Putting the Stars Within Reach:

NASA 3D data-based models in 3D print and virtual reality applications, and their potential effects on improving spatial reasoning skills and STEM interest in underrepresented groups of young female learners

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Abstract

This study examined the effects of data-based astrophysical 3D models delivered via computer based interactions, virtual reality, and 3D prints, on spatial reasoning skills and interest in science, technology, engineering, and mathematics (STEM) for females aged 9-12, in particular from underrepresented groups. Underrepresented, or underserved, audiences refer to the demographic status of, and the services that are offered or presented to, segments of a community, typically not currently being served within a larger population that might benefit from such services (Williams et al., 2009). Research to date has not focussed on the development of STEM interests and spatial reasoning skills of young females, particularly at the time when such young learners are forming potential identities in or with STEM and beginning to think about educational and career-related options. STEM interest has been shown to be a critical component of developing a STEM identity, and can be intertwined with issues of confidence and self-efficacy for young female learners (see e.g., Bian et al., 2017; Blotnicky et al., 2018; Fouad, & Smith, 1996; Simpkins et al., 2006). Mental manipulation and understanding of 2D or 3D objects has been posited as an important STEM skill, helping to indicate future mathematical success, science performance, and potential pursuit of STEM careers (Ganley et al., 2014; Hegarty & Waller, 2005; Rafi et al., 2005; Uttal & Cohen, 2012; Verdine et al., 2014).

A mixed methods design was used for this research. In Study 1, a qualitative approach examined potential obstacles to and challenges in working in STEM field for females from underrepresented groups. Unstructured interviews with 11 adult females representing diverse groups and various STEM careers yielded important historical perspectives, along with recommendations for building STEM careers for young females today. The recommendations from Study 1 generated three areas that informed the development of Study 2: the critical role of having a strong mentor, role model, or support system in place along the STEM pathway; the need to work with and engage females in STEM activities and subjects when they are as young as possible, preferably while in primary/elementary school; and the importance of developing a sense of STEM self-efficacy in young females.

Study 2 was a quantitative study that investigated the overall research question. Participants were three different groups of young female learners (*n* = 100), ages 9 -12. The participants worked directly with data-based astrophysical 3D models, in short term interventions in formal and informal educational workshop settings. The interventions concatenated concepts driven by current astrophysical data models, providing authentic learning experiences in full and half day formats through coding, 3D modeling, 3D printing and virtual reality, and delivered by women researchers in STEM. The results showed that such interventions that utilized real world data manipulations and 3D applications as part of hands-on activities significantly increased STEM interest for the participants from underserved groups. Results were not significant for increasing spatial ability.

The results are discussed in terms of the need to extend exposure to STEM activities and interventions for females younger than middle school, especially in underserved areas, to encourage interest and self-confidence in further STEM education and future careers. The research also offers recommendations on how to better approach the evaluation of and potential improvement of spatial reasoning skills that take into consideration age and cognitive appropriateness. This study holds promise for helping to engage young and underserved females who might otherwise not have confidence in their abilities or even be aware of their potential to contribute in STEM areas.

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Firstly, I would like to thank my husband John and my children Jackson and Clara, as well as my mother Christine, and the rest of my family (here, I also include my dog Juno), for putting up with me during the entire PhD process. My husband, particularly, took on so much while I was busy with this work, and my children never seemed to begrudge me the extra time spent reading, and writing, and reading and writing some more. They are my Universe.

I was, long ago, the little kid who loved going to school, who looked forward to each and every September with glee. It seems I never grew out of that love as I have been a life-long learner, and in school, really, more than out of it during the course of my life.

To that effect, I must express my eternal gratitude to my advisor Prof. Lisa Smith, my science auntie, without whom this thesis would never have happened. She encouraged me to think big and dream bigger, and I would not be typing this page if it had not been for the encouragement to leap out of my smaller Universe into one a bit bigger. She provided continuous support during my studies, gifting me with me large cupfuls of her patience and perseverance, a healthy dash of her brilliance, and a big sprinkle of her faith in me on top.

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I close by sending out a Universe worth of gratitude to my entire group working with NASA's Chandra X-ray Observatory. I particularly call out Kathleen Lestition who provided the opportunity to join the Chandra team straight out of my undergraduate program, who saw something special and encouraged me to go down paths that hadn't yet been cleared, or that didn't have visible endpoints. Without such support then, I wouldn't have managed to get to this point now. I also heartily thank my science bestie Megan Watzke for hearing me talk about "the thesis" ad infinitum.

Finally, to all the future scientists out there, especially those who might not yet believe it of themselves, the Universe is yours to discover!

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Chapter 1. Introduction

Introduction

This chapter will address the background and origins of the study to investigate the quantifiable effects of data-based 3D models on improving spatial reasoning skills and interest in STEM (science, technology, engineering, and math) fields in under-represented groups of young female learners. This chapter begins by describing the researcher's experiences and interests in relation to the study question, then expands into a brief discussion of the issue at hand. The significance of the research is then presented. The chapter concludes with the outlined structure of the thesis and a list of frequently used or notable terms.

Background

At seven years old, I proudly announced to my parents that I was going to be an astronaut when I grew up. Even though they could not drag me on an amusement park ride more adventurous than a bumper car, my parents apparently thought it best not to discourage me. I had one of those little white plastic Space Shuttle models with a working cargo bay, and for months I would fly it around my room and make up pretend missions with pink and blue Care Bears serving as the crew. Alas, I finally realized that with such a sensitive stomach, being an astronaut was not the career for me. However, with a supportive family and plentiful resources in my school district, I remained committed to working in science.

I completed undergraduate work in biology, specifically molecular biology and parasitology. My interests at the time were focused on bacteria and disease. I was looking through a microscope, at subjects like *Ixodes Scapularis* (the deer tick) and the spirochaetes that can be transmitted from the stomach of ticks to the human blood stream, potentially leading to Lyme disease. But as I neared completion of that degree, which I had quite honestly struggled a bit through, I found that I was more attracted to the computer as a tool for science than I was to any bugs or bacteria. I transitioned into a computer science graduate program after finishing biology, and would continue on to work on the technical side of a NASA space-based mission for over two decades.

Working at this junction of computer science and physics as a young entry-level woman in the late 1990’s and early 2000’s was daunting at times. I recall attending a technology-based conference when I was 23 where I felt incredibly out of place as one of the only young women there among hundreds of participants. At science conferences and meetings I occasionally had to listen to remarks about my appearance, which would leave me feeling that I did not quite belong, even though I had a supportive team back home at my place of work as well as in my personal life. Again, the solid support structure around me kept me anchored in my STEM goals.

Fast forward a little over a decade and I had taken a much more active role presenting the scientific and technological concepts that I worked on with many groups in my local communities to improve communications with different audiences and promote access points to the data. One such presentation was for my 10-year old daughter’s 5th grade class, where I discussed how stars in the Universe evolve, providing a hands-on activity using origami to help demonstrate how massive stars can “unpack.” One of my daughter’s classmates came up to me after the activity and said, “I didn’t know mommies could be scientists.” It was 2015. That simple statement from a young girl about to enter middle school, where a series of placements and decisions would (at least partially) encourage – or discourage - her on a career path, greatly affected me. Though I had been working with young female learners on and off for a good portion of my career, I realized then that I wanted to, needed to, learn much more.

In one of my areas of expertise, computer science (Arcand, 2016), researchers have noted that computer science is the only STEM pathway that has had a *decrease* in the number of women obtaining undergraduate degrees since 2002 (Larson, 2014). In my other field, astronomy, the American Astronomical Society Committee on the Status of Women in Astronomy reported that as of 2013, there were only 95 female full professors in astronomy in the U.S. as compared to 548 male full professors of astronomy (Hughes, 2014). More generally, women made up only about 24% of the U.S. STEM workforce as of 2015 (Noonan, 2017), an improvement from the 7% reported in 1970, but still far from parity. UN Women reported, from studying data on 14 different countries, that female students graduate with a Bachelor's degree, Master's degree, and Doctoral degree in science-related fields at levels of 18%, 8%, and 2% respectively, as compared with 37%, 18% and 6% respectively for male students (Luchsinger, 2017).

