Effect of mixed media visualization on learner perceptions and outcomes

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Abstract

This pilot study examines the effect of mixed media visualization on learner perceptions and outcomes in 3D spatial modeling. The context for this study is a university first year undergraduate interactive media and design course. Meta analytic studies in the use of visualizations show positive improvements in learning outcomes among low and high spatial learners. But often these studies are focused on single media and virtual representations. Many multimedia learning studies do not take into consideration important factors that could influence the appropriate selection of media. This exploratory study aims to address this from a learner's perspective through the evaluation of physical and virtual media (3D Printed, Virtual Reality and 2D Projection). This exploratory study produces several core guidelines for more in-depth research on the interaction between media for improved learning in domains which really on visualizations and manipulations. The aim is that through more meaningful learning activities centered on the media affordances learner engagement is improved leading to improved outcomes.

Keywords: 3D Printing, Virtual Reality, 2D Projection, Mixed Media Learning

INTRODUCTION

The use of visualization as positive learning support tools are well documented and accepted (Mayer 2005). Numerous academic disciplines incorporate a variety of 2 and 3-D projections and haptic manipulations including medical anatomy, architecture, geography, chemistry and media/game design (Freitas and Neumann 2009). In addition, training has been improved in areas such as nuclear power plant operations and astronaut training (Dalgarno and Hedberg 2001).The fundamental question is not whether visualization affects learning but how to take advantage of the various visualization media, lesson sequencing and student reflection so that instructions and learning can be more effective (Kozma 1991; 1994).

Meta-analytic studies of 2D and 3D visualization show positive improvements in learning outcomes among low and high spatial learners (Höffler 2010). However, these studies are to date inconsistent (Huk 2006). While some learners learn better when provided with non-dynamic media affording them the opportunity to build their own mental model, other learners learn better through provided virtual dynamic models or physical haptic manipulation (Hwang and Hu 2013). No particular media is necessary for learning, nor is a particular method, however both media and methods of incorporation into a curriculum influence learning by influencing each other. Choices have to be made as media constrains and enables methods and methods take advantage of media capabilities (Kozma 1991; 1994). Typical studies examine only single media coding of the visualization (Höffler 2010) but secondary modality or multi-modal instruction is important (Mayer 2002; 2005; Moreno and Mayer 1999). The specific context of this exploratory study was an introductory 3-D modeling and media unit at a small university. In this class, learning is considered to be an active process influenced by prerequisites of the learner (Mayer 2002) and the class required numerous "hands-on" exercises in learning to create accurate renderings of real-world 3-D objects.

Three visualization technologies were used in the term to teach specific modelling principles. The technologies were 2D (flat screen visualizations of 3D objects), a full-immersion Virtual Reality environment and a 3D printer capable of creating small objects from coded plans. As prior research has revealed strengths and weaknesses in the impact of any single technology on learning, and that learners themselves have different styles and capabilities, this research focused on the synergy among the visualizations to create and reinforce the material to be learned. Thus the first research question was:

RQ1: *"How do learners perceive the comparative capabilities of visualization media to support learning?"*

But as learning is a process of gaining new knowledge (of the material in the curriculum) and familiarity (with the technology) it is reasonable to assume that learners perceptions will differ between specific lesson tasks and will change over time. Thus a second question was articulated as:

RQ2: *"Do learners preferences for visualization technologies change with task or over time?"*

The three technologies were used in combination to support the curriculum and students were required to keep weekly journals reflecting on their engagement with each technology and the learning engendered from each technology. The effects of the mixed media visualizations on learning were evaluated through qualitative analysis of the journals (and supplementary comments) and academic performance in the class. This paper presents a rationale for a mixed media approach which affords positive impacts on student learning outcomes in the context of 3D spatial modelling and discusses future research to extend this work into other learning domains which use visualizations.

LEARNING, AND TEACHING, WITH TECHNOLOGY

Research into teaching and learning with new technologies is a current and relevant area of enquiry (Muller et al. 2006). Educational institutions are increasingly engaged with integrating new technology into the delivery of course materials and in the provision of alternate methods for learning (Johnson et al. 2013). Educational technology has seen a shift from media as conveyors of methods to media and methods as facilitators of knowledge-construction and meaning-making on the part of learners (Kozma 1991; 1994). There is however, criticism of innovative technology as technology for technology sake (Hooper and Rieber 1995).

