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# Toward Future 'Mixed Reality' Learning Spaces for STEAM Education

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## Abstract

Digital technology is becoming more integrated and part of modern society. As this begins to happen, technologies including augmented reality, virtual reality, 3d printing and user supplied mobile devices (collectively referred to as mixed reality) are often being touted as likely to become more a part of the classroom and learning environment. In the discipline areas of STEAM education, experts are expected to be at the forefront of technology and how it might fit into their classroom. This is especially important because increasingly, educators are finding themselves surrounded by new learners that expect to be engaged with participatory, interactive, sensory-rich, experimental activities with greater opportunities for student input and creativity. This paper will explore learner and academic perspectives on mixed reality case studies in 3d spatial design (multimedia and architecture), paramedic science and information technology, through the use of existing data as well as additional one-on-one interviews around the use of mixed reality in the classroom. Results show that mixed reality can provide engagement, critical thinking and problem solving benefits for students in line with this new generation of learners, but also demonstrates that more work needs to be done to refine mixed reality solutions for the classroom.

## Introduction

Digital technology is becoming more a part of our everyday life with new and innovative technologies required to solve ever increasing problem complexity (Hajkowicz et al., 2016). Additionally, Jones, Ramanau, Cross and Healing (2010) argue that students expect to be engaged by their environment, with participatory, interactive, sensory-rich, experimental activities (either physical or virtual) and opportunities for input. They are characterised as more oriented to visual media than previous generations (Thompson, 2012), preferring to learn visually by doing rather than by listening or reading. This has resulted in a shift away from traditional face-to-face, didactic lectures and tutorials to self-direction and technology-enhanced teaching and learning through multiple modes and methods of delivery (Keppell, Suddaby, & Hard, 2011).

With these changes in mind, it has been suggested that the use of visualisation in teaching classrooms is a key means of improving learning, skills and outcomes, particularly in disciplines that support the development of practical skills (Freitas & Neumann, 2009; Höffler, 2010). To enhance students' conceptualisation, manipulation, application, retention of knowledge and their skills, visualisations in the classroom must follow specific learning design (Mayer, 2014; Moreno and Mayer, 2007). In part, these visualisations must prime the learner's perception, engage their motivations, draw on prior knowledge, avoid working memory overload through specific learning objectives, provide multiple presentation modalities, move learners from shallow to deeper learning and allow learners the opportunity to apply and build their own mental models (Paas & Sweller, 2014). The fundamental assumption(s) of visualisation and their use in the classroom are: that no single technology offers a silver bullet for students to grasp specific concepts (Moreno & Mayer, 2007); multiple representations must take advantage of the differences between the representations (Ainsworth, 2014); and students learn through a variety of approaches (Mayer, 2014).

Science, Technology, Engineering & Math (STEM), also, referred to as STEAM with the inclusion of Arts would seem an excellent vanguard for this visualisation and technology change. STEAM subject matter(s), are often suitable for 3d (visual and physical) presentations because they benefit from the observation that multiple 3d modes of engagement can be reinforcing and synergistic within the teaching pedagogy. This is especially important as it is often acknowledged that student learning in these environments can be difficult (Johnson, 2012).

With this in mind, technology visualisation has already been leveraged in various ways in the STEAM classroom. Pellas, Kazanidis, Konstantinou and Georgiou (2016) report on the use of virtual worlds in the STEM classroom as a way to encourage creativity and innovation, emphasising Arts. Keefe and Laidlaw (2013) take a similar approach, reporting on the use of virtual reality in the classroom, taking students out of the room and into a virtual setting, where painting and construction can be used to illustrate STEM concepts. Taking a more physical approach, Oner, Nite, Capraro and Capraro (2016) report on the use of 3d printing in the classroom, specifically with secondary students, with students being encouraged to model their designs and print them on the 3d printer. Similarly, Hamner and Cross (2013) discuss the use of robotics in the K-12 classroom to teach STEM concepts and encourage creativity. Hoban, Loughran, and Nielsen (2011) similarly discuss the use of slow motion animation in the STEAM classroom as a way for students to understand the steps of a concept and recreate them. Finally, Castro-Alonso, Ayres and Paas (2015) discuss the use of visualisations in combination with embodied cognition as a mechanism to improve instruction within the STEAM classroom, especially as it relates to dynamic visualisations. However, even given these visualisation examples the majority of prior work in visualisation use within the classroom has been formed around explanatory words and 2d pictures (Ayres, 2015) with less attention to complex skills learning environments using innovative techniques such as interactive visualisations, games and simulations.

To assist with this innovation, technologies such as 3D printing (3DP), Augmented Reality (AR), Virtual Reality (VR) and Mobile Bring Your Own Devices (BYOD) are becoming available for use commercially and thus able to be incorporated into the classroom. Mixed reality (MR), a continuum of these innovative technologies, provides a framework to position real and virtual worlds (Milgram & Kishino, 1994), resulting in the development of new paradigms, tools, techniques, and instrumentation that allow visualisations at different and multiple scales. They also enable the design and implementation of comparative mixed reality pedagogy across multiple disciplines (Magana, 2014). The 2017 NMC Higher Education Horizon Report (Adams Becker, Cummins, Davis, & Yuhnke, 2017) and 2016 Technology Outlook for Australian Tertiary Education Report (Adams Becker et al., 2016) specifically highlight case studies using these technologies as key educational technologies and drivers for learner engagement.

