Project 140: Improving the effectiveness of design meetings in projects with smartphone AR

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Abstract

Visualisation and collaboration plays a significant role in shaping the Architecture, Engineering and Construction (AEC) industries, as these abilities are often used during design meetings. Despite the fact that paper drawings are developed in Computer Aided Design (CAD) software to assist in visualisation, it is evident that paper drawings creates inefficiencies in these industries during design meetings. The ability to collaborate is also vital as it dictates the interactions between different parties in meetings. Research shows that AR can significantly enhance the user's visualisation and collaboration abilities, while still being able to communicate naturally similar to paper drawings. An smartphone-AR based prototype was developed to allow the building model to view, manipulate and edited. The research aim was to determine the how smartphone AR is able to facilitate the effectiveness of design meetings. This was done by undertaking a series of trials to measuring the differences in the user's visualisation and collaboration capabilities with smartphone AR in comparison to paper drawings with 32 participants. The results show strong indication that AR allows users visualise buildings efficiently with greater accuracy and confidence compare to paper drawings. Additionally, participants have expressed strong affinity with AR over paper drawings. Furthermore, it is evident that smartphone AR is more feasible than head-mounted AR devices, as it is widely accessible and lower costs.

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1. INTRODUCTION

The Architecture, Engineering and Construction Industries are heavily influenced by the effectiveness of design meetings amongst different stakeholders, which requires highly efficient collaborations amongst different parties, such as building design inspection between engineers, client and architects (Dino Bouchlaghem, 2005). These complex interactions can lead to poor communication due to the lack of consistent understanding of the model, particularly as the model becomes more sophisticated, which could result in delays and higher cost. Furthermore, the mental visualisation ability differs between different parties and also has a significant contribution to design meetings. It is evident that people tend to take longer to visualise 3D models from a 2D perspective (Tory, Atkins, Möller, & Kirkpatrick, 2006). Hence, ineffective design meetings are also contributed by the inability to visualise 3D models in a timely manner.

Although the majority of design meetings are primarily paper-based due to the ability to intuitively annotate to indicate specific changes (Tory & Staub-French, Qualitative analysis of visualization: a building design field study, 2008). However, it is evident that paper drawings tend to stagnate the rate of visualisation during meetings (Tory, Atkins, Möller, & Kirkpatrick, 2006). Therefore, the current method of collaboration such as analysing paper drawings collectively is unable to construct a mutual mental image in efficiently (Tory & Staub-French, Qualitative analysis of visualization: a building design field study, 2008). On the other hand, most design work nowadays are created with 3D Computer Aided Design (CAD) software. This is due to the higher level of engagement provide with 3D models (Ku, Pollalis, & Shelden, 3D model-based collaboration in design development and construction of complex shaped buildings, 2008), which assists in enhancing the effectiveness of interaction (Mehrbod, Staub-French, Mahyar, & Tory, 2019). As a result, a medium that can facilitate the visualisation process similar to engaging with 3D model, without compromising the level of interactivity similar to 2D paper drawings is deemed to be most suitable for design meetings.

Augmented Reality (AR) can alter the user's perspective by overlaying virtual content on the physical world (Henderson & Feiner, 2010). One of the main advantage of AR is its ability to allow the users to interact with the virtual content without compromising in the user's concentration on the physical environment and ability to communicate efficiently (Regenbrecht, Wagner, & Baratoff, 2002), especially for smartphone-based AR. Furthermore, there are studies which have explained why AR is beneficial including higher level of engagement and collaboration (Perdomo, Shiratuddin, Thabet, & Ananth, Interactive 3D Visualization As A Tool For Construction Education, 2005).

The main research objective will be to analyse the feasibility of implementing smartphone AR in design meetings in comparison to paper drawings. This leads to following three research questions to be evaluated:

Question 1: How does smartphone AR facilitate the user's visualization process relative to paper drawings?

Question 2: Does smartphone AR affects the efficiency of communication during design meetings?

Question 3: Does smartphone AR offer similar benefits as head mounted devices such as Hololens?

A smartphone-based AR prototype was developed and used to conduct series of trials with human participants to obtain qualitative and quantitative data. These data will be used to assess the benefits of using smartphone AR compare to paper drawings. The final results was then evaluated and compared to previous trials to compare and determine whether if it offers similar benefits as head-mounted devices such as HoloLens.

2. LITERATURE REVIEW

2.1. AEC Industries

The Architecture, Engineering and Construction (AEC) Industries contribute significantly to New Zealand's economy. These sectors collectively comprise approximately 8% of New Zealand's total GDP as of 2015 (Valuing the role of construction in the New Zealand economy, 2016). Additionally, it comprises over 10% of New Zealand's total employment, making it the 5th largest sector in New Zealand (Future demand for construction workers, 2017). Therefore, it involves sophisticated collaborations amongst professionals from a wide range of disciplines throughout the different stages of AEC projects (Alarcón & Mardones, 1998).

Stages within AEC projects can be divided into two main categories: Design and Construction. The design phase involves the utilisation of technical drawings with models and specifications in order to achieving the requirements from the client. Once again, it requires many variations of different stakeholders for design meetings. This creates potential for the misunderstanding, causing inefficient design meetings and subsequently high cost and time delays, which can adversely affect the country as a result of its significance in the economy and other sectors. The construction phase is primarily consist of contractors that are responsible for the delivery the project (Howell, 1999).

Currently, there's an increasing in the usage of Computer Aid Design (CAD) and Building Information Modelling (BIM) software to produce technical paper drawings as a result of the decrease in cost and increase in usability in recent years (Calderon-Hernandez & Brioso, 2018) (C & Jenkins, 2001). Furthermore, these tools allow different users to access project-related design information simultaneously, in particular large construction projects (Dino Bouchlaghem, 2005).

2.2. Mixed Reality

There are two main variations of mixed reality in the reality-virtuality continuum: Augmented and Virtual reality as shown in figure 1 (Milgram & Kishino, 1994). The diagram helps in distinguishing between the two types of mixed reality based on their exposure to the physical world. On one side, the environment consists of primarily physical objects. Whereas, the environment on the other side comprises mainly virtual objects.

