Visual Thinking in Virtual Environments: Evaluating Multidisciplinary Interaction through
Drawing Ideation in Real-time Remote Co-design

By

Alex Close

A thesis submitted to the Faculty of Graduate and Postdoctoral Affairs in partial fulfillment of the
requirements for the degree of

Master of Design

in

Industrial Design

Carleton University, Ottawa Ontario

© 2020, Alex Close

ABSTRACT

This study analyzed three different remote sketching paradigms to find recommendations for future remote multidisciplinary co-design systems. These included virtual reality freeform drawing, tablet drawing, and uploading images of paper drawing. Drawing in VR could potentially be useful for convergent ideation and visualizing designs that require large-scale spatial thinking or human-scale interaction. The tablet was shown to be easy to use and applicable for a wide variety of design scenarios and paper showed strength in divergent or sequential ideation. The results indicate that perception of media might affect the use of digital tools – this difference in perception was shown between disciplines. Notably, users of VR for collaboration might need more time to explore and develop skills since the medium is so new. The results of this study contribute to further understanding of how digital media can affect the design process when communication between stakeholders needs to be remote.

Keywords: multidisciplinary, co-design, virtual reality, remote collaboration, sketching, ideation

ACKNOWLEDGEMENTS

I want to thank my supervisor Steven Field for his enthusiastic support and insight during this project, and for always telling me what I need to hear, not what I want to hear. His high standards and passion have inspired me and none of this would have been possible without his support. I would also like to thank my co-supervisor Rob Teather for his support and for letting me take a glimpse into the world of VR.

This study would not have been possible without the openness and enthusiasm of my 12 participants. I learned something from each one of them and they all provided valuable feedback to my research. I would also like to thank my MDes colleagues as well as other bright people I have met in classes or clubs at Carleton. I want to thank the professors that allowed me to take classes outside of my area of expertise, even as far as Mongolia, as well as the professors I was a teaching assistant for, each one of whom inspired me and brought me confidence through this process.

Finally I would like to thank my family and friends. In particular I want to thank my mom Menka for seeing me through the best and worst of times throughout this process, and my aunt Zlata for pushing me to continue to pursue what I am capable of, and supporting my adventure into the unknown.

TABLE OF CONTENTS

Abstract	ii
Acknowledgements.....	iii
Table of Contents.....	iv
List of Figures	vii
List of Tables.....	ix
List of Appendices.....	x
Preface.....	xi
Glossary	xiii
1 INTRODUCTION	1
1.1 Rationale	2
1.2 Research Question & Hypothesis	4
1.5 Contribution	5
2 LITERATURE REVIEW	7
2.1 Theoretical Context	7
2.1.1 Modernity and Global Interactions.....	8
2.1.2 Contemporary System Design	9
2.1.3 Global Interactions.....	9
2.2 Sustainability and Complex Design Problems.....	10
2.2.1 Nomadic Cultures and Sustainability	11
2.2.2 Design in Canada	13
2.3 Diversity and Innovation.....	14
2.3.1 Collaborating Across Disciplines.....	15
2.3.2 Co-design	19

2.3.5 Distributed Stakeholders	20
2.4 Visualization and Design Communication	22
2.4.1 Basic Reasoning Strategies	23
2.4.2 Visual Thinking and Communication.....	24
2.4.3. Spatial Reasoning	26
2.4.4 Mental Models and Representation	27
2.5 Design Tools.....	31
2.5.1 Comparing Ideation Approaches	32
2.5.2. Sensorimotor and Cognitive Demands	37
2.6 Digital Collaboration.....	39
2.6.1 Remote Collaboration	39
2.6.2 Co-design in Virtual Reality	42
2.7 Human-Computer Interaction Considerations	43
2.7.1 Immersion and Presence	44
2.7.2 Interaction Methods.....	45
2.7.3 Virtual Time, Perception, and Activity	47
2.8 Literature Review Insights	48
3 METHODS	51
3.1 Approach	51
3.1.2 COVID-19 and Remote Testing	51
3.2 Participants.....	52
3.3 Study Design	53
3.4 Apparatus.....	54
3.5 Procedure.....	58

3.6 Data Collection Methods	59
4 RESULTS	62
4.1 Pretest Survey	62
4.2 Post-Test Survey	64
4.2.1 Collaboration	65
4.2.2 Individual Ideation	69
4.3 Observation	73
4.3.1 Quantitative	74
4.3.2 Qualitative	76
4.4 Open-Ended Questions and Focus Groups	81
4.4.1 Open-Ended Survey Questions	81
4.4.2 Focus Groups	84
5 DISCUSSION	90
6 RECOMMENDATIONS & FUTURE RESEARCH.....	97
7 LIMITATIONS OF STUDY.....	105
8 CONCLUSION.....	107
9 REFERENCES	110
10 APPENDIX	129

LIST OF FIGURES

Figure 2-1. Literature Review Map	50
Figure 3-1. Multiplayer Drawing App.....	55
Figure 3-2. Conceptboard	55
Figure 3-3. Researcher Testing VR Application before Pilot Test, Pilot Test Set up	57
Figure 3-4. Methods Map	61
Figure 4-1. Pretest Survey Results.....	63
Figure 4-2. Trends in Pretest Survey Results	64
Figure 4-3. Collaboration Survey Total Results	67
Figure 4-4. Collaboration Survey Disciplinary Distribution	68
Figure 4-5. Individual Visualization Survey Total Results	72
Figure 4-6. Individual Visualization Survey Disciplinary Distribution	73
Figure 4-7. Average Number of Design Elements/Disciplinary Pairing	75
Figure 4-8. Average Number of Design Elements/Medium.....	75
Figure 4-9. Iterations/Medium.....	75
Figure 4-10. Gesture Communication (Crouching through Doorway, Collaboration Between Participant 7 and 9 – Artist and Computer Scientist)	76
Figure 4-11. Labeling Parts of the Design (Collaboration between Participant 7 and 9 – Artist and Computer Scientist).....	78
Figure 4-12. Sequential Collaboration via Paper Approach (Collaboration Between Participant 10 and 12 – Engineer and Designer)	79
Figure 4-13. VR Collaboration (Participant 10 & 11 Engineer and Artist)	80
Figure 4-14. Tablet Collaboration (Participant 2 & 3 Engineer and Designer)	80
Figure 4-15. Paper Collaboration (Participant 4 & 5 Artist and Computer Scientist)	81

Figure 4-16. Visual Coding of Qualitative Data	89
Figure 6-1. Areas of Future Research.....	97

LIST OF TABLES

Table 2-1. Disciplinary Frameworks	15
Table 2-2. Sample Stakeholders and Roles	21
Table 2-3. Reasoning Strategies	23

LIST OF APPENDICES

Appendix A. Email Recruitment	129
Appendix B. Brief	133
Appendix C. Consent Forms and Pretest Survey	136
Appendix D. Survey 1	144
Appendix E. Survey 2 and Debriefing Document	147
Appendix F. Pretest Survey Results	155
Appendix G. Quantitative Results	156
Appendix H. Collaboration Survey Results (1 st Section of Survey 1&2)	157
Appendix I. Individual Survey Results (2 nd Section of Survey 2)	159

PREFACE

As a visual artist my work focuses on questioning how we go about constructing or simulating unmappable “reality” or our perception of it. I question embodiment in non-places or simulacrum, and the way we go about forming pathways, borders, or segments – physically or psychologically. To navigate this virtual or subconscious, and imagined (future) world, I build dynamic, sometimes hyperreal spaces that might be soaked in industrial or digital fossils but are suspiciously void of humans. Items of technology are seen as “wild things” – things to be discovered in the wild and made use of, or things that develop further without human intervention. In this vein, I think about the relationship between technology and mythology, and fictional spaces within real spaces.

I loved my master’s program at the Glasgow School of Art before this. However, being so immersed in visual art made me feel like I was missing something important about contemporary life and technology – as if I was out of the loop. I felt that I could not bring my skills or ideas into conversation with anyone outside of this esoteric bubble. I found myself thinking that fine art lacks the dynamism or ambition of other creative disciplines today - that it was in some way left behind in the tides of global change.

Every time I tried to venture into an area outside of my expertise, it was difficult for me to explain why I was there, or what I had to contribute. I always had to start from scratch, and I would usually keep my background a secret. I went to archeological expeditions, worked for homeless charities and in construction, talked to rocket scientists and pipeline engineers, trying to learn as much as I could from them. Unfortunately I always felt like they thought I had very little to offer them, that there was nothing of value that they could learn from me. Was the art world really where I belonged? Could I provide more value if I escaped it completely?

Much of this experience was based on youthful anxiety about the grass being greener on the other side. It is also, however, what made me look to step out of my comfort zone and challenge myself in different cultural circumstances, and other disciplines or professions in hopes of engaging in more meaningful conversations about contemporary issues. Though I had some support, it was not unanimous. In fact I faced some undeniable hostility because of my apparent audacity. This showed me that even though interdisciplinary has become a bit of a buzz word, cross-disciplinary approaches are still not always respected and welcomed. I suppose crossing borders has always been challenging, but my experiences made me consider what kind of role I can play in building bridges.

Since my previous master's degree was practice based, I wanted to spend time digging deeper into my theoretical interests while also finding out what my role is as an artist at this point in time. Because my background is not in industrial design (or computer science) I was challenged and had the opportunity to break apart my ideas and get better - both in theory and practice. Before I started this program I had never used illustrator before, did not know of any 3D modeling software, and had never tried virtual reality outside of rollercoaster simulations in the mall. Of course this made some of my questions and approaches naïve, but it also made me able to look at these things from a different perspective. I am thankful that I got to jump into a world I thought I would never be let into, and that I got to learn much more through collaboration than I have in the past. Engaging in meaningful multidisciplinary conversations allowed me to learn more about how I can facilitate them in the future. Though I am still thinking about where I fit in as a creative person, I am much closer to understanding it than I was at the beginning of this program. I feel like I have a stronger voice and more confidence to go through the path of finding out, even if it seems confusing.

GLOSSARY

Activity Theory – Activity is understood as transformative (to both subjects and objects), and supposes that consciousness and activity are inextricably linked. People are socio-culturally embedded and not processors or system components.

CAD – Computer aided design.

CAVE – Wall projection based 3D environment.

Cognitive Offloading – Physical action and external environment cues to reduce cognitive demand, for example writing down a reminder.

Convergent – Merging, moving towards unity.

Degrees of Freedom – In virtual reality this refers to the tracking of motion. 3DOF would refer to only tracking the rotations of pitch, yaw and roll, whereas 6DOF would include forward – back, up – down, as well as rotations.

Divergent – Tending to be different or developing in different directions.

Non-Mediation – Not mediated or translated by anything, nothing is intervening in the experience.

Performative – Referring to action and enactment. Challenges the existence of independent objects with fixed or given properties or boundaries and instead focuses on situated and relational practices in which identities, effects, and boundaries are intertwined

Simulacrum – In a postmodern context this refers to something that replaces reality with its representation. No longer referential, these places or objects are models of real without origin in reality.

Stereoscopic – An image with the illusion of depth that is made by presenting the viewer with 2 slightly different images coordinated to each eye.

Technocentric – A value system based on technology and science, and the ability of technology to control or protect the environment.

Telepresentation: The experience of feeling fully present in and interacting with a location other than one's actual physical location (in contrast to perceiving a simulated space).

Traditional Knowledge, IQ (or Inuit Quajimajatatuqangit) - Directly translates to “that which Inuit have always known to be true.” It is a term used to describe Inuit epistemology or the Indigenous knowledge of the Inuit.

Uni-Disciplinary/Intradisciplinary - Only involving one discipline (e.g. everyone involved in the collaboration was a designer).

Vergence-Accommodation Conflict - The conflict that occurs when your brain receives mismatching cues between the distance of a virtual 3D object (vergence), and the focusing distance (accommodation) required for the eyes to focus on that object. This can lead to focusing problems, and eye fatigue/strain.

STEAMM+D - Science, technology, engineering, arts, math, medicine, and design.

1. INTRODUCTION

The development of the internet and instantaneous networks of connectivity make remote communication a hallmark of global connectivity. Designing non-linear systems such as the internet exemplifies a contemporary trend towards the need for a more holistic understanding of products within broader social, cultural, philosophical and material contexts. Complex problems, like climate change for example, often require many different areas of expertise to tackle design problems. A specific example of this kind of challenge is design for remote Indigenous communities in Northern climates. Climate change can lead to dramatic changes to lifestyle, which is an added difficulty combined with the interaction between economic development and traditional lifestyle. The presence of many imported products that do not fit in with traditional lifestyle or current needs, as well as the effects of climate change are difficult problems to solve (Dawson 2008). To contribute to solving some of these issues using design, people from various areas of expertise, experience, and visual vocabularies might need to collaborate.

Questioning how people from various backgrounds can effectively collaborate ultimately led this research to focus on remote multidisciplinary collaboration. Though a multidisciplinary approach is not always needed, there are areas where people from different domains can integrate and overlay their knowledge to develop more nuanced and effective solutions to problems (Georgioulas 2012). Though collaboration in real life can be difficult, collaboration in a digital space can have its own challenges due to the lack of face-to-face interaction (Hughes and Stapleton 2005). More research on how these digitally mediated processes affect the design process could help find key characteristics to incorporate into a system for people with different areas of expertise to be able to ideate together to face some of these complex problems.

1.1 Rationale

The purpose of this study was to examine the current tools available for remote multidisciplinary collaboration in design, and to question how remote communication in the early stages of design could be improved. It also looked at the characteristics of the design process through digitally mediated systems, and how differences between approaches could affect ideation.

Though co-located collaborations are typically favourable, remote collaboration has become standard practice for geographically dispersed team members for many companies and research teams (Gumienny et al 2011). This can be especially true when locations are remote and costly for frequent travel. Even in distributed teams, co-design processes could be important to consider. Co-design processes, or processes of creative co-operation, aim to involve people in the design process who could provide valuable insight and ideas that one discipline alone might not have. The term co-design can refer to the organizing of open innovation processes; this could mean collaboration between people from different organizations or disciplines, or involving users or customers as participants in the design process (Steen 2013).

This study was structured as a case study of multidisciplinary design collaboration between visual artists, industrial designers, engineers and computer scientists (the last two were categorized in the same group for this study – see section 3.2). It specifically chose disciplines that are traditionally known to use visualization in some way (though not a rule). As a study of collaboration between people who have different areas of expertise and visual vocabularies, it tested how different digital and visual ideation paradigms affect the design process. This study was not aimed at examining collaboration between cultures, but rather served as a theoretical starting point and sample of the collaboration between people from different skill backgrounds. As a case study of people from

different disciplines, it aimed to uncover the types of changes or characteristics in the design process noted across systems during a multidisciplinary collaboration rather than make conclusions about the disciplines.

The creation of visual artifacts helps designers externalize their thoughts and can act as a common language between stakeholders (Li et al 2016). Though there are various brainstorming and ideation methods used by designers, sketching was chosen for this study because free-hand drawings and sketches allow for great flexibility, speed and intuitiveness for communicating ideas in design ideation (Leon 2014b). Also, maintaining a sketchy aesthetic has been noted by some to reinforce creative fluidity in the early design stages (*McVeigh-Schultz* et al 2018). Sketching, however, is not just used by artists and designers, but also by engineers, scientists, and mathematicians among others to come up with and express ideas. In each of these cases there might be different reasons for drawing, and different forms and vocabularies to communicate ideas (Ahmad et al 2013, Avsec & Savec 2019). Ultimately, drawing can be understood as a visual trace of our cognitive processes and it can be seen as a record of how we understand, perceive, and process our experiences (Brew & Kantrowitz 2013). Due to this ideation method's simplicity, history, and importance across various disciplines, it was the method of choice for this study.

Three drawing conditions were chosen for this study; virtual reality freeform drawing, tablet and stylus drawing, and pen and paper drawing (uploaded to collaboration site). Virtual reality has been shown to be useful and efficient for early prototyping in design. Since the forms are immediately present in 3D as they would be in real life, less interpretation could lead to better spatial understanding and cognitive offloading (Jin and Lee 2019). A drawing tablet was chosen because it utilizes a tactile surface similar to analog drawing, but since drawing can be done directly onto

desktop, has the benefit of simultaneous collaboration. Traditional drawing was also examined due to the immediacy and familiarity, and because it is still the most commonly used and most important way to iterate and communicate non-verbal ideas for designers (Leon 2014b).

1.2 Research Question & Hypothesis

Overarching Question:

How can multidisciplinary co-design be effectively facilitated remotely while leveraging different skill backgrounds through drawing as brainstorming in digital and visual communication paradigms?

Specific Questions:

1. Could VR provide benefits to the early ideation stages of design in a multidisciplinary setting?
2. What are the effects of specific remote drawing and communication paradigms (e.g. paper drawing & upload, tablet drawing, virtual reality drawing) on the design process in terms of individual visualization as well as collaborative interactions?
3. How will varying skill backgrounds affect the design collaboration process with these systems?

Hypothesis :

Digital and visual communication can provide benefits to remote communication. It is expected that virtual reality will improve the ideation stages of design, and will be the most collaborative and intuitive while allowing for simultaneous translation of ideas between disciplines through immediate 3D representation. The tablet approach will have the most

novel ideas due to scale and immediacy, and the paper medium will be the most divergent in terms of ideation. It is expected that there will be different preferred media based on the skill backgrounds of participants.

1.4 Contribution

Since much of the technology exists for purposes like remote co-design, more research needs to be done on how these media affect the design process in terms of how it changes strategy, or whether it influences the ideation process in some way. This study contributes to further understanding of how digital media can affect the design process when communication between stakeholders needs to be remote. Recognizing the working methods and finding best practices for each type of collaboration resulting from these team efforts, as well as the contributions of the individuals who engage in these activities are important to consider when evaluating results that might lead to hybrid approaches (Shanken 2005).

Some work has been done examining multidisciplinary and intradisciplinary (within discipline) collaboration through data representation such as post-it notes, symbols, or scientific data in virtual reality, and work has also been done comparing digital ideation strategies (including VR) to their physical counterparts such as sketching or creating lo-fidelity prototypes (Keefe et al 2005, Diamond 2019, Rahimian et al 2011). To date, no research has been done specifically on comparing virtual reality to other digitally mediated sketching ideation methods in a multidisciplinary setting. It is in this gap that this study aimed to provide insight.

Though there are many ways of using visualization in the design process, this thesis focused specifically on the exploratory, generative ideation stages of design and on sketching as an ideation

method. By analyzing the strengths of each drawing paradigm chosen for this study, the results produced guidelines and recommendations of things to consider when choosing or developing a future system for remote multidisciplinary design collaboration. In addition to industrial design, this research could also be relevant to fields like human-computer interaction, fine art (especially interdisciplinary or community-oriented practices), and cognitive psychology.

2. LITERATURE REVIEW

To examine the interaction of visualization, digital tools, and the multidisciplinary design process, this literature review will begin by providing a theoretical context for the current global environment of design. It will note why and where multidisciplinary or diverse perspectives could be needed, and some key changes in design theory and practice that have happened over the last century. The review will particularly consider contemporary design challenges in Canada such as climate change, sustainability, and designing for Northern climates. The review chronicles some core ideas of visual communication by examining different disciplines and comparing reasoning methods and spatial thinking. Furthermore, it looks at the evolution of design tools and some promising tools of the future – with specific focus on digital collaboration and virtual reality. It will also summarize work that has been done to date in comparing ideation methods in virtual reality and other digital systems, as well as approaches used for multidisciplinary collaboration. By synthesizing these key ideas, the review brought to light important things that need to be considered when choosing effective media for sketching ideation, with specific application to remote multidisciplinary collaboration.

2.1 Theoretical Context

To establish context for this study, the following section highlights some important characteristics of the digital era and its relation to modernity. It also notes some challenges in global interactions and how this relates to contemporary design. These challenges include contemplating non-places and the reconstruction of time, labour and locality due to global connectivity and digital media.

2.1.1 Modernity and Global Interactions

Carpo (2011) argues that the characteristically modern age of “mass-produced, standardized, mechanical, and identical copies [can] be seen as an interlude, and a relatively brief one – sandwiched between the age of handmaking, which preceded it, and the digital age that is now replacing it” (Carpo 2011 p. 10). This digital age can be characterized by the abolishing of space/time due to digital environments, and finding validation in the emphasis of technology to overcome physical limitations (Gonzalez Ruibal 2014). It emphasizes an abandoning of an object driven past in favour of an attribute driven future - i.e. past characteristically modern mass-manufacturing, and further towards not only customization (similar to handmaking) but self referentiality - due to rapid evolution. In this new age, Gonzalaz-Ruibal (2014) notices a *recognition* of the flaws of being modern (exposed by post-modernism), but also thinks that we have not been able to overcome modernity’s troubles. The stage of hyper or super-modernism, as defined by some authors, both exaggerates and retains some of modernism’s characteristics. It is defined by excess, such as material overabundance, self-reflexive individuality and spatial overabundance.

Super-modernity is also marked by the shift from places to non-places – namely places that do not foster symbolic relationships or a shared heritage (and are thus self-referential) (Gonzalez Ruibal 2014). One example of a non-place is a place whose role is to neutralize the sense of alienation in a foreign environment (such as airports or amusement parks). Non-places can also include simulacrum – places that are beyond just copies of the real, but situations that exceed reality and create their own truth (Gonzalaz-Ruibal 2014). In these simulated places such as online networking platforms or virtual reality, a person can simultaneously inhabit two spaces – the

real and virtual, “straddling ostensibly polarized worlds which are becoming increasingly blurred” (Corrigan 2015 p. 1).

2.1.2 Contemporary System Design

In North America the beginning of the 20th century was characterized by local linear engineering of complicated systems (Boy 2013). The 21st century, on the other hand, has opened up the opportunity for holistic designs of non-linear systems such as the internet. Boy (2013) notes that during the 20th century, we were “building the means and looking for purposes, now we have identified interesting purposes and must integrate the means because it is technologically possible” (Boy 2013 p. 3). Complexity, diverse interaction, and lightning fast global connectivity through digital communication have created an atmosphere very different than the early stages of industrialization. Boy (2013) observes that we have begun to understand the importance of chaos theories as opposed to reductionism to better thrive on our planet (Boy 2013). An example of chaos theory is that a butterfly flapping its wings in Colorado could lead a series of events that would influence a tornado to happen in Saskatchewan (Bishop 2015). At a very basic level this implies that everything is interconnected. Boy (2013) argues that a cross-disciplinary approach with new conceptual models is necessary for this contemporary paradigm of interconnectivity. This would include augmenting local linear approaches to engineering with holistic non-linear approaches to design.

2.1.3 Global Interactions

In a digital era with an emphasis on overcoming physical limitations such as geographic distance, and an abundance of non-places that are elusive to local specificity, Chung (2012) notes that discourses on global media seem to emphasize seamless integration of different cultural and

material elements. Much of the rhetoric around the ubiquity of technology and global communication seems to believe that this creates a space for Western and Non-Western stories, ideas, and information paradigms to exist as fragments of a unified global narrative (Chung 2012). It is almost described as a “soup” of floating cultural identities and fragments – a transnational space that is free from geographic, temporal, and cultural constraints (Chung 2012). Having this “rhetorical exuberance attached to the notion of seamlessness falsely suggests a utopia built on shaky assumptions of effortlessness, borderlessness, and frictionlessness.” (Chung 2012 p. 87). Chung (2012 p. 109) argues that this misconception of a “global connectivity that assumes a facile fusion of heterogeneous elements of territorial materiality” needs to be revisited. In other words, interaction between people with different backgrounds through contemporary media is not without significant challenges, and that globalism is not a utopian, effortless collaboration where everyone is on an equal playing field. Chung (2012) stresses that borders exist, whether they are between countries, cultures, generations, disciplines etc. They might not, however, have to be erased for meaningful interactions to occur (Chung 2012).

Some radical postmodernists propose a reconsideration of the realities of construction (e.g. labour and time) (Jacob 2011). This produces several questions: when communication has to be digital, how can we reconsider the position of labour, time and locality? Can physical and tactile communication be preserved by communicating through digital means? Can a digital space be one that a person can be physically embodied in?

2.2 Sustainability and Complex Design Problems

Issues of climate change can affect future supplies of air, water and food (Schneider et al 2007 as cited in Brown 2010). Brown (2010 p. 3) notes that “global issues such as these generate local

issues, and it is the sum of the local issues that has generated the local issues in the first place.”

Complex social and environmental issues like these can rarely be solved with existing models of inquiry and decision-making (Brown 2010).

Several authors note that it is important to examine not only tradition but also emerging global patterns (such as those in Northern climates), as these problems are interconnected with global sustainability and contemporary life (Brown 2010, Wenzel 2013). Though this study eventually evolved into focusing on remote multidisciplinary collaboration, this part of the literature review was an important part of forming the context from which the research question developed. The following sections overview several of the issues examined in the early stages of the literature review that eventually led the researcher to question how people from different skill backgrounds and visual vocabularies could contribute to a design project.

2.2.1 Nomadic Cultures and Sustainability

The influences of climate change are made particularly apparent when designing for Northern climates because biophysical changes due to climate change disproportionately affect these areas (Gondor 2016). When designing for Russia’s Arctic, Makhutov et al (2015) note that Arctic ecosystems are fragile, especially in a time where climate change is beginning to show dramatic effects. Things that can improve economic development can also harm traditional lifestyle of people who still live in these remote Northern landscapes (Gondor 2016). Even small effects on the ecosystem could have drastic effects on lifestyle. For example, certain places to hunt will become dangerous or unreachable, and some animals might disappear (Wenzel 2009). It is for this reason that Makhutov et al (2015) stress that close attention needs to be paid to Indigenous traditional life and other human factors when building or bringing products to these areas. This

reflects the perspective of some authors who question how sustainable it is to maintain a technocentric view of innovation (Dam and Siang 2017).

Traditional nomadic communities are experiencing particularly detrimental effects on lifestyle due to climate change. In Mongolia, of the country's 3 million people, almost half live the traditional nomadic herder lifestyle outside of major cities (Gardiner 2019). Dramatic changes in temperature and weather patterns (typically a dry summer followed by a colder than normal winter) threaten their lifestyle by killing livestock (Gardiner 2019). This combined with other motives such as economic problems, or seeking a better education for their children, leads many people to choose to migrate to the city where some continue to live in Gers (traditional nomadic housing). This produces over-congested outskirts of town that are tightly packed with no universal infrastructure for heating or electricity (Gardiner 2019). Many of these houses are heated by coal in the winter which further pollutes the city. Addressing urban in-migration, and encouraging sustainable and innovative design options to improve the lives of people who still chose to live remotely are multifaceted challenges. They require reflection from a variety of disciplines including anthropology, climate science, urban planning, industrial design, and engineering among others.

Encouragingly, renewable energy projects are continuing to gain ground concerning remote and less developed towns in Mongolia (Sovacool 2012). For communities that live remotely, there was an initiative in 2011 that brought solar panels to 40 000 herder families, making them self-sufficient (Sovacool 2011). This provides an interesting example of how the integration of sustainable technology with traditional lifestyles can reveal a symbiotic relationship.

2.2.2 Design in Canada

Like other remote communities such as those in Mongolia and Siberia, climate change has affected the ecosystems of the Arctic in Canada, making a traditional lifestyle more difficult. The rapid change from a traditional nomadic hunter/gatherer society to a modernized and more sedentary one has led to many challenges for Northern Inuit communities (De Meulemeester 2018). Among the challenges that remote Northern communities face in Canada, a major issue is that products exported from Southern manufacturers and design teams to Indigenous Arctic communities can make it challenging to preserve traditional customs. They are also sometimes not well suited to the environment in which these people live. Dawson (2008) notes that while visiting with an Inuit family one would see individuals sewing caribou hides in their living rooms, or sitting on the floor of the kitchen eating dried caribou meat or muktuk (whale blubber). These practices appear out of place because the spatial layouts of the houses built in these communities in recent decades map out the routines and practices of a different culture – that of Euro-Canadians (Dawson 2008). The spatial use in traditional Inuit housing is very different than the structure imposed by this Euro-American/Canadian modernism. In this case it is clear that architects failed to take the needs of users into account, and the people of these communities have responded by using the space according to their own needs (Dawson 2008).

In the midst of these challenging circumstances, Wenzel (2013 p. 182) argues that the changes remote Inuit communities in Canada have faced over the last 60 years is “an example of the adaptability of subsistence societies to new and ostensibly disruptive technological, economic, and social inputs.” Wenzel argues that the dilemma confronting Inuit and increasingly other groups of hunter/gatherers is not specifically the entrance of money or its increasing necessity for traditional food acquisition, but that southern penetrations - such as economic influences - introduce a

different pattern of labour allocation than their traditional way of living – namely the sale of individual work rather than collective action. Contact with market economies is now a reality and plays a critical part in their livelihood (Wenzel 2013). However, Wenzel also argues that Inuit subsistence has been responsive in accommodating novel variables including environmental disturbances and that there have also been positive adaptations or interactions with modernity. An example of this is that “snowmobiles and motorboats [began to] facilitate kinship-based hunting and food-sharing networks that would have otherwise been at a minimum badly stressed by the social and ecological costs of traditional technologies,” (Wenzel 2013 p. 186). The complex interaction of multiple influences (including some positive interactions with modernity) complicate the binary of technocentric versus traditional. This brings forth the question of how emerging technology might fit into communicating or solving problems through design.

2.3 Diversity and Innovation

As Joyce et al (2010 p. 58) note, “innovation occurs when experts recognize the analogous qualities of ideas from distant conceptual realms, identify ways they can be usefully connected, and work to realize them”. Fedorowicz (2008) also emphasizes that in many design scenarios, the most creative or innovative ideas are generated when internal and external team members combine their complementary skills and perspectives in new ways. Collaboration, however, can be challenging due to communication, skill, and perspective differences between disciplines, cultures, ages, and even personality types. Identifying best practices and working methods for each type of collaboration is important in order to propose models for evaluating the hybrid products/outcomes resulting from these team efforts, as well as the contributions of the individuals who engage in these activities (Shanken 2005).

2.3.1 Collaborating Across Disciplines

Collaborating across disciplines can take many forms. These can be classified into several distinct frameworks for the exchange of knowledge (table 2-1).

Disciplinary Framework	Characteristics of Team
Cross-Disciplinary	<ul style="list-style-type: none">-General term referring to an activity with 2 or more disciplines-The boundaries of disciplines are crossed, but not necessarily by blending of techniques or ideals <p>(Seel 2011)</p>
Multidisciplinary	<ul style="list-style-type: none">-Closely related to cross-disciplinary-Different disciplines work together, each draw on specific disciplinary knowledge-Work sequentially or in parallel to solve problems <p>(Jensenius 2012, Mitchell 2005)</p>
Interdisciplinary	<ul style="list-style-type: none">-Work jointly, but still from discipline specific backgrounds-Integrate knowledge and methods from different disciplines using a synthesis of approaches <p>(Jensenius 2012, Mitchell 2005)</p>
Transdisciplinary	<ul style="list-style-type: none">-Breaks down traditional disciplinary boundaries-Can over time create new hybrid disciplines-Unity of intellectual frameworks beyond the disciplinary perspectives (draws together concepts, theories and frameworks from various parent disciplines) <p>(Jensenius 2012, Mitchell 2005)</p>

Table 2-1. Disciplinary Frameworks

Brew and Kantrowitz (2013) note that the contemporary fluidity between disciplinary boundaries shows the value of thinking skills in favour of domain-specific knowledge. When multiple disciplines collaborate, participants can integrate and overlay their knowledge, creativity, analytic

capabilities, and preferred approaches to deriving solutions (Georgoulas 2012). Haas (2012) notes that this diversity of perspectives can stimulate richer cognitive processing. A richer level of cognitive processing can lead to more novel ideas available for exchange and feedback between the parties involved. This is important because in contemporary design problems, pre-existing knowledge might not be enough (Leenders et al 2003).

Thompson (2015), however, mentions that rigorous disciplinary (the separation of disciplines) can be thought to combat the perils of “sloppy thinking” which threatens to undermine the forcefulness and authenticity of analytical results. This author suggests that a consequence of co-research (or involving end users in design) is that it might muddle the boundaries of expert and layperson. Thompson (2015) therefore argues for the importance of maintaining disciplinary rigour while engaging in the integration of disciplines through friction and hybridity.

If interdisciplinary or multidisciplinary models of collaboration take place (for example combining art and science), methodological and epistemological issues raised by this type of collaborative work will arise (Brew & Kantrowitz 2013). If different disciplines speak different languages then they need to find a way to understand each other in the design process.

STEAMM+D & Indigenous knowledge: Lachman (2018) states that graduates working in STEM fields should be able to engage with the toughest questions of our time: what, where and how our new inventions should be engaged (Lachman 2018). An approach called STEM to STEAM is an initiative that began at the Rhode Island School of Design in 2010 that proposes bringing art and design to STEM education and research to create a model that will better prepare future generations for the 21st century innovation economy. By integrating science, technology,

engineering and mathematics with creative disciplines such as fine art and design, this promotes the integration of creativity and rationalization – a back and forth process (Boy 2013). STEAM is centred on creative problem solving for complex problems that emphasizes learning by doing, expressing *and* critiquing, as well as exploring possible futures to foster sustainable innovation (Boy 2013, Diamond 2019).

Diamond (2019) notes that Bill Buxton and Saul Greenberg – leaders in the human computer interaction field value how the working processes of artists and designers combine embodied and rational knowledge and their work often evolves from an iterative process of observation, experimentation, sketching, abstraction, repetition, and critique – tools that break the incremental research model often used in traditional STEM disciplines. Designers in particular are able to position technical research within a broader framework in connection with a larger system of effects (Diamond 2019). In summary, Diamond emphasizes the need to use cross-pollinating approaches to bridge the gap between capability and future possibility which she deems the “Imagination Gap.” By bringing art and design into STEM collaboration, this will bring empathy, imagining problems from diverse perspectives, and being able to draw upon creative ability and resourcefulness to solve problems.

An example of a STEAM collaboration that lead to breakthrough scientific discoveries is a 2003 multidisciplinary project that involved an artist, a computer scientist, a geneticist, and a mathematician (Diamond 2019). The collaboration ignited the geneticist’s focus on complexity theory applications to “cell biology, formulations of a post-modern biology, and mind-body medicine” and served the artist’s interest in artificial life, complexity theory and aesthetics (Diamond p. 1852). It ultimately led to the breakthrough discovery of stem cell plasticity and

helped to reveal relationships between previously invisible phenomena. This project also mobilized art and design to further scientific research without subsuming the artist's interests (Diamond 2019).

Furthermore, Cook, Bush, and Cox (2017) did a study on STEAM training by asking elementary school students to create a model roller coaster. Because both engineering and art practices focus on how structure and aesthetics contribute to functionality, the students were able to synthesize their scientific understanding of flow in the system through their appreciation of aesthetics and feelings of thrill associated with roller coasters (Cook, Bush and Cox 2017). The inclusion of arts thinking in this project allowed students to learn that manipulation of the visual aesthetics affect the energy flow of the system. This then determines the system's functionality, leading to a more thoughtfully conceptualized and purposeful design. As Thompson (2015) notes, disciplinary rigour is important, but learning from a cross-disciplinary framework can provide insight and multidimensional understanding to participants from different disciplines.

Another area that should be considered as part of STEAMM+D collaboration (particularly in Canada) is Indigenous Traditional Knowledge. In environmental assessment for example, traditional knowledge can complement science through factual observation of land, current and past uses of it, methods for conservation, land ethics, life on the land and culture, as well as spiritual relationships to the environment among other things. How traditional knowledge is to be collected and used to inform environmental assessments, design, or urban planning however, is a complicated topic (Gondor 2016). In addition to traditional knowledge, it could also important to learn from the Indigenous approach to, and perception of modernization (such as interaction with contemporary media, products, or lifestyle).

Cultural expression can be a means to uncover and express scientific discoveries. One example is that network theories are compatible with Indigenous philosophy that sees technology as part of natural systems where humans are relational actors (Diamond 2019). Diamond (2019) emphasizes that Indigenous knowledge can be complementary and important to consider in design or STEAMM+D collaboration because of the reflective, place-based, and relational perspective that is grounded in specific understanding of responsibility, future impact and temporality.

2.3.2 Co-design

Friedman (2013) notes that co-design and value sensitive design are established approaches to design, technology, and development that include engagement with people who will be using the product/system, reflection by designers, and incorporation of human values throughout the design process. It can also mean sharing and combining knowledge across disciplines Steen (2013 p. 1) indicated that co-design is “collective creativity as it is applied across the whole span of a design process.” This could include applying different cultural knowledge systems to the problem-solving strategy, or applying practical insights from different professions.

A major benefit of this approach can be the providing of specific, pragmatic feedback to the design case – real users can explain exactly what needs to be changed in the design according to their experience using it (Friedman 2013). Focusing on the value of the user can lead to higher quality, more differentiated or customized products that suit people’s circumstances (Chisholm 2016). It can also foster stronger relationships between the product/service provider and their customers (Steen et al 2011). Co-design between stakeholders from different disciplines can be “the process in which actors from different disciplines share their knowledge about both the design process and

the design content,” this can be done to achieve the larger common objective - developing a solution to a design problem (Steen 2013 p. 1).

Co-design situations can, however, be challenging. Communication between stakeholders might be further complicated by restraints from users and society (Chou and Wong 2015). For example, some of these valuable stakeholders might have different ways of reasoning or symbolizing/representing information. This could potentially lead to misunderstandings in the design process that could hamper the benefits of working together to solve a difficult problem.

2.3.3 Distributed Stakeholders

Herter, Brown and Ovtcharova (2013) state that “collaborative scenarios have gained increased relevance in many disciplines and are indispensable in modern product manufacturing scenarios,” (p.1). These teams are frequently comprised of members from distributed locations. The success of such a co-located team will depend on its ability to collaborate effectively across distances (whether that is physical, cultural, or disciplinary) (Fedorowicz 2008). Support for innovation (including time, resources, and managerial co-operation) can influence the success of the team (Fedorowicz 2008). This means that finding the right tools and strategies to facilitate collaboration during remote design collaboration can have a significant effect on the outcome. The following list shows a sample of several disciplines that could be involved in a multidisciplinary design scenario that aims to work on a complex design problem (elaborated on in table 2-2).

- Industrial Designers
- Visual Artists
- Business Leaders

- Engineers
- Scientists
- Technicians (e.g. Manufacturing or Computers)
- Anthropologists and Archaeologists
- Government/Public Sector
- End-users or Community Members

Stakeholder	Role
Industrial Designer	<ul style="list-style-type: none"> -Design research, locating products in cultural context -Human factors such as ergonomics and empathy -Envisioning new forms/products, while being aware of manufacturing specifications -Synthesizing ideas and creating/testing prototypes -Facilitating co-design <p>(Veryzer & Borja de Mozota 2005, Steen 2013)</p>
Visual Artist	<ul style="list-style-type: none"> -Difficult visual problems -Community context, philosophy, history -Symbolism and material context -Radical ideas, new connections/combinations between things, new visual techniques, formal aesthetic <p>(Keefe et al 2008, Shanken 2005)</p>
Engineer	<ul style="list-style-type: none"> -Technical expertise -Informed attitude of structure, physics and environment -Practical mindset to bring alive ideas of designers of artists -Without them designs can be incomplete or illogical <p>(Kara & Georgoulas 2012)</p>

Business Management	-Distributing goods, developing services -Financial or advertising strategies (Gribbin, Young & Aftab 2017)
Scientist	-Crucial to many design problems today especially those including climate and sustainability -A well-informed empirical backbone of research has to precede any design that is sustainable or concerned with long-term effects. (Pearce et al 2009)
End-Users/Community Members	-Experts in their own experience, therefore understanding of and ideas about requirements of system/product -System/product will likely be a better fit to their needs if they are involved (Steen 2011)

Table 2-2. Sample Stakeholders and Roles

It is worth noting that there are specializations within each of these disciplines, and each discipline's capabilities likely extend past those mentioned here and can blend with the strengths of other domains.

2.4 Visualization and Design Communication

The following section explains where different types of reasoning strategies might be used and how they can differ between disciplines. It also notes the importance of sketching as an ideation method in various disciplines, as well as spatial reasoning and the development of mental models. Another highlighted area is the significance of the trace or artifact in social and material interaction and the role digital or intangible artifacts might have on the design process as intermediary or boundary objects that can influence action.

2.4.1 Basic Reasoning Strategies

There are several basic reasoning strategies that are employed in work and day to day life (*figure X2*). These reasoning strategies and the frequency/place of their application can be influenced by factors such as disciplinary training and cultural knowledge (Yang and Lee 2020).

Reasoning Strategy	Description
Deductive	-Logical approach, top-down deduction from one or more premises to reach conclusion -If $A=B$ and $C=B$ then $A=C$
Inductive	-Broad generalizations from specific information to find probable theories -E.g. “Every year there is a tornado in this area in July, therefore this July there will be a tornado.”
Abductive	-Imaginative reasoning -Carrying forward logic - observation to theory, accounting for observation -One day you noticed that the jar of cookies had been opened and milk had been spilled all over the floor in the morning - you would assume that someone in the house had done this

Table 2-3. Reasoning Strategies (Douven 2011)

In theoretical pursuits, abductive reasoning may be used in most disciplines, but in daily practical applications of varying disciplines, there are notable distinctions in common reasoning strategies. For example, artists typically have a tacit understanding of perception and cognition, and most often employ abductive reasoning (Keefe 2005). This can be useful for inferring theories based on large amounts of disjointed data (Keefe 2005, Hessel 2015). When engineers are involved in a design project, they typically start from a purely quantitative analysis and might employ software

tools to demonstrate their argument (Kara & Georgoulas 2012). This is a very different approach to the qualitative and spatial approach of designers, and indicates that engineers typically employ deductive reasoning when solving day to day problems in their discipline (Kara & Georgoulas 2012). Like engineering, scientific disciplines tend to use quantitative analysis and therefore deductive reasoning frequently to find solutions to problems or explanations to phenomena.

A study by Cramer-Peterson, Christensen, and Ahmed-Kristensen (2019) indicates that in the stage of idea generation, designers most often show a pattern of abductive-deductive reasoning.

Abduction is noted to be essential for design thinking and can be used to frame a problem and propose ideas in the first part of ideation, whereas deduction can explore and concretize these initial ideas (Steen 2013). Additionally, different designers might use different types of design thinking. In a 2018 study by Lee et al, designers who frequently employed deductive reasoning engaged in correcting and modifying predetermined design ideas sequentially (Lee et al 2018).

Contrastingly, designers who favoured inductive reasoning tended to explore design ideas through non-sequential evaluation (Lee et al 2018).

As Lee et al (2018) indicate, there can be individual differences in design thinking. It is important to note that in addition to differences between disciplines, individuals within any discipline may carry preferences for certain types of reasoning.

2.4.2 Visual Thinking and Communication

Designers use visual thinking and communication frequently (Avsec & Savec 2019). Core parts of design thinking such as predictive analysis and model testing rely on visual ability

(Avsec & Savec 2019). Li et al (2016) note that, in the case of design, the purpose of employing a

visualization method during brainstorming is not simply to create an image or object, it is to provide relevant information that will further the design process. When using visual communication to design, there are several time-honoured methods. Examples of these are physical prototypes from materials such as foam or paper, sketching, CAD models, mood boards, and storyboarding - among many others (Li et al 2016). Designers arrive at their optimal solutions to a problem through constant feedback loops - they apply their tools to analytic, synthetic, and creative processes to arrive at these solutions, often using spatial and qualitative reasoning (Kara & Georgoulas 2012). Patterns occur through observation and as more projects occur, revealing preferences about certain approaches (Kara & Georgoulas 2012).

Other disciplines also use visual means to communicate ideas. For example, sketching is not just used by artists and designers, but by architects, mathematicians, engineers, scientists, and other professionals to explore ideas and discover new ones. Each of these disciplines might employ different methods, tools, representations, forms of spatial reasoning, and even vocabularies to convey ideas - each with a different purpose behind their visual thinking (Ahmad et al 2013, Avsec & Savec 2019). Each of these disciplines might also use different types of creativity; these can include conceptual creativity, aesthetic creativity, technical creativity, and constructional creativity (Avsec & Savec 2019). Though these might all be communicated visually, their graphical expression might vary, especially across disciplines (Avsec & Savec 2019). For example, compared to designers, when working on the same projects, engineers might lean towards efficiency in structure as an end goal. Structuralists might maintain that the beauty of a building stems from its efficiency (Kara & Georgoulas 2012). Contrastingly, designers might think that efficiency is the enemy of possibilities (Kara & Georgoulas 2012). Crilly (2016) notes another important difference in ideation strategies between designers and engineers. While designers might come up with more

novel ideas, engineers might be more focused on how those solutions might actually solve the problem (Crilly 2016).

Brew and Kantrowitz (2013) highlight the idea that contemporary interdisciplinary methodologies for studying drawing are raising new questions about the position it has in research in many disciplines, and the role of visualization and “creative thinking” in scientific enquiry. Drawing can be understood as the visual trace of our cognitive processes – a record of how we perceive, understand, and process our experiences (Brew & Kantrowitz 2013). Van der Lugt (2002) references previous research indicating that sketching plays an important role in re-interpretation – re-interpretation can in turn lead to new knowledge and this leads to further re-interpretation – this is important at an individual and group level. The essential mental processes of restructuring and combining are two processes that are influenced by expertise in sketching and individual creativity (Verstijnen et al 1998). Though visual imagery might be important, it is not always easy to convey, since relationships between concepts communicated across several disciplines are different than concepts communicated within the same discipline (Herter, Brown and Ovtcharova 2013). How knowledge transfer interacts with visualization in engineering and design also remains largely unanswered (Avsec & Savec 2019).

2.4.3 Spatial Reasoning

Visio-spatial reasoning is important in multiple professions including design, fine arts, engineering and science. Spatial information includes shapes, locations, paths, relationships among entities, and relationships between those entities and frames of reference (Newcombe and Shipley 2015).

Representing this information cognitively helps people navigate the physical world, and construct or manipulate objects. There are two types of spatial representations – ones that are intrinsic to

objects and ones that are extrinsic – or exist as relationships between objects or between objects and frames of reference (Newcombe and Shipley 2015). The skill of mental rotation and object manipulation is an intrinsic-dynamic skill, whereas perspective taking (viewing an entire environment from multiple perspectives) is an extrinsic-dynamic skill (which relates to the ability to navigate (Newcombe and Shipley 2015)). Various authors point towards the partial distinction of performance across these spatial skills. Research indicates that artists are more likely to excel at intrinsic or object based spatial reasoning, whereas scientists are likely to be spatial visualizers, indicating different types of abstract reasoning from spatial information (Newcombe and Shipley 2015). Additionally, people from domains such as the social sciences or humanities are shown to not necessarily form abstract representations in either visual-spatial or visual-object models, even though they score high in abstract verbal processing (Kozhevnikov 2015). There are of course individual differences in these abilities, as well as distinctions within each field according to subject area or specialization (e.g. astronomy vs. biology).

2.4.4 Mental Models and Representation

Internal representations and external representations of objects and spaces are interrelated (Zhicheng and Stasko 2010). This relationship, and further, the relationship between one person's internal representation and another person's reinterpretation can be complicated (Zhicheng and Stasko 2010). Mental representations can be formed of mental imageries (rich in colour, texture, or form) or spatial relationships or combinations between them (Zhicheng and Stasko 2010). In addition to changing spatial configurations, the creation of a mental model can involve changing the underlying system logic and behaviour. Mental models are similar to mental maps, but can often be more abstract. People's physical actions (which can include the act of sketching and the act of moving around in space or manipulating objects in space) can achieve internal/external

coupling – the coupling of internal mental models and external models (Zhicheng and Stasko 2010). Visualization can be used as a functional tool to create these mental models, though visualization is not innate and takes learning with the specific system or context. Interestingly, Zicheng and Stasko (2010) observe that in domains such as engineering, new innovations and discoveries are not always made as a result of logical inference or deduction, “but via mechanisms such as analogy and simulative modeling” (Zhicheng and Stasko 2010 p. 1002).

Hewitt (1985) notes that pattern of thought can be personal and intuitive or in some cases based on the rules of the industry. There may be domain specific principles that underly the use of certain graphic forms or visualizations – these might be stricter in a discipline like engineering compared to fine art (Greenstock 2011). Abstracted models mirror the common understanding and information demand within each discipline (Herter, Brown and Ovtcharova 2013). In collaborative situations where multiple stakeholders have different backgrounds, specific conceptual models that are tailored to each discipline can complicate the communication process since the same mental models are not shared. There are increasing areas where different types of visualizations can overlap, for example artificial life, molecular biology and cell visualization – examples of contemporary situations where artists and scientists collaborate (Atwood & Barbour 2003, Keefe 2005, Diamond 2019). Herter, Brown and Ovtcharova (2013) recommend that in some of these challenging multidisciplinary cases, arranging conceptual models in 3 dimensional space can be a way to overcome visual complexity issues. They argue that a 3D approach can show a holistic view of the space, and is therefore able to present hierarchy and spatial relationships accurately in space rather than representing them on a 2D surface which requires interpretation (especially when different visualization and notation methods exist between disciplines).

Intermediary and boundary objects: Representation via intermediate objects (such as prototypes), or artifacts/entities (such as sketches) during a collaboration process refers to the concept of imbedding ideas into an object, or writing something into the material of the object (Vinck 2009). In a way, this intermediate object represents the person who designed it by materializing their intentions, their work/thought habits, their relationships, actions, perspectives, and compromises (Vinck 2009). However, the interesting part here is that when an idea goes from internal model to external representation, the transition is marked by a change (Vinck 2009). This artifact cannot be reduced simply to the intentions of the author - the materialization has caused it to be something more. The creator of this trace might be surprised to learn that the trace they made contained an element that they had not thought of – something that is not necessarily wanted or controlled, and can even be a betrayal (Vinck 2009). This intermediary object therefore introduces something in the collaboration process that partially escapes the actors (Vinck 2009). These objects or artifacts participate in the construction of compromises and knowledge that is shared between the team members (Vinck 2009). They can mobilize actions like induction, facilitation, reconsideration, prevention, among other things, and can help shift the point of view of the people involved (Vinck 2009). Shanken (2005 p. 9,10), however, notes that if a goal of multidisciplinary collaborations is the “creation of hybrid forms, what have been referred to as ‘boundary objects,’ that transcend the disciplinary limits of any single field, then the evaluative methods particular to a given discipline may not offer adequate measures of success or failure.” In other words, the value of artifacts from multidisciplinary collaborations is sometimes difficult to assess.

Another way of thinking about intermediary or boundary objects is shown by Budach, Patrick and Mackay (2015) in relation to Inuit traditional culture. In this context, objects or artifacts are thought to have the potential to connect people across contexts, time, space, life-worlds, and

generations (Budach, Patrick & Mackay 2015). Relating to activity theory, these authors suggest that material objects can have specific effects on human interaction which can strongly relate to the material properties of the object and not just the semiotic definitions we ascribe to them, similar to the observations by Vinck (2009). For example, if someone looked at a manufactured hammer in a Western context, the attributes of that activity would be tied to it, whereas the object itself could have other properties and could be used for other activities in a different semiotic context. Harris (2011) focuses on highlighting and analyzing the way Indigenous people perceive space, move around in space, navigate, leave marks in the landscape, and tell their own stories of the space, indicating that dwelling, sensual experience and cognition are inseparably combined. This point of view acknowledges that humans are part of the natural world without the binary reductionism found in Cartesian constructs (Johnson et al 2016).

In relation to digital artifacts, in “Western” society, “tangible objects have typically been seen to carry the weight of “aura, evidence, the passage of time, and the evocation of power through the authority, knowledge, and privilege we assign them,” (Dawson 2011 p. 397). Multi-media products (e.g. digital images) or artifacts that lack clear materiality are often seen as temporary, superficial and modern (Dawson 2011). Witcomb, 2007 (as cited in Dawson 2011) observes that this does not appear to be the case for the Maori. When using virtual or augmented reality for cultural preservation, they regarded rendered images as living presences, the same way they would have treated original objects. This interesting perspective poses questions about the role of materiality and digital or intangible artifacts and their effect on the design process as intermediary objects that can mobilize actions.

2.5 Design Tools

Tools are fundamental to all human tasks (Gänshirt 2012). A tool connects an individual to other people by mediating activity - the tool can influence their interaction and output (Fjeld et al 2002). Vosinakis and Koutsabasis (2012) note that the characteristics of a tool can change the activity itself. Tools that transform us (like fire, wheels, or cars) become a part of us (Featherstone & Burrows 1996). They cause the groups of people who use it to evolve and eventually mutate, effectively transforming the culture that uses it – sometimes in a good way and sometimes in a bad way (Featherstone & Burrows 1996).

Tools help in representation as well as communication. The limitations, capabilities, and characteristics of the tool can alter the exploration and communication in the design process. In certain situations, when an individual is presented with tasks, a person can use artifacts as tools, or will create tools out of their understanding (i.e. mental models). These tools will then become part of cultural context for others, connecting a person not just to their physical surroundings, but also to other people (Vosinakis & Koutsabasis 2012). According to activity theory, humans' relationship with their physical surroundings and socio-cultural surroundings are co-evolutionary – humans control their behaviour not just from internal urges but also from external use of artifacts (Fjeld et al 2002).

Aside from prototyping capabilities, it is important to find how a tool can support a designer's act of cognitive evaluation towards more creative ideation since this is an important part of the design process (Lee et al 2018). In addition to drawing tools and digital tools, tools may also encompass things like gesture, language, and mental models. Non-verbal communication such as eye-contact and gestures are also important in communication.

2.5.1 Comparing Ideation Approaches

In the very early stages of the development of graphical communication systems, Ivan Sutherland (1963) developed the “Sketchpad” a software for graphical manipulation, noting that “it is only worthwhile to make drawings on the computer if you get something more out of the drawing than just a drawing” (Sutherland 1963). This budding software displayed its possibilities through its ability to create large numbers of shapes with precision and ease – such as the creation of repetitive patterns (Sutherland 1963). Additionally, this software helped in the understanding of linkages – with regards to the behavior and appearance (Sutherland 1963). For example, in the recreation of a bridge, Sketchpad allowed the structure to be graphically displayed at the same time as having accurately computed results graphically displayed (Sutherland 1963). This meant that experimenting by modifying parts of the structure of the bridge would allow someone to see the change this would make in the force distribution (Sutherland 1963). Since then, CAD software’s quality, precision, and the ability to handle large amounts of information (visual and non-visual) and defining/applying changes changed the design process dramatically from analog to largely digital methods. In addition to this, digital manufacturing has added the possibility of serial variations, or mass customization instead of the mechanical mass-production that characterized modernity.

Though CAD has brought enormous changes and benefits to design, physical sketching and prototyping has still been shown to be far superior in terms of conceptual design in early design stages (Lee 2019). These early design ideation stages include quickly manifesting and memorizing ideas (Shih, Sher & Taylor 2015). Maintaining a sketchy aesthetic can reinforce creative fluidity and prevent people from being too precious about a singular idea (*McVeigh-Schultz et al* 2018). CAD on the other hand, is most useful for complex problem solving. Since the computer-

developed model is accurate, it could help designers alter and refine their design thinking. In the way that sketching is limited for certain stages of the design process due to its imprecision and inefficiency for developing patterns/quantities or present forms in movable 3D form, desktop CAD also has limitations. These include circumscribed thinking and premature fixation (Veisz et al 2012). In a 2012 study Veisz et al note that one participant believed that CAD can force designs to be more practical, which can potentially limit creativity. CAD systems oblige “designers to generate an early precise external representation of the object to be designed and to use highly structured rules, which orient their reflections and do not correspond to the automatic process of creation” (Lee et al 2018 p. 301).

Ultimately, designers prefer to switch back and forth between these modes at will (Shih, Sher, & Taylor 2015). However, they sometimes struggle when transferring information from the conceptualization stages to the CAD stages of design since the majority of existing geometric modelling requires a high degree of specialization from the users to achieve the form they want (Ibrahim & Rahimian 2010). This constricted approach makes it difficult for novice designers to externalize their idea, and also makes collaboration more difficult when some members of the team might not have (or need) this amount of expertise in geometric modelling software (Ibrahim & Rahimian 2010).

Due to the significant difference between these tools, research shows that there is a potential gap between commonly used CAD and physical sketching in the design process (Barricelli et al 2016). In examining this gap, some researchers have proposed gesture-based input for CAD, but the limitations of using a 2D display to show 3D activities requires designers to use extra cognitive resources (Jin and Lee 2019). Lee et al (2018) note that organic digital sculpting tools can provide

immediate visual stimuli and increased decision capacity to users, thereby encouraging them to escape the traditional limitations of CAD. Lee et al (2018) argue that digital tools are increasingly being seen as “a representation of visual design thinking and a cognitive mechanism” demonstrating underlying patterns of thought for design (Lee et al 2018 p. 311).

Tactile feedback is an important part of physical drawing that can also be achieved in tablet or table-based digital drawing. These methods, however, have been noted in some cases to have a lack of control, pressure sensitivity, friction, or immediacy of paper drawing, and also have a long learning curve (Cooper et al 2009). Nonetheless, drawing tablets have grown in popularity and can work well for collaboration even if there less control than a traditional approach – a participant in Hammond’s 2015 (p. 103) study notes, “The pencils were easier to control than the pen. However, it is more difficult for a group of people to draw with the same picture on a single sheet of paper collaboratively.” Though drawing with a tablet may not be as immediate as physical drawing, its capabilities when drawing using an application like Photoshop, for example, can include layering, quick erasure, malleability of size, vivid colour, and minute detail (McGlynn 2020). This could be especially useful for collaboration.

As a design system, many authors have noted that VR also shows promise as a visualization tool (Featherstone & Burrows 1996). The idea of virtual reality was first documented in 1863, then called a stereograph – a contraption involving mirrors to create a stereoscopic image (an image with the illusion of depth) for the viewer (Thompson 2017). It has since then evolved to many variations of 3D user interfaces. These include high immersion & high resolution head-mounted displays, CAVE systems – where an image is projected on walls around the user, fishtank VR which uses stereo-viewing on a desktop display, and augmented reality which blends virtual and real

information/imagery/objects (Qi et al 2006, Urey et al 2011) . There are also variations of 3D displays that include 3D viewing for movies, and more recently the development of light-field displays or holograms (Urey et al 2011). The most prominent useful applications for immersive virtual reality include vehicle simulation, vehicle design, entertainment, architecture design review, scientific visualization, military training, phobia therapy, and entertainment (Bowman and McMahan 2007).

The usefulness of VR for design is evident in both the creation of artifacts or prototypes as well as evaluation. It can speed up the process of visual refinement and convergence on a design idea by eliminating the time and money needed for physical prototypes (in some design cases) (Ahmad et al 2013). Brooks (1999) argues that VR shows the most promise, though, in changing not the artifacts but the actual design *process*. Rahimian *et al* (2011) compared collaborative 3D sculpting in VR (the team comprised of several architects) with creating low fidelity foam architectural models. This study showed that the physical models not only took longer, but they argue that working in the 3D virtual environment actually improved the unexpected discovery of spatial relationships and features. Sculpting in VR also changed the conversation from ordinary clarifications to new proposals and arguments (Rahimian et al 2011).

3D displays have many benefits over traditional monoscopic (image from a single viewpoint) displays. The stereoscopic display allows the viewer to see the image in 3D by using visual depth cues (Urey et al 2011). This is particularly important for precision tasks in short ranges, such as manipulation of objects (Urey et al 2011). Stereo images and head tracking allow users to use their intuitive capacity to understand stereopsis and motion parallax – phenomena they would experience from interpreting 2D projections of the real world in the retina and perceiving this as

3D (Bowman & McMahan 2007). When a person walks through an immersive space, their understanding of the space improves, and is different than it would have been with traditional representations like sketches, renderings or photos (Attef 2019).

There are some cases where the ability to think in terms of complex 3D environments can be fundamental to the design process. In these cases, allowing designers to move around the space while they construct it might not only make the process easier, but it could also change the way these designers appreciate and utilize space and scale when coming up with ideas, as well as helping to iron out issues during development and evaluation stages (Designing in VR 2017).

Working in 3D at the start could mean that fewer models will need to be produced as the “3D real-space sketches will be easier to interpret than paper sketches,” (Dawood 2017 p. 1). Ban and Hyun (2019) noticed that when car designers iterated on paper, they often distorted their drawings to make their designs look more dynamic. This exaggeration might make the designs look more attractive, but often makes them un-manufacturable. Referring back to a 3D model in these early design stages might minimize the discrepancy between the original concept and a manufacturable design (Ban and Hyun 2019).

Though VR as a design system shows promise, there are clear limitations and challenges for its use in serious or productive work, and is not at the point of replacing either traditional physical sketching or desktop CAD. Currently, desktop CAD is excellent at creating precise 3D models - being immersed in a 3D environment might not be necessary for many design cases. Also, traditional sketching is a technique that designers have used for many years and has clear benefits for ideation. Another major challenge is tactile feedback in both design and evaluation. Though there is technology that exists for tactile feedback in VR, it is often bulky and complicated. Haptic

feedback can be integrated in controllers, but whether this truly provides a benefit needs to be further researched.

Furthermore, virtual reality poses a unique challenge to our understanding of tools by blurring the boundaries of representation and telepresentation (feeling present in a place other than one's actual location) (Featherstone 1996). In VR, the “the border between a tool and reality is rather unclear; information technology can provide the user not only with representations of objects of reality but also with a sort of reality as such, which does not obviously represent anything else and is intended to be just one more environment with which the individual interacts” (Fjeld et al 2002 p. 4). Artifacts shaped by interactions with technology or code can still have a distinct appearance, history, properties and authorship, regardless of the fact that it does not have material substance (McCullough, 1998). Even though this “tool” is not present in physical reality, one can still perceive it or be embodied in it as if it was real. It can thus shape the way people work with or interact with each other and might therefore profoundly affect the way that things are designed (Featherstone & Burrows 1996). This can complicate one's understanding of the use of artifacts and space and the relationship of the author to them.

2.5.2 Sensorimotor and Cognitive Demands

Like drawing on paper, Israel et al (2009) emphasize that when drawing for ideation in VR, maintaining a sketchy, rough, unfinished character to the lines (open/twisted lines) is crucial to the associativity and ambiguousness of the sketches and that maintaining this character is essential to supporting creativity and problem-solving in the early design stages. However, Arora et al (2017) note that depth perception in virtual space can be confusing – determining where lines intersect might be a challenge, especially when trying to draw perfectly straight lines in 3D space with no

resistance. Since a person's whole body is moving in VR, one needs to be really precise, leading to higher sensorimotor demand (Machuca et al 2018). Designers that are accustomed to using a flat surface for drawing might find this particularly frustrating. Perceptual ability, familiarity with the interface, and affordances of the interface can all influence the way lines or shapes are constructed in 3D space (Arora et al 2017). Interestingly, Alkemade et al (2017), note that when participants used gestures to communicate in VR compared to the same gesture-based approach on a desktop display, participants had less trouble with depth perception, and the VR condition was shown to help their hand-eye coordination, suggesting that some issues in connecting lines could be a skill issue and could be resolved with practice. Supporting this point of view, Machuca et al (2018) note that most errors in drawing come from delusion (errors in the conception of the image) rather than illusion (errors in perception), and that this is largely due to individual differences in visual attention.

Rahimian et al (2011) note that in a design collaboration, architects noticed visuo-spatial features more in a 3D virtual environment than in low-fi foam models. Rahimian et al (2011) also reference previous research that explains how the association between mental cognition and the perception of physical attributes can offload the mental load which can in turn improve creativity. In other words, having a form represented in 3D with little need for translation or interpretation, means that less needs to be kept in the working memory so more focus can be kept on creating new forms or making adjustments. Additionally, a study by Lee et al (2018) aimed at analyzing the roles of digital design tools in design thinking found that 3D sculpting apps (on a desktop computer) caused designers to undertake more conceptual thinking (active image reasoning and evaluation) compared to conventional sketching. This counter-intuitive result suggests that digital media might have a specific advantage in the conceptualization stage due to the immediacy of 3D visual stimuli.

This study also noticed that while drawing on paper led to more divergent or lateral thinking, using the 3D sculpture tool led to more convergent thinking, such as gradually increasing the complexity and concreteness of the design. This shows that both sketching and organic 3D sculpting tools support different types of ideation (Lee et al 2018).

2.6 Digital Collaboration

Remote digital collaboration can be useful, but also poses challenges compared to co-located collaboration. This section highlights some of these challenges as well as positive characteristics of remote collaborations. It also notes several successful cross-disciplinary collaborations using VR in fields such as medicine, archaeology, and scientific visualization.

2.6.1 Remote Collaboration

When creating design teams, Bürdek (2005) notes that contemporary design firms need a more extensive scope and depth of expertise to be competitive. This includes the need to work in distributed and decentralized environments in addition to employing co-design solutions. Wang (2007) notes that this collaborative design approach is primarily focused on creating “what-if” scenarios that have to be jointly imagined. Many existing CAD tools “are designed so that they limit access for people who don't have a certain level of vocabulary or a particular education,” but some people who are good at imagining objects, spaces and forms can usually create manipulate and scale clearly using their imagination (Dawood 2017 p. 1). Finding a tool to access these abilities could be especially important for collaboration with end users or communities, as well as disciplinary stakeholders that are not designers.

Featherstone (1996) expresses that virtual and real communities seem to mirror each other in “chiasmic juxtaposition”. Just as virtual communities can have attributes of real communities, real communities can depend on the imaginary. Featherstone (1996) argues that what makes a community vital to its members is the treatment of the communications as meaningful and important. The medium for this communication and stakeholders’ perception of it is therefore important to consider when creating harmonious collaborative teams that can become microcosmic communities.

Al-Kodmany (2002) notes that VR offers a way for individuals from diverse backgrounds to communicate through a visual language that mimics the way people interact with the environment in the real world. Al-Kodmany (2002) argues that VR technologies can enable the temporal and sensory experience of place to become non-place specific, and that these techniques can elicit a very high level of audience engagement.

Though ostensibly valuable, collaborative brainstorming in virtual reality or across desktop computers has clear differences and limitations compared face to face interaction. The immateriality of labour in this space also makes it difficult to assess. Importantly, Hughes and Stapleton (2005 p. 1) note that “subtle human to human interaction is severely limited in these totally virtual environments, [providing] poor support for the physical expression of passion and personality,” this can include eye contact and gestures which are a very important part of non-verbal communication. In education scenarios, features such as voice chat and performing gestures such as pointing are essential to the remote communication process (Koutsabasis 2012).

Traditional tools may create a social learning environment that enables participants to talk about a project together, to interact and propose ideas. If used alone, “computerized tools may lack the

ability to draw people into meaningful interaction with the data and each other” (Al-Kodmany 2002 p. 190).

Successful collaborations can often be observed to show some characteristics of flow. American-Hungarian psychologist Csikszentmihalyi (as cited in Tan et al 2015) defines flow as being in a “positive mental state of total autotelic engagement when performing optimally challenging tasks towards a series of goals,” (Tan et al 2015 p. 254). In computer games, this can even be achieved even with unnatural input devices or with unrealistic graphics. It is a phenomenon typically experienced when one is working alone (painting, music, computer coding), or in highly effective collaborative situations such as jazz ensembles or sports teams. Flow is often hard to achieve in design collaboration, and might be even more challenging when collaboration is remote.

Interestingly, Sutton and Hargadon (1996) indicate that some people are more efficient at coming up with ideas when they are alone rather than in a face to face brainstorming session, likely due at least in part to reduced self-consciousness. Several studies indicate that there might be a need to analyze public versus private places in the remote collaboration process. In other words, participants might need time to test and develop their own strategies before embarking on group brainstorming and presenting their ideas. In these cases, reduced self consciousness and higher sense of control (ability to edit ideas before they are shown) offered by some digitally mediated systems might lead to increased creative flow (Koutsabasis 2012, Sutton and Hargadon 1996). Though remote collaborative ideation can be difficult, there might be some unexpected benefits to digital mediation in certain cases.

2.6.2 Co-design in Virtual Reality

Though many researchers and practitioners recognize the value that cross-disciplinary approaches and co-design can provide, actually applying this can be challenging and thus often avoided (Newman 2014). There are also many cases where uni-disciplinary methods are sufficient if not superior. Krakauer (as cited in Newman 2014) however, argues that to produce something new “you need to bring people together who don't normally stand cheek by jowl,” (Newman 2014). The following are some examples of interesting projects and solutions produced from unusual collaborations using virtual reality.

Archaeology and Cultural Preservation: In cultural preservation, virtual reality environments can provide a means of simulating how the placement of natural and artificial light sources might affect a person’s perception of an interior space. This could include considering dimensions, or even how light or shadow could be used strategically to draw attention to or hide certain areas/spaces in a dwelling (Levy, Dawson & Arnold 2004). Levy Dawson and Arnold (2004 p. 27) note that this line of research may provide new insights into “how humans use the built environment to manipulate social relationships through sensory perception.” Discussions with Indigenous elders while reverse engineering and reconstructing an ancient Thule Whalebone house suggest that the sense of ‘presence’ generated by 3D viewing enhanced their feelings of connectedness to their past. This suggests that virtual reality and 3D technology might be useful in establishing new discourses in archaeological interpretation, as well as assisting in the exploration, construction, and maintenance of cultural identities through knowledge repatriation (Dawson 2011).

Medicine: Hong et al (2017) describe the use of collaborative VR spaces that allow scoliosis patients to be actively involved in the creation of their brace, thereby increasing personalization in

the design process. Using VR is an opportunity to merge the technical design space and the perceptual design space, involving input from physicians, garment designers and patients (Hong et al 2017).

John Krakauer (as cited in Newman 2014) developed a multidisciplinary team to develop a new way of maximizing stroke patients' recovery time within the timeframe of 3 months. This was done by having stroke patients play a virtual reality game where the organic movements of a dolphin would be reflected by the slightest movements of the patient's arm in a sling. An eclectic and unexpected multidisciplinary team consisting of an artist/ animator, a computer scientist, an engineer and a neuroscientist came together to develop this project.

Scientific Visualization: Keefe et al (2005) describe a scenario where artists, scientists and computer programmers collaborated to create scientific visualizations such as arterial blood flow, or of the fluid dynamics and wing shape deformations that allow bats to fly. They noticed that artists could fill an important role in the visualization design pipeline due to their unique source of visual insight and iterative approach when tackling complex visual problems. They found, however, that with the tools at the time, artists had a hard time experimenting or creating visualizations or design ideas in VR without a background in computer programming (Keefe et al 2005). This further displays the need for effective communication and collaboration between the team members of different disciplines, as well as the development of the right specific tools for each design case.

2.7 Human-Computer Interaction Considerations

The following section explains immersion in the context of VR and how these kinds of systems could be useful. Other areas noted are the current hardware and interaction methods available, as well as challenges posed by virtual space in terms of rethinking spatial experience since perception and understanding can affect activity.

2.7.1 Immersion and Presence

Immersion in 3D user interfaces refers to the objective level of fidelity of the sensory stimuli (in relation to physical reality) that are produced by the display and interaction systems (Bowman & McMahan 2007). In other words, the more a system provides realistic visual, tactile, audio, vestibular, olfactory or other sensory cues, the more immersive it is. For example, a high resolution 3D desktop display is less immersive than a high resolution head-mounted display because in the second case, the user is experiencing a more realistic simulation of the space as less information from the real world is involved in the experience. Contrastingly, presence refers to a person's subjective feeling of "being there" in a virtual environment. Certain scenarios benefit from people feeling high presence in the environment – such as treatment of phobias, where treatment would not work if the person did not at least somewhat feel present in the scary virtual experience (Bowman & McMahan 2007).

Throughout the collaborative design process, VR users have reported feeling as if they are in the world as opposed to observing it from the outside like they would with a desktop CAD (Koutsabasis 2012). Some would argue though, that applications such as design or scientific and engineering visualization do not necessarily require the feeling of "being there" or *presence*, they could still, however, benefit from a high *immersion* system. Bowman and McMahan (2007) predict

that more immersive systems would result in improved task efficiency, higher levels of accuracy, and greater overall understanding of data. A higher level of immersion can also lead to greater spatial understanding – this is particularly beneficial for applications such as scientific visualization, design review, and virtual prototyping (Bowman & McMahan 2007). Gruchalla (2004) quantitatively shows that editing oil well-paths in an immersive virtual environment can be completed significantly faster and more accurately than using a desktop display for the same task. A higher level of spatial understanding was also shown in Schuchardt and Bowman's 2007 study about cave visualization, showing that high immersion is typically beneficial for applications that require the visualization of complex irregular 3D data sets such as geological, biological and weather systems (Schuchardt & Bowman 2007). Additionally, immersive environments are typically characterized by less information clutter, as opposed to a large amount of graphic information such as icons on a computer screen (Schuchardt & Bowman 2007).

2.7.2 Interaction Methods

Santos et al (2009) explain that while research has been done on developing highly immersive systems from a technical standpoint, not enough system evaluation has been done with end-users in mind. Though immersive systems have many benefits, they also have limitations. The most immersive systems (head-mounted displays) are often expensive, bulky and have usability issues. These prohibitive costs could potentially be avoided by emerging VR applications such as lower cost desktop systems, table based systems and non-stereoscopic viewing approaches (Santos et al 2009). Some of these options might, however, eliminate some of the benefits of immersion (Koutsabasis 2012).

Lower immersion systems that might have potential for design ideation include systems where users can manipulate objects on a screen while viewing them in stereo, or manipulating/making objects through gestures, touch input, or another input like mouse/keyboard while having those actions reflected on the screen (in 3D), as well as these same approaches with a single viewpoint image (monoscopic). There are also different approaches to a virtual environment that surrounds the user – for example in CAVE systems the images are projected around the user. This approach has been useful for scientific visualization and some argue that this system is better for embodiment because the person does not have bulky equipment and their kinetic actions are the same as they would be in real life so it feels very natural (Keefe et al 2008, Tcha-Tokey 2017). There is also augmented or mixed reality which can produce images over top of reality.

In some cases, separating degrees of freedom, or having the option to switch back and forth depending on the task could make manipulation tasks easier (Mendes et al 2016). In this vein, some authors, advocate for a plane-based approach for design sketching in VR (using some kind of physical or virtual restriction to provide a plane to draw on) because it can add precision and simulate drawing on a drafting board, others say that this might limit creativity (Machuca et al 2018). Some authors argue that for design sketching tasks however, maintaining freedom might be important so as to maintain rather than restrict creativity during the design process (Seichter 2007). Since preserving a rough, sketchy aesthetic (by having even small movements mapped) would create messy, open and unrefined lines – mistakes here can lead to unexpected discoveries and insights, similar to physical sketching (Israel et al 2009). The best approaches for digital & virtual sketching and the role of plane-based assistance needs to be further researched.

Additionally, some new devices that are being developed use a pen-like device which seems more intuitive and similar to hand-drawing tools employed by artists and designers than the regular

controllers that come with popular headsets (Pham and Steurzlinger 2019). These prototypes, however, are not yet widely available on the market.

2.7.3 Virtual Time, Perception and Activity

Wood (1998 as cited in Smith 2009 p. 97) notes that the Western idea of time can be thought of in two categories: “Newton's vision of an 'absolute, true, and mathematical time' which exists independently of human presence, and St. Augustine's vision of 'lived-time,' which recognizes the importance of the phenomenal realm and puts human subjective experience at the heart of temporality”. Further phenomenological views of time include the Aboriginal Australian view of time where it can be seen as circular rather than linear – for example events are placed in time (closer or farther) according to their importance for the individual or community (Janca & Bullen 2003). In the difficult space where reality and virtuality coexist, some authors suggest a new understanding of virtuality - one where “reality and virtuality are combined through the synchronicity of shared experience to create a new reality, something unlike the material world we live in” (Smith 2009 p. 106). This virtual shared experience creates a place where people can view the world from multiple perspectives simultaneously – a space where "synchronization replaces spatial unity" (Smith 2009 p. 99). Smith notes that virtual space has the potential to be real, though it may not always be so. In other words, cyberspace can be a way to create a time in which we perceive ourselves to be in a space.

Some psychologists have begun to examine motor control through recognizing that acting and knowing are dependent on each other and intertwined (Rosenbaum 2005). What one perceives affects the way one acts and vice versa because perception and conceptual understanding are in a sense the same capacity (Rosenbaum 2005, Brew & Kantrowitz 2013). Else (2018) highlights how

easily our perception and understanding can be challenged in the medium of virtual reality. Else (2018 p. 48) argues that “the activity of a person interacting with the virtual space cannot be considered separately to an understanding of the space itself.” This is particularly relevant to an understanding of our body within this environment, and how VR can destabilize the understanding of our ‘self’ in space. Chittendren (2018 p. 381) emphasizes that VR can bring “visible changes to the temporal-spatial structures used to represent information and contribute towards a rethinking of the vocabularies of spatiality and spatial experience”. It calls not only on different practices of making but also of viewing and reading (Chittendren 2018). As shown in Rahiminan et al’s 2011 study, interface type can have an effect on the type of conversations that occur within a design scenario (e.g. clarifications versus novel ideas). Slater (2009) notes that virtual reality has often been seen only as a means of simulating existing experience, and rarely as a medium in its own right that can create new forms of experience – this is something that can be further questioned and explored (Brooks Jr 1999 as cited in Slater 2009).

2.8 Literature Review Insights

The following summarizes some of the key points found during the literature review process that helped to build, influence and alter the research question and methodological approach.

Due to certain characteristics of the contemporary era of design such as a faster dynamic of interconnectivity, there are different challenges and demands in design than there were in the last century, requiring multiple areas of expertise. The literature highlighted the importance of co-design and why multidisciplinary collaboration could be necessary. Additionally, the review process highlighted that *how* ideas are brought into action is important. This encompasses social as well as material interaction, since externalizing ideas is valuable for developing ideas at both an individual

and group level. Visual inventories, however, vary between individuals, cultures, and disciplines. For example, though engineers and artists both tend to score high in spatial visualization skills, engineers tend to score higher on extrinsic visualization (relations between objects, navigation) and artists are more likely to excel in object based or intrinsic spatial visualization (mental rotation) (Newcombe and Shipley 2015). These differences, as well as differences in reasoning and communication strategies can make design ideation challenging.

Throughout this review, the researcher looked at several systems for remote collaboration. Human computer interaction was considered with the goal of picking an appropriate remote design collaboration medium for testing. This started by exploring 3D sketch-based and sculpting/object-based interaction over a desktop, these same paradigms in VR, as well as using different levels of immersion. Review was also done on previous methods of digital collaboration and design tools and specific strengths of each approach. For example, CAD modeling and sketching both have unique strong points in the design process. Ultimately, a fully immersive VR system was chosen to be compared to a drawing tablet (similar to traditional drawing) and a paper and upload method to maintain the widely used traditional sketching approach. Fully immersive VR was chosen as the literature review determined that this had the most promising implications for spatial awareness, embodiment, novel ideas and real-time 3D collaboration.

Another important insight found throughout this review is that more research needs to be done on the design process and human factors of using virtual reality for sketching. Because VR can blur the line between representation and telepresentation it poses a unique challenge to our perception and understanding. This is important because the characteristics of the tool can change the activity itself (Koutsabasis 2012).

Figure 2-1. Literature Review Map

3. METHODS

3.1 Approach

The research for this study was done using a mixed methods approach that included literature review throughout the whole process, observation, surveys, open-ended questions, and focus groups. The study phase of primary research was based on creating mock design ideation sessions to simulate a multidisciplinary collaborative design challenge. To analyze what took place during the tests, subjective feedback was collected from the participants, and the design challenges were observed to extract a qualitative and quantitative evaluation of the performances in each condition. Focus groups got richer subjective feedback on the systems used. The study compared freeform sketching in virtual reality to analog paper drawing, and tablet drawing for remote communication (each condition also allowed for audio communication between team members). A visual representation of the methods and procedure can be seen in figure 3-4.

3.1.2 COVID-19 and Remote Testing

The COVID-19 pandemic caused the testing to be undertaken later, and in a different way than originally expected. Originally, the study was meant to have 24 participants – 8 from each discipline. Unfortunately, this needed to be cut in half to 12 due to timing, distribution logistics, and participant readiness for remote testing. Though it made things more difficult from a logistics and consistency perspective, the main idea for this study was already remote communication. The situation was therefore not a hindrance, but merely realistic. It was a reminder of the necessity of remote communication in some cases, and the realities of some practical issues and challenges to be looked at for future research.

Originally the study was planned to be undertaken at the Carleton University campus where the researcher would be able to monitor participants and they would each have the same space to work with and equipment set up for them before the test. With testing during the pandemic, this was not the case. Equipment was delivered to participants via courier and a volunteer. Each participant was responsible for setup before the study – sometimes with contrasting physical parameters (space available) for each participant to use during the VR portion of the test. Focus groups and all other communication was done via Skype or telephone (for technical problems).

3.2 Participants

Twelve participants in total were recruited for this study via email and snowballing – four from each of the following disciplinary categories:

1. Engineering (including software engineering or computer science)
2. Industrial design
3. Visual art

To simulate a multidisciplinary co-design scenario, these specific areas of study/professions were chosen from the disciplines noted in section 2.4. Since sketching and visual thinking were specifically focused on in the design process for this study; each of these areas were picked since they likely have some experience in visualization. Ultimately, each area of expertise was chosen because the researcher aimed to bring different types of visualization backgrounds and perspectives to the design process, though the areas chosen are only samples and not fully representative of a realistic multidisciplinary design scenario. Engineering and computer science were considered part of the same category for the purposes of this study because they both traditionally use deductive reasoning in day to day tasks for their discipline (though not a rule) (Kara & Georgoulas 2012).

To be eligible, participants had to be 18+ and could be undergraduate students, graduate students, or professionals in one of the above-mentioned disciplines. Participants of either gender and handedness with either normal or corrected-to-normal vision were welcomed to participate. The study did not require the participants to have any experience in any CAD software or drawing, but it was expected that most people in these domains will have at least some experience working in this way. The participants were also not required to have any experience in VR or computer gaming. The varying level of experience with VR and CAD was considered representative of a co-design situation with diverse stakeholders.

3.3 Study Design

This study used a within-subjects design where all participants experienced all conditions. The independent variable was the medium for collaboration. This had 3 levels – physical drawing on paper (uploaded to Conceptboard throughout the test), tablet drawing (directly onto Conceptboard), and VR drawing (drawing within the VR space). A control variable was audio – they were able to communicate using audio in the same way across each condition. An attribute variable was area of study/profession of the participants. The dependent variables that were examined include collaboration process, effect of the difference in skill background, as well as creativity and visualization capabilities within each medium. These variables were a starting point and led to other insights as the study evolved.

Each person completed two full tests - each with a partner from a different discipline. The test was comprised of three 10 minute segments – each with a different design medium and slightly varying design challenge. The challenge was to create a greenhouse for an arctic or cold climate with a harvesting path and some form of lighting. The variations included a soil-based, hydroponic and

aquaculture based greenhouse. Though slightly varied, the researcher expected that difference between these challenges is unlikely to have a large influence on design process. These design challenges as well as the medium (VR/tablet/paper) were counterbalanced. For the sake of consistency and to limit the amount of variables, erasing and changing brush size or colour was not allowed in any of the conditions. Video was also not included since sketching was the main activity being analyzed. Freeform sketching in VR was chosen to maintain the loose, sketchy aesthetic that is known to reinforce creative fluidity (*McVeigh-Schultz et al 2018*).

3.4 Apparatus

The following is a list of items used for the study. There were two sets of equipment that were delivered in boxes to participants on the day of their testing.

Hardware:

- Oculus Rift CV1 headset, sensors, and controllers
- VR-ready laptop with the following specifications: Intel Core i7-7700HQ CPU, an NVIDIA GeForce GTX 1070 GPU, and 16GB RAM
- Drawing tablet - XP-Pen G430S
- Smartphone (supplied by participants)

Other Items:

- Paper for analog drawing condition.
- Each participant also used a desk or table and had a clear space in their room to walk around for VR condition.

Software:

- Multiplayer VR drawing application

- Conceptboard
- Skype

Figure 3-1. Multiplayer Drawing Application

Figure 3-2. Conceptboard

VR Drawing Application Design

The researcher looked at several current drawing applications available for the Oculus Rift. Most of these either did not have the option for multiplayer, used prismatic shapes such as cubes to create scenes, or included too many additional items in the scene such as detailed avatars and animals or backgrounds. Since only sketching was needed for this study, the

application used for the freeform VR drawing condition was created from a template from Normal VR using the Normcore multiplayer plugin (figure 3-1). The app was made using Unity and was kept virtually the same as the template aside from removing several items such as blocks that were in the scene. This particular app design was chosen because it is a very basic version of a drawing app with a gridded floor and empty space. For this particular study, the process of sketching for collaboration was focused on, so having additional items, or capabilities such as adding cubes or other shapes in the space were not needed. The freeform sketching approach was to be analyzed to see greater differences in sketching and visual vocabularies and collaboration between disciplines (there is more room for translations and style). This drawing app also included very basic avatars that included a black sphere for a head and black egg shapes for hands.

Conceptboard

This online site provided the capability for real-time drawing, zooming in and out, erasing, creating shapes, and uploading photos all on a lightly gridded background similar to the drawing application (figure 3-2). For this particular study, only the pen tool was used for the tablet condition, and only uploading photos were used for the analog drawing condition. There was also a symbol that indicated where each person's mouse was that changed in real-time when the person moved it.

Scenario 1: Virtual Reality Freeform Drawing

Hardware: Oculus Rift CV1, laptop

Software: Multiplayer drawing app

Scenario 2: Tablet Drawing

Hardware: XP-Pen G430S Drawing tablet with pen stylus, laptop

Software: Conceptboard

Scenario 3: Paper Drawing and Upload

Hardware: Smartphone (for camera), laptop

Software: Conceptboard

Other Items: Paper and sharpies

Before equipment was distributed for testing, a pilot test was done to find out some of the issues that participants could face during set up or during the collaboration process (figure 3-3). The researcher noted these to help solve any technical issues that might occur during testing. It also gave guidelines of how many prompts to give during the collaboration process, what worked well, and what caused participants to get frustrated. Though every participant is different, this gave a base to help design the final test.

Figure 3-3. Researcher Testing VR Application Before Pilot Test, Pilot Test Set Up

3.5 Procedure

Testing took place over the span of two weeks, from July 6th to 17th with focus groups the following week of July 20th. The following describes the procedure for the study after recruitment emails were sent.

Phase 1: Scheduling

1. Participants contacted the researcher to schedule a day/time to participate in the testing.

From this, the collaborative pairings were scheduled, and the times for drop-off/pick up of equipment were scheduled.

2. Before testing began, the researcher sent out an email that instructed each participant to complete the pre-test survey/consent forms¹. This email also included links to the surveys to be completed during the study, as well as tips on set up and contact information in case of technical issues.

Phase 2: Testing

3. At the beginning of each test, the researcher met on Skype with the two people who would be collaborating and gave a brief background on the study, the conditions, and the structure of the test. The beginning of the test was also used to sort out any technical issues with either of the media to be used (technical issues, however, sometimes happened at random times during the study).
4. The researcher set up screen and audio recording which ran for the duration of each test. This was later used for observational analysis.
5. The researcher explained the design challenge to be completed, and the medium to be used for the first 10 minute segment of the test. The participants then began the first segment while the researcher observed. This was repeated for the second and third test.

6. The researcher instructed participants to complete the appropriate survey after each test. Survey 1 would be completed after each person did their first test and Survey 2 after they had completed both tests¹.

Phase 3: Focus Groups

7. After testing was completed, the researcher hosted several focus groups that were each around 30 minutes long for further feedback (two participants who could not fit this into their schedule were interviewed for around 15 minutes each separately). All sessions were audio recorded.
8. Participants were thanked for their time and notified that they might be contacted again for clarification on responses. After completing Survey 2, each participant was sent a gift card of their choice.

3.6 Data Collection Methods

Pre-Test Survey: Before the tests took place, the multiple choice pre-test survey recorded responses to questions on area of study/profession, gaming and computer experience, CAD and drawing experience, VR experience, and collaboration experience (see Appendix C). The data was later analyzed using codification, and was used as a way to see trends in how people with different backgrounds reacted to the study.

Post-Test Survey: Two post-test surveys were completed by each participant (Survey 1 after the first test, Survey 2 after the end of both tests) (see Appendix D&E). These surveys collected responses using a 5 point Likert scale system (1= strongly disagree and 5=strongly agree). The second test also included two open-ended questions; how participants would describe each system

¹ All surveys were completed via Qualtrics, gift cards were sent out through Tango via Qualtrics.

and anything that surprised them or that they struggled with through the design process. These open-ended questions were later coded visually along with the qualitative feedback from the focus groups and observations. The method of visual coding for user response analysis involved sorting responses using size, colour, and location to find insights and trends (Kumar 2012). The first part of the post-test survey evaluated collaboration, self-consciousness, and usefulness of visualization skills with each system, as well as the effect of the system on the understanding of their partner's ideas. This part was completed twice – once in Survey 1, and once in Survey 2. The second part evaluated the effect of the conditions on individual ideation processes such as expressiveness, intuitiveness, potential for flow, control over lines and spatial reasoning approach. Codification and statistical analysis was used to analyze the results of these surveys.

Observation: By observing the design scenarios through screen and audio recording, the researcher noted quantitative metrics that included the amount of new objects in the design in each condition, and the amount of iterations in each condition. These metrics were also compared across disciplinary pairings. Through qualitative analysis of the observed data, the researcher also noted the kind of interactions, style differences, and specific actions using each method. These observations were coded by representing the data visually to find patterns or themes in design approaches.

Focus Groups: Informally structured focus groups talked about any observations participants had about the collaboration process, visualization or other notes about the media that they used. They were also asked about ideas for a future system and what they would like to/would not like to see for a remote design collaboration tool. To analyze this qualitative feedback, the data was sorted visually to note themes and connections.

Figure 3-4. Methods Map

4. RESULTS

4.1 Pretest Survey

The pretest survey gathered data about the participants including basic background information as well as experience using certain digital media and previous collaboration experience. The participants were in the age range of 21-41 with 2/12 participants being undergraduate students, 5/12 being graduate students, and 5/12 being professionals. There were four people that represented each area of study/profession. Figure 4-1 shows the distribution of responses, and figure 4-2 shows some trends noticed. A trend was noted in questions where at least 3/4 people had the same answer. These were compared to later results.

Unsurprisingly, most participants (75%) had never used virtual reality before. Five participants (41.7%) use a computer more than eight hours per day, two (16.7%) use a computer for 7-8 hours per day, four (33.3%) use it for 4-5 hours per day, and one (8.3%) uses a computer for 1-3 hours per day. Two participants (16.7%) play computer games daily, three (25%) play several times per month, three (25%) play once per month, and four said that they never play. Two participants (16.7%) noted that they use computer aided design software (CAD) daily, five participants (41.7%) use it several times per month, two (16.7%) use it once per month, and three never use it.

The participants were also asked to self-assess their analog and digital drawing skill. Analog drawing referred to using traditional media such as pen and paper to draw and digital drawing skills referred to using digital media such as a pen and tablet to draw. Two participants (16.7%) considered their analog drawing skill level to be high, six (50%) considered it moderate-high, three (25%) considered it to be low-moderate, and one (8.3%) considered it to be low. In terms of digital drawing experience, one participant (8.3%) considered their skill to be high, four (33.3%)

considered it to be moderate to high, three (25%) considered it to be low-moderate, and four (33.3%) considered it to be low. Also, eight people (66.7%) never participate in drawing collaboration, but three participants (25%) do this or once per month and one (8.3%) does this several times per month. Only one participant (8.3%) participates in remote collaboration daily, four (33.3%) participate in remote collaboration several times per month, three (25%) do so once per month, and four (33.3%) never participate in remote collaboration.

Figure 4-1. Pretest Survey Results

TRENDS

<i>ENGINEERING/COMPUTER SCIENCE</i>	<i>VISUAL ART</i>	<i>INDUSTRIAL DESIGN</i>
↓ Drawing Collaboration Experience ↓ VR Use	↑ Drawing Collaboration Experience ↓ VR Use ↓ Computer Games	↑ Analog Drawing Skill ↑ Digital Drawing Skill ↑ CAD Experience ↓ VR Use ↓ Drawing Collaboration Experience

Figure 4-2. Trends in Pretest Survey Results

4.2 Post-Test Surveys²

The first part of the post test surveys assessed the participants' experience in the collaboration process and consisted of 4 questions. This part of the survey was completed twice by each participant (once in Survey 1 and once in Survey 1). Twenty four responses per condition (VR, tablet, paper) were therefore recorded for each question. Each question was answered on a Likert scale (1=strongly disagree, 5=strongly agree). A graphical representation of responses can be seen in figure 4-3 and 4-4.

The second part of the post-test surveys consisted of six questions about the participants' perception of the individual visualization and ideation process. Each person answered this portion of the survey once, and there were therefore 12 responses per question per medium. A graphical representation of the responses for this part of the surveys can be seen in figure 4-5 and 4-6.

² For the results section, engineers and computer scientists will usually be referred to as engineers for the sake of simplicity and since they were in the same disciplinary grouping for this study.

4.2.1 Collaboration

The first question of this section (Q1) aimed to uncover which media allowed participants to work together on ideas or whether they thought about design ideas individually throughout the process. 19 of responses (79%) indicate that in VR, they did not agree that they worked on design objects individually. In other words, most people felt like they worked together to modify design ideas in VR. In the tablet condition, 10 responses (41.7%) disagreed that they worked on design objects individually more than modifying each others' designs, and in the paper condition, 17 responses (70.8%) indicate that they *agreed* that they worked on design objects individually more than modifying each other's designs. These responses indicate that overall more people thought that they worked on design objects together in the VR medium and that they felt like there was less modifying of each other's ideas in the paper condition, with the tablet condition sitting somewhere in the middle. The indications of these results support the hypothesis that the VR condition could improve the collaborative synergy during the design process.

Q2 asked whether or not participants found their visualization skills useful in the collaboration. 18 responses (75%) indicate that participants' found their visualization skills to be useful in VR, whereas 23 responses (95.8%) indicate that their visualization skills were useful in the tablet condition, and 20 responses (83.3%) indicate this for the paper condition. The tablet condition was superior here as almost all participants found their visualization skills to be useful in this condition, though the other two media were not drastically far behind. Notably, more visual artists disagreed with their visualization skills being useful in the VR condition ($3.1\bar{x}$) compared to paper - where they all agreed. Industrial designers also scored VR lowest of the three on this question with $\bar{x}$ 3.4. Contrastingly, some engineers/computer scientists disagreed with their visualization skills being

useful in the paper condition (that was scored at $\bar{x}$ 3.6), but all thought they were useful in the tablet and VR conditions.

Q3 asked about participants' self consciousness with the system. The differences here were not substantial between media. In the VR condition, 12 responses (50%) indicate that they did not feel self conscious about their drawing skills. Fourteen responses (58.3%) indicate that they did not feel self conscious in the paper condition. In the tablet condition, eight responses (33.3%) indicate that they did not feel self conscious and 12 (50%) of responses indicate that they did. Most of the people who felt self conscious in the tablet condition were engineers (seven responses or 87.5% of the total for that discipline), whereas most people who did not feel self-conscious in the paper condition were artists (seven responses or 87.5%). The responses for the VR condition were fairly evenly distributed across disciplines.

Q4 asked participants to either agree or disagree on whether or not the design medium helped rather than hindered their understanding of their partner's ideas. Eighteen responses (75%) agreed with this statement for the VR system, 21 responses (87.5%) agreed with this statement for the tablet system, and eight responses (33.3%) agreed for the paper system. No one disagreed with this statement for the tablet condition, the two responses that disagreed for the VR condition were artists, and the paper condition had a mix of responses from each discipline. VR was expected to help the most in understanding of ideas, however the tablet system was again superior here, though it was followed closely by the VR condition, whereas the paper drawing and upload condition scored much lower.

COLLABORATION SURVEY TOTAL RESULTS

Figure 4-3. Collaboration Survey Total Results

DISCIPLINARY DISTRIBUTION

Legend:

- Engineering/Computer Science (Average Score)
- Industrial Design (Average Score)
- Visual Art (Average Score)

Figure 4-4. Collaboration Survey Disciplinary Distribution

4.2.2 Individual Visualization

Question one, four, and five of the individual visualization section (see figure 4-5,6) asked the participants to agree or disagree with questions relating to creative expression such as expressiveness, intuitiveness of visualizing ideas with the system, and losing track of time [a characteristic of flow (Tan et al 2015)]. Q1 asked whether it was easy to be expressive with each system. Eight people (66.7%) agreed that it was easy to be expressive in the VR system, with most strongly agreeing. Seven people (58.3%) agreed that it was easy to be expressive with the tablet system, and nine people (75%) agreed for the paper system. The participants who disagreed with the expressiveness of the VR system were artists, the people who disagreed with the expressiveness of the tablet were engineers and artists, and the artists all agreed that the paper condition was expressive. Q4 asked the participants to agree or disagree about whether visualizing their ideas with the medium was intuitive. Eleven participants (91.6%) agreed that it was easy to visualize ideas in the VR medium, seven (58.3%) agreed for the tablet approach, and nine (75%) agreed for the paper approach. All engineers agreed that the VR medium was intuitive, whereas most (three out of four) disagreed about the tablet. Artists all agreed that the paper condition was intuitive and all but one agreed for VR. The industrial designers all thought the tablet and VR were intuitive for visualizing ideas and one person disagreed about the paper approach. Q5 asked participants to agree or disagree about whether they lost track of time using each system because they were so immersed in the task at hand. Ten participants (83.3%) agreed for the VR system, four (33.3%) agreed for the tablet condition, and one (8.3%) agreed for the paper condition. All industrial designers said that they strongly agreed that they lost track of time while using the VR medium, and all disagreed for the paper approach. All engineers agreed that they lost track of time in the VR approach and most (three out of four) artists disagreed that they lost track of time using the tablet.

Two Friedman tests were done to compare the differences in conditions across Q1, Q4, and Q5 which related to creative expression. To perform the test, the values for each of these questions were combined (according to participant and condition). The first Friedman test compared the total scores for all participants, and the differences were not statistically significant ($FM=2.33 < 6.54$ critical value at significance level $\alpha \leq 0.05$). By looking at the scores across disciplines, as noted previously when analyzing disciplinary distributions, the researcher noticed that the artists generally scored the VR condition lower than other media in these questions on creative expression. Based on this observation, a second Friedman test was conducted that included only the scores between the industrial designers and engineers. This second Friedman test did find a statistically significant difference ($FM=9.66 > 7.14$ critical value at significance level $\alpha \leq 0.05$). Further post-hoc analysis using a Fisher test using data from only the engineers and designers determined that the differences between all conditions were significant with the difference between the VR and paper condition to be the greatest in difference [$\bar{y}_a - \bar{y}_b = 0.93$, $\bar{y}_a - \bar{y}_c = 1.64$, where all > 0.59 (least significant difference)]. A least significant difference test (Fisher test) was used due to the low sample size, and limits the power of this result; however it is an interesting significance to note when comparing with other data. This result is consistent with previous survey data and qualitative analysis, and the opposite of what was originally predicted. Artists were expected to pick up on the expressive capabilities of VR more than the other two disciplines; they however had the least enthusiastic support of the medium.

The VR and tablet approach were both expected to score low in the control of lines. Q2 showed that 11 participants (91.6%) agreed that they had good control of their lines in the paper condition, and nine participants (75%) did not have good control of their lines in the tablet condition.

Surprisingly though, only four participants (33.3%) thought they did not have good control of their lines in the VR condition while six participants (50%) agreed that they did have good control over their lines while drawing in VR.

Q3 focused on spatial relationships. Nine participants (75%) agreed that they focused on large-scale patterns or spatial relationships more than individual objects/forms in VR, seven participants (58.3%) agreed that they focused on this with the tablet approach, and six participants (50%) agreed for the paper condition. The tablet condition and VR condition were expected to be similarly conducive to thinking about large scale patterns or spatial relationships. The results somewhat align with this, but indicate that the VR condition has a slight advantage in holistic spatial reasoning.

Q6 asked about whether the participants found that the benefits of the system outweighed the negatives. Eight participants (66.7%) agreed that the benefits of the VR system outweighed the negatives, whereas five participants (41.6%) agreed about the tablet condition, and four participants (33.3%) agreed about the paper condition. Two people strongly disagreed about the benefits of the VR condition, four strongly disagreed about the paper condition, and two disagreed about the tablet condition. Three out of four artists did not think that the benefits of the VR system outweighed the negatives, and three out of four engineers did not think that the benefits of the tablet approach outweighed the negatives. The industrial designers scored the VR and tablet approach equally, and the artists scored the tablet approach slightly higher than the paper approach ($\bar{x}$ 3.25 compared to 2.75 respectively).

INDIVIDUAL SURVEY TOTAL RESULTS

Figure 4-5. Individual Visualization Survey Total Results

DISCIPLINARY DISTRIBUTION

Figure 4-6. Individual Visualization Survey Disciplinary Distribution

4.3 Observation

Qualitative and qualitative data were obtained from observing video and audio-recordings of the collaboration sessions. To extract quantitative data from the video recordings, the researcher tallied the amount of design ideas as well as iterations made while using each medium. During this observation, the researcher considered a novel design element any new object or idea that was sketched, whereas an iteration was considered a modification or redraw of any of the existing

design elements. Qualitative observations included the kinds of interactions during the collaboration sessions as well as trends noticed in strategy or actions as well as notable statements by participants or struggles they had during the ideation sessions.

4.3.1 Quantitative

While using the tablet medium, the average amount of new design elements was 10.8 per session (130 total for all tablet tests). The average amount of new design elements in the VR medium was 10.1 new elements per session (121 total elements for all VR tests), and 7.5 in the paper condition (90 new elements total). Though this aligns with the hypothesis that more ideas would be created in the tablet system, the VR approach is not far behind, whereas the paper condition has much fewer ideas than expected, but this may have been influenced by the slow upload speed to the app. The amount of design elements created was also compared across disciplinary pairings. The artists and engineers came up with slightly less novel design ideas during the collaboration than the designers and artists or the engineers and designers. Both of the latter collaborations had a similar amount of design ideas at an average of 29.25 (117 total) and 29.5 (119 total) respectively whereas the engineers and artists had 26.5 (106 total).

AVERAGE NUMBER OF DESIGN ELEMENTS/
DISCIPLINARY PAIRING

Figure 4-7. Average Number of Design Elements/Disciplinary Pairing

AVERAGE NUMBER OF DESIGN ELEMENTS/
MEDIUM

Figure 4-8. Average Number of Design Elements/Medium

Each collaborative pairing was almost exactly equal in the amount of modifications or redraws of certain design elements [23, 22 (artists and designers), 23]. There was a difference, however, across media. In VR there were notably less iterations than the other two methods (13 compared to 27 for paper and 26 for the tablet approach). This result was also expected since the design process has been noted to be different in paper and VR shown in a study by Lee et al (2018).

ITERATIONS/MEDIUM

Figure 4-9. Iterations/Medium

4.3.2 Qualitative

In the VR condition, hand gestures and full body movements were used to explain or show a certain area of the design. For example, participant 7 (artist) crouched down to enter the door of the greenhouse they created (figure 4-10). In addition to this, several participants waved to each other in VR and virtually hugged. There were also cases where participants placed themselves in the shoes of someone who would be using the space. For example, participant 8 (designer) wondered if a ladder would be needed to reach the top shelves or if it would be accessible while standing.

Figure 4-10. Gesture Communication (Crouching through doorway, Collaboration Between participant 7 and 9 – Artist and Computer Scientist)

The first collaboration had some technical difficulties such as varying heights in VR. The engineer also spent time talking about practical considerations such as the filtration system whereas the artist was less vocal. During this artist's collaboration with a designer, however, they talked about the role

of the greenhouse in a community setting as well as expanding the boundaries conceptually (such as adding jet packs). The engineer and designer of this triad decided to put the greenhouse on skis or a continuous track so it was mobile. Though there was noticeably less talk in the paper approach, the engineer and designer came up with contrasting ideas from which they then continued to iterate. Interestingly, participant 10 and 11 (engineer and artist) focused on community and actions within the greenhouse as well as practicalities and how these related to structure. For example, since the greenhouse was meant to be a public space, they added a decorative feature in the tank, a place that is not public access for storage and caretakers, as well as an entrance area to keep the cold out, and a bench.

Several participants (of all three disciplines) began the process by sketching the shipping container shape first to create a boundary, using the grid on the ground for guidance. Developing a strategy like this for the drawing beforehand was important for some participants, and they saw the process as less about brainstorming or ideation and more about the output or illustrating what they already know. For example, participant 9 (computer scientist) developed a drawing strategy for his first collaboration and carried this through with much similarity in the second one (across all media). Participant 7 and 8 (artist and designer) adopted a similar strategic approach. In some cases, a strategy developed for other reasons. For example, participant 4 noticed that the first time they had drawn too big and they did not have the room to finish their drawing, so for the second time, they suggested drawing a smaller scale model of the greenhouse in VR. Another action/strategy that was consistent across most collaborations was the intention to label specific parts of the design (figure 4-11). Aside from labeling items, this also included notations such as dashed lines, and arrows in the VR, tablet, and paper approach. Interestingly, there were some moments that were more

spontaneous than strategic, such as noticing details in size and shape of the drawings that influenced participants to add items or expand sections.

Figure 4-11. Labeling Parts of the Design (Collaboration Between Participant 7 and 9 - Artist and Computer Scientist)

Participant 10 (engineer) and 12 (designer) used the paper condition closest to how the researcher intended, as they uploaded pictures frequently throughout the collaboration process to show the other participant what they were thinking (figure 4-12). From here they modified their designs and created new iterations. Other groups such as participant 7 (artist) and 9 (computer scientist) did not use this approach as intended, and only uploaded a couple of photos of designs they worked on individually through the process.

Figure 4-12. Sequential Collaboration via Paper Approach
(Collaboration between Participant 10 and 12 - Engineer and Designer)

Several participants were observed to be drawing shaky lines that were not level or well connected. Interestingly though, there were several participants (7 & 10) who created surprisingly straight and proportionate lines. As observed in the survey results, control of lines in the tablet approach was overall poor. The people who were most comfortable with this approach were people who had used tablets often in the past (in this study these were mostly industrial designers).

Figure 4-13. VR Collaboration (Participant 10 & 11 Engineer and Artist)

Figure 4-14. Tablet Collaboration (Participant 2 & 3 Engineer and Designer)

Figure 4-15. Paper Collaboration (Participant 4 & 5 Artist and Computer Scientist)

4.4 Open-Ended Questions & Focus Groups

The open-ended questions and focus groups obtained rich qualitative feedback about each system. This included positive and negative notes about each system, as well as ideas for future systems. Feedback included ideas on individual use of the systems as well as social interaction with digital media.

4.4.1 Open-Ended Survey Questions

Consistent with survey results, artists had the most negative things to say about the VR condition, and the most positive things to say about a paper/analog approach. Contrastingly, the engineers all expressed enthusiasm for the VR approach, whereas the industrial designers overall liked both the VR and tablet approach, with some emphasizing the practicality and ease of use of the tablet. Some technical notes on the VR system include that it was messy, disorienting, limiting, finicky, and occasionally jarring. Participant 1 (artist) noted that it was confusing and Participant 4 (artist)

noted that though the system was fun, it was hard for her to connect her lines and spending significant time doing this would be taxing. It was also hard for her to create in a vacuum-like space. Navigating the space, as well as physical boundaries were also challenges noted by participant 6 (designer).

Contrastingly, participant 10 (engineer) noted that it was easy to navigate the VR space since the dimensions are present, unlike the tablet or paper approach, noting that this was “easily [his] favourite approach”. Some engineers and designers also noted that it was less work since you could see angles naturally instead of having to represent them in 2D. Some other positive notes included the ability to use hand gestures and body movement to communicate, and that the approach was open and fluid. It was also noted to be fascinating, immersive, engaging, intuitive, easy to use, fun and novel. Participant 5 and 12 (computer science and designer) both noted that it was an amazing experience for collaboration. Participant 12 (designer) felt like he was in the same room as his partner working on the same object and participant 5 (computer science) felt that he could express and illustrate his ideas on a much larger and more interactive scale that he could not do before.

The tablet approach was noted to be difficult to use, clumsy, messy, and annoying. Participant 3 (designer) noted that the sketches were messier because there is a learning curve with drawing with a tablet. Participant 10 (engineer) noted that due to his unfamiliarity with the tool, it was decidedly difficult to express anything. Some positive notes were that there was synergy, it was practical, convenient, simple, straightforward, easy and fast. Participant 8 (designer) was enthusiastic about the tablet approach, noting that it was intuitive, communicative, real-time, fun and engaging. Participant 5 (computer science) noted that though it was useful for collaboration, it was nowhere near as enjoyable to use as VR. Participant 10 (engineer) thought that a different style of tablet

would work better where the image was presented directly on the screens, and participant 4 (artist) noted that it would be great to upload photos for materials, textures, or inspiration to the same board.

Most people noted that the paper approach was cumbersome, clunky, individualistic, isolated, slow, awkward, and less enjoyable to use. Participant 7 (artist) noted that there was limited iteration in this method (presumably meaning the system of having to upload). Participant 10 (engineer) also noted that though it was relatively easy to communicate with this method given his familiarity with the tools, though his 3D drawing skills are poor compared to orthographic projection (most drawings produced during the collaborations were in 3D perspective). Using paper, however, was widely noted to be easy, efficient, comfortable, familiar, reliable, traditional, and easy access, and participant 4 (artist) noted that this could be valuable in addition to the tablet approach.

Participants also made miscellaneous observations about the test in general. Participant 4 (artist) saw it as working towards an output (creating drawings) and that she was missing the tactile and human element. Participant 11 (artist) felt that some parts of the collaboration process were stilted and that they were not working towards a common goal. Both participant 7 and 10 (artist and engineer) noted that working with someone who had a positive, open and curious personality helped a lot in the collaboration process. Participant 7 (artist) was surprised that the verbal part of the collaboration and developing strategy was a very important aspect of the coordination of effort and division of tasks. Participant 8 (designer) struggled with getting a sense of scale, the limited time communication and hurdles of working with a new person. Participant 1 (artist) noted that the VR and tablet approach would take a while to master the tool (VR more so) Participant 5

(computer science) noted that next time he would like the ability to erase and he would like more space to move around in VR.

4.4.2 Focus Groups

The importance of analog drawing and tactile approach was noted by several of the artists.

Participant 1 (artist) noted that it is especially so because the mediation between idea and expression is more immediate with physical media. Participant 11 (artist) agreed, and noted that this system used in this study is not the way she typically uses drawing to collaborate. She noted that she often collaborates with other artists by showing the other person her drawings via video stream. Participant 1 (artist) also agreed that showing drawings over video stream would be the best approach for collaborative ideation. He also noted that since he is older and did not grow up with computers, he recognizes that people's ability to express themselves with digital media could be different for younger people. Participant 8 (designer) also noted that physical drawing is important but not necessarily a make-or-break for her, "a tablet is totally doable". Participant 11 (artist) thinks that drawing is really key for communication and that she emphasizes her thoughts and explanations with drawings. She thinks that this can be done with a stylus, but until it is more seamlessly integrated it will not replace drawing.

Participant 4 (artist) said that not spending time on the computer has made her life much easier.

Participant 1 (artist) considers himself a technological neophyte who prefers to stay away from it as much as possible. He expressed that he does not find technology useful. Part of his artistic practice is based on cross-sense modalities, and he expressed that technologies such as VR often focus too heavily on vision instead of using multiple senses simultaneously like we do naturally. Participant 7 (artist) noted that there might be generational resistance to using digital tools, and that it might

depend on people's aptitudes and experience. Some people might specifically not want to engage with technology, and this depends a lot on their experience educational or professional background.

Participant 2 (engineer) and 5 (computer science) seemed less supportive of analog media.

Participant 5 noted that traditional media is useful but he has no special attachment or value to it.

Participant 2 (engineer) said that people are generally more familiar with drawing and that some artists might be efficient with it now just because they are more used to it, but when "we get used to the other drawing tools, the VR and tablet will be more effective". This engineer expressed the importance of skill development and that for example, a lot of digital artists use drawing tablets today to come up with work that is sometimes better than physical media. Participant 6 (designer) supported this and said that there is a foundation for every skill you develop, in VR or a 3D environment you might even be able to develop these skills faster if you already have the foundation in 2D drawing. Participant 2 (engineer) also noted that the problem with physical drawing is that there is no way that it can be collaborative and real-time where you can both work on the same drawing (a characteristic he noted to be important because it is easier to fix problems this way).

Several participants noted that the tablet was the easiest method to use for this experiment.

Participant 6 noted that a tablet is a good way of using the 2D drawing approach but in real-time.

Though he felt more comfortable in a 3D environment, drawing in 2D was not a hindrance.

Similarly, Participant 11 (artist) said that if a person is working with someone who is able to mental-image things while drawing in 2D, that 3D space might be overkill in terms of brainstorming or early ideation. Consistent with the observation of the collaboration scenarios, participant 8

(designer) noted that in the VR condition they just decided what to draw and then drew it, and spent very little time brainstorming. This participant noted that the tablet was “by far the easiest method for this experiment”. Participant 7 (artist) also thought the tablet was the easiest method but only because of the barriers of the tools in VR such as the lack of an ergonomic pen to draw in, and inability to change brush type. Participant 3 (designer) agreed that the controller itself can have an impact with how people interact with the design and that making it more ergonomic could be helpful. Participant 5 (computer science) noted that he liked using the pen in the tablet approach, but found it was not very fun or accurate. He thought that to really incorporate analog drawing into the real-time paradigm one would have to find some way to scan in real-time instead of the tablet.

Participant 4 (artist) noted that VR was better for the design process in a way because it was 3D. Participant 7 (artist) also noted that working in 3D definitely changed the design process for him, and that it was “epic.” Being able to see people’s hands and make gestures in VR was a playful element that both participant 1 and 11 (artists) found important. Participant 5 (computer scientist) noted that the types of ideas that you could convey were different across media. He felt that the crazier ideas were more natural to convey in VR. Participant 2 (engineer) also noted that seeing in 3D changed the design process because partners could check each angle at the same time, and the dimensions are present so it is more straightforward with less interpretation. He noted that having different designers in the same room in VR “will help a lot for group discussion”. Participant 5 (computer science) noted that when he drew in 3D, he felt he could notice subtle spatial details - “since your brain is thinking naturally you can respond to something as if you were in that space, without having to interpret and imagine everything”. Participant 3 (designer) also thought that the human scale of VR was an asset as it was easy to be in the place they were designing.

Though she was more supportive of incorporating analog media, participant 11 (artist) noted that she experienced a moment in VR where her partner and her were drawing different parts of the shape and joined it together to complete it, that this moment of synchronicity was interesting. Similarly, though he expressed criticism of the VR space due to its technical glitches and lack of multisensory capabilities, participant 1 (artist) noted that he does think that embodiment in a virtual space is possible. He felt like this actually started to happen to him towards the end of the collaboration but is not sure how far it can be taken without experiencing technical glitches. Participant 7 (artist) expressed that he thinks that all the ingredients exist for VR to be a very useful remote collaboration tool but things just need to be put together. It seems “natural and obvious” to him, and that the biggest challenge currently is the user interface. Participant 3 (designer) also noted that when there were no technical difficulties in VR it was “awesome, it flowed really well, and we bounced ideas off each other well”. She thinks that “VR will be the new necessary tool in design” since being able to do more creative exploration without making expensive prototypes can save time and money.

Participant 5 (computer science) thought that VR has a lot of potential for social interaction since it is a more personable and natural interaction than any other digital platform, including video calls (where he mentioned we are still just pictures on a screen whereas in VR you can see actual 3D gestures). He thought it was “so much more fun and open” and he could even tell his partner’s personality through their movements (slow and relaxed vs. excitable). Participant 7 (artist) also noted that one of the most important things in VR for the future is its networking capabilities and that this could be really important for distributed communities contributing to a design project. Participant 4 (artist), however, noted that the type of design process that might work very well for someone might be terrible for someone else. She also said that videos and gestures are important

and that it is hard to gauge a reaction from just a voice or in VR. She also noted that she would struggle to work in some of these ways because it is not indicative of her abilities. Participant 4 noted that she thinks VR can be a useful tool for art and design or connecting things, but she has her reservations about it because it is not accessible for a lot of people. She thinks that using it as is would lose a whole group of people that might work best in the tactile way. Participant 7 (artist), however, noted that currently there is no seamless experience with any kind of remote collaboration method, it is all clunky in some way.

Participant 11 (artist) proposed finding tools that allow for visual working but that are integrated with some application that people are already using such as Google docs, where you can go in and edit it on your own time. Participant 8 (designer) also agreed with this, but said that the methods that exist for this are not necessarily easy or intuitive. Participant 1 (artist) mentioned that VR might be a really interesting tool for people who are not able-bodied, and that perhaps this can give them more abilities in the design space. Participant 11 (artist) also noted that this type of system could be important for assisted imagination or assisted empathy to simulate an experience that a designer might not actually have. Participant 7 (artist) also noted that it should be easier for people who are not programmers to create or modify the environment or tools for their specific needs. He noted one of the important things that stood out to him in the VR condition was the time-based aspect of it – he sees it as not just making marks but making marks that take place in physical space through time. Specifically, to communicate the wholeness of an idea, he emphasized that you need to have the movement or performative element (where VR has a lot of potential).

For future systems, some suggestions were adding line weight and texture variation to the VR approach, as well as being able to make pressurized marks in space and be able to import assets

and previous sketches. Unlike participant 4 (artist) who did not like designing in a vacuum-like space, participant 3 (designer) was cautious about adding any extra things such as a background as it would make it “fussy and difficult.” Space differences seemed to be a challenge for most people in VR, and that actually being able to walk around and see in 1:1 scale would make a big difference (participant 8 – designer. Participant 5 (computer science) and 7 (artist) agreed that the ability to hand scale objects would be useful so you can walk around a smaller version of sketch. Participant 11 (artist) also noted that it would be interesting to try VR without a device mounted on the body (potentially a CAVE approach). Participant 3 (designer) noted that it would be really interesting to incorporate this VR approach to an easily accessible platform such as Google cardboard (if there were controllers available for this). For a tablet approach participant 3 (designer) noted that immediate visualization would be great but that this is currently very expensive. She also noted that there is a pen that records movement that could be useful so you could still draw analog since drawing on paper is still best for quick iteration.

Figure 4-16. Visual Coding of Qualitative Data

5. DISCUSSION

This experiment revealed some key factors that should be considered when creating a future remote collaboration method with sketching as an ideation method. The tests also showed that though most people worked well together and came up with innovative ideas in different disciplinary combinations, there was a noticeable difference in the perception of media across the disciplinary groups examined in this study.

The unexpected scrutinizing perspective three out of four of the artists had about technology uncovered something interesting about collaboration media. Their reservations about emerging digital media approaches point not only to the artists in this study's previous use of technology but also to a philosophical choice to use technology less often. Two of the artists noted that they have purposely strayed away from technology and are trying to adopt more analog media in their practice. Richard Colson (2007 p. 19) notes that "throughout history, people with expertise in a certain craft are often skeptical or even hostile toward new technology that can threaten the value of their hard-acquired skill." This could be especially true when the new technology seems complex and overwhelming and might require time, resources, and dedication to learn (McGlynn 2020). If new media such as VR can be useful in collaboration with people who have this perspective, their point of view would need to be valued and considered, since more complex technology is not always the best solution. Questioning *why* we are using a certain medium, the philosophical approaches behind it, the semiotic indications it has, and the effects on emotion or creative process is something that was seen through assessing these artists' reaction. If these views are present in people who have had previous interaction with CAD or digital resources, this might indicate an area to be looked at further when working with people in a remote co-design scenario who have no experience with CAD or other computer programs. These artists have seen a lot of

technology and *choose* to be away from it. This might be different for someone who does not have the same historical, semiotic and philosophical background knowledge on technology and media's role in culture that artists do, or for someone who has very little experience in a technocentric society. It would therefore be important to further explore how people's perception of or attachment to media can affect their process while using a tool.

People from a technical background (engineers and computer scientists) were unanimously supportive of the VR approach. This could be due to their higher comfort level with technology (such as more computer games played – three out of four play several times per month whereas three out of four of the artists never play), less attachment to the semiotic or conceptual significance of the media, and more interest in the capabilities or efficiency of the media. Similarly, as Lee et al (2018) note, people who favour subsequent evaluation or a deductive reasoning approach in the design process tend to make decisions outside the functional or aesthetic influence of the digital tools through the design process. According to Lee et al (2018), the functional or aesthetic properties of the tool might therefore have a greater influence on the creative process of people who use abductive reasoning more frequently. Keefe (2005) notes that artists use abductive reasoning often, however, reasoning methods can also vary within disciplines. For example, the 2018 study by Lee et al compared contrasting reasoning patterns of different designers. To further explore these differences in reasoning patterns and their affect on the design process in a multidisciplinary setting, differences within disciplines would also need to be explored further while using digital systems such as VR.

In addition to the criticism of the VR approach, each artist agreed that it has potential to enhance the design process in some way, and that it would be possible to feel embodied within a virtual

space. Overall, examining each collaboration process showed that VR had strength in specific areas. VR scored highest in large scale spatial reasoning [as opposed to focusing on individual objects and forms (75% compared to 58.3% for the tablet approach and 50% for paper)], and participants noticed details of space such as serendipitous ideas about where to put things and which areas to expand. There was more talk about scale and relating the body to space during the design process. Also, it was noted in open-ended questions as well as surveys that VR was highly collaborative (79% worked on design ideas together compared to 41% for the tablet approach and 16.7% for paper), and excelled in areas of creative expression (Q1,4,5) such as expressiveness, intuitiveness of visualizing with the medium, and losing track of time [a potential characteristic of flow (Tan et al 2015)]. A statistically significant difference was found when combining scores for these questions across conditions for designers and engineers/computer scientists. Being immersed in the design space and being able to see the whole design in 3D was very helpful for some participants since it was more efficient than having to translate into multiple views in a 2D plane (cognitive offloading). Several participants also noted that it was “open” and seemed less restrictive than the other two approaches. This indicates that a VR drawing approach has potential in collaborative design scenarios where spatial relationships between angles and objects are important. Its capabilities in creative expression and embodiment also show unique potential for co-design. Specifically, participant 7 (artist) noted that to communicate the wholeness of an idea, the movement or performative element can be very important – full-body gesture-based recording of expression is where VR sketching has a lot of potential.

VR scored low in the amount of iterations as predicted (13 compared to 27 for paper and 26 for tablet) as well as usefulness of participants’ visualization skills (75% compared to 95.8% for the tablet approach and 83.3% paper). Less iteration might point to a different type of ideation. For

example, as opposed to divergent and lateral thinking shown in paper ideation, it might show gradually increasing complexity and concreteness of design as well as convergence of design ideas (the high score in working on design objects together also points towards this) (Lee et al 2018, Lee 2020). This, however, needs to be tested further since factors such as lack of familiarity with the tool, lack of space and the ability to erase and scale, as well as the size of the brush strokes could also have made participants more tentative with the tool. Also since drawing in VR is not very common yet, pictorial conventions have not yet been established in this space in terms of drawing, as compared to traditional paper drawing. In other words, best practices for getting the most out of this type of drawing have not been found yet, which might explain why some people did not find their visualization skills useful with this method.

Although the tablet may not have produced as much enthusiasm, or as polarizing views, it emerged as a quiet but important competitor. It was practical, easy to use, and visualization skills were useful (95.8% of participants agreed), and helped participants understand their partners' ideas (87.5% agreed compared to 75% for VR and 33.3% for the paper approach). For some early ideation sessions, this might be enough. Participants who had the most experience using tablets in the past felt the most comfortable with this approach (industrial designers), whereas participants who did not have experience using it felt the most frustrated at their inaccuracy with their lines. The tablet approach also scored highest in the number of new design elements (10.8 compared to 10.1 for VR and 7.5 for paper), and participants came up with almost as many iterations in this approach as paper (26 compared to 27 for paper). Results show that the type of ideation while using the tablet and desktop approach in this particular study leaned towards more object-based ideation rather than large scale spatial relationships (only 58.3% focused on the relations between design objects more than individual design objects compared to 75% for VR and 50% for paper). This could be

useful for object-based ideas or conceptually evaluating what is to be put in the design space (rather than spatially or formally evaluating how elements converge) in a complex design scenario, though more research can be done in this area.

The analog drawing approach also stood out in some areas such as familiarity, accessibility, and tactility, as well as amount of iterations. The system of uploading, however, was cumbersome and less collaborative than the other approaches since participants could not draw in the same space/same board. Even though the system was noted as separated and annoying for this test, it was interesting to see people present individual ideas before further modifying and changing them. A real-time collaborative approach (like VR or tablet drawing) might eliminate some of these initial divergent ideas if a participant feels that their partner would not agree. Where the tablet and VR approaches might be superior in synergy and convergence of ideas, a more separated approach might allow participants to iterate independently which might lead to more divergent ideas. Other areas where physical drawing excelled were in expressiveness (75% compared to 66.7% for VR and 58.3% for the tablet approach) and control of lines (91.6% agreed they had good control compared to 50% for VR and 75% of participants noting that they had poor control of their lines with the tablet). Some artists also indicated that the tactile aspect of analog media is still important as a lot of people feel most comfortable working this way, so it could still be a useful part of a remote collaborative design setting when combined with another real-time approach.

Though most people thought that VR was intuitive for visualizing ideas even if they did not have experience using it (nine out of 12 participants had never used VR before yet 91.6% agreed in surveys and this was further supported by focus group discussions), getting the most out of the medium might take a lot more exploring to find the most effective techniques. A difficulty for

example, was seeing where lines connected in space. Though this might be influenced by the chisel tip of the brush used for this study, it could also potentially be resolved with practice. Interestingly though, some people were observed to have great control of their lines (an engineer and artist both stood out here) in terms of keeping them steady and level. It can be speculated that this is due to experience building or sculpting in 3D or excellent kinesthetic awareness of their body in space due to sports, since neither of these people had drawn in VR before. 75% disagreed that they had good control of their lines with the tablet and this frustration was also noted during focus groups. Though this did not seem to hinder the collaboration process in this particular study, the high level of control in the paper approach shows another area where traditional media is still competitive. It seemed as though a tablet approach could be a middle-ground and perhaps replace paper as it still has the tactility that freeform VR sketching lacks. This study showed, however, that an analog approach is still important and that there might be better ways to incorporate traditional drawing in remote collaboration that were not explored in this study.

Furthermore, fewer than expected participants focused on stretching the formal or conceptual boundaries of the greenhouse. Participant 4 (artist) noted that she thought of the drawing process as output instead of sketching as an ideation process – this was also noticed by observing several of the others while collaborating. Some people used sketching as less of a brainstorming method or a way to evolve a particular idea and more as a way to illustrate a design idea (across all media). This could have been in part due to how the test was conducted and lack of emphasis on this goal, but also further solidifies the need for design thinking training, as well as training with the specific media, even with industrial designers as part of the collaboration. Drawing, collaboration, and visualization are all skills that differ depending on the media used, and skills in each of these could vary at the individual level. Practice and training, as well as emphasis and clarification of the goals

of the brainstorming session during briefing, the type of design prompts given, and even timing are important things to consider to get the most out of brainstorming sessions, especially with new media.

Additionally, people from different backgrounds could need varying levels of practice to effectively communicate together. Since learning how to brainstorm is difficult in general, trying to do this in VR is an added challenge since its ideation capabilities are still relatively unexplored in terms of drawing. Else (2018 p. 48) notes that “when you are exploring movement within VR you are exploring the body interacting with a type of space that we simply have not encountered before.” When thinking about visual artwork (such as a painting), Barbara Bolt (2004 p. 1) (as cited in Else 2018) considers it to no longer be a passive object, but something that goes beyond the range of being a thing – “painting no longer merely represents or illustrates reading. Instead, it performs.’ This perhaps suggests that VR is an ‘actual’ virtual container for a ‘perceptual’ virtual experience.” Similar to how painting can be seen as a multi-layered activity where painter and painting cannot easily be separated, “the medium of VR is not so much defined by the equipment, but by the activity that takes place between the user and the spaces created.” (Else 2018 p. 39) Poulsen and Thøgersen (2011 p. 43) note that the integration of verbal conversations and body movements to express a design idea “cannot simply be explained as gestures accompanying and supporting the verbal expressions, but it points to a more fundamental embodied level of human existence.” Since it is not mimicking drawing on paper, this indicates that more research needs to be done on how drawing in VR changes not just visualization and sketching techniques but also complicates our perceptual and meaning-making experience.

6. RECOMMENDATIONS AND FUTURE RESEARCH

Based on the results of this study, several potential areas for future research were uncovered. Key characteristics of each drawing method were also noted as recommendations for putting together a future collaboration system. Listed below are some of these guidelines as well as areas of future research (seen in figure 6-1).

Figure 6-1. Areas of Future Research

Drawing Systems:

Combined Approaches: Though a single method approach might work in a short term ideation session, a combined approach (e.g. tablet and VR, paper and tablet, paper and VR) could take advantage of the strengths of each drawing medium in longer ideation sessions. This could be especially important when people come from different backgrounds and have different

visualization or drawing approaches. Since the artists in this study noted the importance of the immediacy and tactility of physical drawing, finding a more useful way to incorporate analog drawing and other tactile brainstorming methods into remote communication could be valuable when including people who are more comfortable working this way. This study particularly focused on sketching, but mixing ideation strategies (e.g. sketching and mindmapping) could also be a way to allow participants to work in ways they feel most comfortable all within one space. More research can be done on the relationship between sketching and mind-mapping or other brainstorming methods not explored in this study using the same three paradigms (VR, tablet, paper) in a remote setting.

For more complicated design problems, drawings that can be continuously referred to (instead of just showing sketches via video stream) would be useful since details of the drawings will be present in one place. An example of this would be to combine uploading images of drawings with a tablet approach, since areas of the drawing can be pointed out with the tablet drawing and changes can be made over top of the image in real-time. It would also be interesting to bring traditional sketches into a VR environment so they can be referred to there. Other ways of combining approaches could be testing the effect of tactile feedback in VR such as using a tablet or hard surface to assist in VR drawing. It could also be useful to be able to save these 3D sketches as 3D files that can be scaled and referred to while on a desktop computer through a platform such as Conceptboard, or when building more refined CAD models. Regarding mixed approaches, it could be important to look further into how different ways of combining convergent and divergent approaches can affect the design process.

Hardware/Software Changes: One of the main suggestions that participants had about the VR software was to have the ability to change brush style/texture, size, colour, and pressure. This could make the process not only more fun to work with but more representative of design ideas. This could also be applied to the tablet approach (already available but not used for this study - see Study Design 3.3). In addition to changing brushstrokes/textures, it might be interesting to test 3D sculpting on desktop and in VR for multidisciplinary collaboration, and explore augmented reality or different display types (such as CAVE) for 3D visualization. While it has been shown that being in a fully immersive environment can improve hand-eye coordination, comparisons between different levels of immersion in 3D user interfaces for collaborative design tasks are difficult to find.

Several participants noted that it would be useful to be able to scale and move complete drawings. These could then be referred to for further iterations. In addition, most people felt the need to label parts of their drawings. This can be challenging in VR and it was especially so during this study due to the size of the brush strokes. Being able to change the size/style of the brush could help with this, or having the option to use text to put in labels. Some of these options are inefficient though, and much easier on a desktop.

In terms of a tablet approach, several participants noted that a tablet with immediate visualization would work well for remote collaboration. In thinking further about how to incorporate analog tactile skills, another option to retain the feeling of drawing on paper could be to use a gesture sensing pen where drawings on paper can be directly transferred to a computer in real-time (Zhang et al 2019).

Human Factors: Future research in this area could consider ergonomics and experiment with alternative controllers. An example could be assessing a VR pen shaped controller which would be more similar to a typical drawing tool and might be better suited than traditional VR controllers. Prototypes of these exist but are not available widely on the market yet (Logitech VR Ink Pilot Edition 2020). Though this study was originally imagined as a community centred project where several people (e.g. within a design team) would have access to the same equipment, instead of having it set up individually, it might still be interesting to question how to make VR more accessible by looking at inexpensive options such as Google cardboard. Using these less expensive options, however, could be tricky because tracking (which is essential for sketching) is not common and challenging. A cordless approach like the Oculus Quest might be useful for the future, since it is slightly less expensive and less bulky than the Rift.

Perception and meaning making while drawing or collaborating in VR should also be considered since drawing in mid-air without tactile feedback does not exist in reality – the body is interacting with a kind of space that it has not encountered before (Else 2018). Future research could also consider the difference between artists and engineers or other contrasting disciplines with regards to their philosophy or semiotic interpretation of VR and how this affects their output or process in collaboration. More research could also examine the reactions to VR or its effects on collaboration when stakeholders have had little experience with technology or do not live in an urban setting where it is ubiquitous.

Furthermore, being in VR for a long time can be tiring, especially when full body movements are used for drawing. This needs to be considered when picking an approach or how to combine approaches. Physical tiredness from moving the body is not necessarily a bad thing within reason,

but vergence-accommodation conflict causing eye fatigue is a limitation to consider with current hardware.

Gestures & Movement: Gestures were clearly important in the collaborations observed in this study. Future research could look solely at gestures in remote collaborative drawing sessions. Since the VR approach incorporates full body movement, this is a particularly interesting area to look at. Comparing different types of avatars and how this affects collaboration in the design process could be useful. It would also be interesting to examine how people use their whole body to communicate their design ideas in 3D space – this could include walking, crouching, jumping, crawling and more.

Ideation & Collaboration Process

Public vs. Private Spaces: Differences between public and private places for collaboration could be an important area for future investigation. Specifically, this would mean allowing time for participants to come up with ideas individually before sharing them with partners. This could be important to explore further because an approach that might be more collaborative might not necessarily be the most creative. Though the paper and upload approach was slow and annoying for this study, there might still be something important in a slower and more segmented approach (even for early sketching ideation stages) while combined with real-time communication. Though the converging aspect of collaborative real-time sketching (particularly in VR) is a strength, giving people time (or space) to think of ideas individually could allow some more divergent ideas to come through that may have been discarded in a group session more focused on converging ideas. Synchronous interaction as seen in VR is important for quality collaboration, but reciprocal interaction as seen in the paper approach is important for creative fluency (Zhou et al 2020). Zhou

et al's recent study found that people situated in private spaces are more fluent in generating ideas than those in common areas. This is important to consider, especially in digitally mediated spaces – for example, a future study could look at different rooms in VR for individual work and for collaboration.

Reasoning Methods: To further analyze differences between disciplines a future study could have tighter parameters around reasoning strategies, computer use and other background characteristics. This could be important since there are some artists who work with digital media, and some engineers who might not be interested in virtual reality as a method. Since there are artists who use VR or digital media frequently, their perception might be totally different than an artist who primarily uses physical material.

As Lee et al (2018) note, there are differences between designers in terms of reasoning methods. This complicates the process of using any tool as one person's process with it might be different than another person's (even within disciplines). A tool that might be very useful for someone might not be as effective for someone else. It could therefore be valuable to compare groups that have been observed to clearly favour contrasting reasoning styles (e.g. abductive/deductive), or that have clearly defined differences in use of digital media (e.g. using technology frequently versus explicitly avoiding it).

“Threeing”: Participant 1 (artist) brought up the idea of the “threeing” process in collaboration. This process involves having three people switch roles during a collaboration process by passing around a baton – the colour coordinates with the role (initiator, reactor, and mediator) (Ryan 2009). This process is meant to disrupt and transcend the traps of dualism such as positional

arguments and emotional constraints (Ryan 2009). The designers seemed to be a middle ground between the more contrasting disciplinary backgrounds, so this could be an appropriate triad with which to explore the idea of “threeing” further.

Further research could explore the “threeing” approach within the context of restricted time limit short collaborations or “speedstorming”. For example, there could be a longer timeframe study that allows for many short 3-5 minute sessions. In this case participants could sequentially collaborate with multiple people from different disciplines in a relatively short timeframe - this could be useful since not everyone will be collaboratively compatible. Restricted time limits have been shown to keep the conversation focused and help participants get to the heart of their ideas by candidly sharing their expertise with less time for small talk or distractions (Joyce et al 2010). Threeing and speedstorming would be particularly interesting to combine in VR since the system can be tiring to use for an extended period of time, and thus might work well for shorter brainstorming sessions.

Kinesthetic Awareness and Skill in VR: Visualization skills were overall the least useful in VR compared to tablet and paper drawing, even though participants noted that visualizing their ideas with this medium was intuitive. An approach based on body movement and kinesthetic awareness as seen in VR freeform drawing could be more about moving the body and leaving marks in space rather than on paper. Because this is so different than traditional drawing, it would be interesting to further examine the effect of skill development and ways to best utilize the intuitive capabilities of VR for presenting and creating design ideas and where it could be particularly useful. For example, it could be useful for sculptors or even athletes who have strong kinetic skill, as well as Indigenous communities such as the Inuit who have particularly strong tactile and kinetic skills due to years of

material adaptation (Tagalik 2009). In any of these cases, it will take time and practice to find the true possibilities of the medium when the stakeholder has developed enough skill to be able to work in the space intuitively and effectively as they would in other media. It is important to note that not everyone has the same potential or desire to develop skill in this way, suggesting that a combined approach might be the most realistic when multiple areas of expertise are involved in co-design.

Though challenging, it would also be interesting to find a way for people who have physical disadvantages to be able to communicate design ideas more effectively than they would in real life by taking advantage of the capabilities of VR, and whether there is a way for them to use this medium to draw.

Organic Forms: The decision to design greenhouses for the design challenge may have had limitations. Having to pick a subject that was more focused on formally expressive ideas ran the risk of being confusing for the engineers (having fewer practical parameters or opportunity for deductive reasoning). The greenhouse option included more practical parameters but may have lacked the expressive opportunities of some other design challenges. Also, many of the items drawn in the space were not organic forms such as the square for the outside of the shipping container. Freehand drawing is not the most efficient for drawing straight lines, but might have more potential for organic form development. For a future study it would be interesting to do the same test with a more expressive or open-ended design challenge. Whether this would still work with engineers, computer scientists, or other people from a technical background would need further research.

7. LIMITATIONS OF STUDY

Due to the need for equipment to be distributed due to the COVID-19 pandemic, the researcher was not able to set up equipment beforehand to make sure that everyone had an equal amount of time trying it out before the study. Though set up was made as simple as possible (e.g. info sheet, colour coordinated stickers), there were still some frustrating and sometimes unexpected technical difficulties that needed to be dealt with remotely. Having participants set up equipment was inextricably a part of the study and could have influenced their perception of the media. This was particularly so with people who have not used technology like VR before or are not as comfortable with computers. Nevertheless, this was in a way an important flaw of the study because it exemplified the very real practical issues of needing to implement digital collaboration methods, especially with something as complex as VR.

A practical issue with the way this study was run is that some people either ran out of space or did not have the same physical parameters to work with (for example someone's room may have been a different shape than their partner's and they could not reach certain areas of the design). Due to the lack of space for the VR portion, the tests therefore needed to be cut from the original 15 minutes to 10. This was not dramatically different, but future studies might benefit from a longer timeframe study that would include either a longer time for collaboration, or many more shorter timeframe sketching ideation sessions within the same study.

The tablet used was entry level and inexpensive due to financial constraints - a higher quality tablet may have allowed the participants to have better lines. Additionally, since the researcher is not a software developer, the applications used may not have been perfectly tailored to the study. For example, the chisel tip in the VR condition was limiting, and there was no option to erase. This no-

erase rule carried through to the other methods for consistency and may have made designs messier and more frustrating. Also, the app used for the tablet and paper collaborations was slow at uploading images which could have affected sketching ideation with the paper method.

The survey results were interesting to note in combination with the qualitative data, but not reliable enough on their own to define characteristics about each discipline. The sample size for this test was lower than expected (12 people) due to the limitations imposed by COVID-19 - because of this small sample size, individual personalities could have influenced the results. There are also different focuses within each discipline which might affect how they interface and interact with the systems. If a larger sample size was tested, and COVID-19 did not impose challenges in the logistics (e.g. delivering equipment), sample groups would have been more uniformly represented. Since this study was focused on developing recommendations and finding stand out observations and areas to be looked at for further research, multidimensional data analysis including rich qualitative feedback and was used to make up for the low sample size.

8. CONCLUSION

Tactility, local specificity, and the subtlety of face-to-face interactions in real space cannot yet be replaced by the digital world. Sometimes, however, remote communication is necessary or might be beneficial. Though this is seen explicitly in the case of the COVID-19 pandemic, it is also seen in the growing need for co-design in a global and local context due to complex social and environmental issues. Since many different areas of expertise might be needed to create appropriate solutions to these complex problems, sharing the ideas of multiple disciplines in early ideation stages is a case study that this project aimed to explore.

An area missing in the literature about collaboration or ideation in VR is comparing VR to other distributed real-time methods in a multidisciplinary setting while using sketching for ideation. To address this gap, this thesis aimed to answer the question: *how can multidisciplinary co-design be effectively facilitated remotely while leveraging different skill backgrounds through drawing as brainstorming in digital and visual communication paradigms?* To answer this, three sketching approaches were compared as part of a digital collaboration process. VR freeform drawing was compared to tablet drawing, and uploading images of paper drawings. Each participant took part in two collaborations, each with a partner from a contrasting discipline – visual art, industrial design, or engineering/computer science. Data was collected through observation of video/audio recording as well as surveys and focus groups.

Three out of four of the artists in this study emphasized the need to maintain the accessibility, materiality and immediacy of traditional drawing. The paper approach showed divergent ideas between participants in the collaboration process – an important thing to consider for future research since there might be benefits to a system that is reciprocal rather than simultaneous.

The study showed that VR produced convergence in the design process in terms of connections between objects as well as people (since participants often moved to create objects together). This indicates that VR could be useful for designs that benefit from the convergence of design ideas and gradually increasing complexity of design ideas, as well as those that require large-scale spatial thinking such as figuring out angles or the placement of certain objects, buttons, or forms within a structure or object. This could be especially useful when what is being designed is something in which a human will be working, walking around, or interacting with other people. Other benefits of this approach include the openness, human scale and performative aspects; namely, using full body movements to leave traces and express the wholeness of ideas. This relates to embodied design thinking where ideation and evaluation can be simultaneous (with less interpretation since it is already 3D), and could be particularly important for co-design.

The tablet maintained the tactility of traditional drawing (with the added benefit of real-time collaboration), as well as a picture-based approach in contrast to embodied trace-making and ideation in VR. Where the VR sketching system used in this study seems to have relatively specific applications, the tablet system examined seems to be sufficient for a wide variety of designs. It was shown to be beneficial for coming up with a large amount of novel ideas, and could be especially useful due to its straightforwardness and practicality when stakeholders are seasoned in 2D drawing and visualization.

It was expected that VR sketching would be an easy way for people from various disciplines to use to collaborate. The study found, however, that users of VR for collaboration might require more time to explore and develop skills compared to other approaches, even when it is used for designs that could potentially benefit from this approach like human-scale designs that rely on placement

of objects or angles. It could therefore be important to see how practice can specifically affect the drawing or design process in VR (as compared to other media) in addition to the need for design thinking and brainstorming training in multidisciplinary settings.

Where some people might be able to express themselves well in 3D with full body gestures, others might be hesitant to use a system they feel is not immediately indicative of their skills. If VR is to be used as a design ideation method, it has to provide clear benefits to that particular design as well as being appropriate for the stakeholders involved. There are also practical and philosophical considerations about encounters with digital media that might affect some people's ability to use the tool more than it affects others - in this study this was revealed in the difference between disciplines.

To effectively facilitate multidisciplinary co-design using sketching ideation, this study noted the specific areas where sketching in VR could provide benefits to ideation and where other approaches such as tablet drawing or analog drawing are sufficient. Sketching in VR could be helpful in specific cases, and in combination with other visualization approaches. When creating a future sketching collaboration system, it could be useful to find appropriate ways to combine media for the disciplines involved, the individuals, and the specific design challenge so each stakeholder can express themselves in the most effective way possible. Ultimately, this research study showed that it is important to question how new media such as VR can expand design thinking. There are many practical and philosophical issues with the implementation of emerging technologies such as VR that affect the ability of some people to use these tools effectively for ideation more than it affects others. Exploration of new approaches and technologies such as VR can still be valuable to consider, even if they seem uncomfortable or impractical at first.

9 REFERENCES

- a. Leon, M., Laing, R., Malins, J., & Salman, H. (2014). Development and testing of a design protocol for computer mediated multidisciplinary collaboration during the concept stages with application to the built environment. *Procedia Environmental Sciences*, 22, 108-119.
- b. Leon, M., Doolan, D. C., Laing, R., Malins J., and Salman, H. (2014) Application of Interactive Surfaces to Support Computer Mediated Collaborative Design Environment. 18th International Conference on Information Visualisation, Paris, 281-286, doi: 10.1109/IV.2014.30.
- Ahmad, Mahdjoub, Bluntzer, Sagot, & Sagot, K. (2013). *A Tool Proposition to Support Multidisciplinary Convergence in Immersive Virtual Environment: Virtusketches*.
- Al-Kodmany, K. (2002). Visualization Tools and Methods in Community Planning: From Freehand Sketches to Virtual Reality. *Journal of Planning Literature*, 17(2), 189-211. <https://doi.org/10.1177/088541202762475946>
- Arora,R., Kazi,R.H., Anderson,F., Grossman,T., Singh, K., and Fitzmaurice, G. (2017). Experimental Evaluation of Sketching on Surfaces in VR. In Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems (CHI '17). Association for Computing Machinery, New York, NY, USA, 5643-5654.DOI:<https://doi-org.proxy.library.carleton.ca/10.1145/3025453.3025474>
- Attef, B. O. A. (2019). *Mixed Reality: A New Tool for Architecture* (Doctoral dissertation, Carleton University).

- Atwood, J. L., & Barbour, L. J. (2003). Molecular graphics: from science to art. *Crystal growth & design*, 3(1), 3-8.
- Avsec, S., & Savec, V. F. (2019). Creativity and critical thinking in engineering design: the role of interdisciplinary augmentation. *Global Journal of Engineering Education*, 21(1), 30-36.
- Barricelli, B. R et al. "Semiotics of Virtual Reality as a Communication Process." *Behaviour & Information Technology* 35.11 (2016): 879-896. Web.
- Bishop, R. (2015, October 13). Chaos. Retrieved August 23, 2020, from <https://plato.stanford.edu/archives/spr2017/entries/chaos/>
- Bolt, B 2004 'Art beyond Representation: The Performative Power of the Image'. New York: I. B. Tauris
- Bowman, D. A., & McMahan, R. P. (2007). Virtual reality: How much immersion is enough? *Computer*, 40(7), 36-43. doi:10.1109/MC.2007.257
- Boy, G. A. (2013, August). From STEM to STEAM: toward a human-centred education, creativity & learning thinking. In *Proceedings of the 31st European conference on cognitive ergonomics* (pp. 1-7).
- Bradford, L. E., Vogel, T., Lindenschmidt, K. E., McPhedran, K., Strickert, G. E., Fonstad, T. A., & Bharadwaj, L. A. (2018). Co-design of water services and infrastructure for Indigenous Canada: A scoping review. *FACETS*, 3(1), 487-511.
- Brew, A., Kantrowitz, A., & Fava, M. (2013). Drawing connections: New directions in drawing and cognition research. *Tracey: drawing and visualisation research*.

- Brooks, F. P. (1999). What's real about virtual reality?. *IEEE Computer graphics and applications*, 19(6), 16-27.
- Brown, V. A., Harris, J. A., & Russell, J. Y. (Eds.). (2010). *Tackling wicked problems through the transdisciplinary imagination*. Earthscan.
- Budach, G., Patrick, D., & Mackay, T. (2015) "Talk around objects": designing trajectories of belonging in an urban Inuit community, *Social Semiotics*, 25:4, 446-464,
DOI: [10.1080/10350330.2015.1059575](https://doi.org/10.1080/10350330.2015.1059575)
- Bürdek, B. E. (2005). *Design: History, theory and practice of product design*. Walter de Gruyter.
- Carpo, M. (2011). *The alphabet and the algorithm*. Mit Press.
- Chek Tien Tan, Tuck Wah Leong, Songjia Shen, Christopher Dubravs, and Chen Si. 2015. Exploring Gameplay Experiences on the Oculus Rift. In Proceedings of the 2015 Annual Symposium on Computer-Human Interaction in Play (CHI PLAY '15). Association for Computing Machinery, New York, NY, USA, 253-263. DOI:<https://doi-org.proxy.library.carleton.ca/10.1145/2793107.2793117>
- Chisholm, J. (2016). What is co-design? Retrieved June 18, 2020, from <http://designforeurope.eu/what-co-design>
- Chittenden, T. (2018). Tilt Brush painting: Chronotopic adventures in a physical-virtual threshold. *Journal of contemporary painting*, 4(2), 381-403.

- Chou, W.H. and Wong, J. (2015), From a Disciplinary to an Interdisciplinary Design Research: Developing an Integrative Approach for Design. *International Journal of Art & Design Education*, 34: 206-223. doi:[10.1111/jade.12017](https://doi.org/10.1111/jade.12017)
- Chung, H. J. (2012). Media Heterotopia and Transnational Filmmaking: Mapping Real and Virtual Worlds. *Cinema Journal*, 51(4), 87-109. doi:10.1353/cj.2012.0071
- Clemmensen, T., Ranjan, A., and Bodker, M. (2018). How cultural knowledge shapes core design thinking – a situation specific analysis. *CoDesign*, 14:2, 115-132, DOI: 10.1080/15710882.2017.1399146
- Cook, K., Bush, S., & Cox, R. (2017). From STEM to STEAM. *Science and Children*, 54(6), 86.
- Cooper, M. M., Grove, N. P., Pargas, R., Bryfczynski, S. P., & Gatlin, T. (2009). OrganicPad: an interactive freehand drawing application for drawing Lewis structures and the development of skills in organic chemistry. *Chemistry Education Research and Practice*, 10(4), 296-301.
- Corrigan, M. (2015). Hard-boiled simulacra and cybernetic cartographies: other virtual worlds in the fiction of Salman Rushdie and Haruki Muakami. *Textual Practice*, 29(5), 801–824. <https://doi.org/10.1080/0950236X.2014.998704>
- Cramer-Petersen, C. L., Christensen, B. T., & Ahmed-Kristensen, S. (2019). Empirically analysing design reasoning patterns: Abductive-deductive reasoning patterns dominate design idea generation. *Design Studies*, 60, 39-70.

Crilly, N, & Vasconcelos L. (2016). Inspiration and fixation: Questions, methods, findings, and challenges. *Design Studies* Volume 42 January 2016 pg. 1-32. Retrieved from: <https://doi.org/10.1016/j.destud.2015.11.001>. Date Accessed: November 8 2018.

Dam, R., & Siang, T. (2017). Design Thinking: New Innovative Thinking for New Problems. *Interaccion Design Foundation. Recuperado el, 19.*

Dawood, S. (2017, Aug 04). New VR sketching tool looks to make product design "quicker and more efficient". *Design Week (Online)*, Retrieved from <https://proxy.library.carleton.ca/login?url=https://search-proquest-com.proxy.library.carleton.ca/docview/1926386357?accountid=9894>

Dawson, P. (2008) Unfriendly Architecture: Using Observations of Inuit Spatial Behavior to Design Culturally Sustaining Houses in Arctic Canada, *Housing Studies*, 23:1, 111-128, DOI: [10.1080/02673030701731258](https://doi.org/10.1080/02673030701731258)

Dawson, P., Levy, R., & Lyons, N. (2011). 'Breaking the fourth wall': 3D virtual worlds as tools for knowledge repatriation in archaeology. *Journal of Social Archaeology*, 11(3), 387-402. <https://doi.org/10.1177/1469605311417064>

De Meulemeester, J. (2018, October 29). Food Insecurity in Northern Canada. Retrieved June 13, 2020, from <https://pulitzercenter.org/projects/food-insecurity-northern-canada>

Designing in VR. (2017, 08). *3D World*, , 36-39. Retrieved from <https://proxy.library.carleton.ca/login?url=https://search-proquest-com.proxy.library.carleton.ca/docview/2048046426?accountid=9894>

- Diamond S. (2019). Addressing the imagination gap through STEAMM+D and indigenous knowledge. *Proceedings of the National Academy of Sciences of the United States of America*, 116(6), 1851–1856. doi:10.1073/pnas.1808679115
- Douven, I. (2011) 'Abduction'. *The Stanford Encyclopedia of Philosophy (Spring 2011)*, available at: <http://plato.stanford.edu/entries/abduction>.
- Else, J., 2018. Climbing the Virtual Stepladder: Exploring the Reality of Virtual Worlds in Performance. *Body, Space & Technology*, 17(1), pp.34–50.
DOI:<http://doi.org/10.16995/bst.295>
- Featherstone, M., & Burrows, R. (Eds.). (1996). *Cyberspace/cyberbodies/cyberpunk : Cultures of technological embodiment*. Retrieved from <https://ebookcentral-proquest-com.proxy.library.carleton.ca>
- Fedorowicz, Jane, et al. "Creativity, innovation, and e-collaboration." *International Journal of e-Collaboration*, vol. 4, no. 4, 2008, p. 1+. *Gale Academic Onefile*, https://link-gale-com.proxy.library.carleton.ca/apps/doc/A191767186/AONE?u=ocul_carleton&sid=AONE&xid=6ac11306. Accessed 13 Jan. 2020.
- Fjeld M et al. (2002). Physical and virtual tools: activity theory applied to the design of groupware. A special issue of CSCW: activity theory and the practice of design 11(1-2):153–180
- Freitag, S., Weyers, B., & Kuhlen, T. W. (2016). Examining rotation gain in CAVE-like virtual environments. *IEEE Transactions on Visualization and Computer Graphics*, 22(4), 1462-1471.

- Friedman, B., Kahn, P. H., Borning, A., & Hultdgren, A. (2013). Value sensitive design and information systems. In *Early engagement and new technologies: Opening up the laboratory* (pp. 55-95). Springer, Dordrecht.
- Gänshirt, C. (2012). *Tools for ideas: Introduction to architectural design*. Walter de Gruyter.
- Gardiner, B. (2019, March 27). Kids suffer most in one of Earth's most polluted cities. Retrieved August 23, 2020, from <https://www.nationalgeographic.com/environment/2019/03/mongolia-air-pollution/>
- Gondor, D. (2016). Inuit knowledge and environmental assessment in Nunavut, Canada. *Sustain Sci* 11, 153–162. doi:10.1007/s11625-015-0310-z
- González-Ruibal, A. (2014). Supermodernity and Archaeology.
- Grahame F Thompson (2016) Interdisciplinary complexities. *Journal of Cultural Economy*. 9:3, 322-329, DOI: [10.1080/17530350.2015.1090471](https://doi.org/10.1080/17530350.2015.1090471)
- Greenstock, L., & Wright, J. (2011). Collaborative implementation: Working together when using graphic symbols. *Child Language Teaching and Therapy*, 27(3), 331–343. <https://doi.org/10.1177/0265659010396778>
- Gribbin, J., Young, R., and Aftab, M.(2017) Understanding the dynamics of attitudes within a design and business focused collaboration. *Strategic Design Research Journal*, 10 (2). pp. 126-133. ISSN 1984-2988
- Gruchalla, K.: Immersive well-path editing: investigating the added value of immersion. In: Proceedings of IEEE Virtual Reality, Chicago, IL, pp. 157–164, 27–31 March 2004

- Gumienny, R., Gericke, L., Quasthoff, M., Willems, C., & Meinel, C. (2011, June). Tele-board: Enabling efficient collaboration in digital design spaces. In *Proceedings of the 2011 15th International Conference on Computer Supported Cooperative Work in Design (CSCWD)* (pp. 47-54). IEEE.
- Haats, T. (2012). *Creative synergy in interdisciplinary design collaboration: using speedstorming to generate ideas* (Doctoral dissertation, Carleton University).
- Halskov, K. & Christensen, B. T. (2018). Designing across cultures. *CoDesign*, 14:2, 75-78, DOI: 10.1080/15710882.2018.1459101
- Hammond, T. (2015). Dialectical creativity: Sketch-negate-create. In *Studying Visual and Spatial Reasoning for Design Creativity* (pp. 91-108). Springer, Dordrecht.
- Harris, C&R. (2011). Information and Communication Technologies for Cultural Transmission among Indigenous Peoples. The Electronic Journal of Information Technologies in Developing Countries. <https://doi-org.proxy.library.carleton.ca/10.1002/j.1681-4835.2011.tb00318.x>
- Herter, Brown, & Ovtcharova, J. (2013). *A Visual Language for the Collaborative Visualization of Integrated Conceptual Models in Product Development Scenarios*.
- Hessels, S. (2015). Extreme Environments: Hong Kong's Art+ Science Expeditions. *ISEA2014 Dubai: Location*, 211.

- Hewitt, M.(1985) Representational Forms and Modes of Conception; an Approach to the History of Architectural Drawing, *Journal of Architectural Education*, 39:2, 2-9,
DOI: [10.1080/10464883.1985.10758387](https://doi.org/10.1080/10464883.1985.10758387)
- Hong, Y., Bruniaux, P., Zeng, X., Liu, K., Chen, Y., & Dong, M. (2017). Virtual reality-based collaborative design method for designing customized garment for disabled people with scoliosis. *International Journal of Clothing Science and Technology*.
- Hughes, C. E., & Stapleton, C. B. (2005, July). The shared imagination: Creative collaboration in augmented virtuality. In *HCI International* (pp. 22-27).
- Ibrahim, R., & Pour Rahimian, F. (2010). Comparison of CAD and manual sketching tools for teaching architectural design. *Automation in Construction*, 19(8), 978-987. doi:10.1016/j.autcon.2010.09.003
- Irani, L., & Dourish, P. (2009). Postcolonial Interculturality. In *Proceedings International Workshop on Intercultural Collaboration*. 249-252
- Israel, J.H., Habakuk, J., Wiese, E., Mateescu, M., Zöllner, C., and Stark, R. 2009. Investigating three-dimensional sketching for early conceptual design—Results from expert discussions and user studies. In *Computers & Graphics* 33, 4 (Aug, 2009), 462-473.
- J. Zhang, H. Bi, Y. Chen, J. Chen and Z. Wei, "SmartWriting: Pen-Holding Gesture Recognition with Smartwatch," *ICC 2019 - 2019 IEEE International Conference on Communications (ICC)*, Shanghai, China, 2019, pp. 1-6, doi: 10.1109/ICC.2019.8761758.
- Jacob, S. (2011). Beyond the Flatline. *Architectural Design*, 81(5), 24-31. DOI:10.1002/ad.1292

- Janca, A., & Bullen, C. (2003). The Aboriginal concept of time and its mental health implications. *Australasian Psychiatry*, 11(1_suppl), S40-S44.
- Jensenius, A. R. (2012). Disciplinarity: intra, cross, multi, inter, trans. *Jensenius, AR, blog posts*, [Megtekintve: 2015.03. 05.], University of Oslo, [http://www. arj](http://www.arj), (2012/03), 12.
- Jin, Y., & Lee, S. (2019). Designing in virtual reality: a comparison of problem-solving styles between desktop and VR environments. *Digital Creativity*, 30(2), 107-126.
- Johnson, J.T., Howitt, R., Cajete, G. *et al*. Weaving Indigenous and sustainability sciences to diversify our methods. *Sustain Sci* 11, 1-11 (2016) doi:10.1007/s11625-015-0349-x
- Kara, H., & Georgoulas, A. (2012). *Interdisciplinary design : new lessons from architecture and engineering*. Cambridge, Massachusetts: Harvard University Graduate School of Design.
- Keefe, D. F., Acevedo, D., Miles, J., Drury, F., Swartz, S. M., & Laidlaw, D. H. (2008). Scientific sketching for collaborative VR visualization design. *IEEE Transactions on Visualization and Computer Graphics*, 14(4), 835-847.
- Keefe, D. F., Karelitz, D. B., Vote, E. L., & Laidlaw, D. H. (2005). Artistic collaboration in designing VR visualizations. *IEEE Computer Graphics and Applications*, 25(2), 18-23.
- Kozhevnikov, M. (2015). Visual-object versus visual-spatial representations: Insights from studying visualization in artists and scientists. In *Studying Visual and Spatial Reasoning for Design Creativity* (pp. 193-204). Springer, Dordrecht.
- Kumar, V. (2012). 101 design methods: A structured approach for driving innovation in your organization. *John Wiley & Sons*.

- Lachman, R. (2018). STEAM not STEM: Why scientists need arts training. *The Conversation*, 18.
- Lee, J., Ahn, J., Kim, J., Kho, J. M., & Paik, H. Y. (2018). Cognitive evaluation for conceptual design: cognitive role of a 3D sculpture tool in the design thinking process. *Digital Creativity*, 29(4), 299-314.
- Leenders, Roger & Engelen, Jo & Kratzer, Jan. (2003). Virtuality, communication, and new product team creativity: A social network perspective. *Journal of Engineering and Technology Management*. 20. 69-92. 10.1016/S0923-4748(03)00005-5.
- Levy, R. M., Dawson, P. C., & Arnold, C. (2004). Reconstructing traditional Inuit house forms using three-dimensional interactive computer modelling. *Visual Studies*, 19(1), 26-36.
- Li, K., Tiwari, A., Alcock, J., & Bermell-Garcia, P. (2016). Categorisation of visualisation methods to support the design of Human-Computer Interaction Systems. *Applied ergonomics*, 55, 85-107.
- Logitech VR Ink Pilot Edition - VR Stylus for Creativity, Control & Precision. (n.d.). Retrieved August 18, 2020, from <https://www.logitech.com/en-roeu/promo/vr-ink.html>
- Machuca, M. D. B., Asente, P., Stuerzlinger, W., Lu, J., & Kim, B. (2018, October). Multiplanes: Assisted freehand vr sketching. In *Proceedings of the Symposium on Spatial User Interaction* (pp. 36-47).
- Maguire, M. (2001). Methods to support human-centred design. *International Journal of Human-Computer Studies*, 55(4), 587-634.

Makhutov, N. A., Moskvichev, V. V., & Fomin, V. M. (2015). Designing machinery for the Arctic:

A problem of socioeconomic development of Russia's eastern regions. *Herald of the Russian Academy of Sciences*, 85(1), 79-86.

Mason, M. (2012). Environmental Democracy. *London: Earthscan Publications, Ltd.* p.

24. ISBN 1853836184.

McCullough, M. (1998). Abstracting craft: The practiced digital hand. Massachusetts: MIT Press.

McGlynn, M. (2020). Paper to Pixel: An Exploration of Digital Drawing. Retrieved 2020, from

<https://aaltodoc.aalto.fi/handle/123456789/43803>

McVeigh-Schultz, J., Kreminski, M., Prasad, K., Hoberman, P., & Fisher, S. S. (2018, June).

Immersive Design Fiction: Using VR to Prototype Speculative Interfaces and Interaction Rituals within a Virtual Storyworld. In *Proceedings of the 2018 Designing Interactive Systems Conference* (pp. 817-829).

Medina, S. (2017). The Cold Rush: Designers Begin Looking to the Arctic. Retrieved May 06,

2020, from <https://www.metropolismag.com/architecture/cold-rush-designers-look-arctic/>

Mendes, D., Relvas, F., Ferreira, A., Jorge, J. (2016) The benefits of DOF separation in mid-air

3D object manipulation. In the *ACM Conference on Virtual Reality Software and Technology - VRST 2016*, pp. 261-268.

Mitchell, P. H. (2005). What's in a name?. *Journal of Professional Nursing*, 6(21), 332-334.

- Newcombe, N. S., & Shipley, T. F. (2015). Thinking about spatial thinking: New typology, new assessments. In *Studying visual and spatial reasoning for design creativity* (pp. 179-192). Springer, Dordrecht.
- Newman, C. (2014). John Krakauer's Stroke of Genius. Retrieved August 24, 2020, from <https://www.nationalgeographic.com/news/2014/9/140929-krakauer-medicine-stroke-neurology-rehabilitation/>
- Pearce, T. D., Ford, J. D., Laidler, G. J., Smit, B., Duerden, F., Allarut, M., ... & Goose, A. (2009). Community collaboration and climate change research in the Canadian Arctic. *Polar Research*, 28(1), 10-27.
- Pham, D. M., & Stuerzlinger, W. (2019, November). Is the pen mightier than the controller? a comparison of input devices for selection in virtual and augmented reality. In *25th ACM Symposium on Virtual Reality Software and Technology* (pp. 1-11).
- Qi, W., Taylor II, R. M., Healey, C. G., & Martens, J. B. (2006). A comparison of immersive HMD, fish tank VR and fish tank with haptics displays for volume visualization. In the *ACM Symposium on Applied Perception in Graphics and Visualization*, pp. 51-58.
- Rahimian, F. P., Ibrahim, R., Rahmat, R. W. B. O. K., Abdullah, M. T. B., & Jaafar, M. S. B. H. (2011). Mediating Cognitive Transformation With VR 3D Sketching During Conceptual Architectural Design Process. *ArchNet-IJAR : International Journal of Architectural Research*, 5(1), 99-113. Retrieved from <https://proxy.library.carleton.ca/login?url=https://search-proquest-com.proxy.library.carleton.ca/docview/862364076?accountid=9894>

Remi Alkemade, Fons J. Verbeek & Stephan G. Lukosch. 2017. On the Efficiency of a VR Hand Gesture-Based Interface for 3D Object Manipulations in Conceptual Design. In *International Journal of Human-Computer Interaction* 33, 11 (Nov, 2017), 882-901, DOI: 10.1080/10447318.2017.1296074

Rosenbaum, D. A. (2005). The Cinderella of psychology: the neglect of motor control in the science of mental life and behavior. *American Psychologist*, 60(4), 308.

Ryan, P. (2009). *The Three Person Solution: Creating Sustainable Collaborative Relationships*. Purdue University Press.

Schuchardt, P., Bowman, D. (2007). The benefits of immersion for spatial understanding of complex underground cave systems. *Virtual Reality Software and Technology: Proceedings of the 2007 ACM Symposium on Virtual Reality Software and Technology; 05-07 Nov. 2007*, 121-124. <https://doi.org/10.1145/1315184.1315205>

Seel, N. M. (Ed.). (2011). *Encyclopedia of the Sciences of Learning*. Springer Science & Business Media.

Seichter, H. (2007). Augmented reality and tangible interfaces in collaborative urban design. In *Computer-Aided Architectural Design Futures (CAADFutures) 2007* (pp. 3-16). Springer, Dordrecht.

Seonghoon Ban and Kyung Hoon Hyun. 2019. 3D Computational Sketch Synthesis Framework: Assisting Design Exploration Through Generating Variations of User Input Sketch and Interactive 3D Model Reconstruction. *Computer-Aided Design* 120, (Nov, 2019), DOI:10.1016/j.cad.2019.102789.

- Shanken, E. A. (2005). Artists in industry and the academy: collaborative research, interdisciplinary scholarship and the creation and interpretation of hybrid forms. *Leonardo*, 38(5), 415-418.
- Shih, Y.T., Sher, W.D., and Taylor. M. 2015. Understanding creative design processes by integrating sketching and CAD modelling design environments: A preliminary protocol result from architectural designers. In *ArchNet-IJAR* 9, 3 (Jan, 2015), 76-92.
- Slater, M. (2009). Place illusion and plausibility can lead to realistic behaviour in immersive virtual environments. *Philosophical Transactions of the Royal Society B, Biological Sciences*, 364:1535, pp. 3549-3557.
- Smith, B. (2009). On reality and virtuality: A study of time-spaces in plowing the dark. *Mosaic : A Journal for the Interdisciplinary Study of Literature*, 42(3), 95-108. Retrieved from <https://proxy.library.carleton.ca/login?url=https://search-proquest-com.proxy.library.carleton.ca/docview/205343367?accountid=9894>
- Sousa Santos, B., Dias, P., Pimentel, A. *et al.* Head-mounted display versus desktop for 3D navigation in virtual reality: a user study. *Multimed Tools Appl* 41, 161 (2009). <https://doi-org.proxy.library.carleton.ca/10.1007/s11042-008-0223-2>
- Sovacool, B. K., & D'Agostino, A. L. (2012). A comparative analysis of solar home system programmes in China, Laos, Mongolia and Papua New Guinea. *Progress in Development Studies*, 12(4), 315-335. <https://doi.org/10.1177/146499341201200404>

- Sovacool, B. K., D'Agostino, A. L., & Bambawale, M. J. (2011). Gers gone wired: lessons from the renewable energy and rural electricity access project (REAP) in Mongolia. *Energy for Sustainable Development*, 15(1), 32-40.
- Steen, M. (2013). Co-design as a process of joint inquiry and imagination. *Design Issues*, 29(2), 16-28.
- Steen, M., Manschot, M., & De Koning, N. (2011). Benefits of co-design in service design projects. *International Journal of Design*, 5(2).
- Søren Bolvig Poulsen & Ulla Thøgersen (2011) Embodied design thinking: a phenomenological perspective, *CoDesign*, 7:1, 29-44, DOI: [10.1080/15710882.2011.563313](https://doi.org/10.1080/15710882.2011.563313)
- Sutherland, I. E. (1964). Sketchpad a man-machine graphical communication system. *Simulation*, 2(5), R-3.
- Sutton, R., & Hargadon, A. (1996). Brainstorming Groups in Context: Effectiveness in a Product Design Firm. *Administrative Science Quarterly*, 41(4), 685-718. doi:10.2307/2393872
- Tagalik, S (2012). The role of indigenous knowledge in supporting wellness in Inuit communities in Nunavut. *Prince George, National Collaborating Centre for Aboriginal Health (online at: <http://www.nccah-ccnsa.ca/en/>)*.
- Tate, J., Mulugetta, Y., Sharland, R., Hills, P., Voogd, H., & Pezzoli, K. (1998). Policy Forum: Sustainability : The Technocentric Challenge [with Comments]. *The Town Planning Review*, 69(1), 65-86. Retrieved June 18, 2020, from www.jstor.org/stable/40113777

- Tcha-Tokey, K., Loup-Escande, E., Christmann, O., & Richir, S. (2017, September). Effects on user experience in an edutainment virtual environment: comparison between CAVE and HMD. In *Proceedings of the European Conference on Cognitive Ergonomics 2017* (pp. 1-8).
- Thompson, C. (2017). Stereographs Were the Original Virtual Reality. *Smithsonian Magazine*.
- Urey, H., Chellappan, K.V., Erden, E. and Surman, P., 2011. State of the art in stereoscopic and autostereoscopic displays. *Proceedings of the IEEE*, 99(4), pp.540-555
- Van der Lugt, R. (2002). Brainsketching and how it differs from brainstorming. *Creativity and innovation management*, 11(1), 43-54.
- Veisz, D., Namouz, E. Z., Joshi, S., & Summers, J. D. (2012). Computer-aided design versus sketching: An exploratory case study. *Artificial Intelligence for Engineering Design, Analysis and Manufacturing : AI EDAM*, 26(3), 317-335. doi:<http://dx.doi.org.proxy.library.carleton.ca/10.1017/S0890060412000170>
- Verstijnen, I. M., van Leeuwen, C., Goldschmidt, G., Hamel, R., & Hennessey, J. M. (1998). Sketching and creative discovery. *Design studies*, 19(4), 519-546.
- Veryzer, R. W., & Borja de Mozota, B. (2005). The impact of user-oriented design on new product development: An examination of fundamental relationships. *Journal of product innovation management*, 22(2), 128-143.
- Vinck, D. (2009). From the intermediate object to the boundary object: Towards taking into account the work of equipment. *Anthropology of Knowledge Review*, Vol. 3, 1 (1), 51-72. doi: 10.3917 / rac.006.0051.

- Vosinakis, S. & Koutsabasis, P. (2012) Problem-Based Learning for Design & Engineering Activities in Virtual Worlds, *PRESENCE: Teleoperators and Virtual Environments*, 21:3, MIT Press
- Wang X. (2007) Mutually Augmented Virtual Environments for Architectural Design and Collaboration. In: Dong A., Moere A.V., Gero J.S. (eds) Computer-Aided Architectural Design Futures (CAADFutures) 2007. Springer, Dordrecht
- Wenzel, G. W. (2013). Inuit and modern hunter-gatherer subsistence. *Études/Inuit/Studies*, 37 (2), 181–200. <https://doi-org.proxy.library.carleton.ca/10.7202/1025716ar>
- Witcomb A (2007) The materiality of virtual technologies: A new approach to thinking about the impact of multimedia museums. In: Cameron F and Kenderdine S (eds) *Theorizing Digital Cultural Heritage: A Critical Discourse*. New York: MIT Press, 35–48.
- Wood, J. (1998). Re-designing the Present. *chapter in The Virtual Embodied, by John Wood (editor), Routledge (London and New York), 7.*
- Yang E.K., & Lee, J. H. (2020) Cognitive impact of virtual reality sketching on designers' concept generation, *Digital Creativity*, DOI: [10.1080/14626268.2020.1726964](https://doi.org/10.1080/14626268.2020.1726964)
- Zhicheng Liu, & Stasko, J. (2010). Mental Models, Visual Reasoning and Interaction in Information Visualization: A Top-down Perspective. *IEEE Transactions on Visualization and Computer Graphics*, 16(6), 999–1008. <https://doi.org/10.1109/TVCG.2010.177>

Zhou, N., Kisselburgh, L., Chandrasegaran, S., Badam, S., Elmqvist, N., & Ramani, K. (2020).

Using social interaction trace data and context to predict collaboration quality and creative fluency in collaborative design learning environments. *International Journal of Human-Computer Studies*, 136, 102378-. <https://doi.org/10.1016/j.ijhcs.2019.102378>

APPENDIX

Appendix A

EMAIL RECRUITMENT

Subject: Invitation to participate in a research project on remote multidisciplinary co-design through virtual reality and digital systems.

Attach poster to body of email:

Looking for Participants for a Research Study on:

VISUAL THINKING IN VIRTUAL ENVIRONMENTS

*Evaluating Multidisciplinary Interaction Through Drawing
Ideation in Real-Time Remote Co-Design*

Hello,

My name is Alex Close and I am a Master's student in the School of Industrial Design at Carleton University. I am working on a research project under the supervision of Prof. Stephen Field, co-supervised by Prof. Robert Teather.

I am writing to you today to invite you to participate in a study entitled "Visual Thinking in Virtual Environments: Evaluating Multidisciplinary Interaction through Drawing Ideation in Real-time Remote Co-design". This study aims to evaluate the design ideation process in digital and virtual environments by assessing collaboration as well as individual visualization. To be eligible for this study, you must be either a professional or student in one of the following disciplines: industrial design, visual arts, engineering, or computer science and must be 18+.

This study involves two design sessions that will happen over the span of one day (unless a scheduling conflict occurs) where you will test three different drawing/ideation methods to collaborate to solve a design problem with a partner from a different discipline. After each session, you will complete a post-test Likert scale survey with some additional open-ended questions. With your consent, the mock digital design session will be audio-recorded, and through screen-sharing, the session will also be video recorded. Once the audio recording has been transcribed, recording will be destroyed. Recordings are mandatory for participation.

After each daily group has completed the testing, you will participate in a focus group to provide more information on your experience.

After debriefing and equipment setup (up to 15 minutes), each ideation condition will last 15 minutes. Since each design session will include 3 conditions, the total testing time will be 1.5 hours. After the testing is completed, the post-test surveys will take approximately 15 minutes to complete. Finally, the focus group should take up to 15 minutes to sum up any additional thoughts participants had throughout the study.

As a token of our appreciation for participating in this study, we will be providing you a \$15 gift card to a brand of your choice (via Tango Card). The compensation is yours to keep, even if you choose to withdraw.

Care will be taken to protect your identity - this will be done by keeping responses confidential and allowing you to request that certain responses not be included in the final project.

You will have the right to end your participation in the study at any time, for any reason, up until three weeks after the study is completed. If you choose to withdraw, all the information you have provided will be destroyed.

Any hard copies of data (including any handwritten notes or USB keys) will be kept in a locked cabinet in possession of the researcher. Research data will only be accessible by the researcher and the research supervisor.

The ethics protocol for this project was reviewed by the Carleton University Research Ethics Board, which provided clearance to carry out the research after May 25th 2020. The study will take place from July 7th to July 18th.

CUREB-B Clearance # 112749

If you have any ethical concerns with the study, please contact the Carleton University Research Ethics Board-B (by phone at 613-520-2600 ext. 4085 or via email at ethics@carleton.ca).

If you would like to participate in this research project, or have any questions, please contact me at alexclose@carleton.ca

Sincerely,

Alex Close

Appendix B

1. Introduce Participants
2. Covid-19 information (we understand the lack of space and the technical issues that might come with setting this up. It is not an ideal situation. Be aware of your space and the amount of time you have to draw in VR so you don't bump into anything.
3. Sort out technical issues before test (including uploading photos).

BACKGROUND:

The idea for this research project began by thinking about design in Canada. In the North there are a lot of imported Southern goods that just don't consider traditional lifestyle or current needs enough – this is a case where there is not enough communication between stakeholders who live in different locations.

From here I started thinking about multidisciplinary teams in general and how they can collaborate. Ultimately, I decided to focus on methods of remote co-design (collaborative design) using drawing as a brainstorming process. When stakeholders are in different locations and come from different disciplines they might have different skill backgrounds, visual vocabularies, and visualization strategies. So for how this affects the design process, this study focuses specifically on sketching as an ideation method in the early stages of design, before designers use more advanced CAD tools. There are obviously many types of brainstorming and stages of design including research that is paramount in any design scenario. This study just focuses on a small part of this – how different methods of drawing ideation can affect the design process during remote multidisciplinary collaboration.

DESIGN TASK:

- Will be broken up into 3 10 min tests with slightly different parameters
- Shipping container greenhouse for an Arctic climate.

- Things to think about-sustainable, community oriented (inviting and easy to use, and formally innovative).
- How you choose to interpret the brief, or which view(s) of the container you choose to represent is up to you, and something you can decide with your partner.
- Don't worry about making your designs perfect – wacky ideas are great, and it's fine if the design is a bit illogical and if the final artifact is less than pretty. We are simply assessing the ideation process between you and your partner and the unique perspective you can each bring to this challenge. Most importantly, have fun!

****If they ask about dimensions, they are typically 8ft tall and 8ft wide and 20 or 40 feet long. We do not expect this to be adhered to strictly, it's just an idea of the shape of the box.**

****I know this is a lot of info so feel free to stop me at any time to ask questions!**

Tablet– Each pick colour, only use pen and move/zoom tools, no shapes, no erasing, can only move.

Paper – You are not allowed to draw over your sketches using the tablet.

VR – Remember that you cannot erase!

A. SOIL BASED:

- Potatoes, carrots, root vegetables.
- Path for people who will harvest or take care of the plants to walk through, and some form of lighting. The rest is up to you, including how you choose to use the shipping container.

B. HYDROPONIC:

- Hydroponic means that these plants will be able to grow without soil, and just with water that has nutrients added to it.

- Beans, tomatoes and peppers.
- Again, there will need to be a pathway for harvesters and some form of lighting.

C. AQUA CULTURE:

- Aquaculture can include plants or animals that live in bodies of water. For this, try to focus on plants such as kelp and algae, or smaller animals such as mussels or shrimp.
- Also harvesting pathway and form of lighting.

Appendix C

8/31/2020

Qualtrics Survey Software

Default Question Block

Informed Consent Form

Name and Contact Information of Researcher:

Alex Close, Carleton University, School of Industrial Design, Faculty of Engineering and Design
Email: alexclose@carleton.ca

Supervisor and Contact Information:

Stephen Field Carleton University, School of Industrial Design, Faculty of Engineering and Design
Email: stephen.field@carleton.ca

Project Title:

Visual Thinking in Virtual Environments: Evaluating Multidisciplinary Interaction through Drawing
Ideation in Real-Time Remote Co-Design

Carleton University Project Clearance

Clearance #: 112749

Date of Clearance: May 20 2020

Invitation

https://carletonu.ca1.qualtrics.com/Q/EditSection/Blocks/Ajax/GetSurveyPrintPreview?ContextSurveyID=SV_bc2IWpdSTjoQQzrD&ContextLibraryID=U... 1/8

You are invited to take part in a research project because you are part of a discipline that could potentially be involved in a multidisciplinary co-design situation. The information in this form is intended to help you understand what we are asking of you so that you can decide whether you agree to participate in this study. Your participation in this study is voluntary, and a decision not to participate will not be used against you in any way. As you read this form, and decide whether to participate, please ask all the questions you might have, take whatever time you need, and consult with others as you wish.

What is the purpose of the study? This study aims to access insights from people with different skill types through collaborative design ideation. We seek to evaluate methods of accessing diverse visualization strategies to solve difficult design problems. Since some stakeholders might be in different locations, we will be evaluating the benefits of different digital drawing communication paradigms in a co-design setting. This will benefit not only the people involved in the design process but also final users due to improved designs that are made with input from people with diverse areas of expertise. What will I be asked to do?

If you agree to take part in the study, we will ask you to:

- Complete two mock design ideation sessions each including three types of remote digital drawing/brainstorming. Each session will be completed with a partner from a different discipline.
- Complete a survey after each testing scenario, and participate in a focus group afterwards.
- The surveys will be using a Likert scale format and will include some open-ended questions. They will be done online using Qualtrics.
- The study will take place remotely - you will be able to participate from home.
- Each design session will last approx 45 minutes. The entire testing scenario will therefore be around 1.5 hours per participant excluding debriefing and consent forms, equipment set up (up to 20 min), surveys and focus group (up to 20 min each). Depending on availability of participants, these two sessions might be split up with varying time in between. All participants will, however, receive a break in between sessions of at least 10 minutes.
- The co-design interaction will be screen-recorded and audio recorded. Recordings are mandatory for participation.

Risks and Inconveniences

We do not anticipate any risks to participating in this study.

Possible Benefits

You may not receive any direct benefit from your participation in this study. However, your participation may allow researchers to better understand how virtual and digital systems can leverage different skill types in a co-design process.

Compensation/Incentives

You will be paid \$15 in the form of a gift card to a brand of your choice (via Tango Card) once all surveys are completed via Qualtrics.

No Waiver of your Rights

By signing this form, you are not waiving any rights or releasing the researchers from any liability.

Withdrawing from the Study

If you withdraw your consent during the course of the study, all information collected from you before your withdrawal will be discarded. Additionally, if you begin the study but then decide to withdraw before the surveys have been completed, you will receive 50% of the compensation. However, if you decide to withdraw after the surveys are completed, you will keep the entire gift card.

After the study, you may request that your data be removed from the study and deleted by notice given to the Principal Investigator (named above) within 3 weeks after your completion.

Confidentiality

https://carletonu.ca1.qualtrics.com/Q/EditSection/Blocks/Ajax/GetSurveyPrintPreview?ContextSurveyID=SV_bC2IWpdSTjoQZrD&ContextLibraryID=U... 3/8

We will remove all identifying information from the study data as soon as possible, which will be after audio is transcribed. We will treat your personal information as confidential, although absolute privacy cannot be guaranteed. No information that discloses your identity will be released or published without your specific consent. Research records may be accessed by the Carleton University Research Ethics Board in order to ensure continuing ethics compliance. All data will be kept confidential, unless release is required by law (e.g. child abuse, harm to self or others). The results of this study may be published or presented at an academic conference or meeting, but the data will be presented so that it will not be possible to identify any participants unless you give your express consent. You will be assigned a code [or pseudonym] so that your identity will not be directly associated with the data you have provided. All data, including coded information, will be kept confidential. Your data will be stored and protected by Qualtrics, in a server located in the USA but may be disclosed via a court order or data breach.

Data Retention

After the study is completed, your de-identified data will be retained for future research use. Photos and audio recordings used will not show the participant.

New Information During the Study

In the event that any changes could affect your decision to continue participating in this study, you will be promptly informed.

Ethics review

This project was reviewed and cleared by the Carleton University Research Ethics Board [CUREB B]. If you have any ethical concerns with the study, please contact Carleton University Research Ethics Board (by phone at 613-520-2600 [ext. 4085 for CUREB B] or by email at ethics@carleton.ca).

- ☐ I voluntarily agree to participate in this study.
- ☐ I grant the researcher above from Carleton University permissions to audio record my voice and video record and photograph my likeness and/or actions during the study.
- ☐ I give permission to the researcher to distribute videos/photographs obtained during this research project in research presentations, publications, for educational purposes or any other venue.

Please write the date of completion of this form (mm/dd/yyyy).

Please type in your name.

Default Question Block

Pre-Test Survey

City:

Age:

Occupation

- ☐ Undergraduate Student
- ☐ Graduate Student
- ☐ Professional

Area of Study/Profession

- ☐ Engineering
- ☐ Computer Science
- ☐ Industrial Design
- ☐ Visual Art

How frequently do you use a computer?

- ☐ 1-3 hours/day
- ☐ 4-5 hours/day
- ☐ 7-8 hours/day
- ☐ 8+ hours/day

How often do you play computer games?

- ☐ Never
- ☐ Once per month
- ☐ Several times per month
- ☐ Daily

How often do you use computer assisted design (CAD) software?

(e.g. Solidworks, Adobe Suite, Rhino 3D, Fusion 360)

- ☐ Never
- ☐ Once per month
- ☐ Several times per month
- ☐ Daily

What is your 2D analog drawing self-assessed skill level?

(Ability to use traditional media such as pen and paper to sketch/draw)

- ☐ Low
- ☐ Low-moderate
- ☐ Moderate-high
- ☐ High

What is your 2D digital drawing experience - self assessed skill level?

(Ability to use digital media such as drawing tablet to sketch/draw)

- ☐ Low
- ☐ Low-Moderate
- ☐ Moderate-high
- ☐ High

How often do you use virtual reality?

- ☐ Never
- ☐ Once per month
- ☐ Several times per month
- ☐ Daily

How often do you participated in remote collaboration?

- ☐ Never
- ☐ Once per month
- ☐ Several times per month
- ☐ Daily

How often do you participate in drawing collaboration?

- ☐ Never
- ☐ Once per month
- ☐ Several times per month
- ☐ Daily

Powered by Qualtrics

Appendix D

8/31/2020

Qualtrics Survey Software

Default Question Block

TEST 1 - Collaboration Process

Participant Name:

Part 1A

Please write the name of the system that your team used in the first 10 minute block of the test (e.g virtual reality, tablet drawing, paper drawing).

Collaboration Process

To assess the system that you wrote above, please rate the following statements according to accuracy.

	Strongly disagree	Somewhat disagree	Neither agree nor disagree	Somewhat agree	Strongly agree
We worked on design objects individually more than modifying each other's designs.	☐	☐	☐	☐	☐
The drawing system helped rather than hindered my understanding of my partner's ideas	☐	☐	☐	☐	☐
My visualization skills were useful in this collaboration	☐	☐	☐	☐	☐
I felt self-conscious about my drawing skills with this system	☐	☐	☐	☐	☐

https://carletonu.ca1.qualtrics.com/Q/EditSection/Blocks/Ajax/GetSurveyPrintPreview?ContextSurveyID=SV_3NR1KIfGwCowfZz&ContextLibraryID=U... 1/3

Part 1B

Please write the name of the system that your team used in the second 10 minute block of the test (e.g. virtual reality, tablet drawing, paper drawing).

Collaboration Process

To assess the system that you wrote above, please rate the following statements according to accuracy.

	Strongly disagree	Somewhat disagree	Neither agree nor disagree	Somewhat agree	Strongly agree
We worked on design objects individually more than modifying each other's designs.	☐	☐	☐	☐	☐
The drawing system helped rather than hindered my understanding of my partner's ideas	☐	☐	☐	☐	☐
My visualization skills were useful in this collaboration	☐	☐	☐	☐	☐
I felt self-conscious about my drawing skills with this system	☐	☐	☐	☐	☐

Part 1C

Please write the name of the system you used in the third 10 minute block of the test (e.g. virtual reality, tablet drawing, paper drawing).

Collaboration Process

To assess the system that you wrote above, please rate the following statements according to accuracy.

8/31/2020

Qualtrics Survey Software

	Strongly disagree	Somewhat disagree	Neither agree nor disagree	Somewhat agree	Strongly agree
We worked on design objects individually more than modifying each other's designs.	☐	☐	☐	☐	☐
The drawing system helped rather than hindered my understanding of my partner's ideas	☐	☐	☐	☐	☐
My visualization skills were useful in this collaboration	☐	☐	☐	☐	☐
I felt self-conscious about my drawing skills with this system	☐	☐	☐	☐	☐

Powered by Qualtrics

https://carletonu.ca1.qualtrics.com/Q/EditSection/Blocks/Ajax/GetSurveyPrintPreview?ContextSurveyID=SV_3NR1KIfGwCowfZz&ContextLibraryID=U... 3/3

Appendix E

Default Question Block

TEST 2 - Collaboration Process

Participant Name:

Part 2A

Please write the name of the system that your team used in the first 10 minute block of the test (e.g virtual reality, tablet drawing, paper drawing).

Collaboration Process

To assess the system that you wrote above, please rate the following statements according to accuracy.

	Strongly disagree	Somewhat disagree	Neither agree nor disagree	Somewhat agree	Strongly agree
We worked on design objects individually more than modifying each other's designs.	☐	☐	☐	☐	☐
My visualization skills were useful in this collaboration	☐	☐	☐	☐	☐
I felt self-conscious about my drawing skills with this system	☐	☐	☐	☐	☐
The drawing system helped rather than hindered my understanding of my partner's ideas	☐	☐	☐	☐	☐

Part 2B

https://carletonu.ca1.qualtrics.com/Q/EditSection/Blocks/Ajax/GetSurveyPrintPreview?ContextSurveyID=SV_emOVTwbw2Yb8xox&ContextLibraryID=... 1/9

Please write the name of the system that your team used in the second 10 minute block of the test (e.g virtual reality, tablet drawing, paper drawing).

Collaboration Process

To assess the system that you wrote above, please rate the following statements according to accuracy.

	Strongly disagree	Somewhat disagree	Neither agree nor disagree	Somewhat agree	Strongly agree
We worked on design objects individually more than modifying each other's designs.	☐	☐	☐	☐	☐
My visualization skills were useful in this collaboration	☐	☐	☐	☐	☐
I felt self-conscious about my drawing skills with this system	☐	☐	☐	☐	☐
The drawing system helped rather than hindered my understanding of my partner's ideas	☐	☐	☐	☐	☐

Part 2C

Please write the name of the system that your team used in the third 10 minute block of the test (e.g virtual reality, tablet drawing, paper drawing).

Collaboration Process

To assess the system that you wrote above, please rate the following statements according to accuracy.

	Strongly disagree	Somewhat disagree	Neither agree nor disagree	Somewhat agree	Strongly agree
We worked on design objects individually more than modifying each other's designs.	☐	☐	☐	☐	☐
My visualization skills were useful in this collaboration	☐	☐	☐	☐	☐
I felt self-conscious about my drawing skills with this system	☐	☐	☐	☐	☐
The drawing system helped rather than hindered my understanding of my partner's ideas	☐	☐	☐	☐	☐

PART 3 - Individual Ideation Process

Recall your experience using each different drawing method (virtual reality, tablet, paper) across both tests. The following questions will ask for your assessment of each of these systems in relation to your individual ideation and visualization process through these challenges.

Part 3A

Visualization & Drawing Process

System: Tablet Drawing

	Strongly disagree	Somewhat disagree	Neither agree nor disagree	Somewhat agree	Strongly agree
It was easy to be expressive with this system.	☐	☐	☐	☐	☐
I had good control of my lines with this system.	☐	☐	☐	☐	☐

	Strongly disagree	Somewhat disagree	Neither agree nor disagree	Somewhat agree	Strongly agree
I focused on large scale patterns or spatial relationships (the relationships of objects/forms to other objects/forms) more than on individual objects/forms.	☐	☐	☐	☐	☐
Visualizing my ideas with this medium was intuitive.	☐	☐	☐	☐	☐
I was so immersed in the task at hand that I lost track of time.	☐	☐	☐	☐	☐
I found that the benefits of the system outweighed the negatives	☐	☐	☐	☐	☐

Part 3B

Visualization & Drawing Process

System: Virtual Reality Freeform Drawing

	Strongly disagree	Somewhat disagree	Neither agree nor disagree	Somewhat agree	Strongly agree
It was easy to be expressive with this system.	☐	☐	☐	☐	☐
I had good control of my lines with this system.	☐	☐	☐	☐	☐
I focused on large scale patterns or spatial relationships (the relationships of objects/forms to other objects/forms) more than on individual objects/forms.	☐	☐	☐	☐	☐
Visualizing my ideas with this medium was intuitive.	☐	☐	☐	☐	☐

	Strongly disagree	Somewhat disagree	Neither agree nor disagree	Somewhat agree	Strongly agree
I was so immersed in the task at hand that I lost track of time.	☐	☐	☐	☐	☐
I found that the benefits of the system outweighed the negatives	☐	☐	☐	☐	☐

Part 3C**Visualization & Drawing Process***System: Paper Drawing & Upload*

	Strongly disagree	Somewhat disagree	Neither agree nor disagree	Somewhat agree	Strongly agree
It was easy to be expressive with this system.	☐	☐	☐	☐	☐
I had good control of my lines with this system.	☐	☐	☐	☐	☐
I focused on large scale patterns or spatial relationships (the relationships of objects/forms to other objects/forms) more than on individual objects/forms.	☐	☐	☐	☐	☐
Visualizing my ideas with this medium was intuitive.	☐	☐	☐	☐	☐
I was so immersed in the task at hand that I lost track of time.	☐	☐	☐	☐	☐
I found that the benefits of the system outweighed the negatives	☐	☐	☐	☐	☐

PART 4

Open-Ended Questions

For each system that you worked with, write several words that represent your experience.

Recall your collaboration process. Was there anything you struggled with or something that surprised you?

What is your email address?

Block 1

Debriefing Form

Name and Contact Information of Researchers: Alex Close, Carleton University, School of Industrial Design, Faculty of Engineering and Design
Email: alexclose@carleton.ca

Supervisor and Contact Information: Stephen Field Carleton University, School of Industrial Design, Faculty of Engineering and Design Email: Stephen.field@carleton.ca

Project Title: Visual Thinking in Virtual Environments: Evaluating Multidisciplinary Interaction through Drawing Ideation in Real-Time Remote Co-Design

Carleton University Project Clearance Clearance #: 112749 Date of Clearance: May 20 2020

What are we trying to learn in this research?

This research examines the relationship between remote digital design methods and visualization techniques in a multidisciplinary collaborative scenario. The pre-test survey will note your disciplinary background and assess previous tech, drawing and collaboration experience. We are interested in learning if the type of design ideation platform will influence the collaborative process between groups with different skill types, as well as the effectiveness of visualization in the brainstorming process.

Why is this important to scientists or the general public?

Previous research has shown that virtual reality is a promising tool to bridge the gap between CAD and physical sketching in the design process since it can combine the strengths of both approaches in a singular medium. VR has also been shown to improve spatial understanding and can provide various benefits to the creative process. Less is known, however, about the specific factors that lead to successful multidisciplinary ideation through drawing. There is also not as much known about how specific drawing paradigms change the design process especially when people have different ideation methods due to skill backgrounds. Since many design problems today are complex in nature and will require multiple areas of expertise (and in many cases remote communication) it is important to find out how to leverage different reasoning and visualization methods to improve the collaborative ideation process.

What are our hypotheses and predictions? We predict that drawing in virtual reality will encourage spatial thinking and allow participants to be more expressive and visualize forms easier than if they were drawing on a 2D surface. We also, however, predict that drawing on a 2D surface – particularly on physical paper - will allow the participants to have more control over their drawings, and that the scale of 2D drawing formats might produce more novel ideas. Overall, we predict that VR could potentially benefit a part of the design process by improving visualization and collaboration in the early brainstorming stages of design when remote communication is necessary.

Where can I learn more?

Barricelli, B. R et al. "Semiotics of Virtual Reality as a Communication Process." Behaviour & Information Technology 35.11 (2016): 879–896. Web.

Rosenberg, M., Vance, J., Oliver, J., & Terpenney, J. (2015). Exploring the role of large-scale immersive computing environments in collaboration between engineering and design students. ProQuest Dissertations Publishing. Retrieved from <http://search.proquest.com/docview/1706908882/>

Shanken, E. A. (2005). Artists in Industry and the Academy: Collaborative Research, Interdisciplinary Scholarship and the Creation and Interpretation of Hybrid Forms.

Leonardo, 38(5), 415–418. doi: 10.1162/leon.2005.38.5.415

<https://www.nationalgeographic.com/news/2014/9/140929-krakauer-medicine-stroke-neurologyrehabilitation/>

Is there anything I can do if I found this experiment to be emotionally upsetting? Yes. If you feel any distress or anxiety after participating in this study, please feel free to contact the Carleton University Health and Counseling Services at: 613-520-6674, or the Distress Centre of Ottawa and Region at 613-238-3311 (<http://www.dcottawa.on.ca>).

What if I have questions later? If you have any remaining concerns, questions, or comments about the experiment, please feel free to contact Alex Close (Principal Investigator), at: alexclose@carleton.ca. CUREB-B Clearance # 112749 If you have any ethical concerns with the study, please contact the Carleton University Research Ethics Board-B (by phone at 613-520-2600 ext. 4085 or via email at ethics@carleton.ca). Thank you for participating in this research!

Powered by Qualtrics

Appendix F

Ages: 21-41		
TOTAL STATS - PRETEST SURVEY		
Ages 21-41		
Occupation		
Undergrad Student		2
Graduate Student		5
Professional		5
Computer Use		
	1	1
	2	4
	3	2
	4	5
Computer Games		
	1	4
	2	3
	3	3
	4	2
CAD Use		
	1	3
	2	2
	3	5
	4	2
Drawing Skill		
	1	1
	2	3
	3	6
	4	2
Digital Drawing Skill		
	1	4
	2	3
	3	4
	4	1
VR Use		
	1	9
	2	0
	3	2
	4	1
Remote Collab		
	1	4
	2	3
	3	4
	4	1

Appendix G

QUANTITATIVE DATA					
Medium	Average Number of Design Elements		Total Iterations (Either different ideas - separate versions of one design elements or modifications on existing one)		
Tablet	10.8				
VR	10.1		Medium		
Paper	7.5		Tablet 26		
Total Number of Design Elements			VR 13		
Medium			Paper 27		
Tablet	130				
VR	121				
Paper	90				
			Engineers and Artists		
Engineers and Artists	Average	Total	Tablet		
Tablet	10	40	VR		
VR	9	36	Paper		
Paper	7.5	30	Total 23		
Total	26.5	106	Artists and Designers		
Artists and Designers			Tablet		
Tablet	11.5	46	VR		
VR	9.75	39	Paper		
Paper	8	32	Total 22		
Total	29.25	117	Engineers and Designers		
Engineers and Designers			Tablet		
Tablet	11	44	VR		
VR	11.5	46	Paper		
Paper	7	29	Total 23		
Total	29.5	119			
Disciplinary Pairing	Average Number of Design Elements				
Engineers and Artists	26.5				
Artists and Designers	29.25				
Engineers and Designers	29.5				

Appendix H

TOTAL STATS - COLLABORATION Survey 1				
	Likert Scale	VR	Tablet	Paper
Q1	1	5	0	1
	2	3	3	2
	3	2	3	2
	4	1	6	1
	5	1	0	6
Q2	1	3	0	1
	2	1	1	0
	3	0	0	1
	4	2	8	7
	5	6	3	3
Q3	1	3	2	4
	2	2	1	3
	3	4	1	1
	4	2	7	2
	5	1	1	2
Q4	1	1	0	3
	2	0	0	2
	3	2	2	3
	4	3	4	2
	5	6	6	2

TOTAL STATS - COLLABORATION Survey 2					TOTAL STATS - COLLABORATION				
	Likert Scale	VR	Tablet	Paper		Likert Scale	VR	Tablet	Paper
Q1	1	4	5	0	Q1	Strongly Disagree	9	5	1
	2	7	2	1		Disagree	10	5	3
	3	0	2	1		Neutral	2	5	3
	4	0	2	3		Agree	1	8	4
	5	1	1	7		Strongly Agree	2	1	13
Q2	1	1	0	1	Q2	Strongly Disagree	4	0	2
	2	0	0	1		Disagree	1	1	1
	3	1	0	0		Neutral	1	0	1
	4	8	10	7		Agree	10	18	14
	5	2	2	3		Strongly Agree	8	5	6
Q3	1	3	2	4	Q3	Strongly Disagree	6	4	8
	2	4	3	3		Disagree	6	4	6
	3	1	3	2		Neutral	5	4	3
	4	2	3	1		Agree	4	10	3
	5	2	1	2		Strongly Agree	3	2	4
Q4	1	1	0	2	Q4	Strongly Disagree	2	0	5
	2	0	0	2		Disagree	0	0	4
	3	2	1	4		Neutral	4	3	7
	4	4	9	2		Agree	7	13	4
	5	5	2	2		Strongly Agree	11	8	4

ACROSS DISCIPLINES													
		Engineering				Visual Art				Industrial Design			
	Likert Scale	VR	Tablet	Paper		VR	Tablet	Paper		VR	Tablet	Paper	
Q1	Stongly Disagree	3	2	1		2	2	0		4	1	0	
	Disagree	4	1	0		3	2	2		3	2	1	
	Neutral	1	1	2		0	1	1		1	3	0	
	Agree	0	4	1		1	3	2		0	1	1	
	Strongly Agree	0	0	4		2	0	3		0	1	6	
Q2	Stongly Disagree	0	0	2		3	0	0		1	0	0	
	Disagree	0	0	0		0	1	0		1	0	1	
	Neutral	0	0	0		0	0	0		1	0	1	
	Agree	3	6	3		3	5	6		4	7	5	
	Strongly Agree	5	2	3		2	2	2		1	1	1	
Q3	Stongly Disagree	2	0	2		2	2	4		2	2	2	
	Disagree	2	0	0		2	2	3		2	2	3	
	Neutral	2	1	0		1	0	1		2	3	2	
	Agree	1	6	2		2	3	0		1	1	1	
	Strongly Agree	1	1	4		1	1	0		1	0	0	
Q4	Stongly Disagree	0	0	2		2	0	0		0	0	3	
	Disagree	0	0	1		0	0	2		0	0	1	
	Neutral	1	0	1		2	1	4		1	2	2	
	Agree	3	4	2		2	5	1		2	4	1	
	Strongly Agree	4	4	2		2	2	1		5	2	1	

BETWEEN DISCIPLINARY PAIRINGS													
		Engineering + Design				Engineering + Visual Art				Visual Art + Industrial Design			
	Likert Scale	VR	Tablet	Paper		VR	Tablet	Paper		VR	Tablet	Paper	
Q1	Strongly Disagree	3	2	0		2	0	1		4	3	0	
	Disagree	5	2	0		3	2	1		2	1	2	
	Neutral	0	2	1		1	1	1		1	2	1	
	Agree	0	1	2		1	5	1		0	2	1	
	Strongly Agree	0	1	5		1	0	4		1	0	4	
Q2	Strongly Disagree	0	0	1		2	0	1		2	0	0	
	Disagree	0	0	0		0	1	0		1	0	1	
	Neutral	1	0	1		0	0	0		0	0	0	
	Agree	6	7	4		1	4	4		3	7	6	
	Strongly Agree	1	1	2		5	3	3		2	1	1	
Q3	Strongly Disagree	2	1	2		2	1	3		2	2	3	
	Disagree	3	1	1		1	0	2		2	3	3	
	Neutral	2	2	2		3	0	0		0	2	1	
	Agree	0	4	1		1	6	1		3	0	1	
	Strongly Agree	1	0	2		1	1	2		1	1	0	
Q4	Strongly Disagree	0	0	1		1	0	1		1	0	3	
	Disagree	0	0	2		0	0	1		0	0	1	
	Neutral	1	1	1		1	1	2		2	1	3	
	Agree	3	5	3		1	2	2		3	6	0	
	Strongly Agree	4	2	1		5	5	2		2	1	1	

Appendix I

TOTAL STATS - INDIVIDUAL					ACROSS DISCIPLINES												
	Likert Scale	VR	Tablet	Paper													
Q1	Stongly Disagre	1	1	1	Q1	Likert Scale	Engineering			Visual Art			Industrial Design				
	Disagree	1	3	1		Stongly Disagree	0	1	1	1	0	0	0	0	0	0	
	Neutral	2	1	1		Disagree	0	1	0	1	2	0	0	0	0	1	
	Agree	1	4	5		Neutral	0	0	0	1	1	0	1	0	1	1	
	Strongly Agree	7	3	4		Agree	0	1	2	0	1	2	1	2	1	2	
Q2	Stongly Disagre	2	6	1	Q2	Stongly Disagree	0	1	1	1	4	0	1	1	0	0	
	Disagree	2	3	0		Disagree	0	2	0	2	0	0	0	1	0	0	
	Neutral	2	0	0		Neutral	1	0	0	1	0	0	0	0	0	0	
	Agree	4	2	5		Agree	2	0	1	0	0	2	2	2	2	2	
	Strongly Agree	2	1	6		Strongly Agree	1	1	2	0	0	2	1	0	2	2	
Q3	Stongly Disagre	0	1	1	Q3	Stongly Disagree	0	1	1	0	0	0	0	0	0	0	
	Disagree	0	1	2		Disagree	0	1	0	0	0	1	0	0	1	0	
	Neutral	3	3	3		Neutral	1	0	1	1	1	0	1	2	2	2	
	Agree	3	6	3		Agree	1	1	1	1	3	2	1	2	0	0	
	Strongly Agree	6	1	3		Strongly Agree	2	1	1	2	0	1	2	0	1	1	
Q4	Stongly Disagre	1	1	1	Q4	Stongly Disagree	0	1	1	1	0	0	0	0	0	0	
	Disagree	0	4	2		Disagree	0	2	1	0	2	0	0	0	1	0	
	Neutral	0	0	0		Neutral	0	0	0	0	0	0	0	0	0	0	
	Agree	5	5	3		Agree	1	0	0	3	2	2	1	3	1	1	
	Strongly Agree	6	2	6		Strongly Agree	3	1	2	0	0	2	3	1	2	2	
Q5	Stongly Disagre	2	1	3	Q5	Stongly Disagree	0	1	1	2	0	1	0	0	1	1	
	Disagree	0	4	3		Disagree	0	1	0	0	3	0	0	0	3	0	
	Neutral	0	3	5		Neutral	0	1	2	0	0	3	0	2	0	0	
	Agree	4	2	0		Agree	2	0	0	2	1	0	0	1	0	0	
	Strongly Agree	6	2	1		Strongly Agree	2	1	1	0	0	0	4	1	0	0	
Q6	Stongly Disagre	2	0	4	Q6	Stongly Disagree	0	0	1	2	0	1	0	0	2	2	
	Disagree	1	2	1		Disagree	0	2	0	1	0	1	0	0	0	0	
	Neutral	1	5	3		Neutral	0	1	1	0	3	0	1	1	2	2	
	Agree	2	2	3		Agree	1	0	1	0	1	2	1	1	0	0	
	Strongly Agree	6	3	1		Strongly Agree	3	1	1	1	0	0	2	2	0	0	