

# Total recall-ibration: teaching spatial thinking and critical design with virtual reality

Andrew Hart<sup>1</sup>, Gulbin Ozcan-Deniz

<sup>1</sup>Thomas Jefferson University, Philadelphia, Pennsylvania

**ABSTRACT:** Virtual Reality (VR) is an immersive three-dimensional computer generated environment. The concept of VR was introduced in 1960s when helmet mounted display (HMD) devices was introduced to fighter pilots). The technology has improved since then to mature wearable VR devices. Outside of military use, VR can be found in the entertainment and gaming industry, and commonly accessible for home users utilizing entry level technology with smart phones and adapters such as *Google Cardboard*. The technology has crossed from entertainment to education and visualization. Tapped more frequently in design education, utilized for ideation inception through to logistical planning. The power of VR is in its ability to close the communication gap between designer and builder and users of space. Several previous studies have focused on how VR can improve construction scheduling and safety. This tool can also be utilized to bridge from the conceptual and abstract; from teacher to student. VR allows environment designers to test concepts in 'virtual space' at 1:1 scale for themselves and for the critique of others – be they faculty, peers, internal, or reviewers. The utility of this tool comes from its ability to move communication from abstract visualization feedback to conversations held within a virtual representation of the space itself. This paper explores the role of VR in how students learn to design spaces and in how they communicate that space with fellow students, construction managers, and their faculty.

**KEYWORDS:** Virtual Reality (VR), design education, architecture, construction management.

## INTRODUCTION

Virtual Reality (VR) is an immersive three dimensional computer generated environment. The concept of VR was introduced in 1960s when helmet mounted display (HMD) devices was introduced to fighter pilots (Furness, 1989). The technology has improved since then to mature wearable VR devices. Outside of military use, VR can be found in the entertainment (*Total Recall* 1990) and gaming industry (Dawood, N., Miller, G., Patacas, J., & Kassem, M. 2014.), and commonly accessible for home users utilizing entry level technology with smart phones and adapters such as *Google Cardboard*. The technology has crossed from entertainment to education (Messner, Yerrapathruni, Baratta, & Whisker, 2003) and visualization (Shen & Marks, 2015). It is being tapped more frequently in design education, utilized for ideation inception through to logistical planning. The power of VR is in its ability to close the communication gap between designer and builder and users of space. Several previous studies have focused on how VR can improve construction scheduling (Haymaker & Fischer, 2001) and safety (Chen, Golparvar-Fard, & Kleiner, 2013). This tool can also be utilized to bridge from the conceptual and abstract; from teacher to student. VR allows environment designers to test concepts in 'virtual space' at 1:1 scale for themselves and for the critique of others – be they faculty, peers, internal, or reviewers. The utility of this tool comes from its ability to move communication from abstract visualization feedback to conversations held within a virtual representation of the space itself.

## 1.0 BACKGROUND

In the 1990 movie *Total Recall*, action hero Arnold Schwarzenegger's character dons a virtual reality headset to explore fantasy space, action plot aside, the film based on the 1966 short story by Philip K. Dick *We Can Remember for You Wholesale* (Dick 1995), explores the gap between the real and the imagined, the abstract and the visceral. At the heart of both stories, a series of questions align with the experience inherent in design, and design education; *is what I have imagined possible? And, how will the reality be different than the imagined?*

Designers work in the abstract, often at reduced scale to create 'in-real-life' – virtual reality (VR) offers a chance to move beyond the limit of scale to experience. The line between the imaginary and the reality is one in which designers and construction managers must dwell – conceiving of space, its construction, and planning its logistics before it is made physical. This inherently abstract process has spawned the profession of architect, construction manager, renderer, and draftsman/woman. Architects do not in fact build the buildings they design; they draw them – 'imagine them' – and tasked with explaining them in such detail that others can construct them. The education of a student in these abstract processes is, in itself, is a further extension of this abstraction – they emulate the process without actually taking part in it. In part, this is the reason behind the strict standards for training and on site experience outside of the classroom and in design firms and construction sites.