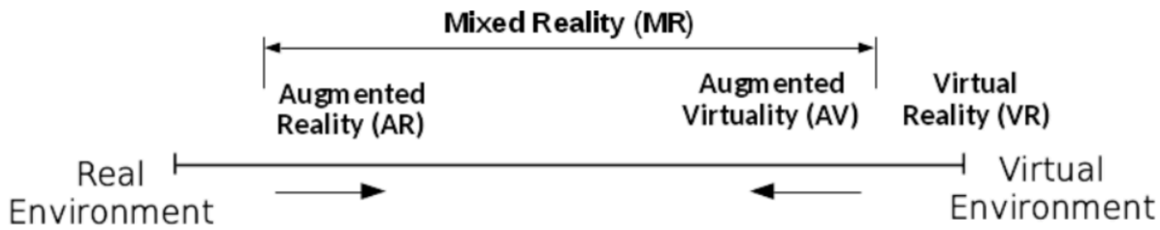

Figure 1: Reality-Virtuality Continuum (Milgram & Kishino, 1994)

Virtual reality (VR) is a medium that delivers an experience in which the user is fully immersed into a 'virtually real' world (Wong, Yu, & Giacaman, 2019), meaning that the user is not exposed to any parts of the physical world environment. This type of mixed reality is often achieved by using head-mounted audio-visual display, which is aimed to completely obstruct the user's hearing and vision to the real world (Bowman & Mcmahan, 2007). The main advantage of VR is its flexibility in being implemented in various different applications. On top of that, it can also be implemented in the AEC industries, where it's able to assist in identifying errors in design and providing guidance to architects.

Augmented reality (AR) is the other variation of mixed reality type, which involves the incorporation of virtual elements to supplement the physical world (Furmanski, Azuma, & Daily, 2002) . Therefore, allowing both virtual objects and the real world to 'co-exist'. One of the unique advantage of AR is its ability to not interfere with the user's perception to the real world during operation. For example, using AR to help students to learn in a sewing workshop (Yip J. , Wong, Yick, Chan, & Wong, 2019). On top of that, it can also be implemented in the AEC industries, such as projecting 3D models for site visits.

2.3. Smartphone AR

Nowadays, not only are mobile phones used as a way of communication, but also commonly used for a number of other purposes such as entertainment and professional. This allows the introduction of AR into smartphones. The camera within a smartphone can be used to interact with the real-world surrounding in real time (Poitras, Kee, Susanne, & Cataldo, 2013). AR technology can also use location-based service and sensor technology to further enhance it by exploring the user's knowledge about their respective surrounding (Harley, Poitras, Jarrell, Duffy, & Lajoie, 2016).

There are two main categories for smartphone AR: Marker-less and marker-based. Marker-less AR is the concept in which data or image recognition determines the user's location and overlay virtual content, this is achieved by using location-based services such as Global Positioning System (GPS) and sensor technology such as accelerometers (Cheng, Chen, & Chen, 2017). Marker-based AR is solely dependent on proprietary labels such as bar code, to identify the device's location and augment virtual content accordingly (Cheng, Chen, & Chen, 2017).

3. MAJOR ISSUES

3.1 Visualisation

Visualisation is the ability in which human attempts to imagine objects or events by building a mental image without seeing them. In other word, it's the ability to picture and manage 3D shapes in the mind (Bouchlaghem, Shan, Whte, & Ganah, 2005). This is similar to spatial ability, which is "the ability to picture and manage 3D shapes within the mind." (Wong, Yu, & Giacaman, 2019) As the visualization ability of varies greatly amongst different individuals, it is quantitively measured by the cognition cost, which is the time taken to visualise.

It is evident that there's a tendency of higher levels of engagement with models in 3D than 2D. Thus, most of the design drawings are now developed in 3D (Tory & Staub-French, Qualitative analysis of visualization: a building design field study, 2008). However, 3D models tends to take more time to be processed than a mixture of 3D models on 2D interfaces (Tory, Atkins, Möller, & Kirkpatrick, 2006). On top of that, some may find it to be unappealing and obscure to look at 3D models from a 2D perspective (Wang, Wang, Shou, & Xu, 2014). Although 2D paper drawing does allow stakeholders within design meeting to be highly interactive, as they can freely draw or annotate to elaborate their thoughts.

3.2 Efficiency in Collaboration

Professionals within the AEC industries must collaborate effectively in order to deliver successful projects. This requires have regular meetings throughout different stages of construction to undertake the decision making process. It is important for the professionals to not only have adequate technical skills, but also being able to communicate effectively to ensure consistent understanding between different parties (Emmitt, 2010). Otherwise, it cause the rise of inefficiencies as a result of poor communication and coordination. This rise of inefficiencies is mainly due to issues with the design of the model (Alarcón & Mardones, 1998).

Currently, there are existing CAD software which are used to enable the 3D models to be manipulate simultaneously by multiple users to minimise the likelihood of varying degrees of interpretation between different parties (Azhar, 2011). However, paper drawing are still primarily used in design meetings. This is because paper drawings allows communication to be made naturally during design meetings, this includes being able to use gestures and expressions to further elaborate on ideas, which is crucial for collaboration (Tory & Staub-French, Qualitative analysis of visualization: a building design field study, 2008).

3.3 Implementation of Augmented Reality

The implementation of AR shows potential for visualising models that are content intensive at lower cognition cost, while enabling user to communicate their thoughts and ideas freely through face-to-face communication similar to 2D drawings (Chu, Matthews, & Love, 2018). The main advantage of AR over 3D visualisation software, is being able to intuitively switch between the virtual and physical world (Regenbrecht, Wagner, & Baratoff, 2002). As a result, this lead to a significant increase in the effectiveness of communication and engagement level in the design process. Furthermore, the enhanced interaction allows stakeholders within the design meeting to take advantage of the facilities within a collaboration room (Dong, Bezadan, Chen, & Kamat, 2013), particularly for smartphone AR since user can still intuitively make gestures and annotations on paper.

Numerous AR prototypes have been implemented and used in wide range of applications within the AEC industries. BIM2MAR is smartphone AR application used to integrate BIM content into smartphone AR effectively and automatically (Williams & Gheisari, 3026). This allows specific content to be augmented at specific locations at exact dimensions using GPS and accelerometer built in the smartphone (Williams & Gheisari, 3026). In a 2013 study, a system known as Hybrid 4-Dimensional Augmented reality (HD^4AR) was developed to support contractors by autonomously determine the location and orientation of an individual based on location and orientation of a photography (Bae, Golparvar-Ford, & White, 2013). Additionally, it allows site engineers and supervisors to have immediately access to information related to site by superimposing over the screen. The motivation behind this is lack of efficiency in the current method of in-site analysis and extracting information (Bae, Golparvar-Ford, & White, 2013).

3.4 Summary

The literature review has introduced the different phases of the AEC industries and it requires different stakeholders to cooperate collectively. It is important to address the inefficiencies in design meetings, as this is part of the decision making process and the AEC industries take up a significant part of New Zealand's economy. Inefficiencies in design meetings are caused due to ineffective communication and high cognition costs in visualisation. Thus, AR was identified to be the most viable solution as it allows user visualise more effectively with the same level of communication as paper drawings. Smartphone-based AR is the most viable AR type, as it is widely accessible at lower costs, along with self-explanatory interface.

4. RESEARCH METHOD

4.1. Experimental Design

The primary objective of the experiment is to conduct a quantitative and qualitative assessment to measure the AR prototype's effectiveness in facilitating the visualization while maintaining effective communication compare with paper drawings. This allows the results to be compared with last year's experiment to determine whether smartphone-based AR follows similar trends as head-mounted AR devices such as the Microsoft HoloLens. The participants will need to first complete a questionnaire for collecting demographic information. This information is used to understand the background of the participants with AR and within the AEC industries.

Similar to last year's project, the first task involves a 3D house model which consists of a number of odd features given in the specification to which the participants must identified. These features can be divided into two main categories: general and specific criteria. Participants would need to indicate the features that fulfils or violates the criteria and their confidence out of ten within 300 seconds. Participants would then use the second medium to identify any remaining criteria. The speed, accuracy and confidence of the each users were recorded as the quantitative data. There were 32 participants in total. Based on the counterbalanced method shown in figure 2, the participants were split into two group of equal number of participants. One of which would attempt this task with the AR prototype first and the other group with the paper drawings first.

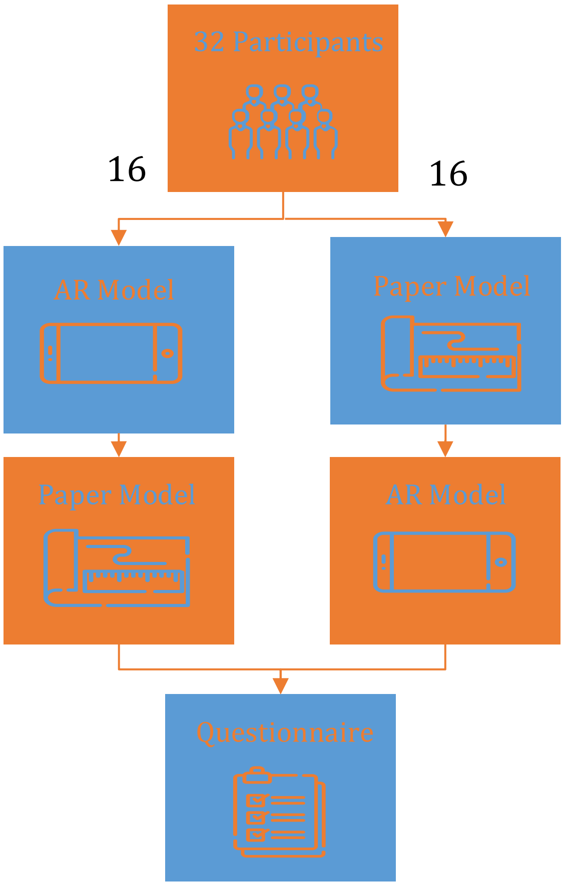

Figure 2: Overview of the experimental method

Task 2 involves the participants to indicate faulty windows and subsequently need to be removed using both mediums. Participants would need to annotate on the paper drawings and highlight the faulty windows in smartphone AR. This task is expected to showcase the AR prototype's ability to allow the users to easily find the faulty windows compare to the paper drawings.

The final task requires the participants to visualise the kitchen design of the house model and discuss the aspects that they like and don't like for both medium separately, along with how does the ease of communication differ between the two mediums. This allows the user to visualise the model from a different perspective as there's no specified criteria that need to be identified.

Lastly, participants are required to complete the post-experimental questionnaire, which consists of questions that's used to understand the feasibility and level of affinity of the AR prototype and paper drawings.

5. PROTOTYPE DEVELOPMENT

5.1. Software development

The software used to develop the AR prototype was Unity 3D. Unity 3D is a multi-platform 3D engine that facilitate the development of 2D and 3D game and applications in virtually all existing platforms from P.C. to Android device and VR/AR Headsets (Zamojc, 2012). Despite being easy enough for beginners, it is also power enough for the likes of professional developers. On top of that, this allowed the assets from previous year's project to be imported into this year's project file. Building model from Revit's 2019 Architecture Basic Sample Project was used as it demonstrates the ability to allow a high degree of customisation and relevant paper drawings.

Initially, ARFoundation was used as the platform API for developing the AR prototype, due to its compatibility for Android and IOS devices (ARFoundation, 2019), which would cater virtually all smartphone devices. However, after the prototype have been developed to a certain extent. It became apparent that ARFoundation was proven to be not be optimised for older and lower tier smartphones, as it heavily relies on the smartphone's depth and surface sensing capabilities. Since the project's aim is to allow the prototype to be used in any smartphone with no significant compromise in performance. ARFoundation was deemed to not be a viable platform for developing the prototype.

Vuforia is another unity software platform used to create Augmented Reality apps. This allows developers to add computer vision functionality to any application, enabling it to recognize images and objects using the camera, and subsequently interact with the physical world in a realistic manner (Leon, 2020). This means any smartphone with a camera is able to identify specific image targets and augment virtual content accordingly. Therefore, catering for less capable smartphones. Furthermore, due to Vuforia being one of the oldest platforms available for AR development. There are more discussions and resources available to facilitate the development of the prototype.

5.2 Prototype features

An easy-to-read tutorial was added to ensure the AR prototype is usable for users across a wide range of experience. Each instruction shows how a particular functionality can be used. The instructions can switched naturally by placing a palm on its respective virtual button (blue area).

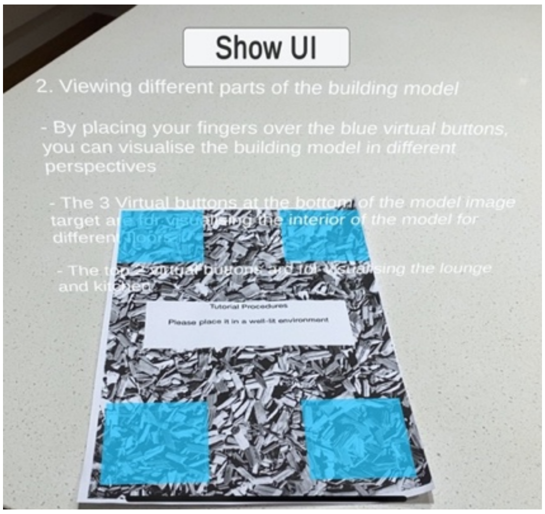

Figure 3: Tutorial Instruction

There are five different building models created for the prototype: Building model with elevated top and bottom floor, kitchen and lounge trial rooms as shown in figure 4 and 5 respectively. The trial rooms are used to conduct section B of the experiment. Once again, these models can be switched interchangeably by using virtual buttons along both sides of the image target.

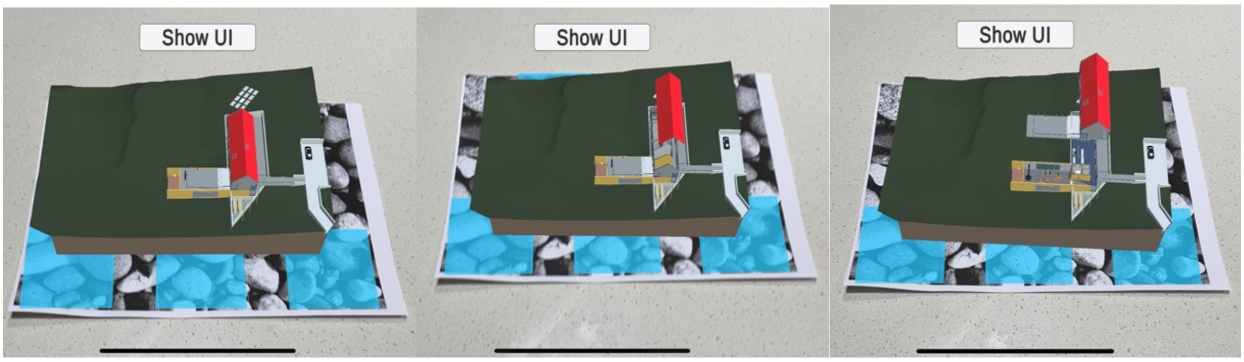

Figure 4: Left: Original Building Model, Middle: Top Floor elevated, Right: Bottom Floor Elevated

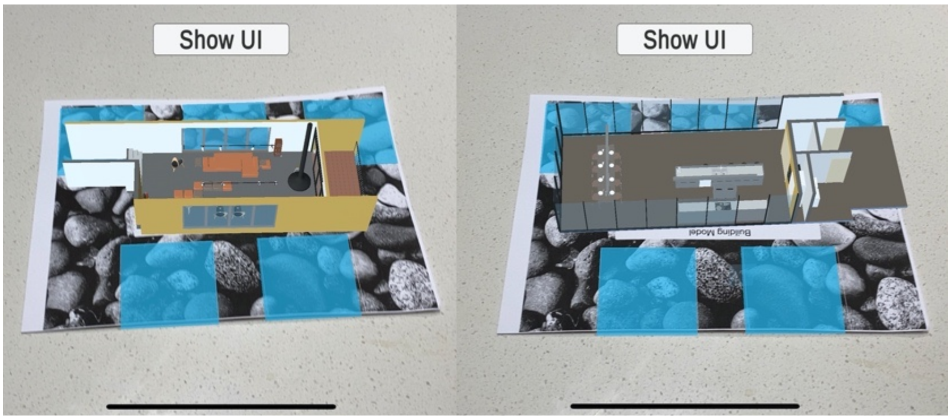

Figure 5: Left: Trial Room for Lounge, Right: Trial Room for Kitchen

This AR prototype consists of 4 interaction modes: Highlight, Delete, Manipulate and Undo. These features can be used to allow users to easily edit and manipulate the house model, which facilitates the visualisation process during design meetings.

The highlight mode can be used to place further emphasise on elements of high concern by allowing the user to change the colour to red, green or blue within the dropdown menu shown in figure 6. This mode can be activate by simply pressing the "Highlight" button (text in bold means the mode is activated) and tap on any elements to change its colour accordingly.

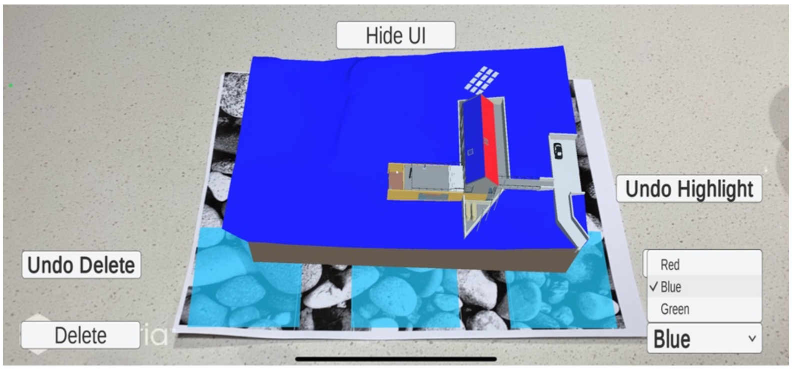

Figure 6: Highlight Mode

The delete mode allows the user to remove any undesired elements within any building models shown in figure 7. Similarly, this feature can be used by tapping the "delete" button and tap on any element for it to be removed. This mode is important as it allows the user to visualise the model without certain elements being shown.

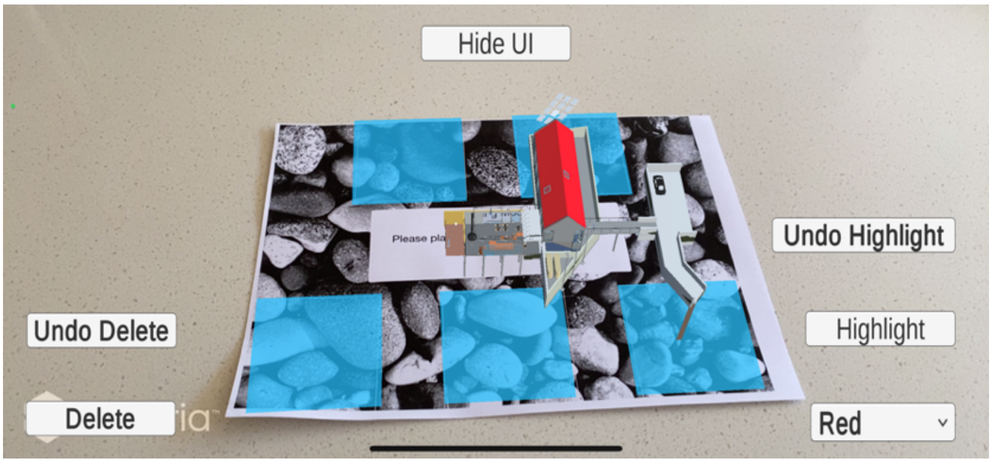

Figure 7: Delete Mode

Both delete and highlight mode each consist of an "undo" button that can be used to revert changes for each features in the order of most recent to least recent. This can be used by first, ensure both modes are deactivated by ensuring the text within the buttons are not bold, then tap on the undo button to revert changes incrementally.

The manipulate mode consists of a number of features that are one and two-finger based gestures, which can be used to allow the building mode to edited naturally. There are three features within this mode shown in figures 8, 9 and 10: Rotating, Scaling and Placing. These features are implemented to allow the user to develop more in depth understanding of the model visually. The placing feature is used to place the building model anywhere within the phone camera's vision, which can be done by simply placing a finger over the model on the phone's screen, then drag and release at the desired location. The rotating feature can be used by placing two fingers over the model and performing a 'twist' movement to alter the orientation of the model. Finally, the scaling feature gave the user the ability to enlarge the size of the model relative to the physical world. This can be performed with a 'zoom in and out' movement using two fingers to decrease and increase the size of the building model respectively.

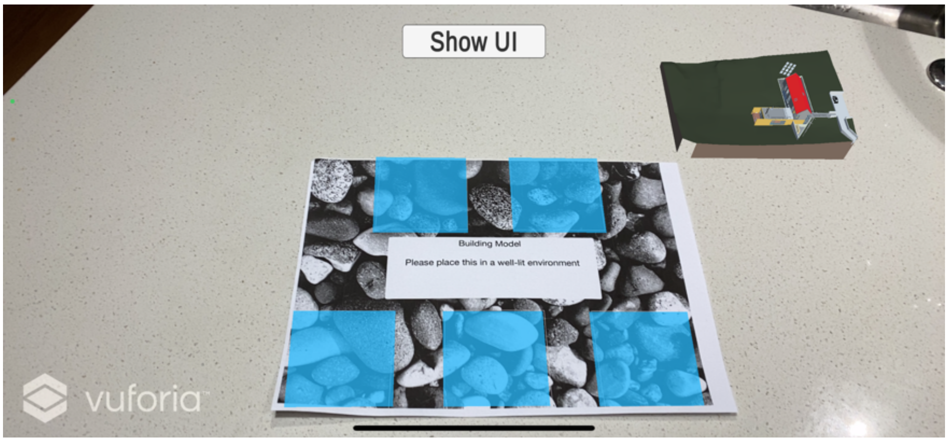

Figure 8: Placing Feature

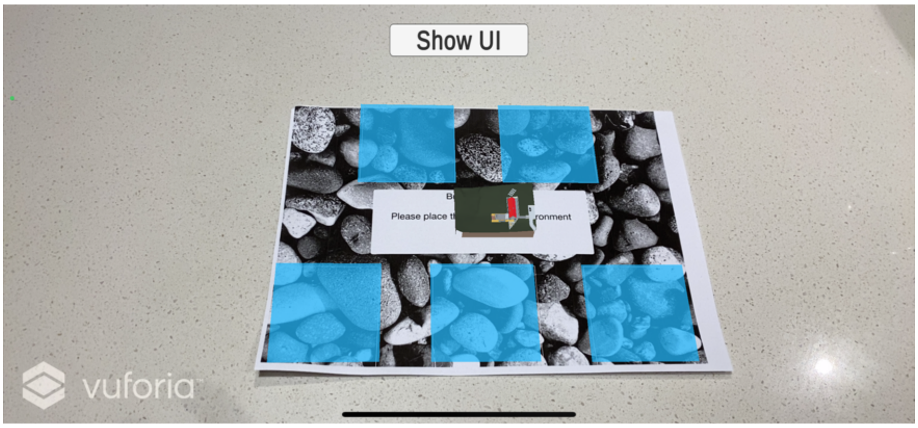

Figure 9: Scaling Feature

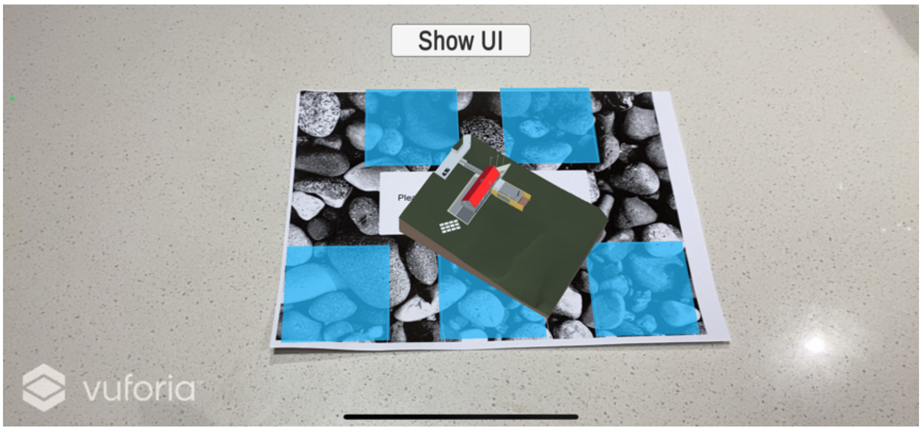

Figure 10: Rotating Feature

6. RESULTS

6.1. Pilot Testing

After the prototype has been developed to be reasonably usable, a small number of participants were selected to test and provide constructive feedback in regards to the features and performance of the prototype.

An issue was identified in which the UI buttons were large enough to cover a substantial proportion of the phone screen, making it harder to manipulate the model. Therefore, a feature was implemented which can hide all other U.I. buttons when none of the features are required.

Another issue was in regards to the order at the undo mode reverts the changes made, as it was reported to be in the order of least recent to most recent. This was subsequently changed to the opposite order in order to be more useful for the users.

6.2 Section A

Section A consists of a series of questions that collects demographic details of each participant to ensure the integrity of the experiment was maintained. Most of the participants were from part IV of Engineering, with a noticeable proportion of participants having PHD and masters background.

Over ¾ of the participants have little or no prior experience with AR, while most of the remaining participants have moderate experience, as shown in figure 10.

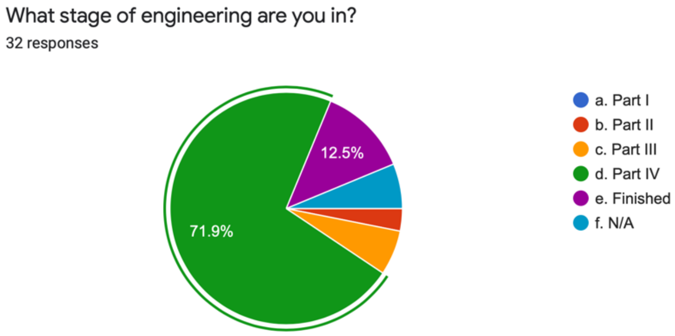

Figure 11: Chart for AR Experience of Participants

6.2. Section B

6.3.1 Task 1 – Correct Answers and accuracy

In order to determine whether the differences between the level of confidence and accuracy were statically significant, Mann-Whitney U test was user as it was determined to be the most suitable method. This is due to the 3 assumptions of this particular method. Firstly, each specimen group were formed randomly, to which was fulfilled as the two participant groups were created randomly. Secondly, the data for this experiment fulfils the assumption of independent readings as each participant has conducted the experiment on a one-on-one basis. Thirdly, all the data for this test are continuous as required. The table below summaries the result for task 1 (Nachar, 2008).

Table 1: Summary of U Test outputs

	Paper First		**AR First**			**Initial**				**All**	
	Paper mean	**AR mean**	**AR mean**	**Paper mean**	**Mean difference in Firsts (A-P)**	**U-value**	**p-value**	**All Paper**	**All AR**	**U-value**	**p-value**
Average correct Answers	5.63	7.25	10.69	1.81	5.06	7.5	2.60E-07	3.72	8.97	51.5	5.34E-10
Average incorrect answers	1.19	0.44	0.44	0.75	-0.75	195.5	3.40E-03	0.97	0.44	704	5.17E-03
Average confidence (correct)	7.90	8.96	8.76	7.15	0.86	37.5	3.45E-04	7.55	8.86	104.5	1.26E-07
Average confidence (incorrect)	5.63	6.00	6.67	4.33	1.03	28.5	0.367	5.10	6.36	85.5	1.77E-01

Based on table 1, average number of correct answers with AR for AR First participants is 10.69, which is substantially higher than paper drawings for Paper first participants. Additionally, the average number of incorrect answers with Paper for Paper first participants (1.19) is noticeably higher than AR for AR first participants (0.44). Finally, the mean level of confidence for correct and incorrect answers for AR first participants is slightly higher than paper first participants. Apart from the average confidence for incorrect answers, it is evident that these difference between the two mediums are statistically significant as the p-value for each is less than 0.05.

Similar trends can also be seen for all AR compare to all paper drawings for average confidence levels, correct and incorrect answers. Furthermore, the p-value for average confidence for incorrect answers is also below the threshold value of 0.05.

Table 2 below showcase the number of participants that have correctly spotted each criteria in both mediums. These criteria are divided into the categories of general and specific shown as green and blue respectively. Overall, the table shows general criteria tend be more likely to be identified on smartphone AR, while specific criteria also indicates similar trend but not as strongly.

Table 2: Total number of correct criteria

Criteria/Features	**Paper (1st)**	**AR(2nd)**	**AR (1st)**	**Paper(2nd)**	**AR(1st)-P(1st)**
Window numbers	11	5	15	0	4
Windows floor to ceiling	7	5	14	1	7
2 Double doors	8	5	15	2	7
10+ Object to sit	11	5	14	2	3
4 types of seats	3	13	11	2	8
8 lights	10	6	16	0	6
Chair not facing window	8	8	16	0	8
Chairs collision	5	11	16	0	11
Table/Chair Collision	1	15	12	0	11
Table Floating	0	7	1	2	1
Toilet on deck	4	12	15	1	11
TV Orientation	6	10	10	6	4
Furnace Orientation	1	10	5	9	4
Cabinet Orientation	5	11	12	3	7

McNemnar Test and Fisher Exact test analysis were implemented to determine the magnitude of statistical significance in the difference with feature identification between both mediums. The McNemnar test is suitable to be used to determine the significance in the difference in performance of the participant from the first medium to the second medium. This is due to the test's main assumptions align with the experimental data: each feature has a binary variable of either found or not found, along with AR first and paper first groups being independent. This allows 2x2 contingency table to be undertaken to determine whether if there's improvements switching from smartphone AR to paper, or from paper to smartphone AR. Based on table 3, since the p-values are less than 0.05 for all criteria. This suggests that there's strong evidence that the performance of participants has improved significant from paper drawings to smartphone AR. On the other hand, only TV and furnace orientation from the general criteria were able to be identified more effectively from smartphone AR to paper drawings.

Table 3: McNemar Test Results

	Paper first		AR first	
Feature/Criteria	**Test statistic**	**p-value**	**Test statistic**	**p-value**
Window numbers	3.20	0.037	inf	0.000
Windows floor to ceiling	3.20	0.037	0.00	0.500
2 Double doors	3.20	0.037	0.50	0.240
10+ Object to sit	3.20	0.037	0.50	0.240
4 types of seats	11.08	0.000	0.50	0.240
8 lights	4.17	0.021	inf	0.000
Chair not facing window	6.13	0.007	inf	0.000
Chairs collision	9.09	0.001	inf	0.000
Table/Chair Collision	13.07	0.000	inf	0.000
Table Floating	5.14	0.012	0.50	0.240
Toilet on deck	10.08	0.001	0.00	0.500
TV Orientation	8.10	0.002	4.17	0.021
Furnace Orientation	8.10	0.002	7.11	0.004
Cabinet Orientation	9.09	0.001	1.33	0.124

Table 4: Fisher Exact Test Results

Criteria/Feature	**T Stat**	**p-value**
Window numbers	1.000	>0.05
Windows floor to ceiling	0.023	<0.05
2 Double doors	0.016	<0.05
10+ Object to sit	0.394	>0.05
4 types of seats	0.011	<0.05
8 lights	0.043	<0.05
Chair not facing window	0.002	<0.05
Chairs collision	0.001	<0.05
Table/Chair Collision	0.000	<0.05
Table Floating	1.000	>0.05
Toilet on deck	0.000	<0.05
TV Orientation	0.289	>0.05
Furnace Orientation	0.172	>0.05
Cabinet Orientation	0.032	<0.05

The Fisher Exact test was undertaken to determine whether the statistical difference is significant between AR first and paper first for each criteria. The experimental data is suitable for this particular test as the number of participants found for each criteria was record, and mutual exclusive categories between paper and AR first. From table 4, there's strong evidence for the significant improvement with AR as the first medium for all criteria except for Window numbers, number of objects to site on, floating table, TV and Furnace orientation.

6.3.2 Task 1 – Time Duration

As shown in figure 11, it is obvious that participants using smartphone AR as their first medium has a strong tendency to obtain correct answers at a more rapid pace than paper drawings, as the gradient for AR is much greater than the gradient for paper drawings. For the second medium, similar trend can be observed where gradient for AR is substantially greater than paper as both lines intersect at approximately the time of 550 seconds. On the other hand, the rate at which correct answers were identified for paper drawings tends to be slower when it's used as the second medium rather than first.

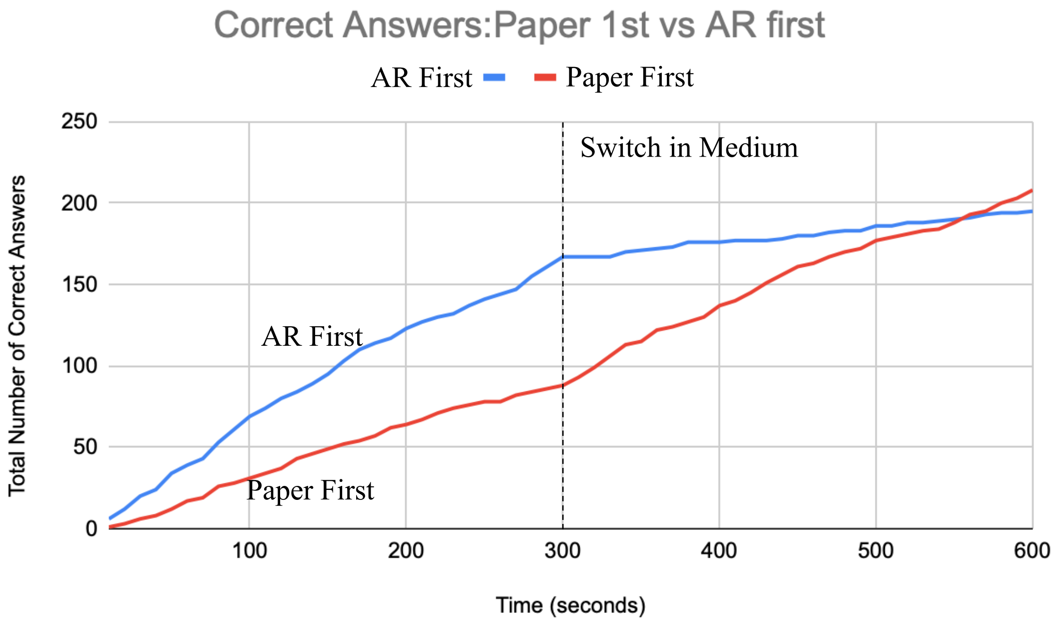

Figure 12: Cumulative Frequency graph for Correct answers of all participants

6.3.3 Task 2 and 3

Task 2 asked participants to indicate that the windows were faulty and needed to be removed on both mediums. Most participants either shaded and annotate with an arrow near the windows for the paper drawings. Whereas for smartphone AR, most participants intuitive used the highlight mode to change the colour of windows. It was found that approximately 81.3% of the participants found it easier to make design changes on AR, based on question 11 of the post-experimental questionnaire shown in table 5 below.

Task 3 involves the participants to discuss their thoughts and opinion on the kitchen design of the building model. Although in general, most participants were able to express their opinion about the kitchen model with both mediums. However, many of the participants stated that the kitchen design was significantly more apparent with AR than paper drawings. This was evident based on the question 4 and 8 of the post-experimental questionnaire, as 100% of participants have stated that it was easier using smartphone AR. This is shown in table 5 below.

Table 5: Rating score from question 1-8

	% Easy or Very Easy	
Question	**AR**	**Paper**
1, 5. How easy would the model be for a non-engineer to understand	100	12.5
2, 6. How easy was it to visualize the room's exterior	90.7	3.1
3, 7. How easy was it to visualize the building's contents	100	6.3
4, 8. How easy was it to express what you liked/didn't like about the kitchen	100	9.4

6.3. Section C

Questions 1-8 required the participants to rate the ease of completing various type of tasks in AR and paper. The results show strong evidence of high rating for smartphone AR compare to paper drawings. These results were evaluated using the Wilcoxon Signed-Rand test, which is appropriate for these data as it compared two group of data, independence of each paired questions and ordinal nature. The final p-value were calculated to be less than 0.05 for all paired questions, meaning that the difference is statically significant.

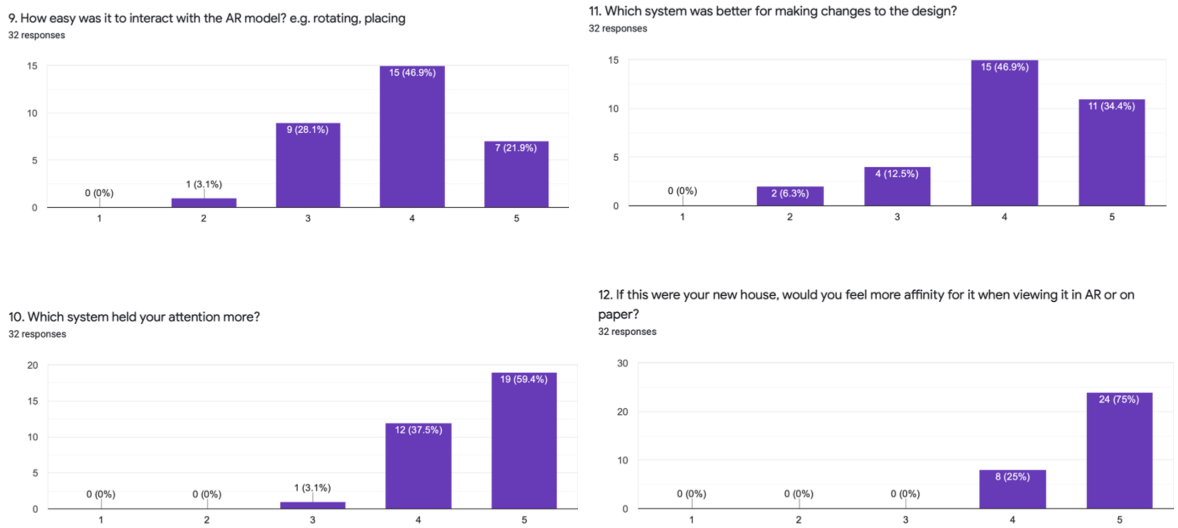

Figure 13: Pie Charts for Question 9-12

Question 9 asked the participants to rank the difficulty of interaction with the AR model on a scale of 1-5 from hardest to easiest. Nearly 70% of the participants give a rating of 4 or higher as shown in figure 12 above.

Question 10, 11 and 12 asked about the affinity of participants to AR and paper drawing medium, along with which system was better for making changes to the design on a scale of 1-5. There's strong evidence that indicates that participants tend to feel more affinity with AR, and they tend to find it easier to make changes to the building design.

7. DISCUSSIONS

Results from task 1 shows that smartphone AR allows the participants to be more effective at identifying errors with the general criteria. Whereas for specific criteria, the effectiveness of AR is less apparent between the 2 mediums. This is most likely due to specific criteria gives a clear indication of the errors within the building model, whereas general criteria require the user to search for in the building model. On the other hand, participants were more likely to have difficulties in visualising the 3D model from a number of different 2D perspectives on paper drawings.

The two most difficult criteria to identify for both medium were the furnace orientation and floating side table. This is due to the fact that the furnace consist of dark colours, along with the small inlet of the furnace which was difficult to be seen. Furthermore, the floating side table requires the model to be at a specific angle in order to be seen, which was difficult as the image target would need to be visible by the phone's camera on the screen. This was near impossible for paper drawings, as the elevation gap between the side table and the floor was too small to be apparent.

The rates at which the participants correctly identify both the general and specific criteria for both medium are determined based on time duration for each medium as shown in figure 11. It is apparent that AR allows users to visual 3D objects at much fast rate than paper drawings. This shows the potential of AR being able to reduce cognition costs in visualising building models in the AEC industries.

For task 2, the results reflect that participants tend to prefer to use AR over paper drawings. This is apparent as participants were found to be hesitant when attempting to annotate clearly on paper to indicate that the windows were faulty and need to be removed. On the other hand, the highlight and delete features of the AR prototype allow the user to intuitively indicate elements of significance. However, these features may not be applicable for all building models, especially if the model structure is complex with a large number of small elements.

For task 3, even though most participants elaborated their thoughts and opinion on the model in a similar manner for both AR and paper. However, many participants have stated that it was substantially more difficult visualise the kitchen design efficiently with paper drawings compare to AR. This provides strong evidence that smartphone AR can be used to effectively visualise the building model, without affecting the way in which the user can communicate during a face-to-face meeting.

In comparison with the experiment with HoloLens from last year. The results of smartphone AR follow closely with last year's experimental results, where the participants found smartphone AR to be similarly more effective and efficient in visualisation 3D models. Along with the fact that smartphone AR is able to retain the elements of face-to-face meetings and lower cost, this makes it a more appealing than HoloLens. Furthermore, the time duration that's required to set up and learn how the use the HoloLens can lower the efficiency of projects within the AEC industries.

8. LIMITATIONS

Although the experiment for smartphone AR was conduct in a similar manner as the experiment for HoloLens from last year. The participate base was entirely different, meaning that only general interpretations can be made to compare the effectiveness of the two mediums for measuring visualisation and collaboration potential. Therefore, it was not impossible to make justified conclusions regarding to whether smartphone AR was effective than HoloLens.

As mentioned earlier, the features found within this application is deemed to be substantially simplified compare to design meetings in real-life scenarios. This is evident as features such as highlight and delete may not be applicable for structures that are highly complex, as it might not be able to completely represent the ability to annotate and sketch on paper drawings accurately. Furthermore, the vast majority of the participants for this experiment were students who have limited experience within the AEC industries, as reflected by the demographic information from section A of the experiment.

Finally, the AR prototype does not have a collaboration feature where multiple user can collaborate on the same building model. This is a limitation as there would be multiple stakeholders who would need to make adjustments and move the model to communicate their ideas efficiently.

9. CONCLUSION AND FUTURE WORKS

In conclusion, the aim of this research project was to assess how AR can improve the visualisation and communication abilities of participants in design meetings. An AR prototype was developed to allow user to edit, view and manipulate a building model with buttons and touch gestures, along with improvements from preliminary trials. An experiment was undertaken with 32 anonymous participants to measure the effectiveness of smartphone AR compare to paper drawing, which involves a series of tasks that's relevant to design meetings. The recorded data were evaluated and show that the AR prototype significant improve the visualisation process of participants, as participants were faster, more accurate and confident in identifying design features. Additionally, feedback from the participants shows strong affinity with the AR prototype over paper drawings, as it indicated to be easier to use for people with and without experience from the AEC industries. Lastly, smartphone AR is deemed to be more viable AR platform than HoloLens as it is more widely accessible and lower cost, while offering similar benefits as HoloLens.

For future work, it is recommended to conduct similar trials with more complex model in order to have a comprehensive assessment in the effectiveness of smartphone AR. Furthermore, the addition of collaboration feature would allow the trials to emulate more closely to a design meeting, as it would allow multiple users with different smartphones can simultaneously edit the building model. Other areas of improvements include making the prototype marker less-based and bugs related to the on screen UI buttons.

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