AR and VR technologies have existed for some time, but the uptake in education has been hindered by cost, expertise and capability. The opportunity for educational uptake is now changing with the recent wave of low cost, immersive, 3d VR technology by vendors such as Oculus Rift (www.oculusvr.com/) and BYOD Mobile VR by Google through Cardboard (vr.google.com/cardboard/). There are also powerful, interactive, 3d visualisation software platforms, such as Unity3d (unity3d.com/), and integrated AR plugins, such as Vuforia by PTC (www.vuforia.com). However, while the latest technology in AR/VR can assist with visual and spatial learning, there is still an innate lack of physical, haptic feedback that one gains through physical media manipulation (Fowler, 2015), due to lack of physicality existing around the digital objects being presented.

In this domain, 3d printing offers a way to bridge the gap between the virtual and the real by providing an avenue for physical, haptic feedback that one gains through manipulation of physical media. 3d printing has seen an explosion in the past five years due to low cost, fused deposition modeling (FDM) systems by makers such as MakerBot (www.makerbot.com). 3d printing at its basic level uses an additive manufacturing process to build objects up in layers using plastic polymer. Although the process can be slow, 3d printing creates direct links between a virtual 3d-based model and the formation of an accurate physical representation from that model (Loy, 2014). This direct linking of object making to computer modelling changes the relationship of the learner to the making of the object and subsequent use, enabling a haptic feedback loop for students who are not creating but rather using the 3d printed objects on their own (Paas & Sweller, 2014) or within an augmented reality simulation (Cowling, Tanenbaum, Birt, & Tanenbaum, 2016).

Technology is thus being applied to the emerging expectations and preferences of today's university students, through the use of virtual worlds, robotics and virtual reality (Adams Becker et al., 2016; 2017). Active and immersive learning engagement and the use of emerging technology, especially in the form of mixed reality visualisation devices, present an increasing potential in combination to enhance university pedagogy.

## Case Studies

Taking this approach of the mixed reality STEAM classroom, three case studies have been selected that showcase this use of mixed reality to encourage skills in the classroom. These selected case studies demonstrate this multimodal concept for several different STEAM classroom designs. All case studies including sample videos, publications and the learning instruments are available from www.mixedrealityresearch.com. Specifically, the below section presents three classroom-based case studies of applied mixed reality pedagogy in 3d Spatial Design (Multimedia and Architecture), Paramedic Science, and Information Technology and illustrate how problem solving and critical thinking could be addressed using these technologies in a STEAM classroom. Each of these disciplines was selected because it relies on multiple, *hands on* forms of visualisation and practical skills development. Insight into these cases can help to guide curriculum designers and teachers of STEAM subjects in making decisions on the use of emerging mixed reality technology by highlighting media properties and lesson sequencing. Provided here are summaries of analyses of these cases, qualitative commentary from the discipline academic that was responsible for teaching the course, and data on learners' outcomes. Further analysis of these studies is presented in the results section. It is hoped that this analysis will help to guide effective use of Mixed Reality Learning Spaces for STEAM classrooms of the future.

## Study 1: 3d Spatial Design - Multimedia & Architecture

This first case study concerns the construction of a new mixed reality classroom environment at Bond University for Spatial Design students in the multimedia and architecture disciplines. For multimedia students, testing was done in one course over three semester offerings spanning three years in the *Interactive Media and Design* subject curriculum. For architecture students, the pedagogical approach was integrated into two courses over two semesters spanning one and a half years in the *Architecture Design Communications* subject curriculum.

Multimedia students in 3d design and modelling create tangible materials in the virtual and physical world for critique, conversation, assessment, inspiration and graduate outcomes. The 3d development pipeline emphasizes the importance of exploring different media representations but typical classroom methods involve only 2d reference images and 3d rendered objects projected in 2d space. These representations often lack the spatial considerations, navigation and manipulation required to truly understand and communicate the learner's designs.

Similarly, spatial visualisation and 3d interpretation are undoubtedly important skills for young architects to develop. The ability to quickly and effectively interpret 3d spaces and forms from 2d drawings and the inverse, to reduce 3d ideas to 2d representations for communication purposes, is generally regarded as a hallmark of the profession. As spatial and geometric ideas become increasingly complex, the industry standard 2d orthographic representations (plans, sections and elevations) tend to convey less information about a design and how it is to be interpreted. The skills required to make these multi-dimensional translations generally require significant experiential development over the course of years and, while experienced architects are adept at performing these translations, there exists a *communication barrier from teacher to student due to this skills gap* (Birt, Hovorka, & Nelson, 2015; Birt, Nelson, & Hovorka, 2015).

Students in the multimedia classroom were exposed to traditional 2d hand drawing and digital 3d modelling and physical fabrication for the purpose of teaching 3d modelling concepts such as lighting and geometry. Additionally, students were tasked with decomposing 3d virtual objects into 2d representations and reassembling these into 3d physical objects. Students were split into two groups to encourage communication (i.e., each group contained 6-9 students, and the instructor was not 'surveilling' during student discussion within the group), reduce visualisation waiting times (due to the limited amount of equipment available), and allow for specific comparisons between the groups' outputs across the semester of study. Over the course of the semester, each group was given equal levels of access to each type of representation.

Table 1 outlines the learning objectives and applied media conditions developed in accordance with the subject design and graduate outcomes.

**Table 1: Learning objectives and how they were addressed in each respective group via mixed reality visualisations**

| Learning Objective | Print | AR | VR | 2d |
|---|---|---|---|---|
| Demonstrate applied knowledge of 3d spatial understanding and communication | A | A | A | A |
| Demonstrate applied 3d geometry construction methods in 3d design | 1 | 1 | 2 | 2 |
| Demonstrate applied knowledge of curved surfaces in 3d design | 2 | 2 | 1 | 1 |
| Demonstrate applied knowledge of material shader algorithms in 3d design | 1 | 2 | 1 | 2 |
| Demonstrate applied knowledge of texture mapping methods in 3d design | 2 | 1 | 2 | 1 |
| Demonstrate applied knowledge of lighting theory in lighting 3d scenes | 1 | 2 | 2 | 1 |
| Demonstrate applied knowledge of Level of Detail in optimising 3d scenes | 2 | 1 | 1 | 2 |
| Demonstrate integrated application of all learning objectives | A | A | A | A |

*All Students (A); Group One (1); Group Two (2)*

The word *demonstrate*, used in Table 1, refers to the higher order skills of analyse, evaluate and create, as reflected in Bloom's Taxonomy.

Tutorials and visualisations to achieve the learning objectives in Table 1 were presented to the learners in the respective groups over twelve weeks. To address problem relevance, representations of each model were created using different mixed reality technology visualisations (i.e. 3d prints, virtual reality models, augmented reality models). An illustrative example of the mixed reality simulation highlighting 3d spatial understanding and communication is provided in Figure 1.

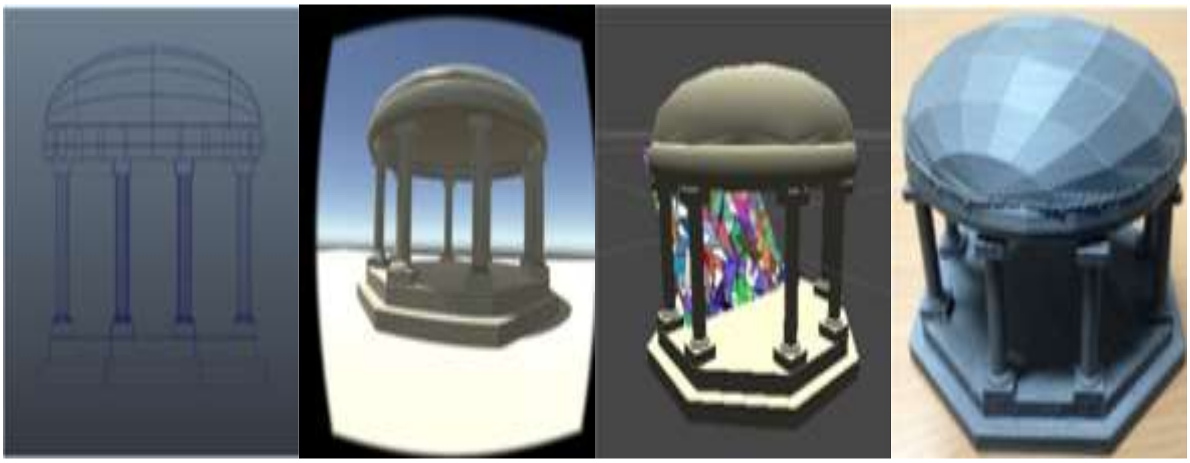

**Figure 1: Different ways of representing a dome on columns - 2d traditional view, VR, AR and 3d printed learning artefacts**

The resulting model *temple* is 3d printed using a MakerBot Replicator and placed into a VR and AR simulation environment using Unity3d, Oculus Rift, Samsung and Vuforia through a BYOD mobile phone. In other words, off the shelf software, 3d printing, and a mobile phone were employed to create these representations. The result affords learner centered active engagement through physical and virtual interaction with the visualisation technologies. Students interacted and explored these visualisations by navigating and manipulating these comparative mixed reality visualisations. This in turn allowed both high and low spatial learners to engage and conceptualise the object. The learners were then presented with traditional 2d reference images and asked to construct their own 3d model example, in this case a bird statue (see figure 2). Results of this intervention suggest that students were able to better translate the 3d spatial objects in their head. Results of this study are presented in Birt (2014) and Birt and Hovorka (2014) with a detailed discussion summary presented in the results section of this paper.