For students of both architectural design and construction management their work in the studio or class environment is rarely at a scale approaching 1:1 construction. VR offers a chance for design education to leap into a digital manifestation of a design idea, test that idea at the experiential and performative scale in a natural, palpable, and interactive way (Fonseca et al. 2013 and Erdoğan Ford, 2017). How will VR effect designers? How will VR engage young design and construction students? What might be best calibrated for this use in their education? Finally, what answers will student find to the same questions posed in the root of design posed be so many designers before them – *Is this design the way I imagined it to be?*

## 2.0 METHODS

Using an existing university VR Lab, HTC Vive Virtual Reality setup with Revit and Rhino three-dimension modeling software students were instructed on the use of the VR interface to review two models one a digital model of an existing building on campus, the second a digital model of their own design. Students were asked to generate verbal feedback in the moment, record peer feedback and fill out a post-session assessment. This assessment was collected and in turn generated an in class discussion. Selections from this discussion and the feedback forms are provided later in this paper.

### 2.1 Technology resources and VR lab

Technology to run the modeling software and the VR program and space includes:

- A VR-ready computer: Generally specified as a 'gaming laptop' or PC, the computer requires processor and video card hardware able to operate the VR software simultaneously with various modeling programs
- A VR head set unit: HTC Vive was used for this experiment. HTC Vive package comes with a pair of VR goggles, 2 controllers (i.e. hand-held devices), and 2 base stations. Goggles are used to show the virtual world to individual users, while controllers allow them to move and interact with objects in the VE. Base stations are needed to track the location of users in the immersive room-scale.
- SteamVR: Software that allows VR to run with the HTC Vive head set
- IrisVR: Software that allows 3D Revit models to be used in virtual walk-throughs. Additionally, Iris VR allows for in model markups, drawing, and annotation which can be screen captured for later use.
- Mindesk VR Plugin for McNeel Rhinoceros 3D Modeling to be viewed in VR
- Extra large mounted flat screen television connected to broadcast VR output from the headset to the monitor (An optional piece of equipment)

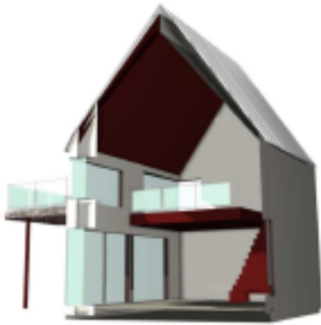
Testing utilized a VR space setup with a 3.5 meter x 3.5 meter x 2.5 meter space with head mounted VR goggles and hand controls tracked via infrared sensors – these are common with setups with hardware from Oculus rift and HTC Vive, this particular study utilized HTC Vive. Alongside this installation for the active VR user is a desk and desktop computer running the 3D modeling software (in this case Autodesk REVIT) and vr plugins, additionally for an a large mobile television setup broadcasts the 'view from the goggles' in real time. The space is in a

flexible tech space co-located near IT services in a library group study area. These conditions noted here, as they proved fortuitous during the VR sessions.

## 2.2 Computer models

Student reviewed two types of models the first type was a model created from existing plans of an actual building on campus, the second was a hypothetical design proposal made by the student or another student (Figure 1). In both model types creation of the digital model was completed in advance of the VR design review.

Most projects in the study were presented as Autodesk REVIT models viewed through IrisVR plugin, but a minority of projects are also small designs produced in McNeel Rhinoceros 3D through MiniDesk VR– both programs have VR plugin software enabling the project to be opened and viewed in VR space. Software support and interface REVIT based projects are considerably more advanced and engage the systems and layers of REVIT more readily – thus these projects could engage students across majors (architecture and construction management) at a higher order of conversation.