There are many reasons as to why more women are needed in STEM, including better job security and pay for women (Langdon et al., 2011), which can have particular impact on the economic stability levels of families (e.g., Anderson, 2016). Beyond equity of representation or issues of economics lie more subtle reasons for improving girls' interest in and potential prospects in STEM fields. From improving critical thinking skills (Duran & Sendag, 2012) to making up well-informed citizenry (Marincola, 2006), STEM issues affect people in the voting booth, in government, in finance, and in the world as a whole. What problems need solving, for whom they are solved, and how they are solved with and in STEM fields is an issue in which all people should participate.

Targeting Spatial Reasoning

Spatial reasoning, the ability to mentally manipulate 2- or 3-dimensional objects to visualize what the objects represent, is currently understood as a critical skillset for a majority of STEM fields. It has long been considered an indicator of success in technical fields, dating back to early 20th century spatial testing on mechanical skills (Shah & Miyake, 2005). Studies have shown that such skills can function as early indicators of later mathematical success (Hegarty & Waller, 2005; Verdine et al., 2014) and of science performance (Uttal et al., 2013), as well as the pursuit of STEM careers more generally (Uttal & Cohen, 2012). Students in middle school classes (ages 11-15) who can successfully complete mental rotations (such as the Tetris block rotation) have been shown to have a higher probability of performing well in science classes, as compared with those learners who cannot (Ganley et al., 2014). The ability to engage in spatial reasoning can, therefore, be an important predictor of achievement in STEM (Dewar, 2018; Uttal et al., 2013; Wai et al., 2009).

Most researchers support the argument that there are differences between males and females in spatial skills, with females exhibiting delayed development (Linn & Petersen, 1985; Maccoby & Jacklin, 1974; Voyer et al., 1995; Yilmaz, 2009). However, there is not a consensus on any explanation for this (Linn & Petersen, 1985; Maccoby &

Jacklin, 1974; Voyer et al., 1995; Yilmaz, 2009). Delays in the development of spatial skills in females have been attributed to a variety of factors ranging from biological, such as hormone differences, to sociological or cultural norms (Yilmaz, 2009). As this is the introduction the groundwork is being layed for this issue, see sections x.x for further detail.,

A growing body of evidence indicates that spatial skills can be improved through targeted programs (Gold et al., 2018; Hwang et al., 2009; Uttal et al., 2013; Yeh, 2007). Hwang and Hu (2013) noted that virtual environments can combine observation and manipulation for learners to improve spatial reasoning skills by providing hands-on digital learning tools and problem-solving activities. The extant literature is not clear, however, on the baseline time limits for such interventions on young female learners. This is further addressed in section xx page xx.

One type of virtual environment includes three-dimensional (3D) modeling, which has become increasingly useful in STEM fields, from chemical compounds and molecules (Bergwerf, 2018), to anatomical representations (BioDigital, 2018), to geographic models of Earth (Cesium, 2018). 3D modeling provides a vehicle to represent and understand scientific data (Khine & Salehm, 2011), particularly when both experts and non-experts are able to manipulate models and gain new perspectives on the data they explore (Amorim et al., 2015; Berra et al., 2014; Craig, Michel, & Bateman, 2013).

Although interacting with scientific 3D data on a computer screen can be powerful, the ability to create a physical manifestation of a model through 3D printing can take things a step further. One of the most popular methods of 3D printing involves additive manufacturing on demand, whereby a material (e.g., sugar, plastic, titanium) is continually added in layers to create an object. Known as fused deposition modeling (FDM), this method has become increasingly more accessible and affordable to consumers over the past 5 years, and has been recognized as having potential for non-experts to work with and learn from 3D models (Takagishi & Umezu, 2017).

As a technologist from NASA's Chandra X-ray Observatory, I collaborated with the Massachusetts Institute of Technology, Harvard University, and Smithsonian Institution specialists in 3D modeling and printing, generating the first-ever 3D print of a supernova remnant using data of Cassiopeia A (Cas A). This unique 3D model, which is freely available for download (see http://chandra.si.edu/3dprint), has been printed and shared with numerous U.S. schools, libraries, Maker Spaces, STEM programs such as Girls Who Code and Girls Get Math, groups of blind and visually impaired persons, members of the Smithsonian Advisory Board, the Smithsonian Secretary, and key politicians such as U.S. Senators Harry Reid, Jack Reed and others.

Rough analyses for preliminary evaluation data (Arcand, 2017b) of self-selected surveys for a small data set (n = 15) of the Cas A model usage amongst American youth populations (middle school to early high school) have shown that such data representation can lead to learning gains and increased interest in astronomy and NASA. This thesis builds on this potential, in particular with female youths. This study explores the outcomes of working with such cutting-edge materials with female youth populations in formal and informal learning environments.

Research Questions

As this thesis concerns young females, especially those in groups who area considered underrepresented, whether by gender, socioeconomic status, special needs/disability, ethnicity/race, income, language, literacy skills, and/or geographic location, it was necessary to gain perspective on possible historical or sociological reasons for young women typically being less engaged with STEM subjects than are young men. Women in STEM have been studied in the literature, but personal recollections have not been examined in light of those recollections as informing current practice. Therefore, Study 1 (qualitative) was designed to address and explore those potentially important historical perspectives to help inform the design of Study 2 (quantitative), which involved working directly with young women. The research questions were:

Study 1:

Specific to STEM fields, what are some of the obstacles and challenges that female-identifying underrepresented groups can face?

Study 2:

What are the quantifiable effects of data-based 3D models and prints on spatial reasoning skills and interest in STEM fields, particularly with young female learners?

Research to date has not focussed on female learners, especially those at an age when they are on the cusp of making educational and career decisions concerning STEM fields. Therefore, this study research used a targeted program designed to assess and potentially improve spatial reasoning skills and interest in STEM fields, using the Cas A 3D data-based model and 3D printing with females aged 11-15. The program was conducted in both formal and informal learning environments, to explore effects on spatial reasoning abilities and interest in STEM fields for underrepresented young females.

Significance of the Research

As mentioned, this research is significant for several reasons. Extant literature has not focussed on the development of STEM interests and spatial reasoning skills of underrepresented young female learners, particularly at the time when such young learners are forming potential identities in or with STEM, and beginning to think about educational and career-related decisions. Spatial reasoning skills are, as noted previously, a very important tool in the learner's toolbox. The amount of time necessary in interventions to impact spatial reasoning skills for such populations also requires examination.

This thesis focuses on specific content areas of astrophysics and computer science, but also incorporates technologies that are more frequently available in formal and informal learning environments in recent years: 3D printing and virtual reality (or other types of extended reality (XR)). The available research at the intersection of astrophysics and computer science with emerging technologies for populations of underrepresented female youths is not plentiful. Investing in younger and underserved populations in STEM is critical to help address inequalities, and must be studied appropriately.

Thesis Outline

Chapter 1

This introduction lays the groundwork for the thesis, including the background, purpose and personal context for two studies that investigate the potential effects of using NASA 3D data-based models on spatial reasoning skills and STEM interest in young female learners.

Chapter 2

Chapter 2 provides background information and a review of the literature behind the development of data-driven 3D scientific models, issues concerning women in STEM fields, and spatial reasoning skills.

Chapter 3

The third chapter describes the researcher's rationale for conducting a thesis with mixed methodologies, utilizing qualitative research for Study 1 to then inform the quantitative research for Study 2. It also provides detail of the instruments and procedures used to collect the data.

Chapter 4

Chapter 4 presents the qualitative and quantitative data and results for the two studies.

Chapter 5

The fifth chapter provides a summary of the thesis and main findings, discussion of the analyzed data and results, contributions to the literature, limitations of the studies, and reflections and suggestions for future research.

Definitions of Terms & Acronyms

The major terms and acronyms used throughout this thesis are provided in alphabetical order below.