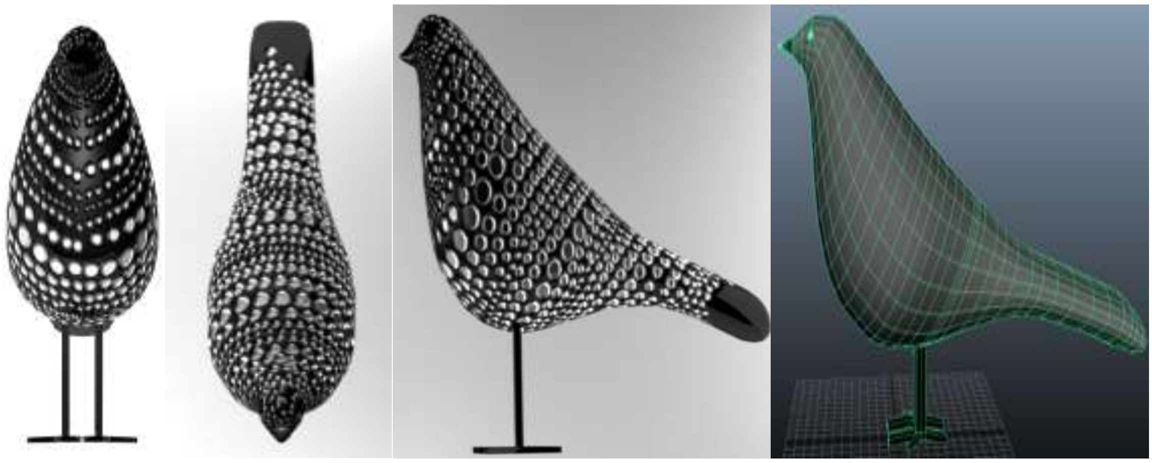

**Figure 2: Traditional 2d reference image of a bird statue shown on the left; Student Maya 3d polygon example shown on the right**

For the architecture classroom, as in the multimedia study, learners were given a series of comparative exercises with two forms of media (2d projections, 3d printed scale models, full scale built environments and 3d VR environments). They were asked to compare and contrast the different media, including the information gleaned from each separately, the difficulty or ease with which the media facilitates accurate interpretation, and ultimately their preference for each exercise. These analyses were provided through reflected blogs (see Figure 3 for an illustrative example of the human scale objective). Results of these blogs are presented in Birt, Hovorka and Nelson (2015) and Birt, Nelson and Hovorka (2015) with summaries presented in the results section of this paper.


**Figure 3: Designing/representing a staircase - 2d traditional view, physical build environment and VR learning artefacts**

## Study 2: Paramedic Science

Paramedical science educators already use physical visualisation for skills development, practice and training, and concept development. This virtual practice is useful because *society does not want paramedics practicing techniques on real people* until they are well trained. Online paramedic students are, however, at a disadvantage in that they cannot train on physical manikins and use physical surgical instruments. This case study stems from a need, identified through course evaluations, for more opportunity for distance students to practice skills (currently, they can only be practiced in a five-day, hands on, residential school).

Discussions between the author and the paramedics discipline academic were focused on what skill(s) could be re-created through a mixed reality approach that would provide the most benefit to the students. In the end, laryngoscopy (looking down the throat) for foreign body removal was chosen as it is classed as a priority invasive skill. Foreign body removal requires confidence and experience to execute correctly. Given that Paramedics do not perform this skill on road very often, it became obvious that this intervention could produce positive learner results compared to teaching approaches used to date in this course.

Due to the distance nature of this case, the "classroom" was not a traditional room but rather a predominantly online, distance learning environment. With this in mind, students over two semesters, spanning two years, were posted 3d printed instruments, and provided with a mobile phone application for augmented and virtual reality simulation. They also received a tutorial video. All items were used to practice skills prior to arrival at the residential school. Development of the tools, feasibility of the design methodology and early results suggested that students benefited from using the mixed reality tools prior to coming to the residential school (Birt, Moore and Cowling, 2017; Cowling, Moore and Birt, 2015; Cowling, Tanenbaum, Birt and Tanenbaum, 2016).

To make things more realistic, a 1:1 scale replication of the actual physical tools is required. In this case, we require a 3d printed Laryngoscope with Mac Blade and Magill Forceps. Through the addition of AR markers, these physical models can be tracked and simulated virtually. For the augmented reality simulation, the decision was made to use the off-the-shelf, game engine development platform, Unity 3d, the Google Cardboard Application Programming Interface (API) (to provide a stereoscopic view) and the Vuforia AR plugin for Unity 3d.

To allow for the correct view point (looking down the throat of the airway in the manikin) and to keep the hands free (to use the printed tools with 3d augmented markers), the decision was made to use the ColorCross Google Cardboard-style headmount - as shown in Figure 4 (right hand side) - for use with the student's own mobile phone. In other words, student would mount their mobile phone into a sort of headset frame, which would enable them a 'view' of the simulated airway, while leaving their hands free to manipulate the 3d instrument. The 3d printed instrument would show up in the image on their phone reflecting where their hands were in space relative to the simulated airway.

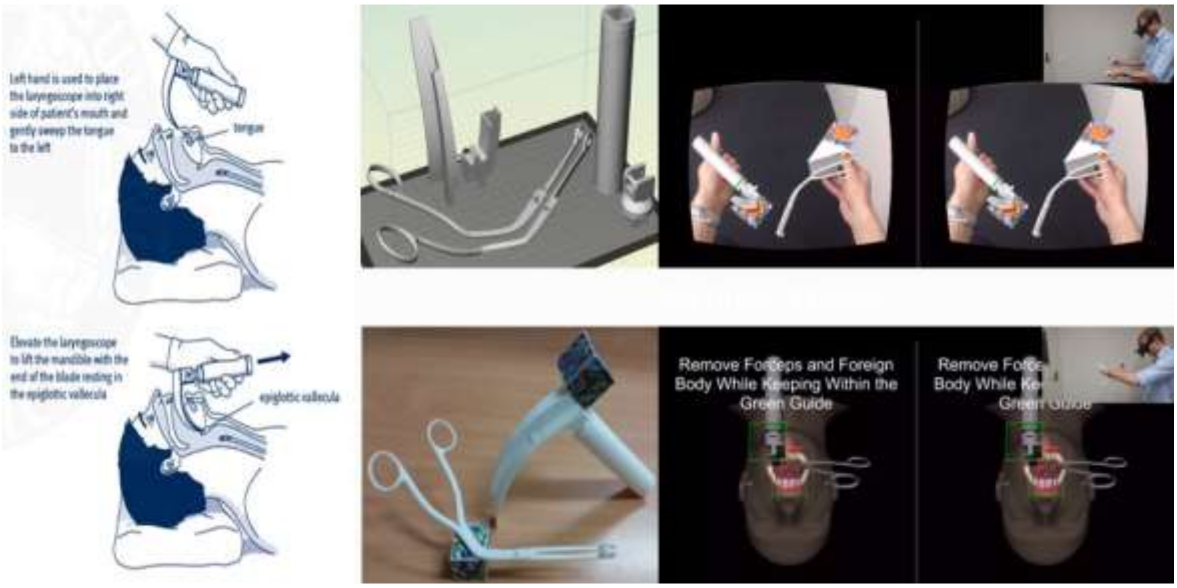


**Figure 4: Steps to perform laryngoscopy for foreign body removal shown are traditional 2d images and the mixed reality visualisation using 3d printed objects and a AR/VR mobile application**

The focus of the simulation to be *task appropriate* means that only pertinent information relating to the key learning outcomes was to be included. To this end, a tutorial was provided explaining to the student how to hold the instruments and use the simulation through both text and audio cues. First, all markers need to be identified by the camera through a process of image recognition. Then, the virtual objects are recognized within the mobile phone/camera view of the actual physical tools.  That indicates to the user that the simulation seen on their phone has 'recognized' the markers and makes them more confident to use the tool to practice their skills.

An airways manikin dummy is displayed in a stereoscopic view, and a series of steps with audio and visual cues is presented to the user. The aim of the simulation is to follow the steps required to insert the Laryngoscope correctly as per Figure 4. then the forceps remove a foreign body lodged in the patient's throat. Cues are provided during the mixed reality simulation to indicate whether the procedure has been successful.

## Study 3: ICT Networking

In ICT networking, students are often exposed to a lot of theory about the way that data travels through a network, though they lack a corresponding physical model. Even in classes where there are physical props (such as routers, switches or networking cables), there is no easy way to show students how the invisible data *packets* travel or *route* over these components, and they remain a black box to many students. Abstract models cannot capture the complexity of the logical models, specifically, the multi-step nature of the traversal of packets. Learners are left with a disconnect between the physical components involved in the process of networking and the underlying theory, such as the OSI and the TCP/IP packet networking model.

Hence, to develop a mixed reality STEAM classroom to resolve this challenge, work began between the discipline expert and the lead author to incorporate the mixed reality pedagogy. It was determined that both the physical and the digital components of a network could be modelled in the physical world and could then be augmented with a mixed reality visualisation pedagogy, e.g., routers and switches could be represented physically and digitally, as could network traffic via augmentation. That would provide the learner with a way to break through the black box of the physical and see how the abstract theory *data* operated between *devices*.

For the physical component, the intervention uses 3d printed stands overlaid with an image target marker that can be recognized by the augmented reality app (see Figure 5). The use of these stands makes it possible for students to build a network by moving physical pieces around. They can shuffle them back and forth to create the configuration desired and add/remove pieces as required for different network designs. This direct linking of object making to computer modeling changes the relationship of the learner to the making of the object and subsequent use, enabling a haptic feedback loop for learners (Paas & Sweller, 2014).

Once the network has been 'built' using the physical objects, students can then simulate a working network using the AR app loaded onto a tablet or smartphone. This app allows students to see how packets flow through the network. It simulates packet flow between specific end devices, such as a client and server computer, or two computers involved in a peer-to-peer connection. Specifically, the intervention scans the image target markers via the mobile device camera using the Vuforia AR plug-in in the Unity3d game engine (see Figure 5). Two iterations of the pedagogy over two years have revealed that students find the simulation novel and interesting, and that concepts such as memorability and interactivity are improved by the mixed reality intervention over the traditional approach (Cowling & Birt, 2015; 2016).

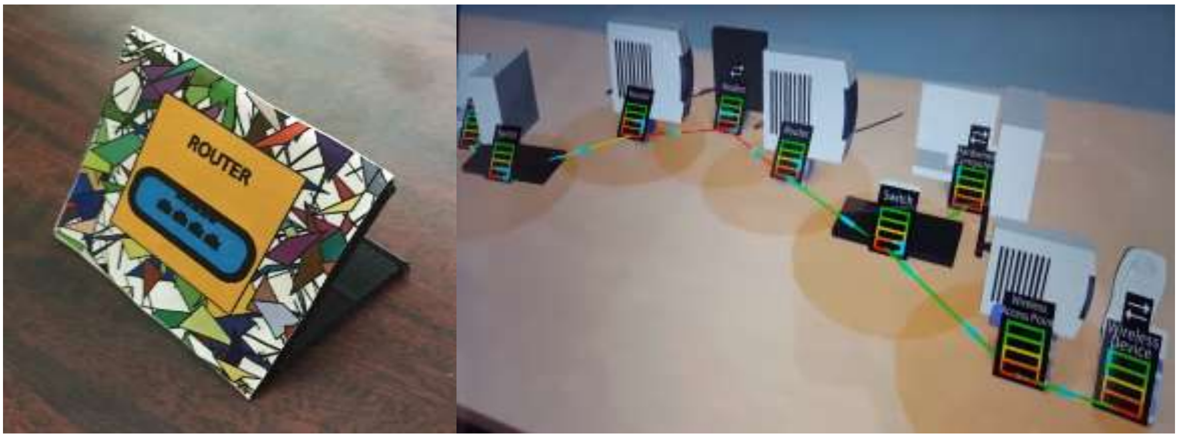


**Figure 5: An example 3d printed marker of a router and augmented simulation view visualising packet flow across devices, which are represented by multiple markers**

## Methodology

For each of the case studies outlined, a design-based research (DBR) methodology (Anderson & Shattuck, 2012) was used, with an underlying action research mentality (Kemmis, McTaggart, & Nixon, 2014) implemented in the conduct of the research in the classroom. Specifically, the four steps of the DBR methodology were followed through the analysis of the problem and design of the simulation solution (as detailed in each section above), followed by the iterative implementation of that solution into the classroom by a discipline academic positioned to evaluate the effectiveness of the solution who provide detailed feedback on the design in the first loop pilot study. This then resulted in a loop back to design refinement and further iterative testing.

To assess the relevance of how the case studies presented led to the development of a future STEAM classroom environment, the data from the above process, including student qualitative comments and staff observations, was combined with additional open-ended one-on-one interview data collected from interviews conducted with the discipline academic for each of the case studies presented. These interviews were covered by the ethics application submitted for each individual case. In these interviews, participants were asked to comment on how the redesigned classroom better supported the key STEAM attributes of *problem solving, critical thinking, creativity,* and *innovation.* They were further asked to reflect on how mixed reality technology affected these attributes. Data from the interviews was collated and transcribed, and themes were identified. These were then combined with existing data from each case study.

## Results

Results from the above methodology are summarised below.

**Spatial Design (Multimedia & Architecture)**
The experience over the past three years, in the context of 3d modelling and multimedia design, was positive. The discipline academic commented that, based on his observations, an *interaction between mixed reality media representations leads to more meaningful learning activities* and the media affordances lead to improved *learner engagement* and *learner outcomes*.

Analysis of the codified learner blogs showed that each visualisation technology had positive, negative and mixed perceptions when it comes to accessibility; usability; manipulability; navigability; visibility; communication; and creativity. Student blog entries suggested that 3d printing offered positives in *haptic feedback and connection between the virtual and physical environment*; VR offered *real-time interaction, improved spatial awareness and defect discovery*; AR offered a *connection to the real world and situational spatial connection*; and traditional 2d offered *high accessibility, ease of use and rapid versioning*.

The discipline academic's advice is that an educational designer in this discipline should *scaffold the learning from the visualisation intervention* by *directly connecting the activity to the students' learning* and *not assume that the learner understands the technology without detailed instructions* and *priming the learner's perception*. Even though these learners are considered *Digital Natives* (Thompson, 2012) and should be considered digitally enabled, all may not be comfortable with the technology.

Similarly, an interview with the discipline academic in architecture highlighted that their observations over the last eighteen months using the mixed reality approach as an educational tool *had shown it to be an overall positive from the perspective of students and staff*.

Student blog entries suggested that they feel *a deeper connection to their work* – they can *experience it* rather than just *imagine it*. When shown the academic during interviews, they evidenced an ability to more readily *evaluate the nuanced spatial qualities as well as the environmental quality* (light, shadow) *issues much more readily than in 2d media*, which serves primarily as an organisational or functional validation tool. Students were characterised by the discipline academic as being able *to visualise and communicate more complex spatial concepts* with many forms of media.

While 2d and simple 3d projections are still the de facto methods of communication, students were described as *showing increased judgement and reasoning* when choosing which versions of these media are displayed for assessment; they were characterised as *better able to employ 2d drawings for more effective communication*.

Students exhibited *excitement to participate in curricular activities* as compared to discussing more traditional learning formats, such as slide-based case-studies. High-tech and experience-based activities tended to elicit *more discussion and participation*. Beyond spatial skills development, *the use of cutting edge technology* was described as *increasing interest in other, related forms of technology*, especially digital tools along the VR pipeline. These include *increased affinity for 3d printing*, *3d modelling software*, and an increased *interest in rendering and texturing* their work.

The negative side was described by the discipline academic, as well. *The technology is still young* and *detail and refinement are lacking* with consideration to the rapid development cycle. The VR models are *not of the same quality as the video games many of the students are used to playing*, which is both good and bad. The VR models were described as still forcing some degree of interpretation and imagination in order to complete the details of the space, but *not as an immersive environment*.

The discipline academics(s) both explained that the technology pipeline, both VR and 3d printing, has skill level demands that are sometimes beyond students just learning 3d modelling software. Concepts such as *naked edges and reversed normals* are sometimes too esoteric. Some of these issues have arisen from the chosen methodology of having students compare their own work in many formats. Specifically, in order to do this in the available class time, students must convert their work from 2d to 3d to physical and VR formats relatively quickly, which helps to explain the limitations on realism in the higher dimensional media. New software workflows will increase conversion speed and quality.

These results suggest that part of the success of this application is firmly based on the ability of the student to evaluate their own work in many media, which develops the skills during design. The multiple media are thus not purely reflective or communication-based tools.

**Paramedics**

The discipline academic indicated that the learners were *very excited* to get the chance to try this new mixed reality driven pedagogy. They found it great to be able to *receive their simulation and tools* and *practice the skills at home*. It helped the learners to feel *more involved in the course* and *less isolated and alone*.

When the 3d printed tools and augmented reality simulation were used by the learners, the discipline academic reported that students had some *struggles with the setup of the equipment* and *progression through the required steps*. This was especially prevalent in the later steps when introducing the Magill forceps and removing the foreign body. The learners commented that *there needs to be more depth in the simulation* my hands seem to pass by the *simulated airways manikin*. The learners commented that they spent *too much time focusing on the markers* and *not on the simulated airways manikin* resulting in frustration when the simulation would restart due to them not progressing through the steps of the skill.

Steps have been taken over the iterations to improve on these issues with the current version reducing these problems with equipment setup, progression and simulation depth. The current simulation introduces more physical haptic resistance feedback during the insertion stage.

Finally, some of the learners commented that they did not get around to using the simulation as much as they would have liked. This time struggle was attributed to other studies, work and family commitments. On reflection, the discipline expert noted that she should have encouraged *more frequent use of the simulation* with a reminder and linkage to the learning tasks. Integration of the simulation into the course was reported to have been relatively seamless. Students exhibited excitement about experiencing a new mode of learning; however, some learners seem to think that it may be "*extra work*" for them.

These results suggest that whilst students found these technologies helped them to be more involved, more work needs to be done to create accurate simulations that minimise technology limitations so that students can focus on skill development.

**Networking**

Reception to the overall idea of the mixed reality pedagogy was good, with the discipline academic and students both commenting on how useful it could be to *help students with their mental model construction especially for abstract concepts*. For instance, during usability testing, students commented in the qualitative section of a survey given that *it was more clarified through this work* and *it's good to work with such networking concepts. ... It gives a user friendly interface, easy to interact and act upon it*.

Through the development of this simulation, it became evident that, with the right level of support, the combination of physical components and digital components can help students to build better mental models. It also became clear that there are many other opportunities to extend the simulation part of the intervention. Once the base model of a physical network is accepted, it should be possible to build on this model to teach more complicated concepts in areas, such as network security.

As highlighted by the discipline academic during subsequent user testing of the mixed reality intervention, it became clear, as with the paramedics, architecture and multimedia studies, that *significant scaffolding was required for learners to use the application*. Although it had been developed as a free-form exercise aided by the simulation, learners *found that the simulation was difficult to pick up and use without some instruction on the use of the markers and how they were recognized by the system*.

Whilst the original brief had always been for this system to be used in a tutorial, testing with students demonstrated that resources would need to be developed to help with the onboarding process, both in terms of help within the application as well as in terms of learning and teaching scaffolding within the class. For example, it was also clear that the use of the triangular markers made it difficult for some users to connect the physical aspects of the simulation to the digital aspects of the simulation. Offline tutorial aspects could connect these two parts in the minds of users, such as the introduction of real components that are then related to the markers in the minds of the users before they are used in the simulation. Finally, these results suggest that mixed reality pedagogy can be especially helpful when modelling theoretical concepts, but that technical limitations again sometime cause problems.

## Discussion

Analysing the results within the framework of this goal of problem solving and critical thinking produces some interesting results. First, it is clear that the introduction of mixed reality to the classroom has the potential to increase critical thinking, in line with one of the key values of STEAM. That was indicated by the comments from the architecture discipline academic that students had a *deeper connection to their work*, comments from the paramedics discipline academic that students felt *more involved with the course*, and comments from the networking students that *it was more clarified through this work*. This is supportive of the commentary on the value of visual media in the classroom, as per Thompson (2012).

Secondly, it is clear from these results that the implementation of a mixed reality STEAM classroom as a direct result of a pedagogical need helps to resolve the issue identified by Johnson (2012) that learning in these environments can be difficult. Comments from the multimedia discipline academic that this classroom produces *more meaningful learning activities*; from the paramedics discipline academic that students were *excited to experience a new mode of learning*; and from the architecture discipline academic that students were *more excited to participate in curricular activities* show that this type of pedagogy-first implementation has the capacity to much more clearly articulate the value of STEAM to students.

Finally, the results also indicate support for the key STEAM concepts of innovation and creativity, as outlined in the cases by Castro-Alonso, Ayres and Paas (2015), Pellas et al. (2016), Oner et al. (2016), and Hammer and Cross (2013). In a similar way to these cases, comments from the architecture discipline academic that students could *experience it, not just imagine it*, and from the networking discipline academic that this work could *help students with their mental model construction especially for abstract concepts* show glimmers of how the tools can be used for students to support creativity and outside-the-box thinking.

However, it is also clear that more work needs to be done to provide a seamless mixed reality experience. In each case, discipline academics identify specific issues that students encountered with each of the classroom environments. Some commonality exists; both the multimedia discipline academic and the networking discipline academic identifying the need for more *scaffolding* of the learning experience. However, there are also problems unique to each individual implementation that need to be solved, with issues as diverse as *model quality* for the architectural students, *simulation preciseness* for the paramedics students and *the lack of haptic feedback*, and the *physicality* of markers for the networking students being presented as problems that need to be solved. It's clear from this list that a one-size-fits-all approach will not be useful with these classrooms, and that, as reported by Magana (2014), a set of new paradigms, tools and techniques will need to be developed to support this new classroom initiative. This is also in support of conclusions by Ainsworth (2014) that multiple representations must take advantage of the differences between the representations.

## Conclusions and Future Work

This paper has highlighted three case studies of applied mixed reality visualisation in 3D Spatial Design, Paramedic Science and Information Technology. Through the use of mixed reality visualisation, and the preference for putting pedagogy before technology through a process of starting with the problem and then solving with technology (rather than the other way around), these case studies demonstrate that it is possible to improve engagement and learning through innovative visualisation technology, such as 3d printing, virtual reality, augmented reality and BYOD mobile devices in the classroom, although there are still technical challenges to be solved.

Details of the implementation in each of these disciplines have been discussed, incorporating evidence from more detailed analysis of these cases, reflections by students, and reflections by instructors. The case studies presented demonstrate a variety of ways that mixed reality visualisations can be used in the classroom, building on the list provided by Freitas and Neumann (2009), to include discipline work in visualisation in disciplines as diverse as multimedia design, paramedic science, architectural design and information technology computer networking. The studies also demonstrate an application of the model proposed by Moreno and Mayer (2007), implementing dual coded multimodal visualisations into the curriculum where appropriate to enhance learning outcomes and skills development. That can be done in line with the higher education goals relevant to a changing student body with changing skill sets and expectations, specifically related to use of innovative technology (Adams Becker et al., 2017), applied use of AR/VR in higher education (Adams Becker et al., 2016) and graduate skills (Hajkowicz et al., 2016).

It is also evident that one can improve the effectiveness of the visualisations in each classroom. For instance, in paramedic science, the construction of the simulation and the learning design prior to use of the visualisation is important and was highlighted as an area of improvement by students and staff. Future trials in this area will therefore experiment with the use of resistance and haptic feedback, VR and AR connection through virtual arms, and stereoscopic views.

In multimedia, more work needs to be done in customised tutorials and how students may be supported and motivated to develop their own models. In architecture, methods are needed to improve the translation skills between 2d to 3d and back again. For networking, more focus on the physical and virtual connection is required linking the kinaesthetic model construction to the physical reality of the network components.

The implementation of mixed-reality visualisation in the examined disciplines potentially has implications for a wide range of disciplines, both within STEAM and outside of this area. This is especially true in areas where visualisation can help with seeing a problem from different perspectives (as in spatial design), skills development (as in paramedics), or in understanding a theoretical model visually (as in networking).

Through the comparison of case studies, the authors have been able to illustrate how visualisation is not a *one size fits all* tool. Different modes and models are required in different situations, as confirmed by the conclusions of Mayer (2014), Magana (2014) and Ainsworth (2014). However, preliminary results are promising, demonstrating that mixed-reality visualisations can be effective to enhance classroom practice, pedagogy, learning practice and skills.

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