Technology by definition applies current or evolving knowledge for useful purpose. Therefore a differentiation between substitutive and innovative uses of technology is required (Garrison and Vaughan 2008). Substitution may enable greater accessibility through distribution channels, efficiencies of scale and timeliness. In contrast, the goal of innovation is to make possible new representations of knowledge which increase engagement and learning. To support the learning process around innovative technologies, learners and educators must enter into a collaboration or partnership with technology that encourages and supports the creation of a community (Barron et al. 1992). The perspective of the classroom therefore changes to become learner-centered (Weimer 2013) emphasizing a wider range of skills (Huk 2006). In this model technology must be justified and student expectations addressed to achieve active engagement (Bonwell and Eison 1991) or presence (Garrison et al. 1999) through technology. The technology must afford (Hooper and Rieber 1995) an improved and real educational benefit and not mere distraction to meet the opportunities that the technology may offer. This leads to improved engagement, more meaningful learning activities, and greater learner responsibility for their own learning.

There are a wide variety of visualization technologies which have become mature and are widely available. These include 2 and 3D visualizations which enable enlargement, rotation, or construction actions, virtual worlds (e.g. Minecraft and Second Life) (Dickey 2005), Virtual Reality (VR) environments which are more immersive, and 3-D printing which enables the rapid production of physical objects from plans.

VR technologies are mature, but the uptake in education has been hindered by cost, expertise and capability. This is now changing with the recent wave of low cost immersive 3D VR technology by vendors such as Oculus Rift™ (http://www.oculusvr.com/) and powerful interactive 3D visualization software platforms such as Unity3D™ (http://unity3d.com/). There is an impending market for commercial VR systems highlighted by the recent acquisition of Oculus Rift by Facebook and vendors such as Sony entering into the commercial VR sector. When considering VR there are three defining factors: (i) illusion of three dimensions, (ii) smooth motion, and (iii) level of interactivity (Wann and Mon-Williams 1996). While the latest technology assists with the first two factors there is still an innate lack of physical haptic feedback that one gains through physical media manipulation (Fowler 2014).

3D printing offers a way to bridge the gap between the virtual and the real. 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™ (http://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 is 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 modeling changes the relationship of the student to the making process. With rapid changes in today's digital economy, learners must adapt and comprehend multiple disciplines and skills in design and technology to remain internationally competitive and motivated (Keppell et al. 2011). It is therefore appropriate and timely to not only adopt these cutting edge technologies but appropriate and necessary for students to learn about these technologies and apply their use in the classroom.

PROJECT CONTEXT AND METHODOLOGY

In the context of learning 3D modeling for media design, spatial visualization is necessary, as it is involved in visualizing shapes, rotation of objects, and how pieces of a puzzle fit together (Sternberg 1990). There are many challenges to visualizing information in 2D and 3D. In the context of this study the problem domain is the acquirement of theoretical and practical knowledge about 3D graphics and design. This is an important topic that should be exercised by students in an interactive design curriculum. The fundamental objectives are exploration of 3D geometry including moving, orienting, constructing, visualizing and communicating. The 3D development pipeline emphasizes the importance of exploring different media representations but typical methods involve only 2D reference images and 3D objects projected in 2D. Höffler (2010), showed that high and low spatial learners show positive improvements in learning outcomes through 2D and 3D visualization but these studies are often inconsistent (Huk 2006). Typically only single media coding methods are examined but secondary modality or multi-modal instruction is important (Mayer 2002; 2005; Moreno and Mayer 1999). In exploring a mixed media approach to learning the use of cutting edge VR technology and 3D printing holds great promise (Fowler 2014; Hwang and Hu 2013; Loy 2014).

In addition, renderings must include correct lighting and textures requiring the ability to virtualize how an object would appear in an environment. Compare that when encountering an image of 3D objects projected on a 2D screen or reference photograph. This is the common media used when teaching students 3D modeling. While these representations enabled learners to visualize the subject for modeling, this information literally falls flat. Many multimedia learning studies have not taken into consideration important factors that could influence the appropriate affordances of media (Dalgarno and Lee 2010) and have thus failed to yield conclusive design guidelines (Samaras et al. 2006).

There are many challenges to visualizing information including choosing between 2D and 3D interfaces, physical or virtual navigation, interaction methods, and selecting an appropriate level of detail (Hwang and Hu 2013). Visualization for teaching and learning is nearly ubiquitous (Gilbert 2005; Presmeg 2008). In general, visualizations represent either reality, or an approximation of a physical reality. In this problem domain cutting edge Virtual Reality (VR) devices could hold the answer as objects can be explored in 3D space. But such virtuality precludes the haptic feedback resulting from manipulation of an object as it is touched and held. While haptic technology may hold out the promise of adding the dimension of touch to digital information, there is no substitute on the near-term horizon for gaining the knowledge that we gain by holding and manipulating a physical 3D object. 3D printing offers a way to bridge this gap between the virtual and the real (Loy 2014).

No particular media is necessary for learning, nor is a particular method however both media and methods influence learning by influencing each other. In good design, media and methods are inexorably confounded (Mayer 2002). Media constrains and enables methods and methods take advantage of media capabilities (Kozma 1991; 1994).

Table 1 outlines the proposed learning objectives and applied media conditions developed in accordance with the pair-wise comparisons used. The technology affordances (Hooper and Rieber 1995) and necessity for a dual coding method (Mayer 2002; 2005; Moreno and Mayer 1999) have been addressed. By providing the opportunity for direct comparison of the media condition and asking immediate feedback from each student, each class enabled students to recognise both what the specific learning objective was and to reflect on which media had a stronger effect on their understanding of the principles.

Table 1. Learning objective and applied media conditions

Learning Objective	Applied Media Condition		
	2D	3D VR	3D Print
Geometry		Y	Y
Curves	Y	Y	
Material Shaders	Y	Y	
Texture Mapping		Y	Y
Lighting & Rendering	Y		Y
Level of Detail		Y	Y

To address problem relevance a technology visualisation is constructed for each learning objective and media condition. An illustrative example of the geometry learning objective is provided in Figure 1. The model is constructed using a benchmark lesson plan (Autodesk 2013) to construct a 3D temple (rendered in 2D). The resulting model is then both 3D printed using a MakerBot™ Replicator2 to create physical scale model and also placed into a VR simulation environment using Unity3D and the Oculus Rift. The result affords learner centered (Weimer 2013) and active engagement (Bonwell and Eison 1991) through physical and virtual interaction with the visualization media. This in turn allows both high and low spatial learners to engage and conceptualize the object before constructing their own example.

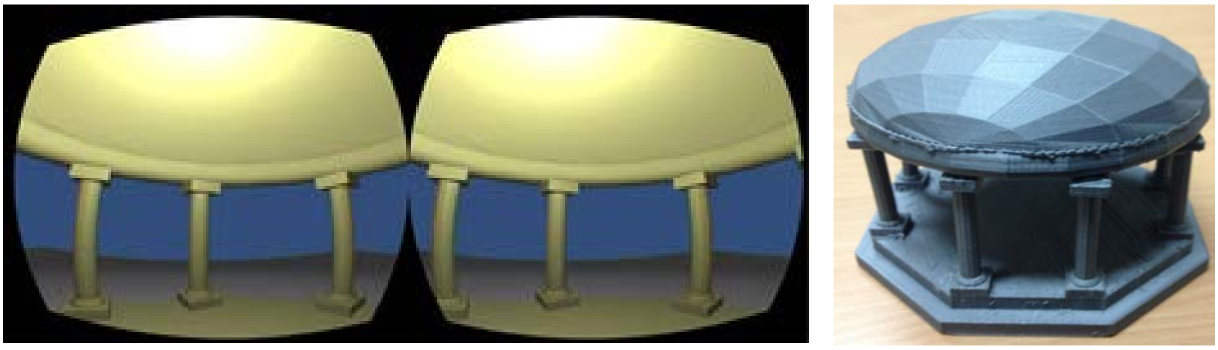

Figure 1: 3D virtual and physical technology visualisation of geometry learning objective

Lessons for each of the learning objectives (Table 1) were created that compared at least two of the visualization technologies. Learning journals or blogs have been shown to allow learners to record their systematic thoughts and facilitate student self-reflection (Garrison and Vaughan 2008). This evaluation method satisfies the need to evaluate the design and is proposed to record learner observations, testing, and simulation experiences of the media conditions. A dual representation is presented in each session for each media condition enabling direct comparison between the media methods. For each learning objective the following stimuli questions were proposed:

1. Which media form(s) engaged you and what aspect(s) made it engaging?
2. Which media form(s) did you find most "sticky" in your understanding of the objective and why?
3. Discuss the differences in media form (clarity, visibility & interactivity) and limitations (constraints).
4. For the purpose of demonstrating the objective to a design team, which media would you use and why?

The research contribution and rigor is achieved through creative development and use of the fore mentioned evaluation method. This enables assessment by the learners regarding media fidelity and implementation method and assessment of the learners by assessing the students through creative assessment using the learning objectives as assessment criteria. The outcomes contribute to existing research literature in education technology and visualisation. This reflects well the modeling development pipeline or prototype development cycle. Through multiple iterations and exposures to the technology students will improve not only learning outcomes but an understanding and working knowledge of the media technology and purpose. Finally, the method requires both technology presentation and discussion and a method of pedagogy improvement to communicate the research to both technologists and learning managers. The outcomes from the learner blogs will be analysed using NVIVO ™ (http://www.qsrinternational.com) and qualitative analysis of students' blogs will be correlated against student outcomes.

RESULTS

The weekly student journals were the primary source of data and the two research questions guided the data analysis. In relation to RQ 1, two themes emerged from the data regarding perceptions of the value of the technologies in learning the course material.

Synergy of Multiple Visualization Technologies

The direct and reflective comparison between technologies revealed a strong interaction among them for learning. None of the technologies was clearly preferred or abandoned. Instead students found that principles learned through the use of one technology were reinforced or complemented by the same exercise performed with another technology. Students noted that "*Each representation fits a niche and serves a purpose for each stage in the production process*" and that "*having multiple forms of mixed media is extremely effective in helping myself, a new learner, to grasp the basics of 3D modelling*". Other students commented that each media provided "*profoundly different experiences*" but that the media provided learning convergences and ability to be conceptually creative. The most common theme can be summarised in the statement that during the term it became *"increasingly apparent that although each representation has its own strengths and weaknesses, in conjunction they all contribute to a more effective blended learning experience"*.

A second theme emerged when analysing the student's texts in relation to the visualization technologies coded according to six visualization criteria: *accessibility, useability, manipulability, navigability, visibility, communication, and creativity.* As expected each technology had positive (P), mixed (M) and negative (N) perceptions. Illustrative quotes are provided in Appendix 1 and the results are summarized in Table 2.

Table 2. Summary of applied media condition perceptions

	2D Image Projection	**3D Printed**	**3D Virtual Reality**
Accessibility	P: available anywhere	N: Time consuming; not readily available	N: not readily available
Useability	P: no additional learning required to use	P: feels natural like real life	N: creates motion sickness; requires extra training
Manipulability	N: manipulation not authentic	P: can handle as real object	M: change aspects but no tactile, haptic feedback
Navigability	N: static, lacks interaction	M: aids spatial awareness but can't navigate internally	P: real-time internal navigation and spatial awareness
Visibility	M: many aspects available but interior is not visible, lacks depth	P: enables connection between real and virtual environment	P: defect visualisation and classification and aspects available
Communication	P: simple with rapid versioning	M: physical model aids communication but slow to manufacture	P: good for demonstration
Creativity	P: bringing to life; not limited to real life	M: making physical reality but limited to physical objects	P: real-time interaction and modification improves creative process not limited to real life

Although students placed high learning value on accessibility and useability, there was strong appreciation for the ability of the technologies to navigate, manipulate and be creative with information via the technologies.

Shifts in Attitude

Results from the second research question were also revealing. Although many students expressed early preferences for specific visualiation technologies, over time their perceptions shifted. Some recognised that *"each media allows unique insights the other does not"* and that *"every medium has something to offer and enrich the experience, 2D assists with initial concept; print best shows the model accuracy; VR allows immersion."* There was broad recognition that all representations have both advantages and limitations and each has select principles that work better or worse with the learning objectives. This was expressed by one student as *"initially I did not conceive the ease and disruption of 3D printing, the importance of kinaesthetic interaction and interactivity aided me most in the learning. The limitations of each representation were complemented by the strengths of their counterpart."*

Interestingly, some students recognized the synergy among the technologies that assisted their learning as expressed in: "*By examining all media representations I could make inferences between each and fill in the gaps that the other representation did not allow. Even when presented with only two representations the knowledge of the third missing representation allowed me to conceptualize the missing parts."* This theme, that a mix of approaches was the most beneficial aspect of the technologies was commonly reflected upon.

One additional theme was seen in the data that related to the learning journals themselves. Many students noted that they had initial preferences based on novelty or excitement. But over time they came to appreciate more "*mundane*" technologies because they were reliable, available and of greater perceived learning value.

DISCUSSION

Proponents of blended learning approaches have long appreciated and advocated for multiple modes of presentation, delivery and content. This pilot exploratory study contributes to this discussion by identifying synergistic effects among visualization technologies. Researched focused on the benefits on a single communication or visualization technology tend to deemphasize the preferences and thus engagement of students with specific affordances of the technologies they are presented with. Disciplines whose subject matter are suitable for 3D visual presentations (e.g. medical anatomy, architecture, geography, chemistry and media/game design) will benefit from the observation that multiple 3D modes of engagement can be reinforcing and synergistic.

The comparisons between delivery modes (e.g. visualization technologies) provided much more than different versions of the same material. The engagement with each technology required reinterpretation of the principles upon which the lesson was focused. This provides students a way to "*reframe*" their own understanding and to "*fill in the gaps*" they observed using other media. These results are entirely consistent with the general principles of the broader blended learning environment which has become quite popular but shifts the focus to multiple delivery modes for the *same learning goal*. We suggest that this is particularly applicable to foundational principles where a deep understanding and the ability to understand the principle in different contexts is important.

Although the material in this pilot subject was the specifics of 3D-modeling, we suggest that the themes observed here are applicable in a wide range of subjects where the visualization criteria are applicable. Any learning with technology will be influence by accessibility and useability as these are substitutive capabilities. For example, work can be handed out in class or distributed via a learning management system. In this example, the function is the same and gains are made in accessibility or efficiency. But visualizations can be greatly improved through the ability to navigate and manipulate the information, not just the technology. These are instances of innovation where it is very difficult to enable these functions without the technologies. For example, medical anatomy classes have a long tradition of physical manipulation of anatomical features. In some instances, direct physical manipulation reinforces visual inspection. It is likely that combining rotatable and constructible anatomical visualizations would be a beneficial addition to introductory classes.

Study Limitations

The exploratory nature of the research was based on a convenience sample of students the first author had in a subject. The examples in each of the media selections were limited by the required subject content and by the time required to prepare complex visualizations for the students to experience. The 3D printed objects were limited to PLA plastic only in multiple colours. There were also of technical limitations in the systems used. The VR system was limited to moving around and through the object - no rotation, scale, moving of object (lack of manipulation) and it was low resolution. Not all students used the VR system as they experienced motion sickness. Some learners confused 2D projection with the modelling tool and spoke about 2D being interactive requires that the journal data be interpreted by the researchers.

Future Work

One primary purpose of this exploratory work was to discover techniques and lessons for comparative presentation of material using mixed media with the goal of extending the study into a wider variety of disciplines. Furthering this work will require refinement of issues including:

- Correlate student perceptions against student results with particular attention to whether changes in preferences (indicating reflection) can be implicated in learning. This would inform curriculum design.
- Determine any causative relationships, e.g. does the technology enable deeper learning or additional learning and how does this inform pedagogy.
- Improve VR system to include manipulation, increase resolution and reduce motion sickness effects improving the simulation and learner experiences with the technology.
- Develop a wide range of specific exercises (3D models, 3D printable objects and VR accessible visualizations) which can be incorporated in class curricula. This will require extensive interaction with other instructor to develop suitable material, establish lesson plans and develop evaluations and assessments.
- The tasks and perceptions need to be related to group work and the learning community in a class. E.g. does the technology enable a community of inquiry in the classroom which leads to increased learning?

This final point was revealed by an insightful comment from a student who noted that technologies provide informal focus for discussion:

"*… one aspect that I found useful was virtual design and how it helped explain a problem that I had not yet thought of …. I now have a better understanding of it because of the laid back chat I had with [instructor] whilst observing the virtual object. …. the real thing that helped me this week was not the visualisation of the product through physical or virtual aids provided but the time in observing them. There was a feeling of just chatting* *with others ….you should possibly consider the ""chat"" as one of your options where although you are explaining something the student feels more comfortable and involved by being able to put in their 2 cents.*"

This is both a recommendation to engage with students regarding what is presented via visualization and a mild rebuke to remember that learning, and teaching, is not about the technology.

CONCLUSION

The primary purpose of this pilot project was to discover techniques and lessons for comparative presentation of material using mixed media with the goal of extending the study into a wider variety of disciplines. The study produces several core guidelines for more in-depth research on the interaction between media for improved learning in domains which really on visualizations and manipulations. This is important as proponents of blended learning approaches have long appreciated and advocated for multiple modes of presentation, delivery and content. This exploratory study contributes to this discussion by identifying synergistic effects among visualization technologies.

REFERENCES

Autodesk. 2013. "Modeling a polygonal mesh from a reference image." Retrieved 27 June, 2014, from http://download.autodesk.com

Barron, L., Bransford, J., Campbell, O., Ferron, B., Goin, L., Goldman, E., . . . KINZER, C. 1992. "The jasper experiment an exploration of issues in learning and instructional design," *Educational Technology Research and Development*, (40:1), pp 65-80.

Bonwell, C. C., and Eison, J. A. 1991. *Active Learning: Creating Excitement in the Classroom*. ASHE-ERIC Higher Education Reports: ERIC.

Dalgarno, B., and Lee, M. J. 2010. "What are the learning affordances of 3-D virtual environments?," *British Journal of Educational Technology*, (41:1), pp. 10-32.

Dickey, M. D. 2005. "Brave new (interactive) worlds: A review of the design affordances and constraints of two 3D virtual worlds as interactive learning environments," *Interactive Learning Environments*, (13:1-2), pp 121-137.

Fowler, C. (2014). "Virtual reality and learning: Where is the pedagogy?," *British journal of educational technology*, DOI: 10.1111/bjet.12135.

Freitas, S. d., and Neumann, T. 2009. "The use of 'exploratory learning'for supporting immersive learning in virtual environments," *Computers & Education*, (52:2), pp 343-352.

Garrison, D. R., Anderson, T., and Archer, W. 1999. "Critical inquiry in a text-based environment: Computer conferencing in higher education," *The internet and higher education*, (2:2), pp 87-105.

Garrison, D. R., and Vaughan, N. D. 2008. *Blended learning in higher education: Framework, principles, and guidelines*, John Wiley & Sons.

Höffler, T. N. 2010. "Spatial ability: Its influence on learning with visualizations—a meta-analytic review," *Educational Psychology Review*, (22:3), pp 245-269.

Hooper, S., and Rieber, L. P. 1995. *Teaching with technology. Teaching: Theory into practice*, 2013, pp 154-170. Needham Heights, MA: Allyn and Bacon.

Huk, T. 2006. "Who benefits from learning with 3D models? The case of spatial ability," *Journal of Computer Assisted Learning*, (22:6), pp 392-404.

Hwang, W.-Y., and Hu, S.-S. 2013. "Analysis of peer learning behaviors using multiple representations in virtual reality and their impacts on geometry problem solving," *Computers & Education*, (62), pp 308-319.

Johnson, L., Adams, S., Cummins, M., Estrada, V., Freeman, A., and Ludgate, H. 2013. The NMC horizon report: higher education edition.

Keppell, M., Suddaby, G., and Hard, N. 2011. *Good Practice report: technology-enhanced learning and teaching*. Australian Learning & Teaching Council.

Kozma, R. B. 1991. "Learning with media," *Review of educational research*, (61:2), pp 179-211.

Kozma, R. B. 1994. "Will media influence learning? Reframing the debate," *Educational technology research and development*, (42:2), pp 7-19.

Loy, J. 2014. "eLearning and eMaking: 3D Printing Blurring the Digital and the Physical," *Education Sciences*, (4:1), pp 108-121.

Mayer, R. E. 2002. Multimedia learning. Psychology of Learning and Motivation, (41), pp 85-139.

Mayer, R. E. 2005. *Cognitive theory of multimedia learning*. The Cambridge handbook of multimedia learning, pp 31-48.

Moreno, R., and Mayer, R. E. 1999. "Cognitive principles of multimedia learning: The role of modality and contiguity," *Journal of Educational Psychology*, (91:2), pp 358.

Muller, A., Muller, D., Eklund, J., and Sharma, M. 2006. The future of multimedia learning: Essential issues for research.

Wann, J., and Mon-Williams, M. 1996. "What does virtual reality need?: human factors issues in the design of 3D computer environments," *International Journal of Human-Computer Studies*, (44:6), pp 829-847.

Weimer, M. 2013. *Learner-centered teaching: Five key changes to practice:* John Wiley & Sons.

APPENDIX 1. Statements from student reflective journals

2D Image Projection	3D Printed	3D Virtual Reality
Accessibility		
P: “available anywhere through learning management system … no specialized equipment required”	N: "time to fabricate … physical limitations of the material … best served for finished product … requires 3D printer … not available at home"	N: "requires VR headset … not available at home"
Usability		
P: “easy to use … standard format … no additional learning required to use… invaluable starting point or general template”	P: “feels natural … real life … easy to use … physical affordances”	P: "easy to use for gaming students … works with existing computing system" N: "motion sickness … low resolution … non-gaming students need tutorial on navigation method … hardware limitations"
Manipulability		
P: "quick ability to change material texture and colour" N: “unable to touch, scale or translate in three dimensions … unable to break down to component parts … unable to change form”	P: “tactile … allows assemble and disassemble ... translate in three dimensions … can change physical form and scale … understanding of model architecture … speed of manipulation” N: “time consuming to change physical form, colour and scale … limited texture (plastic)”	P: "real-time ability to change material texture and colour" N: "no tactile, haptic feedback"
Navigability		
N: “static, lacks interaction … no additional information beyond the presented view … cannot rotate or navigate around in 3D space … cannot navigate internal structure”	P: “physical interaction … twistable and rotatable in 3D space … aids spatial awareness” N: “no additional information beyond the presented view … cannot navigate internal structure”	P: "real-time navigation … navigate internal structure … sense of immersion … aids spatial awareness"

Visibility		
P: “high quality visualization … incorporates rendering pipeline, lighting and global illumination … many simulated material types … texture mapping” N: “difficult to visualize and classify defects … cannot visualise internal structure … lacks depth ... difficult to conceptualise lighting and angles”	P: “physical product … connection between real and virtual environment … degree of depth … aids conceptualisation … highlights initial expectation ... defect visualisation and classification … highlights necessity for good planning and construction accuracy ... version comparison ... highlights unwrapping of texture in a novel way through a physically 2D printed diagram that shows clear defects and seams ... lighting is applied to physical object”	P: "real-time defect visualisation and classification … importance on model accuracy … visualise internal structure … many simulated material types … texture mapping … real-time version comparison … good for early prototyping"
Communication		
P: "quick … simple … rapid versions"	P: "physical model aids communication between individuals … gives complete understanding not seen in virtual" N: "time to fabricate and react to change"	P: "early prototyping to highlight defects and ideas … good demonstration tool … real-time modification"
Creativity		
P: "taking a flat object and bringing this to life … snap shot of a virtual world … not limited to real life"	P: "virtual creative design becomes physical reality … motivation for end result" N: "limited to real life"	P: "real-time interaction and modification improves creative process … created design used in many unique ways in the virtual environment … immerse yourself in the virtual world of your own creation … not limited to real life"