3D print	Creation of a physical copy of a 3-dimensional model, typically by a process of additive manufacturing on demand, in which a type of material, for example, plastic, metal, or sugar, is continually added by layer in order to formulate the object (Arcand et al, 2017).
Augmented reality (AR)	A virtual environment that provides the user with an enhanced version of reality (Azuma, 1997), for example, when digital materials are added over a typical view of a

	person, place or thing. Pokemon Go and Snapchat filters are two examples of popular AR-enhanced applications.
Binary code	A system that uses two digits (1 and 0) to represent information, like an “on” and “off” position of a switch.
Black hole	A dense, compact object whose gravitational pull is so strong that — within a certain distance of it — nothing can escape, not even light. Black holes are thought to result from the collapse of certain very massive stars at the ends of their evolution (Arcand et al. 2019; see also chandra.si.edu/resources/glossary.html).
Cassiopeia A (Cas A)	The remains of a star that ran out of nuclear fuel, collapsed, and exploded in a catastrophic event (Orlando et al., 2016).
Cave Automatic Virtual Environment (CAVE)	Usually characterized as a closed round or cube-shaped room with a ring of high-resolution projectors creating a VR environment that interacts with small headsets worn by the viewers, and the software controlling the application (Juarez et al., 2010). Also known as a YURT (YURT Ultimate Reality Theater).
Chandra X-ray Center (CXC)	Where the mission for the Chandra X-ray Observatory is run, based out of Cambridge, Massachusetts, U.S.A., as part of the Center for Astrophysics | Harvard & Smithsonian.
Chandra X-ray Observatory (CXO)	A NASA space satellite that explores X-ray light from the Universe including supernova remnants, black holes, colliding galaxies, etc. (Tucker, 2017; Wilkes & Tucker, 2019).
Electromagnetic spectrum (EMS)	The full range of light, including radio waves, infrared light, microwaves, optical light, ultraviolet radiation, X-rays and gamma rays.
Extended reality (XR)	Umbrella term that describes the combined category of virtual reality, augmented reality, and mixed reality environments.
NASA	National Aeronautics and Space Administration.
Simulator sickness (SS)	A feeling of illness similar to motion sickness that results from a virtual environment.
Spatial ability	How individuals “mentally represent and manipulate spatial information to perform cognitive tasks” (Hegarty & Waller, 2005, p. 138).
Spatial reasoning	Spatial reasoning skills cover both spatial visualization and spatial orientation that relate to mental rotation skills and

	also orientation as aligned to the individual's self or perspective (Hegarty & Waller, 2005).
STEM	Science, technology, engineering, and math – can be applied to fields of study, subjects, careers.
Supernova remnant	The expanding debris field left over from a star that exploded.
Underserved audience	Demographic status of, and the services that are offered or presented to, a particular group; a segment of the community that is not currently being served by an organization that might benefit from such services (Williams et al., 2009).
Universal design (UD)	A set of principles for designing inclusive and accessible materials that can be used by everyone, in that all users benefit (Luna, n.d.).
Virtual reality (VR)	A technology that simulates a participant's physical self in computer-generated environments that adjust to the user's presence to provide a sense of immersion (Faisal, 2017; Johnson, 2016).

Summary

This chapter presented the background and origins of the study to investigate the quantifiable effects of data-based 3D models on improving spatial reasoning skills and interest in STEM topics with under-represented groups of young female learners, including the researcher's experiences and interests in relation to the study questions. It provided an overview of the significance of the research, outlined the structure of the thesis chapters, and concluded with a list terms and acronyms used in the thesis. The next chapter provides a review of the literature behind the development of data-driven 3D astrophysical models being used in the study, spatial reasoning skills, and specific issues concerning women in STEM fields.

Chapter 2. Literature Review

Background & Literature Review

This thesis investigates the effects of data-based 3D models and prints on spatial reasoning skills and interest in STEM in underrepresented groups of young female learners, where underrepresented refers to a segment of a community that is not currently being served equally or in proportion to need (Williams et al., 2009). It is recognized that those who identify as female can belong to multiple sub groups of learners that are considered to be in the minority. It is also acknowledged that issues of intersectionality, how the interconnected nature of identities combine, can contribute to being disadvantaged and cannot be separated from individuals (Crenshaw, 1991). Additionally, it is recognized that among potential cultural biases, stereotype threats, and/or issues with group and personal identities, there is not any single or simple “fix” for the lack of parity in STEM fields, nor do the young learners need “fixing.” As such, the primary research question for this thesis is:

> What are the quantifiable effects of data-based 3D models and prints on spatial reasoning skills and interest in STEM fields, particularly with young female learners?

This research question will be explored with a quantitative study. The secondary research question, addressed with a qualitative study to help inform the quantitative study, is:

> Specific to STEM fields, what are some of the obstacles and challenges that female-identifying underrepresented groups can face?

This chapter begins with background information on the processing of astrophysical data to create data-based 3D visualizations to provide an outline of the importance of taking audience into account when translating such scientific data, and elucidating the choices necessary to create those data representations to provide context and transparency. The chapter then reviews the literature regarding the development of data-driven 3D astrophysical models, spatial reasoning skills, and specific issues concerning female-identifying participants in STEM fields. Reviewing these concepts was critical for the investigation of the research question.

Background

2.2.1 Astronomy Data: A Universe of 1's and 0's

For millennia, humanity has looked up to engage with the stars. During much of that time, human eyes and hands were the main tools available to record or interpret such celestial information, whether through a petroglyph (rock carving) of an ancient sighting of an exploded star (Than, 2006), or a modern painting of a starry night (Temkin, n.d.).

Figure 2.1

Visualizing the Universe: Cave Paintings and Art

Note. Left: A petroglyph in White Tanks Regional Park, AZ that is thought to show Supernova 1006 (star symbol to right of center) among the constellation Scorpius. Credit: John Barentine, Apache Point, Observatory. (Than, 2006). Right: Vincent van Gogh, a Dutch post-impressionist artist (1853-1890) painted "The Starry Night" from his direct observations as well as his imagination, in 1889 (Temkin, (n.d.)). Credit: Wikimedia Commons/public domain https://commons.wikimedia.org/w/index.php?search=starry+night+van+gogh&title=Special:Search&go=Go&searchToken=4lob9pltt57eaqum5u6oy1yn4#/media/File:VanGogh-starry_night_ballance1.jpg

The invention of the telescope about 400 years ago became a preliminary step towards allowing the human eye to see greater distances (Van Helden, 1977). One of the first users of that original generation of telescopes was Galileo Galilei, who made hand-drawn sketches of his observations that revealed details of our moon and noted the existence of satellites around Jupiter (Edgerton, 1984; Whitaker, 1978). Fast forward to today, however, and the technology of the modern telescope has grown exponentially

(Rector et al., 2015). In just the past few decades, the tools available to create representations of objects in our night sky have stretched far beyond the mechanics of human eyes and human hands. There is now highly specialized equipment and detectors with super human vision exceeding what humans can access from an Earth with ever-increasing light pollution (Globe at Night, n.d.), and eyes sensitive only to visible or optical light (Arcand & Watzke, 2015a; Tucker, 2017).

Each band of the electromagnetic spectrum – the full range of light from radio waves to gamma rays – provides different information and insight about objects in space (Meyers, 2013), most of which was unknowable until work began on electromagnetism in the mid-nineteenth century (Arcand & Watzke, 2015a). Since this unveiling of the different kinds of light, numerous tools and technologies have been created to make visible the invisible. For example, NASA's Chandra X-ray Observatory, launched in 1999, explores a high-energy Universe of objects ranging from exploding stars to black holes and colliding galaxies (Tucker, 2017). Chandra is one of the key tools used to explore parts of the multiwavelength Universe that goes beyond the human senses (Tucker, W. H., & Tucker, K, 2001; Wilkes & Tucker, 2019). An important output from Chandra, as well as from the iconic Hubble Space Telescope and other ground and space-based observatories, is the ever-accumulating archive of data that can be used to learn about our Universe (White et al., 2009).

The modern telescope, therefore, not only magnifies, but also amplifies and makes observable information beyond the visible spectrum of light (Rector et al., 2015). Consequently, the translation process that converts raw observational data to visual representations starts with the information obtained by spacecraft detectors and moves down the data processing pipeline through layers of analysis and software to the final image visual outputs (DePasquale et al., 2015; Rector et al., 2015). This process of translation is discussed in the next section.

2.2.2 Translations: From Binary Code to Binary Stars

When a satellite points at a celestial object, such as a binary star system (a pair of stars that orbit each other), the spacecraft's camera records the photons – the packets of energy – that have been traveling for many billions (or trillions or more) of kilometers and transmits them back to Earth via NASA's Deep Space network, encoded in the form of 1's and 0's (binary code). Next, data processors run scientific coding specific to their data to translate the code into, for example, a table plotting the time, energy, and position of each photon that struck the detector during the observation. Further processing can then be performed with astronomical software depending on the type of data and the needs of the researcher (e.g., Chandra Interactive Analysis of Observations (CIAO, http://cxc.harvard.edu/ciao/)) to in many cases form a visual representation of the object (Arcand et al., 2016). From observation of light, to communication of the recorded data, to transformation of that information into various outputs, people are involved in each step of the creation process (Arcand et al., 2013).

Ultimately, the specialists along that pipeline of data processing convert the raw data into an image, removing potential artifacts from the data, if necessary smoothing the data (i.e., reducing noise so that patterns may become noticeable), selecting the field of view, scaling the image, compositing as needed (i.e., co-adding multiple observations), and adding color (Rector et al., 2017). The choices made by specialists during that translation process are done to preserve the scientific information encapsulated in the data, and showcase the content, while often targeting particular audiences (Arcand et al., 2013; Lynch & Edgerton, 1987). The audiences can consist of experts or non-experts, including subgroups from citizen scientists, educators, evaluators, science media creators, and various members of the media or broader public (Viotti et al., 2019). Considering the audience is an important step during the data production pipeline, as discussed in the next section.

2.2.2.1 Audiences in Visualization Creation.

> . . . the real power of visualization is to give a voice to the long misunderstood data of the world. And with that power comes a great responsibility for the creators of such visualizations. (Werthessen, 2016, p. 1)

The many choices that need to be made in representing scientific information affect user response across the expert to non-expert spectrum (Arcand et al., 2013). To better help researchers understand their audiences, and realize how best to communicate the science underpinning the images, scientists, technicians and educators must understand the perceptions of those audiences in terms of both the astronomical images as well as any supplementary descriptive texts. This section will briefly discuss the research on communicating the science underlying astronomical images, providing findings related to gender where available. It is noted that there is little research on astrophysical and related scientific topics image response as reported by gender; moreover, the extant findings relate primarily to adults. Few studies have been conducted regarding potential scientific image response or meaning making with the population of interest for this thesis, which is young female learners.

Additionally, it is important to note that this is an emerging area of research, with many of the investigations currently being carried out by researchers in the Aesthetics & Astronomy group (A&A; see astroart.cfa.harvard.edu), of which this researcher is a member. Outside of astronomy, there is emerging comparative research in scientific image response for climate science (e.g., Harold et al., 2016; Nicholson-Cole, 2005, O'Neill & Smith, 2014), and in nanotechnology (e.g., Landau et al., 2008). Such studies have investigated communication of concepts in those content areas through scientific images, the relationship between viewing time and perception, aesthetics as applied to the choices made by the creators of scientific imagery, and how meaning is created when viewing images specific to the topical themes. One recurring topic in such articles is the general lack of scientific image response studies. Landau et al. (2008) also asserted that there was a lower perceived status being given to research on the communication of concepts through scientific images. Moving beyond scientific fields, there is some similar image response research that has been done or is currently being undertaken in art (e.g., Brieber et al., 2014; Locher et al., 2007; Smith et al., 2017; Smith, J. K., & Smith, L. F., 2001) as well as advertising (e.g., Phillips, 2000).

The next subsections will examine expert and non-expert differences in reactions to viewing astronomical data, including what is being viewed and how (from visual response to color) and the contextualization of such data.

2.2.2.2 Visual Processing.

In the visual processing of an image, what an expert perceives when looking at an astronomical image is not necessarily what the non-expert perceives. Research reported by the A&A group (L. F. Smith et al., 2011; Smith et al., 2015, 2017a) has shown that the expert tends to move from the science to the aesthetics of an image (Smith et al., 2011; Smith et al., 2015). Experts are likely to comment first on what kind of data are in the image, what individual colors might exemplify, and what the image is meant to represent, and then move on to statements such as, "This is pretty cool" or "That's a lovely image of a galaxy." Non-experts more often move from the aesthetics to the underlying science associated with the astronomical image (L. F. Smith et al., 2011). For example, a non-expert might start by saying, "Wow, that's beautiful!" or "How intense and colorful" before eventually questioning, "What does it mean?" or "What does a scientist see when he or she looks at this?"

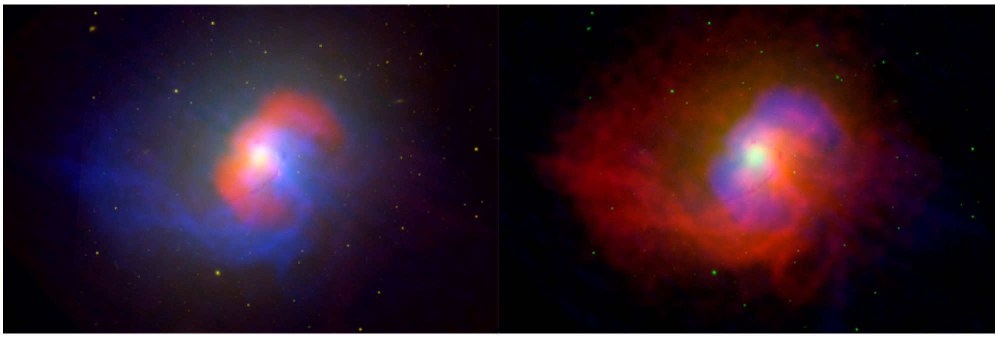
This research suggests, therefore, that non-experts tend to begin with a sense of awe and wonder, and focus first on the aesthetic qualities of the astronomical image being presented. Experts, however, query how the image was produced, what information is being presented in the image, and what the creators of the image wanted to convey before moving to the aesthetics of the image (L. F. Smith et al., 2011, 2015b, 2017a). This is the only research found to date on this specific topic and is an important step in understanding how learners make meaning from astronomical data sets.

2.2.2.3 Color.

Another area in which experts and non-experts differ is the interpretation of colors used in astronomical images. Non-experts tend to visualize red as hot and blue as cool. Indeed, more broadly, humans categorize "warm" and "cool" palettes very clearly as a common constraint across language and culture biologically-based in the human brain (Xiao et al., 2011). L. F. Smith et al. (2011) found, however, that about 60% of experts consider blue as hot, compared to 20% of non-experts. This makes sense when one considers that in astrophysics, scientists classify stars using Planck's law of black body radiation, wherein middle-range stars such as our Sun with surface temperatures around 9,000 degrees F appear yellow, cooler stars around 6,000 degrees F appear red, and hotter stars around 18,000 degrees F appear blue (Gaensler, 2011).

Figure 2.2.

NGC 4696 X-Ray/Infrared/Radio Image in Blue (left) Versus Red (right)

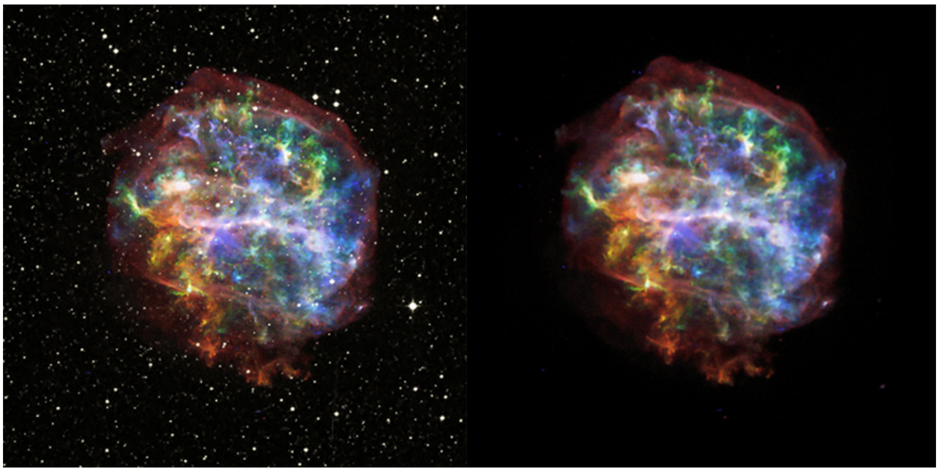


Note. Credit: X-ray: NASA/CXC/KIPAC/S.Allen et al; Radio: NRAO/VLA/G.Taylor; Infrared: NASA/ESA/McMaster Univ./W.Harris

The question arises, therefore, when creating astronomical visualizations that show super-heated material, whether to color such data blue or red for non-expert audiences. The primarily red image might actually convey the heat of the object better than blue to a non-expert audience (see Figure 2.2), even though its color mapping would be considered non-standard for a physicist or astronomer. There is no evidence to date in the literature, however, that these issues of color have been considered for potential interventions for young learners.

Figure 2.3

Supernova Remnant G292.0+1.8 in X-Ray and Optical Light (left) and X-Ray Only Light (right)



Note. Credit: X-ray: NASA/CXC/Penn State/S.Park et al.; Optical: Pal.Obs. DSS

2.2.2.4 Context.

The A&A research has consistently found that providing a suitable contextual background story for scientific data sets helps make images of the Universe more interesting for many viewers (L. F. Smith et al. (2015a, 2017a, 2017b). In an early study, when participants looked at images such as Figure 2.3 without knowing what it is, it might be rated as attractive. But when a well-written and engaging caption was provided along with the image, the aesthetic appreciation of the image significantly increased (effect size of .19) (L. F. Smith et al., 2011). Such research has the potential to inform the creation of astrophysics-related educational activities (see e.g., Arcand et al., 2010).

2.2.2.5 Gender.

Female participants have typically been outnumbered by male participants in studies of astronomical image response, with ratios of 4:1, 3:1, and 2:1, although it is noted that current research has been mostly conducted online with convenience samples (L. F. Smith et al., 2011, 2015, 2017a, 2017b). In-person studies conducted at museums have been more likely to have 1:1 male to female ratios in their samples. (L. F. Smith et al., 2015). Although few astronomical visualization studies to date have reported results by gender, it is useful to review those that reported on the comprehension of astronomical data visualizations by those who identify as female.

In one study (L. F. Smith et al., 2017a) of 1,119 male and 696 female adult participants, males reported significantly higher levels of initial understanding as compared with the females in the study. Analysis showed that initial understanding was related to self-reported knowledge, however. This result is not surprising, as there are a number of studies that have found lower confidence levels in girls and women regarding STEM fields, or over-confidence levels on behalf of boys and men in STEM fields, particularly in mathematics (see e.g., Corbett & Hill, 2015; Heaverlo et al., 2013; Leslie et al., 2015; Pajares, 2005; Perez-Felkner et al., 2017; Sarsons & Xu, 2015; Stoet & Geary, 2018). This finding might be further understood in the context of what has been reported regarding social knowledge of stereotypes, for example, girls aren't good at math or science (Cvencek et al., 2011) (see section 2.6 for a discussion on stereotypes and biases). Studies around such stereotypes have included young men whose self-ratings in science were higher than their female peers when their test results were the same, or young women who reported lower skills in mathematics when their test scores were the same as their male counterparts (Ganley & Lubienski, 2016; Leslie et al., 2015).

Other relevant results were described in two studies that reported on comments by female participants on topics of color and formatting in perceptions of astronomical visualization (L. F. Smith et al., 2015a, 2017a). As part of the data collection, after viewing a set of images, participants were asked what questions they might have for an astrophysicist. In addition to asking questions concerning colors, visual or technological accuracy, and science content, female participants frequently enquired into issues about the fate of the Universe and the nature of existence, as well as in disciplines of philosophy including metaphysics and epistemology. Many of the female participants expressed the desire to learn more about the images but stated that they lacked confidence in their abilities and knowledge related to astrophysics. Such responses were not as prevalent from male participants. It is notable, however, that there were a small number of female respondents who were interested in astronomy visualizations, had technical knowledge, wanted more technical knowledge, and in general wanted more information on images from space (Arcand et al., whitepaper, in progress).

Next Steps

The literature review, presented next, will help establish that females participate in advanced STEM studies at lower rates than males do, and are less likely than males to pursue STEM careers overall. There is some evidence, however, that if young females participate in STEM activities, are assisted to develop spatial reasoning skills, and/or have encouraging role models, they might develop greater interest in and confidence with continuing down STEM pathways.

In addition, 3D printing and virtual reality (VR) and augmented reality (AR) have been shown to be highly engaging in general; yet evidence indicates that technology and computer science are still oriented towards or dominated by males (Larson, 2014; ComputerScience.org, 2020, National Girls Collaborative Project, 2020). Therefore, a high quality STEM program that explicitly makes contemporary science accessible for underserved young females through 3D printing and VR/AR in a focused fashion, including the hows and whys (versus only providing a series of rote facts), that utilizes spatial reasoning tasks, and is presented with positive role modeling, should lead to more positive dispositions and confidence towards STEM-related fields for these underserved females. These topics are explored in detail in this thesis.

In sum, the background information provided indicates that audience must be considered when working with astrophysical data to create such visual representations.

For young female-identifying learners to see themselves on STEM pathways, and to further engage more young women from underserved groups into future STEM careers, it is incumbent upon researchers to put this information into practice. In doing so, interventions created specifically for this audience might help reduce barriers and engage and encourage progress towards these goals.

Literature Review

The following sections review the literature as it pertains to the research undertaken in this thesis.

2.2.3 3D Printing: Reconnecting Science to the Human Hand

3D modeling in science has become commonplace in the past 10 years. From models of chemical compounds and molecules (Bergwerf, 2018), to anatomical representations (BioDigital, 2018), to geographic models of Earth (Cesium, 2018), visual representations of data can "accelerate rapid insight" (Thomas & Cook, 2005, p. 69). 3D modeling offers a relatively new vehicle to represent and understand scientific data, particularly when both experts and non-experts are able to manipulate their models and gain new perspectives on the data they explore (Amorim et al., 2015; Berra et al., 2014; Craig, Michel, & Bateman, 2013).

Although interacting with 3D data on a computer screen can be useful for both specialist and non-specialist audiences, the ability to create a physical manifestation of the model and reconnect science more directly to the human hand – through 3D printing – is a more recent addition to the field of data visualization and representation. 3D printing is a process of additive manufacturing, in which a type of material, for example, plastic, metal, or organic material, is continually added by layer to formulate the object (Grice, Christian et al., 2015). On-demand processes of 3D printing are characterized as fused deposition modeling (FDM) and have become increasingly accessible and affordable for consumers recently (Takagishi & Umezu, 2017). Such processes can make productions of scientific or educational tools possible wherever a 3D printer is located (Clements et al., 2016).

3D printing on consumer scales is still rather new, but the production possibilities are far-reaching. 3D printing applications in science range from plans for an on-demand

and sustainable moon base 3D printed from lunar dust (Klettner, 2013) to medical 3D printing of embryonic stem or skin cells (Everett-Green, 2013).

2.2.3.1 Moving Data From 2D to a 3D Space.

Astrophysical data, and the visualizations from such data, are often two-dimensional (2D). Our perspective from Earth, or even from our farthest-reaching telescopes, primarily offers a flat projection on the sky, but spectral information can restore the 3-dimensionality of the Universe (Ferrand et al., 2016). Although some deep sky surveys, or catalogs, of our Universe contain information about distances to objects for 3D maps of the distribution of stars or galaxies (Devitt, 2012), and large studies are making headway into the 3-dimensional nature of the Universe (Courtois et al., 2013; Mann et al., 2013), it is still less common in the 21st century to have 3-dimensional information about specific cosmological sources that can be easily visualized. Some early, pioneering work in 3D mapping was performed by Geller and Huchra (1998) as they mapped thousands of bright galaxies of a northern part of the observable Universe. The number of specific objects in the Universe that have been mapped in 3D represents a small fraction of the observable Universe; indeed, the process of 3D mapping faces a number of constraints, from data quality and resolution to processing, software, and hardware (Steffen & Koning, 2015). New and upcoming missions are, however, working to try to change some of the constraints. For example, the European Space Agency's Gaia satellite, launched in 2014, is working towards its goal to create a detailed 3D map of a billion stars in our galaxy, the Milky Way (Bauer et al., 2016).

Researchers from computer scientists to astrophysicists, engineers, and other technicians are developing new techniques to help expand astrophysical data visualization within the 2D space and beyond into 3D space (see e.g., works citing Arcand in 2016, 2017, 2018, 2019; Borkin in 2007, 2009, 2010; Christian in 2015; DePasquale in 2013, 2015, 2017; Diemer in 2017; Goodman in 2007, 2009; Madura in 2014, 2015, 2017). 3D visualization lets experts and non-experts view cosmic objects from multiple viewpoints and even virtually travel through them (Arcand et al., 2017; Ferrand & Warren, 2018). Further developments in 3D astrophysical data representation include adding time and velocity, which provide new angles for research and understanding. Research investigating objects over intervals, for example, opening up the *time domain* (Andersen, 2012) can lead to advances in understanding the evolution of stars, galaxies, and the Universe. Also, understanding that objects in the Universe, such as stars, are dynamic can help to negate a common misconception in astronomy that the heavens are static and never-changing (Comins, 2001), an important issue for young learners.

The potential to study celestial objects from multiple sides or viewpoints can provide researchers with a better understanding of how such objects are structured, how the physics underlying them works, and in turn help open access to non-scientists (Arcand et al., 2017; Ferrand & Warren, 2018). Researchers in the field of astronomy, despite the challenges to obtain 3D data, have developed and adapted innovative ways to obtain such information about distant sources, as discussed in the next section.

2.2.3.2 Early Steps in 3D Astrophysics Applications.

Arguably one of the most innovative milestones in the development of 3D imaging in astronomy was the Astronomical Medicine project (see Borkin, 2010). The program adapted brain-imaging techniques and 3D software for use in astrophysical data visualization (Borkin et al., 2007). This technique enabled researchers to generate 3D images of molecular clouds using 3D Slicer software, which could then be interactively included in digital editions of journals, thereby allowing readers to manipulate the 3D model directly in an enhanced PDF (portable document format) (Goodman et al. 2009; Information Today, 2009).

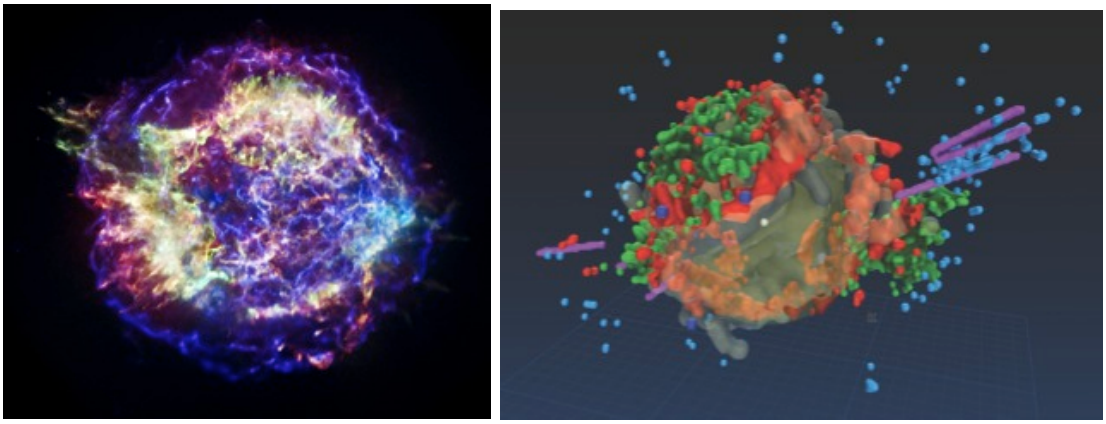
Once Goodman et al. (2009) published their interactive 3D results, the technique was adapted for higher-energy celestial objects, including a supernova remnant Cassiopeia A (Cas A). Cas A was a star about 15-20 times the mass of our Sun (Orlando et al., 2016) that ran out of nuclear fuel, collapsed, and exploded in a catastrophic event. The leftover stellar debris of Cas A continues to expand outwards radially from the site of the explosion’s center (Delaney et al., 2010). To understand Cas A’s dimensionality, researchers used basic geometry and applied the Doppler effect on data from multiple telescopes across optical, infrared and X-ray light. 3D Slicer and similar programs were applied to create a 3D digital visualization of Cas A as an interactive PDF (Delaney et al., 2010).

A version of this 3D supernova remnant was produced (see Figure 2.4) that could be manipulated in a browser by viewing angle and by selection of data set types, for example separated by energy cuts and type (Watzke & Edmonds, 2013). Users could select just the emission of Neon or Argon as observed with Spitzer in the infrared region of the electromagnetic spectrum (EMS), or view the iron emission as detected by Chandra in the X-ray portion of the EMS (Watzke, 2013). Additionally, a fly-through, transparent visualization adapted from the data was converted with commercial 3D software Autodesk Maya (Autodesk.com, 2018) so that textures and colors reminiscent of typical astronomical imaging, and an artistic starfield could be applied for non-expert use of an expert-developed data visualization (Arcand et al., 2017).

This overall Cas A 3D project as described in this section was the first time a supernova remnant had been mapped into 3D based on observational data (Chandra X-ray Observatory, 2009). Producing 3D data of Cas A provided new insights for the researchers who create models of supernovas, that they must calculate for the outer layers of such a star to expel spherically, while the inner layers expel in a disk-like way with multiple jets (Delaney et al., 2010). Additional research groups have worked on 3D modeling of Cas A since the original 2010 Delaney et.al. study, including Milisavljevic and Fesen (2015) and Orlando et al. (2016). This continued research on the dimensionality of the same specific object helps demonstrate the interest and research value of such visualizations for expert uses.

Figure 2.4.

Cassiopeia A in 2D and 3D



Note. Left: 2D Chandra X-ray image of Cas A. Credit: NASA/CXC/SAO. Right: 3D visualization of Cas A that can be manipulated by the user in a browser (http://3d.si.edu/explorer?mid=45). Credit: NASA/CXC/SAO & Smithsonian Institution.

2.2.3.3 Applications of 3D Print Research for Non-Expert Usage.

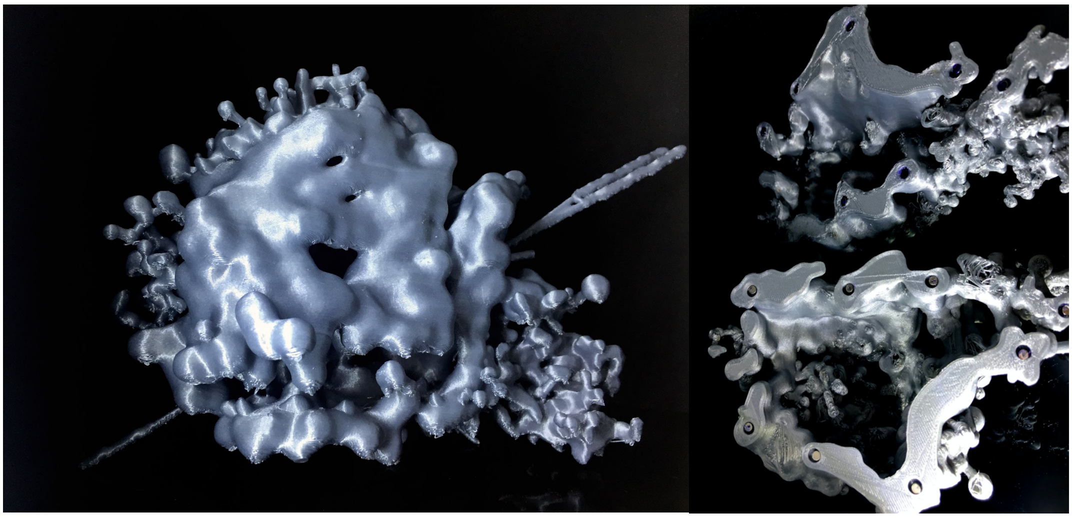
Recent visualization research (L. F. Smith et al., 2017a), explored how unique-looking presentations of an object in deep space, like Cas A 3D, might also affect understanding, engagement, and aesthetic appreciation by non-expert audiences. The online survey asked a convenience sample of adults (*n* = 2,502) to respond to questions regarding a spectrum of Cas A images and videos in 2D, 2D with data-driven time-lapse videos, and 3D, querying what kind of object the image resembled, how appealing the image was to the participant, how much the participant understood of the science, and whether the participant wanted to learn more about the object. Results from this study showed that alternative types of representations, such as in the form of the 3D stills or 3D videos, can and should be used for experts and non-experts, if they are appropriately explained and put into context (L. F. Smith et al., 2017a). Such information, not used to date, holds the potential to be useful in designing research for use in STEM interventions.

As such, though data-based 3D visualizations can be beneficial to non-expert (and expert) populations, the potential also is recognized for non-experts to work with physical 3D models of such data sets. The Cas A project is an example of this. The first-ever 3D print of a supernova remnant was generated from the 3D data (see Figure 2.5a & b.) (Arcand & Watzke, 2016). The Cas A 3D model was formulated in 3D print-ready forms, with support structures (600k triangle OBJ file at 27 MB) and as volumetric data

(ASCII VTK files created from telescope data at 3.94 MB) for printing on most commercial 3D printers (Arcand et al., 2017).

Figure 2.5a & b

3D Printed Cassiopeia A

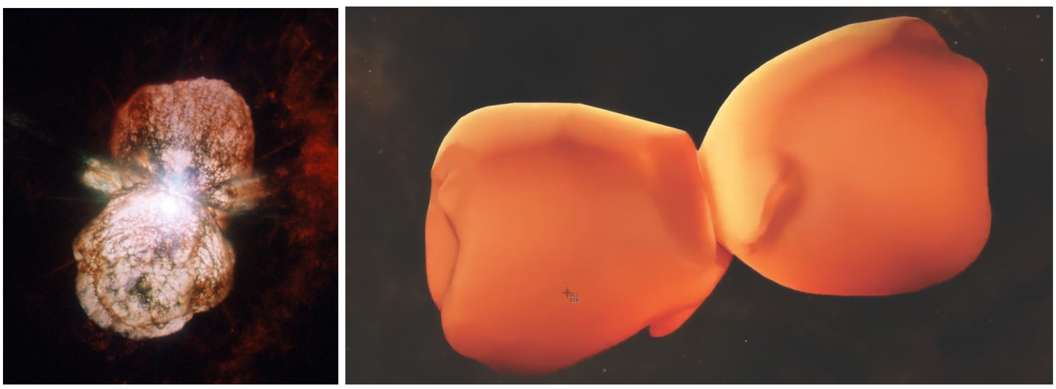


Note. 3D model of Cas A in single (left, a) and dual part (right, b) versions, where dual part offers improved accessibility for visually-impaired audiences. (*http://chandra.si.edu/3dprint/*). Credit: NASA/CXC/K.Arcand

Since the 3D modeling and printing of Cas A, other 3D modeled astronomical objects have also been printed successfully. Moving from stellar death to stellar birth and maturation, researchers have created 3D models of the stellar nursery Eagle Nebula, known more commonly as the *Pillars of Creation*, and the mature star system Eta Carinae and the Homunculus Nebula (Figure 2.6). For these models, researchers used primarily optical observational and spectroscopic data from orbiting and ground-based telescopes to create 3D maps (McLeod, et al., 2015; McLeod & Hook, 2015; Reddy, 2015), though through different mechanisms than described in the previous section on Cas A.

Figure 2.6

Eta Carinae in 2D and 3D



Note. Left: 2D optical image of Eta Carinae/Homunculus Nebula. Credit: ESA/NASA. Right: 3D mapped Eta Carinae/Homunculus Nebula. Credit: NASA/STScI & NASA's Goddard Space Flight Center/CI Lab.

For Eta Carinae, using the SHAPE 3D application, specifically designed for astrophysical data sets (Steffen et al., 2011), astronomers built a printable 3D model of the Homunculus nebula, the bipolar bubble surrounding that star system (Steffen et al., 2014). Further 3D mapping and 3D printing of the Eta Carinae system has also been done across different scales, including the inner winds (Madura et al., 2015). This 3D printing can more clearly display the dimensionality of the system, well beyond that which 2D images can do (Madura, 2017). Importantly, these processes and models also can contribute to designing research on STEM interventions.

There are now other data-driven 3D printed objects from astronomy and planetary geology including, for example, additional supernova remnants (Arcand, Edmonds & Watzke, 2017; Arcand & Watzke, 2019), a binary star system (two stars orbiting each other) (Watzke & Edmonds, 2017), geological maps of our Moon (Ellison, 2014), craters and meteorites on Mars (Capraro & NASA JPL, 2014; Gwinner et al., 2014), asteroids (e.g., Kim, 2018), the Cosmic Web (Diemer & Facio, 2017) and the Cosmic Microwave Background (Clements et al., 2016). The catalog of data-driven astrophysical or geological models continues to grow, and can potentially be used in communicating contemporary science with non-expert audiences.

Astronomical 3D models have been printed and disseminated to U.S. schools and universities, public libraries, STEM programs, government officials, and others (Arcand et al., 2019; Grice et al., 2015). Dissemination has allowed for preliminary testing of the 3D models as discussed briefly in section 2.4.5 below, with researcher examination of user response, potential difficulties in printing quantities on demand, issues when shipping delicate parts, and physical challenges of models being handled by numerous people. However, to date no research has been undertaken to investigate the effects of 3D models on spatial reasoning skills and interest in STEM fields, particularly with young female learners.

2.2.3.4 Applications of 3D Print Research For Non-Expert Usage: Blind and Visually Impaired Populations.

It has been broadly inferred through informal observations that non-expert populations, and specifically students, can potentially benefit from 3D printed models of scientific data (Rennie 2014). Research has been targeted towards learners in higher education, for example, in the modeling of concepts in anatomy, biochemistry, and molecular biology (see e.g., AbouHashem et al., 2015; Hall, et al., 2017; Jittivadhna et al., 2010; Penny, et al., 2017), Rigourous quantitative data of the impacts of 3D printing on young female learners, however, is lacking.

Specifically to populations with visual impairments, however, there are evaluative data that shows potential benefits (Arcand et al., 2019; Christian et al., 2015; Grice et al., 2015). As noted, astronomy tends to be a visuals-heavy field, historically from thousands of years' worth of humans looking up to the night sky to the first generation of telescope users, as well as in modern times with the advent of high-powered multiwavelength distributed spacecraft. Such visualizations have been said to play a significant role in the popularization of astronomy by leveraging "visual economy" (Bigg & Vanhoutte, 2017, p. 118), though they can leave individuals who have no or very low vision behind.

There are an estimated 253 million people worldwide who have visual impairments. Approximately 36 million of the 253 million people are blind, with the remaining 217 million having moderate or severe vision impairments (World Health Organization, 2017). Those with visual impairments have a spectrum of needs that are affected by considerations such as whether blind from birth or later in life, or the ability to read Braille (American Printing House for the Blind, 2016). 3D printed versions of astronomical data have tactile features that have been shown to help communicate both with those who are blind from birth and those who have lost sight, whether all or some, at some time after birth (Arcand et al., 2019; Christian et al., 2015). From "stimulating, building, and reinforcing a person's mental model" of the objects to self-reported comprehension and learning gains, positive outcomes have been reported, including the ability for some participants to visualize the data being modeled (Christian et al., 2015, p. 43).

Evaluations of user experiences with the Cas A 3D printed model and similar data-driven 3D astronomical prints with young adult learners who are blind or visually impaired have demonstrated learning gains (Arcand et al., 2019). Participants' comments ranged from, "I learned what stars looked like when they exploded" to "[I learned] how stars die and if they want to, blow up and 'vomit hot gas'" (Arcand et al., 2019, p.12). The preliminary user studies, with participants ages 16 and up, with the large majority being adults, also suggested that working with the 3D printed models may have an effect on how participants relate to astronomy, or how participants view themselves in relation to science.

Such 3D printed visualizations can, therefore, help provide learners with visual impairments access to astronomical data in a way that is difficult to experience otherwise. Building spatial reasoning skills, additionally, has been shown to be very important for success in STEM (as noted in section 2.6.6), but is often less developed in underrepresented groups (Jones & Broadwell, 2008). When said data are, additionally, coming primarily from observatories built with taxpayer funding in the U.S. and elsewhere, providing equitable access to that data should be a given, and not an exception (U.S. Senate, 2017).

2.2.3.5 Practical Challenges in 3D Printing Astronomical Objects.

There are numerous challenges users may face in 3D printing objects in general, and more specifically in printing 3D astrophysical models. These challenges include navigating diverse sets of file formats, including proprietary formats, working with long print times, handling physically complex models, and removing support structures. Such issues need to be taken into consideration for potential incorporation of 3D prints into producing viable products for STEM programs.

2.2.4 Virtual Reality (VR): Definition & Examples in Astronomy.

Virtual Reality (VR) is a technology that simulates a participant's physical self in computer-generated environments that adjust to the user's presence to provide a sense of immersion. It has been increasingly adopted in the past decade for consumer markets and products. VR has been developing as an idea since the mid-20th century, although practical applications began in the 1980s, with consumer options at market in the 1990s (Faisal, 2017; Johnson, 2016). VR has had some slow starts in its development

(Stein, 2015). For example, in the late 1990s there was a push for browsers to support VRML (Virtual Reality Markup Language) and a host of low-quality 3D web sites available ranging from primitive virtual tours of galleries and spaces to clunky VR-like social meeting spaces that did not reach their portended success (Jensen, 2017).

Gaming, media, and adult entertainment industries have been some of the primary forces behind the recent technological push in the successful commercial development of VR (Morris, 2016), along with healthcare, real estate and architecture based industries (Jenkins, 2019). With this increased output of commercial experiences, there is an opportunity for science and science communication fields to take advantage of increased access to VR technology through the availability of less expensive and more user-friendly equipment than was previously available (Ferrand et al., 2016).

Therefore, not only does VR have the potential to change how science experts visualize and analyze their data, it also holds promise for how those data are communicated with non-experts. From cellular or molecular biology to environmental science, it is increasingly being used in medical settings (Isenberg, 2011). These include applications for virtual surgery training in medicine (Murphy, 2018), helping practitioners obtain a better understanding of brain damage (Hung et al., 2014), and exploring new treatments for Alzheimer's disease (Garcia-Betances et al., 2015). VR has been shown to improve upon existing models of medical training by assisting medical students prepare to help patients in higher risk categories by providing life-like scenarios (Murphy, 2018).

In terms of astronomy, rich astronomical data sets can offer high-resolution, multi-wavelength, multi-dimensional, and lately, even multimessenger data. Multimessenger data in astronomy, goes even beyond the electromagnetic spectrum and incorporates information based on the detection of gravitational waves (Christensen, 2011). The process of translating photons into 2D astronomical images has been well documented and studied (see the previous description in section 2.2.2; see also Arcand et al., 2013; DePasquale et al., 2015; Rector et al., 2017; Rector et al. 2007), but the transformation of that information into 3D forms that take advantage of human perspective, stereoscopic vision, and cognition for VR less so (Ferrand et al., 2016). Although the Universe itself is multidimensional, as Fluke and Barnes (2016) posited, "Are we making the best use of the astronomer's personal visual processing system to discover knowledge?" (p. 1). It can be argued that this question can be extended to non-experts, including school-age children. Thus, although there are extant VR experiences, VR has a way to go in terms of realizing its potential for both educational applications as well as science communication (Arcand et al., 2018; Eriksson et al., 2014).

2.2.4.1 Applications of VR for Non-Expert Usage: The Universe in VR.

From early astrophysical VR applications based in simulated worlds (see e.g., Farr, Hut, Ames, & Johnson, 2009) to more current astronomical VR experiences in standalone applications (see e.g., Arcand, et al., 2018, Ferrand & Warren, 2018, Russell 2020), such experiences comprise a range of types, including artistic imaginings of what might be, mathematically-modeled data constrained by astronomical observations, and 3-dimensional composites of scientific data. For example, one can experience walking among a handful of exoplanets (planets outside our solar system) through science-informed 3D artists' impressions that have been converted into VR worlds (Howell, 2017), traveling across parts of the Martian surface based on data from the Jet Propulsion Laboratory (Good, 2017), walking on the surface of our Sun (Hinode Science Center at NAOJ, 2018), or viewing radio data cubes of the spiral galaxy NGC 3198 (Ferrand et al., 2016).

There is a 360-degree video application, and VR application, for viewing Wolf-Rayet stars (hot luminous stars with mass greater than about 40 suns that are in a late stage of stellar evolution) from the perspective of the supermassive black hole Sagittarius A* (Russell, 2018, 2020; Watzke & Edmonds, 2018). A black hole is a dense, compact object whose gravitational pull is so strong that within a certain distance of it nothing can escape, not even light (Arcand et al., 2019). When an object such as this is quite literally invisible to human eyes, being able to experience its effects on some of the surrounding stars provides a unique view of a system that can be challenging to visualize otherwise (Tucker, 2017; Wilkes & Tucker, 2019).

In addition to these astronomical VR experiences, Arcand et al. (2018) co-created a VR experience of Cas A. This data-driven 3D visualization of Cas A, as presented in the previous section 2.4.1.2, was first created for research purposes (DeLaney et al., 2010), then converted into a digital interactive for non-experts (3d.si.edu, 2013), and then translated as a 3D printed model (Arcand & Watzke, 2016) as part of a responsive pipeline of 3D model outputs for expert and non-expert usage. A virtual reality experience of the data was, therefore, well positioned as a next step towards a multimodal user experience of such 3D data of a dead star (Arcand et al., 2018). VR experiences such as these can be created for large scale 3D immersive environments such as a Cave Automatic Virtual Environment (CAVE), or adapted for a personal VR device, like the Oculus Rift (Clark, 2014). The next subsection will briefly explore these environments along with the technical considerations necessary to run VR applications with young leaners.

2.2.4.2 Technical Considerations for Virtual Reality Applications.

A VR CAVE is typically characterized as a closed round or cube-shaped room with a ring of high-resolution projectors, creating a VR environment that interacts with small headsets worn by multiple viewers, and the software controlling the application (Juarez et al., 2010). These rooms typically allow from two to perhaps eight people (depending on the size of the CAVE constructed, (see, e.g., YURT | Center for Computation and Visualization, n.d.) to experience a VR application simultaneously, with one person leading the VR perspective through his or her master headset. CAVES are often built at universities, museums, and technological or scientific based research groups rather than at private homes or schools.

The Oculus Rift, Go or Quest, on the other hand, is an example of an individual headset communication device for VR, which is a more singular (and also commercially available) form of VR experience. The individual headset communicates with a nearby laptop, gaming system, or similar computational device (Clark, 2014).

Adaptations of data-driven 3D visualizations have also been created for smartphone usage with inexpensive personal VR viewers made in simple minimalist designs out of lightweight plastic or cardboard, such as Google Cardboard, to allow additional entry points for viewers who do not have access to more costly equipment (Chandrashekar, 2018). At today's pricing, Google Cardboard or a similar pop up viewer might cost $5 US (Amazon.com, 2018a), excluding the price of the smartphone or iPod-like device to drive it. An Oculus Rift or Quest will cost perhaps 10 times that amount (Amazon.com, 2018b), and a CAVE perhaps 200 times that or much more (Juarez et al., 2010).

Additionally, the built-in VR-like viewing platform of YouTube is currently a popular platform among both children and adults. One report by a parental app nanny service stated that children under 8 spend 65% of their online time on YouTube, and that the 20 top YouTube children's channels had over 5.2 billion views in October 2015 alone (Family Zone, 2016; Dredge, 2015). Also, A. Smith and Anderson (2018) noted that 73% of adults reported using YouTube. Developers can, therefore, leverage this platform to provide YouTube 360 video versions of their VR applications for wider dissemination to communicate science with non-experts and experts alike, particularly in schools (Burns, 2016). YouTube 360 videos require no additional hardware or specialty equipment, as users can watch them natively within the YouTube application from a smartphone, or via youtube.com in a browser on a laptop or desktop, where the mouse or trackpad provides the interactivity and ability for the user to explore the immersive environment (Borovoy, 2017). This technology, though not as immersive as a full VR experience in a CAVE or headset, is cheaper and easier to access, and could provide greater outreach to underserved audiences, whether underserved in funding, geographic location, or other factors (see section 2.4.8 on underserved audiences) (Chandrashekar, 2018). This holds potential in particular for educational groups or individuals in areas with scarce resources or that are not typically targeted by traditional science communication programs. It can be particularly useful to help inform the development of STEM interventions for young learners who may be located in under resourced areas.

2.2.5 Augmented Reality (AR): Narrative Additions to Science Experiences

Augmented Reality (AR) is a virtual environment that provides the user with an enhanced version of reality (Azuma, 1997). It creates layers of text, image, sound-based elements, and/or other effects to provide additional sensory input, and provides an augmented view for the user experience by typically merging real or "live" and virtual information (Johnson, 2016). AR has been rising in popularity, perhaps even more so than VR, with the number of smartphones, wearable computing devices, and other similar smart devices being promoted to consumer markets (Vogt & Shingles, 2013), and with affordable options being promoted for education (Amer & Peralez, 2014). From popular AR games such as Pokemon Go, which utilizes the user's geolocational information to personalize the interface (Sicart, 2017; Johnson, 2016), to AR animals that zoo visitors can interact with and learn from to help promote conservation (Kiniry, 2017), AR is another useful emerging technology to investigate for designing potential STEM interventions.

Examples of astronomy-related AR applications for free consumer use include Sol AR, a tour of our solar system in AR (Augmented Reality Solar System, 2018), NASA 3D spacecraft in AR, exploring robotic missions such as the Mars Curiosity rover in AR (Dyches, 2018), and USA Today's (2018) 3 2 1 Launch on Space X rocket launch technology via an AR launch simulator. