual and real, is essential to increase the accuracy of the measurements and procedures applied in this research.

Kevin Lynch, in his book "The Image of the City", defines the apparent clarity or "legibility" of a space as the ease with which its parts can be recognized and organized into a coherent pattern [27]. Some authors [28, 29], have already defined the process a person undergoes while trying to understand a physical space. These processes are summarized in table 1.

Table 1 Analysis of how people perceive a real space and the related cognitive process. Reference: [40] [41]

Cognitive Analysis for Spatial Perception

	Process	Dimension	Type of information obtained	Description
1	**Exploring** The individual will explore physical areas in order to orient himself and develop means of locomotion and communication within the given space.	**Cognitive Dimension** The individual thinks about, organizes and keeps information that allows him to make sense of the environment.	Determine fixed or given layout and spatial boundaries	Does the user know what activities and functions can be performed in the environment?
			Environment Experience and definition	
2	**Categorizing** The individual develops categories of information or a taxonomy of the environment, through which he tries to classify characteristics in a space in order to understand it.	**Affective Dimension** Involves our feelings and how they influence our perception the environment and vice versa.	Environmental Sensory information	Does the user know if the spaces in the environment feel narrow, wide, low, high, dark, or illuminated?
		Interpretative dimension The individual will rely on memory points for comparison with newly experienced stimuli.	General and specific information of the environment	Does the user know what are the things in the environment made of? Their materials, textures, and size.

3	**Systematizing** The individual systematizes the environment through analysis of environmental contingencies (events happening in the environment).	**Evaluative Dimension** It incorporates values and preferences, and the determination of good and bad elements in the environment.	Environmental coherency and symbolic meaning	Is the user capable of describing the environment in a coherent way, explaining its parts and different elements?

Previous research [30-32]also shows that Immersive Virtual Environments (IVE) seen through XR technology, are a satisfactory representation of real physical environments. That means that IVE’s are percieved in the same way as real environments. The difference is that IVE’s permit the acquisition of essential information about the client’s preferences during the design phase, by allowing the architect to test different alternatives of design which will normally not be possible due to constraints in time and resources. Hence, MR and VR technologies have a great potential for improving the effectiveness of the design review process, as they display environments that people can understand intuitively, just like real ones.

3. Materials and Methods

3.1. General Information

In an attempt to find a method for combining 2D and XR in design review, the authors of this paper decided to design and perform an experiment in hopes of shedding some light on the subject [28]. This experiment was performed in Taipei, Republic of China (Taiwan) during the first half of the year 2020. During this time, the world was facing a pandemic known as COVID-19, which caused many countries to halt work and normal activities for a period of time. Nevertheless, Taiwan never went into complete lockdown, which allowed this research to be performed with complete normality and be delivered on time.

3.2. Expert Interviews

The Expert interviews provided valuable input for setting the bases for the experiment design in this research [28].The interviews were made in a conversational manner, with a set of predetermined questions about how the experts carried out design review with their clients. The goal was to extract information that would give the researchers a general idea of what methods have been used for design review in recent years according to normal practice, and also to serve as a starting point for beginning the questionnaire and experimental treatment design. The researchers also wanted to identify which aspects of architectural design were the most complex for clients and other users while trying to understand design for the first time. There were four interviewees from the architecture and civil engineering fields. Two civil engineers from Honduras with background in project management, with 16 and 14 years of experience respectively. One architect from Nicaragua with 53 years of experience and one architect from Taiwan, specialized in BIM software and 3D models, with 15 years of experience.

While recording the answers, the researchers noticed there were some aspects all the interviewees naturally agreed upon:

1. The office architectural typology is the easiest for clients to understand, since it has the least number of elements to be explained. The most complex typology is residential as the people involved are more numerous and have different backgrounds.
2. At the same time, comprehension of architectural details (false ceilings, moldings, bases, railings, etc.), and the overall 3D geometry of elements are the hardest aspects for clients to understand and visualize.
3. They also agreed that while explaining design, methods such as: using physical samples and models, as well as size comparison with similar existing physical spaces are really helpful for increasing client comprehension.

The Taiwanese BIM expert also gave very helpful suggestions for this research. He pointed out that MR and 2D might actually work together to explain design, rather than thinking one would replace the other. He suggested both methods should not be analyzed separately, instead they should be analyzed together in order to understand things like: with which method participants are able to see specific elements better? or Which one is better for showcasing general ideas?

Based on the gathered information, and the review from related research, the researchers agreed upon the following:

1. A questionnaire would be the instrument used to measure the percentage of comprehension of the design proposal.
2. The office typology would be used for the creation of the experiment’s design proposal. This decision was taken because the experiment needed to be simple in order to avoid long treatment times and not lose the participants’ attention or enthusiasm in the process.
3. The questions in the questionnaire should move from the general to the specific aspects of design, in order to evaluate how good MR is for visualizing and understanding architectural elements (false ceilings, moldings, bases, etc…) and their properties (thickness, material, texture, etc..).

3.3. System Description

The system used for this research was composed of three main elements: A desktop computer with an i7-4790 CPU, 8GB RAM memory, Nvidia GeForce 750 GPU, and a Microsoft “HoloLens One” Head mounted Display (HMD). For the Geometric data, Sketchup software along with the Sketchup Viewer App for the HoloLens were used for producing the holographic 3D model. The 2D data and initial 3D model was produced with Autodesk REVIT 2018 along with AutoCAD 2018 software.

3.4. Preparation of Geometric Data

For creating the hologram, the researchers used Sketchup and its VR/MR function for the Sketchup Viewer App, since it simplified the process in just two steps: Have a SketchUp model, then upload into the HMD using the app.

The Sketchup viewer app is capable of supporting “full scale size adjustment”, which allows the user to adjust the size of the 3D model to match the exact size of the space it is placed on top of [29]. With its “Table-Top view” function [30] it is possible to anchor the model to a fixed point inside a room and scale it up to 1:1. If the 3D model and the room are the same size and shape, it is possible to create a holographic life-size mockup of the intended space, which made the app suitable for the experiment in this research.

3.5. Variable Definition

The experiment aimed to measure the percentage of comprehension (dependent variable) of a client while looking at an architectural design, by understanding how the absence or presence of MR (independent variable) affects the client’s comprehension effectiveness.

For this reason, participants were randomly divided into two groups:

1. **The control Group (2D group):** This group looked at the design using a printed 2D drawing set that included elevations, sections, 3D renderings, floor plans and architectural details.
2. **The Experimental Group (MR group):** This group looked at the design using the HoloLens and a 3D hologram of the design proposal placed on top of the real site.

3.6. Sampling

While working, an architect might encounter many different kinds of clients, who have different culture, race, gender, age, and levels of knowledge. Clients can come from anywhere, and this last characteristic is especially important as it suggests that the sample for this research needed to be heterogeneous in terms of cultural and academic backgrounds. Thus, the researchers did the random sampling process by advertising the experiment in different places around Taipei where people with the desired characteristics could be found; these places were: Chinese language centers, local companies, sports teams, and universities (bachelor's, master's, and PhD levels). The sample included both Taiwanese people and foreigners from different nationalities, regardless of their background and older than 18 years old. People who arrived at the laboratory for experimental treatment participated on their own accord, and in full possession of their mental and physical faculties. For a detailed list of participants and their backgrounds please look at table 5.

3.7. Data Collection

3.7.1. Interview Method

Expert interviews suggested that regular interaction with clients was done in a conversational manner, and since the experiment needs to replicate as much as possible the real conditions of an architect's work environment, it was decided to use a questionnaire in the format of a Semi-structured interview. According to previous research, this personal interview method can overcome poor response or non-response issues, where good respondents are those who appear comfortable while interacting with the interviewer and provide solid answers with good detail [31]. Semi-structured interviews usually have a questionnaire with predetermined questions, but their conversational nature allows users to explore issues they consider important [32]. At the same time, it gives the questionnaire a certain degree of flexibility to overcome the language barrier that certain participants might have.

3.7.2. Experiment Site

To keep the process simple, short, and easy to standardize, the studio office typology was chosen. This is a kind of small office destined to carry out business and handle processes, with a size that can vary from one single room to an entire floor of a building [33]. Thus the researchers decided to use a room provided by the National Taiwan University (see figure 2), with an area of 66 m^2, located inside the Civil Engineering Research Building (CERB). The size of the room was adequate to create a reasonably complex design without overcomplicating the situation, and it was also suitable to receive participants comfortably since it has bus and bicycle stations in its proximity.

3.7.3. The Architectural Design

In order to know what questions to ask, the researchers had to start by creating an architectural design that that would provide the elements to be evaluated in the questionnaire according to the aspects of perception defined on table 1. This design was meant to challenge the participant's ability to achieve clarity or "legibility" of a space.The evaluated aspects and included characteristics are as follows (see figures 3,4 and 5):

1. **Exploring:**
   <u>Aspects to be evaluated:</u>
   1. Determination of spatial boundaries and layout of the environment; 2. Identification of where activities can be performed; 3. Identification of new and existing elements (demolition plan); 4. Identification of visible and non-visible architectural elements (in this case non-visible refers to elements covered by false ceilings like beams, or elements wrapped by other materials or walls).
   <u>Characteristics:</u>
   The design has many spaces, concretely 5 (see figure 3), with different functions and varying floor levels and ceiling heights. This way the participant was able to understand the space in a three-dimensional aspect and do some exploration to put the design together.

2. **Systematizing:**
   <u>Aspects to be evaluated:</u>
   Environmental coherency (ability to describe the environment in a coherent way and identify its general function).

Characteristics:
The design includes complexity of materials (see figure 5). This means it has many surfaces with different textures to understand if the participant can notice differences in texture, color and size. At the same time, since the design was placed on top of an existing space, a demolition plan was also created.

3. **Categorizing:**
Aspects to be evaluated:
1.Identification of specific information about materials used in furniture and surfaces; 2. Identification of inherent properties of materials (in terms of smoothness, roughness, warmness or coldness); 3. Perception of size and 3D space (in terms of high, low, narrow and wide).
Characteristics:
The design included some polyvalent spaces (see figure 4). This was meant to challenge the participants while they were creating a coherent idea of the space, since some areas had different functions that were understood after looking attentively.

Once the architectural design was finished, the researchers used it as the base to write and classify the questions in the questionnaire and create a measuring tool. The questionnaire draft was tried out, modified and improved through a trial process which included 4 participants. These trials gave out the following conclusions:

1. The amount of time needed to explore the design with MR was 5 minutes.
2. The plans for the 2D group had to be printed in full color (A2 paper size to show the desired scale) in order to ease reading.
3. A specific seat was chosen in the room so that the orientation of the plans would coincide with the orientation of the physical space to make comprehension more straight forward.
4. The draft of the evaluation form was finalized and ready to be implemented (see appendix Table A.1).

Figure 2 EMCA lounge at the 4th floor of the Civil Engineering Research Building at NTU, Taiwan. Existing floor plan (top), view 1 (left) view 2 (right)

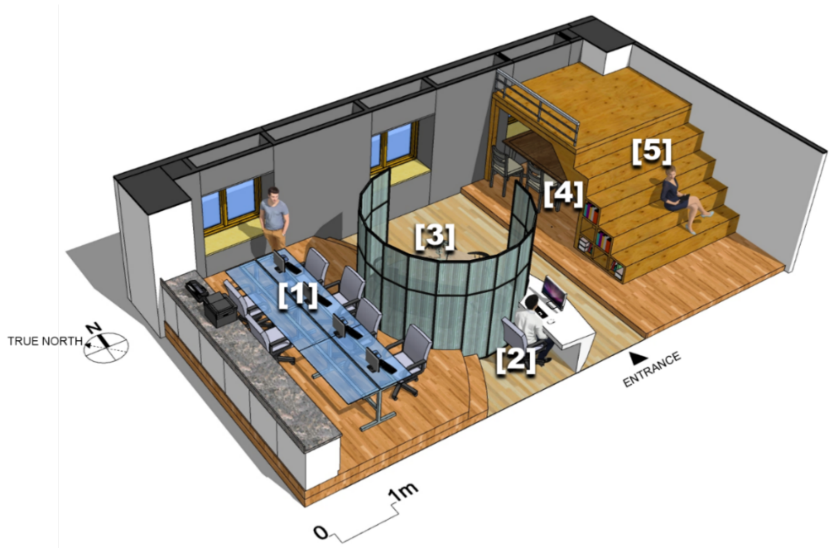

Figure 3 Isometric Diagram of the New Floor Plan. [1] Work Area; [2] Reception; [3] Meeting Room; [4] kitchen; [5] Meeting Hall.

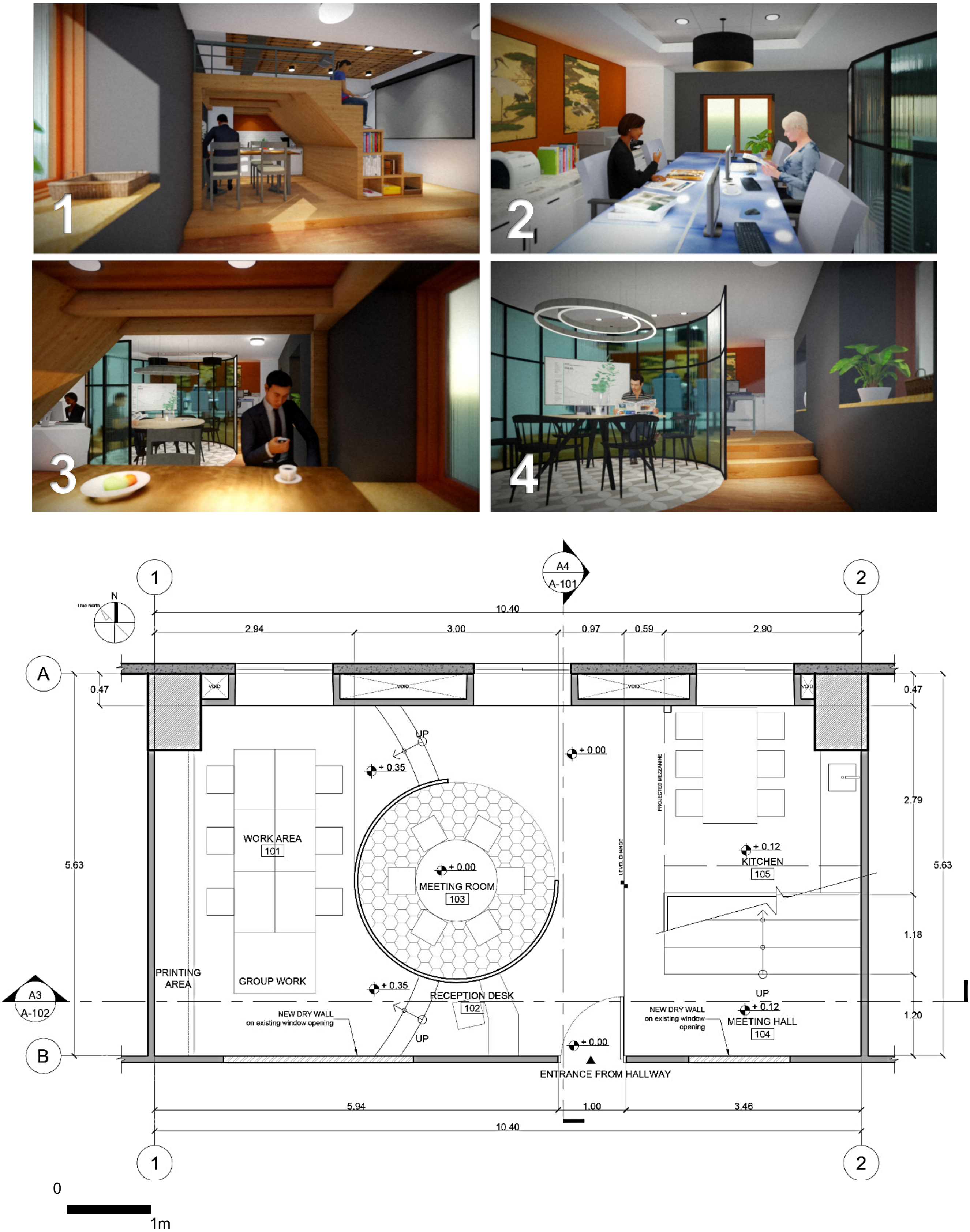

Figure 2 (Up) Renderings: **1** Kitchen and Meeting Hall, **2** Working Area, **3** Kitchen, **4** Meeting Room and circulation space; (down) New Floor Plan.

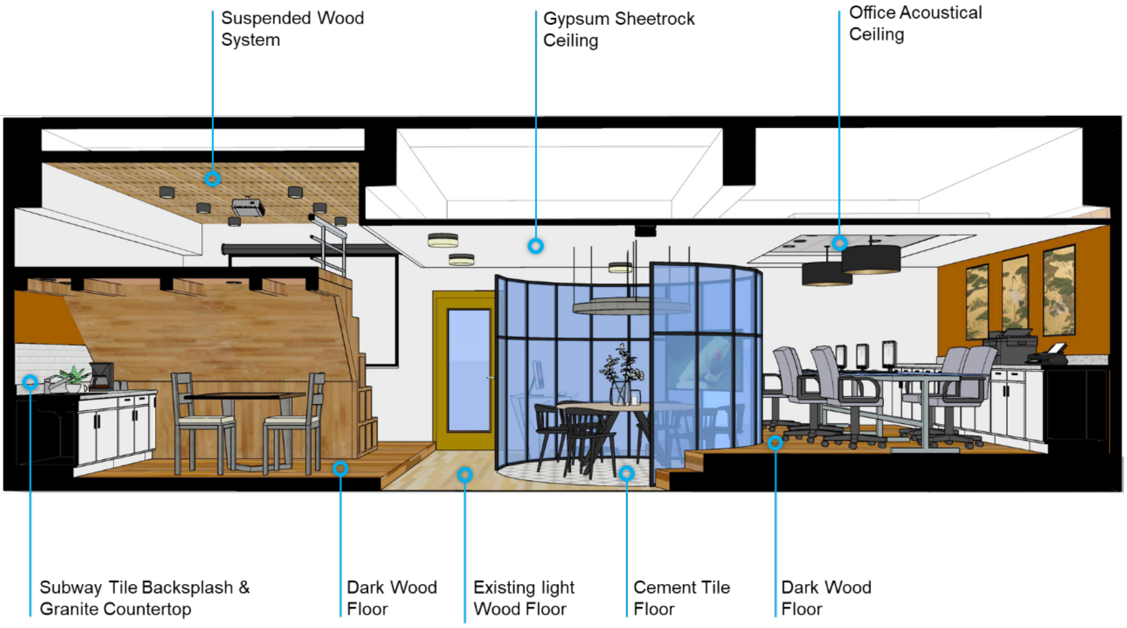

Figure 3 Interior space with material specifications.

3.7.4. The Questionnaire

The final version of the questionnaire included 24 questions about the aspects of design, and the last question (number 25) was "open-end" to assess the participant's level of environmental coherency; there were also 5 questions regarding the interaction with the HoloLens (see table 3). As mentioned before, the questionnaire was based on the literature review, user trials, and expert interview recommendations. The number of questions accurately answered represent the percentage of comprehension the participant had according to the group he was assigned to; each question had a value of 4% to sum up to 100%. At the same time, there was a device interaction test to measure comfort while using the HoloLens, since the researchers initially considered it could be a significant variable in the comprehension process [28]. The following table summarizes the tests applied to the participants:

Table 2 Metrics for the experiment tests. Reference: [14]

Test	Metric	Expected Results	
		MR	2D
Comprehension Level (25 questions)	Questionnaire (24 questions)	85-95% of comprehension	55-75% of comprehension
	Overall comprehension (1 question)	Score 4 or higher	Score 4 or less
Device Interaction (5 questions)	Ergonomic Quality questionnaire	< 4 on all 5 aspects	Does not apply

The responses were then recorded using the evaluation form included in the appendix Table A.1. All the interviews were recorded on video and the experiment treatment was applied identically to every participant to ensure proper results. For a detailed description of the Standard Operating Procedure please go to table 4.

Once the data was collected, the results were tabulated and counted using the evaluation form, in order to obtain averages and percentages needed to understand the results. The following table provides the questions asked during the interview, classified according to the category they belong to:

Table 3 Questionnaire (MREXP-002)

Questionnaire (MREXP-002)	
	EXPLORING
Determination of Layout and spatial boundaries	
01	What are the spaces included in this renovation?
02	What is the overall length and width of the room?
03	Which walls serve as a boundary for the space to be renovated?
Environmental Experience and Definition	
04	In what area of the renovation can you eat your lunch?
05	In what area of the renovation can you sit and listen to a presentation?
06	In what area of the renovation can you work?
07	In what area of the renovation can you take a nap?
08	Is there a space for storing books?
	CATEGORIZING
General Information	
09	What elements of the existing space will be demolished or taken away, and which ones will remain after the renovation is finished?
10	What structural elements (columns, beams, slab) are going to be left exposed (not covered by any kind of material except for paint) and which ones are going to be covered?
Specific Information	
11	How many types of false ceiling are included in the design, what is their material?
12	Are there any curtain or glass walls in this design? How many?
13	How many floor types are included in the design? What is their material?
14	What is the material of the countertops (both kitchen and printing area)?
15	How many types of lighting fixtures are included in the design?
16	What is the material of the kitchen backsplash?
Sensory Information	
17	With the current layout, a person presenting in the meeting room can move around the space while all the chairs are occupied?
18	Could a person walk to the reception area, through the workspace while everyone is seating down working?
19	Are the stairs at the meeting hall wide enough to seat 10 people in each row?
20	Is the space for the mezzanine area enough to allow a person with a height of 1.65 m or more stand up?
21	If you are taller than 1.85 m, will you be able to stand in the kitchen?
22	Is the floor used in the meeting room smooth or rough?
23	Are the materials used for the kitchen countertop and backsplash warm or cold?
	SYSTEMATIZING
Environmental Coherency	
24	What will be the overall function of the space in this renovation? (A place to work, relax or entertain?)
25	Please describe in your own words the renovation that is to be undertaken in this space. (For example, mention what are the main spaces, materials, functions, and feelings the space will have. You can add any other information you consider relevant.)
	DEVICE INTERACTION (based on Likert scale)
26	The HoloLens was heavy
27	The HoloLens was difficult to adjust
28	Your eyes felt sore while using the HoloLens
29	You had motion sickness or dizziness while interacting with the MR model.
30	You were lost or disoriented while exploring the MR model

3.7.5. Standard Operating Procedure

In order to have a clear process while performing the experiment, a standard operating procedure was developed. This procedure served as a protocol while applying the experiment to ensure every participant received the same and equal treatment (see table 4).

Table 4 Experiment Standard Operating Procedure

Experiment Standard Operating Procedure (MREXP-004)	
Group A (2D)	**Group B** (MR)
Group A will be provided only with the renovation's Ready to Submit (RTA) plans and renderings. The researcher will follow the steps as described below: 1. The researcher will read a brief introduction about the experiment and the research. 2. The plans shall be explained by the researcher to make the participant familiar with the content. 3. Participants look at the plans for 5 minutes. 4. After 5 minutes, the researcher will go through the questions, marking which ones the participant is able to answer. (Annex Table A.1, Form MREXP-003) 5. Percentage of questions answered with 2D for this round (R1) should be recorded to this point in section 4 R1 of form MREXP-003. 6. Afterwards, the participant shall be given 2 more minutes to go through the information again in order to answer missing questions. 7. Percentage of questions answered with 2D for this round (R2) should be recorded to this point in section 4 R2 of form MREXP-003.	Group B will be provided only with the MR model and HoloLens. The researcher will follow the steps as described below: 1. The researcher will read a brief introduction to the experiment and the research. 2. Then the researcher shall make sure the model is in place and make sure the participant knows how to adjust the MR gear. 3. Participants explore the model for 5 minutes. 4. After 5 minutes, the researcher will go through the questions, marking which ones the participant is able to answer. (Annex Table A.1, Form MREXP-003) 5. Percentage of questions answered with MR for this round should be recorded to this point in section 4 of form MREXP-003. 6. Afterwards, the participant shall be given 2 more minutes to go through the information again in order to answer missing questions. 7. Percentage of questions answered with MR for this round (R2) should be recorded to this point in section 4 R2 of form MREXP-003.
The sum of the percentages obtained during R1 and R2 shall be added to obtain the total percentage of comprehension presented in table 5. Since the experiment was advertised as a comparison between paper drawings and holograms, the following steps (8-11) were taken to ensure the participants could interact to all the media available in the experiment and had the chance to experience MR.	
8. If there are questions left unanswered, the participant will use the MR headset for 5 minutes to look at the 3D model. 9. The questions that are still unanswered will be asked again. 10. Percentage of questions answered with 2D for this round (R3) should be recorded to this point in section 4 R3 of form MREXP-003. 11. Questions 26-30 should be asked in order to assess user experience with the HoloLens. **End of the session**	8. If there are questions left unanswered, the participant will look at the 2D RTA plans for 5 minutes. 9. The questions that are still unanswered will be asked again. 10. Percentage of questions answered with MR for this round (R3) should be recorded to this point in section 4 R3 of form MREXP-003. 11. Questions 26-30 should be asked in order to assess user experience with the HoloLens. **End of the session**

4. Results

4.1. Participants

Altogether, 42 participants (Male: 26; Female: 16) took part in the experiment, with 20 as part of the control group (2D), and 22 as part of the experimental group (MR). The average age was 26.36 years and they ranged from 20 to 58 years. Regarding academic background, 30 participants were professionals with either a bachelor's or a master's degree, and 12 participants were students from different university majors. Then, 16 out of 42 people had previous knowledge reading plans, either from the industry, empirical experience obtained from buying real estate, or personal house renovation projects. Finally, regarding the participant's cultural background, the sample belonged to 5 different regions in the world: Africa (1), Middle East (1), Asia (15), North America (3), South America (14) and Europe (8). (see Table 5)

Table 5 Participant background and results from cognitive tests according to treatment group

Treatment Group: MR (Experimental)								
N	**Academic Background**	**Age**	**Gender**	**Prof. Exp. (years)**	**Previous 2D Exp.**	**Nationality**	**Test Result % 2D**	**Test Result % MR**
01	Student	20	M	0	No	Honduras	-	88
02	Bachelor's Mass Communication	26	M	3	No	Spain	-	92
03	Student	20	M	0	No	Honduras	-	84
04	Civil Engineering	31	F	2	Yes	Mozambique	-	88
05	Student	21	F	0	No	Japan	-	76
06	Bachelor's International Studies	28	M	0	No	United States	-	96
07	Student	22	M	0	No	Belize	-	84
08	Bachelor's Business and Finance	29	F	0	No	United States	-	72
09	Master's psychology and statistics	26	M	5	No	Spain	-	92
10	Bachelor's Chemical Engineering	26	M	3	Yes	Guatemala	-	88
11	Ph.D Civil Engineering	33	F	3.5	Yes	Taiwan	-	72
12	Student	21	F	0	No	Guatemala	-	92
13	Bachelor's Architecture	24	M	1	Yes	Japan	-	80
14	Bachelor's Civil Engineering	23	M	0	Yes	Taiwan	-	88
15	Master's Architecture	46	M	20	Yes	Taiwan	-	80
16	Master's Construction Management	58	M	30	Yes	Taiwan	-	72
17	Bachelor's Physics	25	M	1	No	Iran	-	88
18	Bachelor's Electrical Engineering	24	M	0	No	Spain	-	96
19	Bachelor's Applied English	32	M	0	No	Taiwan	-	92
20	Bachelor's Computer Science	29	F	4	No	Costa Rica	-	80
21	Bachelor's Nutrition Science	26	M	3	No	Taiwan	-	84
22	Master's Architecture and urban design	26	M	5	Yes	Nicaragua	-	92
Treatment Group: 2D (Control)								
N	**Academic Background**	**Age**	**Gender**	**Prof. Exp. (years)**	**Previous 2D Exp.**	**Nationality**	**Test Result % 2D**	**Test Result % MR**
23	Master's Economics and Finance	31	M	7	Yes	Belgium	88	-
24	Bachelor's Teaching and Translation	28	F	5	No	Mexico	56	-
25	Student	23	M	0	No	St. Vincent and the Grenadines	72	-
26	Bachelor's Agrobusiness	26	M	3	No	Guatemala	80	-
27	Bachelor's Atomic Physics	24	F	0	No	Germany	72	-
28	Student	20	F	0	No	Korea	68	-
29	Student	22	M	0	No	Mexico	72	-
30	Bachelor's Mass Communication	23	F	3	No	Philippines	60	-
31	Student	21	M	0	No	Guatemala	76	-
32	Student	20	M	0	Yes	Spain	84	-
33	Student	21	F	0	No	Honduras	56	-
34	Master's Integral Security	30	M	7	Yes	Spain	72	-
35	Bachelor's Architecture	26	F	2.5	Yes	Taiwan	68	-
36	Bachelor's Civil Engineering	24	F	0	Yes	Taiwan	60	-
37	Student	23	F	0	No	Japan	80	-
38	Bachelor's Civil Engineering	23	M	0	Yes	Taiwan	64	-
39	Bachelor's Computer Information Systems	25	F	0.5	Yes	United States	80	-

40	Master's Biotechnology	28	M	1.5	No	Spain	64	-
41	Student	23	F	0	No	Malaysia	60	-
42	Bachelor's Criminology and Philosophy	30	M	9	No	Puerto Rico	72	-

4.2. Presentation of Results

Effectiveness is defined as the capability of a person or object of producing a decided, decisive or desired effect [34]. In this sense, the results above indicate that MR supported design review is more effective than traditional 2D methods of representation. When a client comes in contact with a design proposal for the first time, MR makes it possible to receive design related information more intuitively by 15%. This is based on the cognitive test carried out by the experimenters, which measured that on average, MR helped participants understand 85% of the total information when using the HMD, while 2D users only obtained 70% of the total information in the questionnaire on the same amount of time (5 minutes).

While looking at the results in table 5 the researchers noticed a direct linear relationship between the use of MR and a higher percentage of comprehension. Thus, it was decided to carry out a linear regression to test this relationship. The initial variables considered in the estimation were: Previous experience reading plans, gender, age, years of professional experience, and comfort level of the HMD (measured in the last five questions of the questionnaire). The variables years of professional experience and comfort level of the HMD were omitted as they turned out to be insignificant while running the first estimations for this model. The final estimation included the variables mentioned on equation 1, which used an alpha level for the p-value of 0.05, and obtained a resulting Adjusted R-squared value of 0.57 (See Table 6 and equation 1).

$$\mathrm{Gcomp} = 83.35 + 14.42\mathrm{MR} + 0.93\mathrm{PlanExp} - 8.36\mathrm{Gen} - 0.38\mathrm{Age} + \mathrm{u}$$

Variable Definition: Gcomp (General Comprehension); MR (Mixed Reality); PlanExp (Previous Plan experience); Gen (gender); Age (age)

Equation 1 Final Equation Model.

Table 6 Estimation output for the experiment.

Dependent Variable: GComp
Method: Least Squares
Date:06/30/2020 Time:15:58
Sample (Adjusted): 1 42
Included Observations: 42 after adjustments

Variable	Coefficient	Std.Error	t-Statistic	Prob.
MR	14.42535	2.412412	5.979640	0.0000
PLANEXP	0.925219	2.484834	0.372346	0.7118
GENDER	-8.356152	2.437746	-3.427819	0.0015
AGE	-0.378674	0.182241	-2.077870	0.0447
C	83.35069	4.866258	17.12829	0.0000
R-squared	0.612502	Mean dependent var	78.09524	
Adjusted R-squared	0.570610	S.D. dependent var	11.28740	
S.E. of regression	7.396388	Akaike info criterion	6.951204	
Sum square resid	2024.142	Schwarz criterion	7.158069	
Log likelihood	-140.9753	Hannan-Quinn Criter.	7.027028	
F-statistic	14.62109	Durbin Watson stat	3.019079	
Prob (F-statistic)	0.000000			

The estimation also passed the respective residual and stability diagnostics meaning that the model was neither heterogeneous nor misspecified. The tests had the following results: Heteroskedasticity test BPG F-statistic of <u>0.20</u>>0.05; White F-statistic of <u>0.62</u>>0.05; RESET Test F-statistic of <u>0.51</u>>0.05(see Tables A.2 to A.4 in the Appendix section). The estimation results show that previous experience reading plans is not significant while using MR. This might suggest that regardless of the initial comprehension level of the person looking (bachelors, masters, PhD, architect or non-architect), MR will help the user understand the design better by 14.42% on every case. This value is close to the estimated 15% mentioned earlier. This supports the statement of previous authors that the level of intuitiveness during the interaction with any given display is what determines ease of comprehension, and not so much the person’s background or experience. In addition to this, the coefficients for Gender [-8.35] and Age [-0.38] show that younger people tend to understand design better by 0.38% for every one-year difference. Also, women seem to have the tendency of understanding 8.35% less than men while looking at architectural design for the first time.

The researchers also used the evaluation form to record and count what type of information (floor plan, notes, section, elevation, and isometric) was used more frequently by the users in the 2D group while trying to understand the design. This was done by counting how many times 2D participants used a specific kind of drawing to give answers during their experiment session. The results indicate that the isometric diagram is the most useful and easiest to read as it can quickly convey information to participants. The second place is for plan drawings (floor plans and elevations), third place is for sections, fourth place for renderings, and last come the notes (see table 7).

Table 7 2D plan information according to frequency of use per treatment session.

2D Plan information Usage frequency					
2D Group Participant Number	Times information was used per session				
	Rendering	Isometric	Notes	Plans	Section
23	8	4	0	7	0
24	1	11	0	1	0
25	1	6	1	10	0
26	5	5	0	9	4
27	0	4	1	9	2
28	1	7	4	2	0
29	3	6	1	5	2
30	0	7	3	6	1
31	2	7	2	2	0
32	1	7	3	8	3
33	3	4	1	2	3
34	2	2	1	9	5
35	0	6	1	7	2
36	4	3	1	4	3
37	2	11	1	3	3
38	2	4	1	6	2
39	0	7	3	6	3
40	2	6	1	3	3
41	0	5	1	4	3
42	0	6	1	5	5
Average times Information was used per session	**1.85**	**5.9**	**1.35**	**5.4**	**2.2**

Regarding how to combine MR and 2D for design review, the researchers recorded which media (MR or 2D) participants used to answer each question, in order to conclude which one was more useful while trying to find the different types of information asked in the questionnaire (see table 8). The greatest amount of points each media could get on every question was 42, implying that every participant used either only MR or 2D to answer. If the difference was zero, in other words, 21 people used MR and 21 people used 2D, then both media were considered to be equally effective for reading the information asked in the question. If the difference between both media was less than 30% (5 points) it was also considered both were equally effective. Finally, if there was a difference greater than 30%, one medium was preferred over the other. The results indicate the following:

1. **Both MR and 2D are suitable for**: Identifying spaces and general layout, identifying were activities can be performed, and identifying heights.
2. **2D plans are suitable for:** identifying specific measurements of the space (Length and width), understanding the demolition plan, and identifying countable elements in the design like number of lamps, switches or sockets.
3. **MR is better for** understanding how elements in the space interact with each other, I.e. if the columns are covered by a specific material or if the false ceiling will cover certain beams. It was especially useful for quickly identifying the specific materials and textures of the design (Ceiling, floor, walls, and kitchen), visually understanding size in terms of width, and understanding innate properties of materials like roughness, smoothness, warmness or coldness.

Table 8 Questions according to media used for answering (MR or 2D).

Media used to answer Questions							
Question	Times media was used to answer		Preferred medium	Question	Times media was used to answer		Preferred medium
	2D	MR			2D	MR	
01	21	21	Both	**15**	32	10	2D
02	41	1	2D	**16**	07	35	MR
03	23	19	Both	**17**	16	25	MR
04	19	23	Both	**18**	15	27	MR
05	12	30	MR	**19**	17	25	MR
06	20	22	Both	**20**	19	23	Both
07	20	22	Both	**21**	21	21	Both
08	20	22	Both	**22**	04	38	MR
09	28	14	2D	**23**	0	42	MR
10	17	25	MR	**24**	20	22	Both
11	05	37	MR	**25**	20	22	Both
12	19	23	MR				
13	09	33	MR				
14	13	29	MR				

Finally, after re-watching the recordings of the process the experimenters were able to identify certain behavior patterns for the participants in each group. First, the MR participants tended to begin the exploration process by noticing the smaller, tiny details like the decorations on the tables or the content of the computer screens. Then, they made a quick scan to identify the spaces in the layout, and finally moved into the broader aspects of the design such as the ceiling and floor materials, illumination, and movable/fixed furniture.

Meanwhile, people who analyzed the design using 2D drawings were able to identify some measurements, and the general layout along with its related activities, mainly by comparing the isometric drawing to the floor plan. Nevertheless, they mostly failed to understand specifics of the design, such as the aesthetics of any particular material or certain inherent material properties such as thickness and texture.

5. Discussion

We see that MR’s advantage is the ability of allowing the user to explore a given space in a way that accurately mimics reality. Since MR headsets, like the HoloLens, do not need prior training, it becomes clear that mixed reality can become a helpful aid for the design review process and make it more efficient. MR allows users to interact with a 3D model while still being able to interact with the real world and read specific information from a printed drawing at the same time.

Based on the results, it is possible to say that if users are provided with isometrics and floorplans along with a 3D hologram they can interact with, their comprehension can be boosted by at least 15% more while looking at a design for the first time.

Figure 4 Representation of user using the HoloLens for looking at the design proposal integrated with the real environment.

It is also possible to assess that the type of interaction the participant has with the design is also an important factor for determining the comprehension level. In other words, the more accurately a display can realistically simulate the interaction between the user and the new space, the better it will be understood.

Correlatively, the correct use of textures can also aid comprehension. By looking directly at materials placed on site, with correct widths and scale, MR´s ability to provide information about material properties such as texture, thickness and appearance was accurate and immediate.

Under this light, MR HMD’s could be capable of aiding architects solve several problems that derive from design-based change orders in the construction site. First, MR’s 1:1 scale display ability can aid in the creation of virtual mock-ups. This function can allow stakeholders to visualize things that usually need a lot of detailing like hand railings, doors, and other small elements, such as bases and crowns, on site without having to carry any cables or heavy equipment; hence, the approval process for design could become more effective.

Additionally, MR has the potential to replace physical material samples. Its ability to accurately represent an element both in thickness and appearance is very valuable for clients and contractors to understand the choices and decisions made by the architect. However, in order for this process to be successful, the architect must make sure to obtain detailed, high-resolution textures to ensure the hologram can be an accurate representation of the intended material.

Finally, during the experiment implementation, the researchers noticed three major limitations regarding the use of MR software:

1. Pixelated low-quality textures with low resolution, can hinder the process of comprehension. For example, floor materials like tiles, could be perceived as carpet due to the size of the pixels.

2. The size of the images used for textures can make the 3D model really big in terms of file size, making it difficult for the processor in the HoloLens to render the image quickly.
3. Bright illumination could affect the correct visualization of holograms, since they may look transparent, and according to the level of brightness, may become hard to see.

6. Conclusions

The work describes the design, and implementation of an experiment which used the holographic capabilities of the Microsoft HoloLens to evaluate its effect on design review effectiveness during the development stage of design. For this purpose, an original architectural design proposal was created, in order to provide a base line that would allow the comparison of participants. They were divided into two groups: a control group, which looked at the design with 2D drawings, and an experimental group, which looked at the design with MR. The quantitative measurement was made with the use of a questionnaire based on aspects of environmental perception provided by the literature review. The questionnaire allowed the calculation of a percentage of comprehension according to how many questions any participant answered according to the assigned group. The results were recorded in an evaluation form, and then were tabulated and counted to produce results.

The processing capacity of the "Hololens One" provided many limitations for this research as the loading times, due to the size of the model, were long. This prevented the researchers from adding more people to the sample due to time constraints. The authors want to encourage other researchers to try out this experiment with a bigger sample, and using Microsoft's Hololens Two as it has better processing power and a wider range of view. At the same time a small interior space with limited sunlight was used for carrying out this research. Further study in larger spaces will be of great value to corroborate the information in this paper. The authors also believe there could still be more to learn by analyzing how MR interacts in outdoor environments and how to overcome the transparency factor mentioned above. Future research on this topic might be oriented towards the following directions: Is it possible to use MR to place a 1:1 model of a building on-site? To what extent can this technology be used to make a preliminary site analysis in the design phase of a project? How much could this help to sell a project? This would complement the information discussed in this paper, and would present yet another application of MR for architecture.

Altogether, the study suggests that MR-based design review process is more effective and significant than 2D drawing-based methods for communicating the architect´s design proposal effectively. The evaluation estimated that MR can boost the comprehension level of any given participant by 15% regardless of his or her academic background. It also provided valuable input regarding how to combine MR and 2D in a way in which the strengths of each one compensates the weaknesses of the other. It is possible to say that the MR technology of the HoloLens, which does not require previous training and allows the user to interact with the real and virtual worlds at the same time, proved to be a very good way of displaying an architectural proposal at initial design review meetings. Finally, it is capable of aiding professionals to avoid long and tedious explanations while presenting a design proposal, and could also replace physical samples and mock-ups, especially when the visual properties of materials need to be analyzed.

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APPENDIX

Table A.1 Evaluation form for experiment application.

EVALUATION FORM (MREXP-003)

Number:		**Group:**	2D		MR	

Participant Information:					
Name		Age		Gender	
Education Level		Experience time			
Specialization area		Nationality			

Number & score			Media used to answer the question						Number & score			Media used to answer the question					
N°	R	S	MR	2D					N°	R	S	MR	2D				
				R	IS	N	P	SC					R	IS	N	P	SC
01									13								
02									14								
03									15								
04									16								
05									17								
06									18								
07									19								
08									20								
09									21								
10									22								
11									23								
12									24								

25. Describe the space by memory and identify its general function
Record participants answer for question 25

Device Interaction questions *Likert scale*						
N	*Strongly Disagree*	*Disagree*	*Slightly Disagree*	*Slightly Agree*	*Agree*	*Strongly Agree*
25						
26						
27						
28						
29						
30						

Number of correct answers						
	R	S	%		S	%
2D	1			MR		
	2					
	3					
TOTAL				TOTAL		

Abbreviations:
Score (S); Section (SC);Rendering (RD); Isometric (IS); Mixed Reality model (MR); Sheet notes (N); Photograph (P); Round in which the question was answered (R). "R" only MR or 2D for 5 minutes, "R2" second round of MR or 2D, "R3" complimentary information from MR for 2D users, and 2D for MR users.

Notes on the process
Record details participants notice in the space such as things on a screen, equipment, details of the furniture, etc.

Table A.2 RESET test for equation 01

Ramsey RESET Test
Equation: 01
Specification: GCOMP MR PLANEXP GENDER AGE C
Omitted Variables: Squares of fitted values

	value	df	Probability
t-statistic	0.667123	36	0.5089
F-statistic	0.445053	(1,36)	0.5089
Likelihood ratio	0.516045	1	0.4725

F-test summary:

	Sum of Sq.	df	Mean Squares
Test SSR	24.71805	1	24.71805
Restricted SSR	2024.142	37	54.70655
Unrestricted SSR	1999.424	36	55.53956
Unrestricted SSR	1999.424	36	55.53956

LR test summary:

	Value	df
Restricted LogL	-140.9753	37
Unrestricted LogL	-140.7173	36

Unrestricted Test Equation:
Dependent variable GCOMP
Method: Least Squares
Date: 06/30/2020 Time: 16:00
Sample: 1 42
Included observations: 42

Variable	Coefficient	Std. Error	t-Statistic	Prob.
MR	46.62040	48.32071	0.964812	0.3411
PLANEXP	3.144145	4.163104	0.755240	0.4550
GENDER	-26.71351	27.62661	-0.966949	0.3400
AGE	-1.272228	1.351943	-0.941037	0.3530
C	183.9881	150.9325	1.219009	0.2308
FITTED^2	-0.014219	0.021314	-0.667123	0.5089

R-squared	0.617234	Mean dependent var	78.09524
Adjusted R-squared	0.564072	S.D. dependent var	11.28740
S.E. of regression	7.452487	Akaike info criterion	6.986536
Sum squared resid	1999.424	Schwarz criterion	7.234775
Log likelihood	-140.7173	Hannan-Quinn criter.	7.077526
F-statistic	11.61044	Durbin-Watson stat	3.027053
Prob (F-statistic)	0.000001		

Table A.3 Heteroskedasticity test for equation 01 (BPG)

Heteroskedasticity Test: Breusch-Pagan-Godfrey

F-statistic	1.592135	Prob. F (4,37)	0.1969
Obs*R-squared	6.167574	Prob. Chi-Sqaure (4)	0.1870
Scaled explained SS	3.212285	Prob. Chi-Sqaure (4)	0.5229

Test Equation:
Dependent Variable: RESID^2
Method: Least Squares
Date: 02/18/21 Time: 23:01
Sample: 1 42
Included observations: 42

Variable	Coefficient	Std. Error	t-Statistic	Prob.
C	57.07801	36.15071	1.578890	0.1229
MR	-24.97414	17.92145	-1.393533	0.1718
PLANEXP	25.92974	18.45947	1.404685	0.1685
GENDER	21.72174	18.10966	1.199456	0.2380
AGE	-0.529473	1.353844	-0.391089	0.6980

R-squared	0.146847	Mean dependent var	48.19386
Adjusted R-squared	0.054614	S.D. dependent var	56.51151
S.E. of regression	54.94667	Akaike info criterion	10.96195
Sum squared resid	111708.1	Schwarz criterion	11.16881
Log likelihood	-225.2009	Hannan-Quinn criter.	11.03777
F-statistic	1.592135	Durbin-Watson stat	1.596844
Prob (F-statistic)	0.196858		

Table A.4 Heteroskedasticity test for equation 01 (White)

Heteroskedasticity Test: White

F-statistic	0.825959	Prob. F (11,30)	0.6160
Obs*R-squared	9.763018	Prob. Chi-Sqaure (11)	0.5518
Scaled explained SS	5.084916	Prob. Chi-Sqaure (11)	0.9270

Test Equation:
Dependent Variable: RESID^2
Method: Least Squares
Date: 02/18/21 Time: 23:01
Sample: 1 42
Included observations: 42
Collinear test regressors dropped from specification

Variable	Coefficient	Std. Error	t-Statistic	Prob.
C	-96.28102	160.9945	-0.598039	0.5543
MR^2	100.0678	141.0442	0.709478	0.4835
MR*PLANEXP	-42.40450	42.11503	-1.006873	0.3220
MR*GENDER	1.445328	44.58816	0.032415	0.9744
MR*AGE	-4.298211	5.528824	-0.777419	0.4430
PLANEXP^2	46.37534	140.2354	0.330696	0.7432
PLANEXP*GENDER	-29.17956	47.81926	-0.610205	0.5463
PLANEXP*AGE	0.508110	5.619150	0.090425	0.9286
GENDER^2	90.81293	154.6430	0.587242	0.5614
GENDER*AGE	-2.173174	6.594215	-0.329558	0.7440
AGE^2	-0.035661	0.171421	-0.208029	0.8366
AGE	5.942935	9.442626	0.629373	0.5339

R-squared	0.232453	Mean dependent var	48.19386
Adjusted R-squared	-0.048981	S.D. dependent var	56.51151
S.E. of regression	57.87896	Akaike info criterion	11.18954
Sum squared resid	100499.2	Schwarz criterion	11.68602
Log likelihood	-222.9804	Hannan-Quinn criter.	11.37152
F-statistic	0.825959	Durbin-Watson stat	1.705996