**Figure 1.** Basic ‘cabin’ student model used in VR (image from the Author 2018)

## 2.3 Subjects

Two constituencies of students reviewed these models CM students and Architecture students. Students participating in the study varied across students between 2<sup>nd</sup> through 4<sup>th</sup> year undergraduates and 1<sup>st</sup> year graduate students.



**Figure 2.** Instructor in Virtual space and physical space (image from the Author 2018)

## 2.4 Procedure

Students were introduced to the VR setup in groups of between 2 to 12 students. Basic interface and safety were reviewed in a instructor-led demonstrations of the system and

physical interface – an optional large TV monitor was helpful in displaying the visuals seen inside the VR headgear to the observers in the class. Computer support staff were on hand for troubleshooting and to ensure proper system operation. After introduction students would take turns individually utilizing the VR setup to explore, assess and offer verbal assessment of the model during the live walkthrough. Students were allowed to explore the space freely. While each student was individually in the VR space classmates would provide guidance, take notes, and prepare for their own exploration. Depending on group size and the students own comfort level with the software students would experience the VR environment for between five to fifteen minutes in the VR space. Students were given the option to return to the VR lab outside of class time for further exploration.

Upon exiting the VR space students were tasked with relaying their findings verbally to their peers for notes and feedback.

Following the session in addition to the design critique of each project each student provided a one page general assessment of their experience providing written feedback to given prompts:

Perception + Navigation

- 1) *Did you feel oriented / disoriented during the VR walkthrough?*
- 2) *What was the biggest surprise or difference between the actual space and the virtual space?*
- 3) *Having viewed the model what can you identify that would benefit the most from changes?*

Details, Mapping + Planning

- 4) *What role did outside students play for your walkthrough?*
- 5) *What helped the most to navigate through the space for review? Outside assistance, digital modeling, reviewing plans, familiarity with the design or existing space?*

Future Recommendations

- 6) *What planning would you recommend to another person going into VR?*
- 7) *What types of details were more easily found in VR than in other formats?*

This written feedback, collected from students both verbally during the VR simulation, after simulation in a 'debriefing' and through written responses. The feedback generated a post-VR session discussion in class on the experience featuring the prompts. This discussion and feedback provided initial findings, recommendations, and best practices for use by future instructors and classes; presented below.

### 3.0 FEEDBACK + FINDINGS

Young designers and young construction management students often struggle with creating reasonably scaled spaces at scale – it is not uncommon for students to work out hallways that are expansively large, or tightly squeezed. Similarly, issues of wayfinding, exit corridors, handrail heights, and other code issues which can be observed plainly in construction can be a challenge to visualize during design. These beginner design issues exist – the challenge is in the identification and resolution. While these issues are abstract in the studio *virtual reality (VR) modeling at one-to-one scale* utilizes a student's own embodied experience and spatial awareness to speed self-identification, critique, and resolution of these issues. The issues described above would commonly be termed 'coordination' in professional practice, and would be fodder of many meetings between designers and construction management teams. Often the real-world implications of code are not experienced until a designer or construction student is working on site – could this experience be brought to the classroom? By pairing architecture and construction management students together utilizing virtual reality the two groups could not only test each other but vault improvements to their designs by following a 'punchlist' style check of the work – emulating a real-world relationship. In this experimental partnership, several questions are posed: What issues would come up most frequently? How would the

learning space need to be adapted? How would VR improve or impede communication? What objectives are expected? What are the drawbacks? Are results more tangible than other models of critique?

After initial testing, several modifications to the learning space and procedures were made to enhance teaching objectives and student application of knowledge. After each session students were requested to fill out a feedback form recalling their experience, a improvements made in thier design and suggest improvements to the lab

### **3.1 Observation of student engagement**

Each student's design was built as a REVIT model ahead of viewing in VR – students were capable of inputting as much information, data, modeling specifics as needed. Projects varied from high detailed to bare-bones digital manifestations of physical models.

Models were then loaded into VR space for students to first walk through their own design to make notes for future adaptations and then to give tours to other students of the design as a narrated walkthrough presentation. Initially these presentations mirrored a similar method utilized in class for a peer reviewed desk critique.

As students were introduced to VR space students went through several stages:

- Energetic engagement and adoption
  - Initial excitement and novelty
  - Wide-reaching exploration
- Detail orientation
  - Detailed observation
- Prompted review
  - Self-analysis
  - Create design improvements

During initial self-guided walkthroughs of their own designs, students are initially 'wowed' by the novelty of the technology and the empowerment of being in their own designed space. This 'wow' factor brought a large audience to the initial testing of the VR lab, when utilizing the VR lab was given as a voluntary topic over 90% of students expressed interest in seeing their design in VR.

Novelty and excitement drives the first moments of a VR experience, students are consumed by fully exploring the extent of their space, initially through vaults of super-heroic climbing, zooming in and out, and transiting through the space. This experience while enthralling for the designer as they explore their creation is difficult to critique, or follow via external monitor.

After an energetic exploration of space the novelty of VR can start to wane. At this point students tended slow their exploration focused on detailed areas of the overall design. Most critiques and adopted changes came from studying stair details, lobby entryways, multistory space, and railings. These more detailed observations provided the most useful time to prompt feedback and design critique through careful close up study of specific design elements both in the VR goggles and externally through monitors.

Most of these initial observations come through a self-analysis or self-identified critique of spaces either performing as intended or not as intended. Ares of design malfunction are more easily identified in VR as the underdevelopment or over complexity of the design can be immediately experienced 1:1. Common self-flagged issues include elements such as handrail collisions, awkwardly scaled spaces, circulation overruns, or collision and headspace issues all of which speedily identified.

Self-evaluation led to discussion of design development and solutions to both enable the utility of the space and clarity of the conceptual spatial ideas. In studio-type reviews where these

issues are viewed through several representations – plan, section, perspective – and this abstraction can lead to uncertainty in the design. In an abstract setting a discussion may feel as if it is preferencing either utility or concept in a zero sum game. In VR clashes between utility or lack of clear design concept are seen simultaneously together in familiar 1:1 3D space – thus the use and idea support of each other at scale giving both weight and relevance to improve design of both issues.

After each VR session, students filled out a feedback form to reflect on the experience and relate observations regarding their own design adaptations as well as improvements to the interface. The vast majority of feedback centered around four common issues: scale, circulation, collision detection, and a surprisingly specific facet of student focus was on code complaint stair railings.

Virtual reality tools will allow us as an architects and designers to create buildings and products intuitively in 3D space so, we can check our designs and walk our professor and clients through our projects. This sensation of being inside a building makes VR an incredibly powerful tool for communicating design intent. Clients often don't have the ability to understand spatial relationships and scale simply by looking at a 2D plan or 3D model. VR can evoke a visceral response in exact the same way that physical architecture can.

Yasaman M. graduate architecture student

### 3.2 Scale

Scale was the most common issue reported – *not knowing how big something 'felt' in context as opposed to knowing how large it measures* seemed to be a particular utility. In fact, when a group of guest practicing architects were invited to test VR they gave similar feedback. Typically students know the height that they are designing to, but perceiving scale in context can be difficult even when designing with a site that within visitation distance. This issue is increasingly more important designers work on sites form which they are physically displaced. Fifty feet can impose a different presence in a rural landscape, a urban neighborhood, or a city center – the emotion of this scale is often an abstraction when dealt with in a model, be it digital or physical. When viewing through VR goggles a student's natural viewing habits, perspective, and body scale are naturally utilized to digest the scale of the design at 1:1.

The VR lab... to give[s] a sense of actual scale and what the space created digitally actually looks like... you can control the sun settings in the model while using VR, I think that can become very useful in seeing how the sun and light activates a space. [Critiques] often talk about what could potentially be weird and awkward to live in, but with VR one can confidently say it is weird, or not, to be in that space because they have the actual scale and they believe they are actually in that space

Tom M.2<sup>nd</sup> year architecture student

### 3.3 Circulation

The natural use of a student's body to engage at their own scale can also extend to wayfinding. A common struggle for beginning designers is constructing comfortable clear way finding in a design. It is not uncommon for complex, overly narrow, overly expansive hallways to run rampant through early designers projects. The realization of a two foot or 15 foot wide hallway is often a concept which remains abstract to students. Experiencing wayfinding through their own eyes students quickly realize if a winding hallway is confusing, too long, or lacks clear signage or clarity of exit routes.

[We] used as a team building exercise, where multiple users can exist in the space and build upon one model or project in real time. One person can design a space and then another can walk around it and change it.

Helen P. 2<sup>nd</sup> year architecture student

### 3.4 Collisions

Interactions between buildings systems is a large benefit of construction management modeling. Often-mechanical systems and structural systems are designed, manufactured and adjusted separately, 'collisions' occur when one system is altered without proper coordination

with another system resulting in the two designed to exist in the same space. Electrical conduit, HVAC ductwork, fire protection and plumbing are made up of rises, bends, and runs in highly three-dimensional twists – identifying areas of high congestion, or intersection is a key coordination focus for these students. Traditional 3D building information modeling (BIM) does have collision detection parameters; however, these are not fully effective. Reviewing these models in the computer show a finite field of view on screen, which can make detailed analysis frustrating. VR review allows students to complete a full visual inspection of the model in detail quickly while simultaneously building familiarity with the project. Students could locate and anticipate not only problem areas but also document and understand the collision of one system over another more quickly and clearly.

To put myself in a building that I had spent countless hours drawing in 3D only helped me realize how much more there is to learn in architecture.

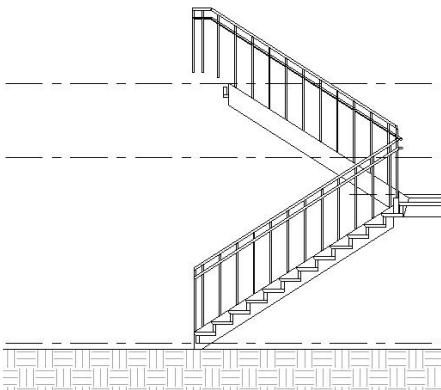
Denis C. 3<sup>rd</sup> year architecture student

The biggest surprise is how the surveyed VR results came out for analysis quickly. Students can experience the surveyed space with accurate measurement[s], and it [can be seen] quickly compared [to the traditional method] ... in which traditional method of field survey ... takes [much longer] to complete.

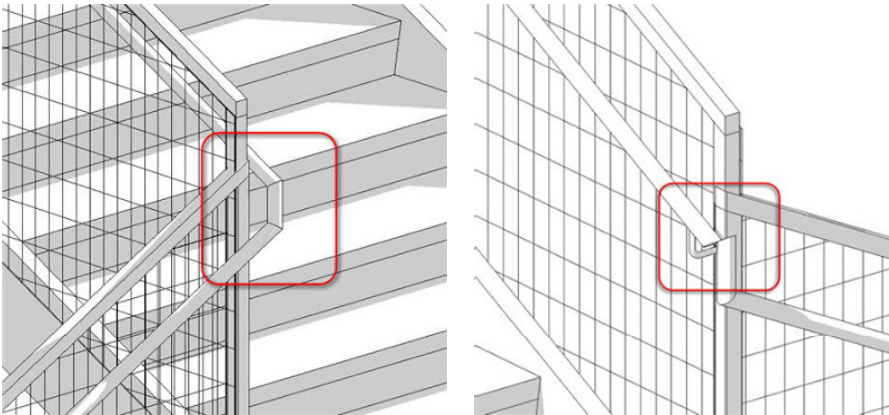
Tran L. graduate construction management student

### 3.5 Railings

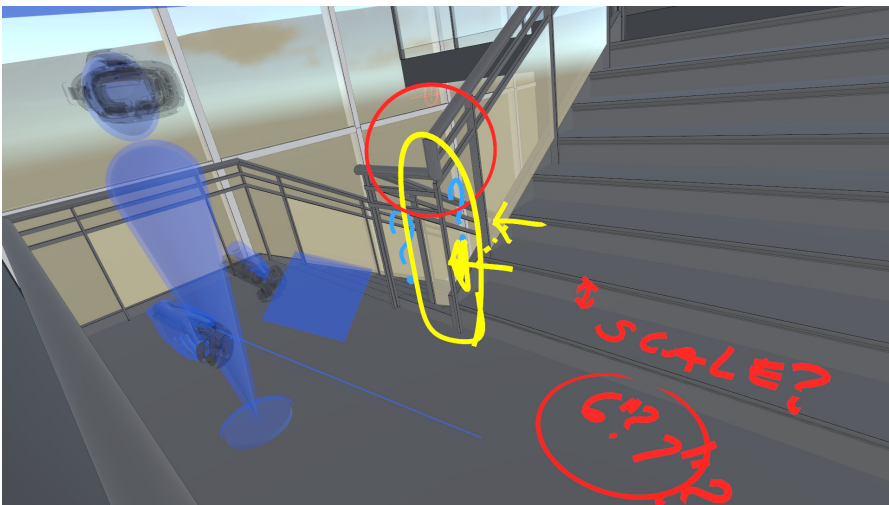
Of note, this particular element – the hand railing – was frequently a key focal point of peer and self-critique by students from both architecture and construction management backgrounds. Similar to building systems railings must be designed with full development through x-y-z axis in a complex spatial choreography. Railings are highly visible often-expressive design details, which must also meet rigorous building codes. A particularly challenging area of design is interior railing return at a stair landing – twisting over a large vertical distance in a short horizontal distance railing is often an area where a design is most challenged or requires a specialized detail. As with collision detection, many BIM programs have automated stair creation, which can implement standard practices automatically but struggles with specialized scenarios. The automatic nature of these programs has a twofold effect. First, since it is usually automated students are not practiced with stair design. Second, the automated *plan* and *section* drawings often do not show the design challenge clearly. Viewed three dimensionally railings and handrail detail issues are immediately recognizable in VR. The additional ability to markup drawings in model, drawing in three dimensions, allows students to start designing and implementing appropriate solutions immediately.



**Figure 3.** Typical presentation of Railing in two-dimensional documentation



**Figure 4.** Typical presentation of railing in three-dimensional model, reveals optical illusion of compliance when viewed from certain angles, and modeling aberration viewed from alternative angle



**Figure 5.** Markup of railing in VR where 1:1 scale reveal errors in model algorithm and necessary modifications to realize code compliance and user functionality (images from the Author 2018)

#### 4.0 RECOMMENDED BEST PRACTICES

In addition to the focus on specific design issues students gave feedback which lead to the establishment of a series of best practices to gain the most out of the experience. Terminology for this practices adopted pilot-styled vocabulary.

- VR training and familiarization session prior to design review
- Pilot and Co-Pilot 'buddy system' to remain task oriented during the walk through
- Flight Plan and design briefing ahead of VR session remain task oriented during the session
- Checklist or punchlist of key design elements and common issues
- Captured design stills / adjusted perspective views for analysis afterwards
- Debriefing to review the VR session and plan changes.

Before any work in the VR lab students paired in groups of a minimum of two people. This partner assisted in the next steps of procedures. The *pilot* working in the VR realm while the *copilot* would operate the hardware, software, provide support, reminders, capture imagery, and keep the pilot on task as well as operating the hardware while their partner was in the VR environment.

Students benefited from having a brief VR session to become familiar with the program – while this was not necessary it did allow students to move through the ‘wow’ stage quickly to begin detailed design analysis, saving time overall

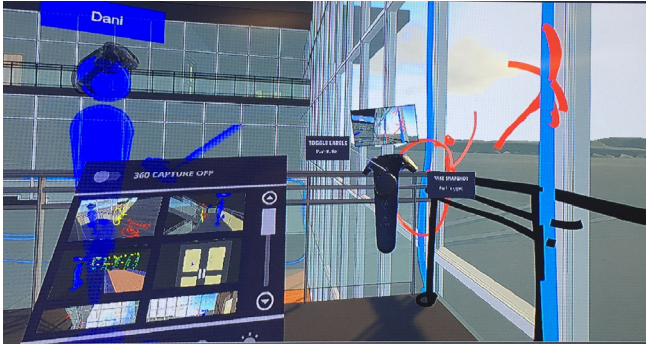


Figure 6. Student's view in Virtual space marking up model (left)

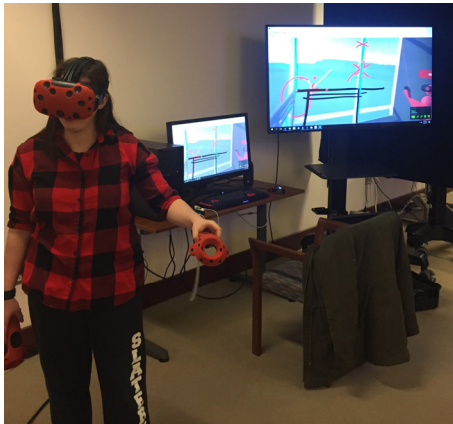


Figure 7. Student in physical space (right) reviewing work (images from the Author 2018)

Teams of two to three students in a pilot (in the VR headset) and copilot/navigator operating the computer responded with better feedback in post VR session discussions. Solo students tended to explore tangentially. Teams of students worked together to stay on task and recorded more materials for their post-session debriefing. Additionally students in co-pilot position stood ready to assist the VR Pilot if they became disoriented, entangled in the lab wires, or reach the limits of the VR lab sensors. This assistance made hesitant students more adventurous in adopting the technology. The co-pilots are also useful for recording data, such as screen captures, written descriptions, or vignettes from on screen for the pilot (who is unable to see or use objects outside of the simulation while the headset is in place)

Ahead of any loading of the VR experience students were notably more focused when they planned a specific goal oriented route ahead of time. Termed the *flight plan* this circulation route kept the team. This exercise meant that the team of students had to state the expected design issues – usually in terms of a checklist or vignette drawings, giving the students diagrams or verbiage to measure against when in the virtual space. The flight plans frequently met with adjustment during the session to take advantage of unexpected design issues requiring attention.

Key to each session was a debriefing, which followed the briefing and the collected information from the session. It is these sessions, and the subsequent feedback forms that evolved both the observations (above) and evolved the best practices for the VR lab sessions. Most importantly, these debriefings allowed for stocktaking of the design in both its conceptual

effects and its design execution and detailing. The debriefing sessions allowed students to verbalize the experience in VR and test it against their peers experiences. Discussions ranged from the broad and conceptual to nuanced details. Common design issues such as out-of-scale elements or building systems collisions students addressed immediately and without guidance. Overall students reacted favorably to the experience and in general professed a desire to utilize VR design more frequently as a check in their design process either independently or as part of a design studio.

Drawbacks identified in the sessions focused on two limitations of the system. First, the mismatched and singular size of the experience was difficult to manage within the bounds of a class, as the *pilot* has an intensive experience while their classmates must wait their turn (only one user can use a VR setup at a time). The closed-loop of the VR experience means that the copilot must rely on verbal descriptions from the pilot. In the lab this was assisted by outputting the VR headset view to a large flatscreen monitor for the class to follow along, however the head movements, which are natural in the VR headset, can be abrupt and unsettling to view for an audience. Second, and more infrequent, some students were unable to use the system due to dizziness or a feeling of disembodiment using the goggles – this sensation was not linked to a proclivity for motion sickness, as several motion-sick prone students were unaffected as well as the reverse. (In most cases the student affected could use the system and eliminate the sensation by using the headgear while seated in movable wheeled office chair).

As a final observation, the reader should note that VR tech is evolving quickly with new technology coming online during the testing of these initial groups of students, and even during the writing of this paper. This rapid expansion and evolution towards more collaborative and shared experiences being some of the latest additions to VR tech available, but occurring outside of the testing boundaries of this study.

## CONCLUSION

Virtual Reality technology continues to increase its permeation of the design environment. As part of a educational system of tools VR can be a potent tools to bring the scalar qualities of architecture into manifested experiential form. The possibilities of this technology are exciting and the novelty of its adoption have led to a fierce interest in the tool – and it is a powerful tool. The closed system nature of the VR headset is perhaps its greatest strength and simultaneously its weakness, it is an almost overwhelming experience for the user in headset, which translates poorly for an on looking audience, limiting its use as a large scale class tool. The greatest utility lies in collapsing the distance (in time) for a student to experience their design in full scale. Where once students might take months or years of work at a firm to see a drawing become built reality (and this tool certainly does not replace that experience), a student's model can be digitized and walked through – enabling both student and teacher to discuss previously abstract issues of scale in an non-abstract format. This in turn enables the teacher/student conversation to include a deeper discussion and understanding of issues of scale, experience, light, and construction. It also empowers students to be self-critical applying their own tactile knowledge of the world to their own work. VR is not a replacement of drawings, or models, but adds another tool to the designers toolbox to interrogate a design more thoroughly and in turn allows teachers and students of design and construction to ask the same questions with greater intent and shared vision – *is this the way you imagined it? How can it be built? And most importantly, How can it be built better?*

## REFERENCES

- Chen, A., Golparvar-Fard, M., & Kleiner, B. 2013. Design and Development of SAVES: A Construction Safety Training Augmented Virtuality Environment for Hazard Recognition and Severity Identification. International Workshop on Computing in Civil Engineering. Los Angeles, LA: ASCE.

## DESIGN THINKING

- Dawood, N., Miller, G., Patacas, J., & Kassem, M. 2014. Combining Serious Games and 4D Modelling for Construction Health and Safety Training. International Conference on Computing in Civil and Building Engineering, (pp. 2087-2094). Orlando, FL, USA.
- Dick, Philip K. We Can Remember It for You Wholesale. New York, NY: Carol Pub. Group, 1995.
- Erdoğan Ford, Seher. More Than Meets the Eye: What Can Virtual Reality Reveal to Architects? *Journal of Architectural Education* 71, no. 1 (2017): 100-02. doi:10.1080/10464883.2017.1260931.
- Fonseca, David, Sergi Villagrasa, Nuria Martí, Ernest Redondo, and Albert Sánchez. Visualization Methods in Architecture Education Using 3D Virtual Models and Augmented Reality in Mobile and Social Networks. *Procedia - Social and Behavioral Sciences* 93 (2013): 1337-343. doi:10.1016/j.sbspro.2013.10.040.
- Furness, T. 1989. Configuring virtual space for the super cockpit. Seattle, WA: Human Interface Technology Laboratory. Technical Report HITL-M-89-1.
- Haymaker, J., & Fischer, M. 2001. Challenges and benefits of 4D modeling on the Walt Disney Concert Hall Project. Stanford, CA: Stanford University.
- Messner, J., Yerrapathruni, S., Baratta, A., & Whisker, V. 2003. Using Virtual Reality to Improve Construction Engineering Education. Proceedings of the 2003 American Society for Engineering Education Annual Conference & Exposition. American Society for Engineering Education.
- Total Recall. Directed by Paul Verhoeven. Performed by Arnold Schwarzenegger. June 1, 1990.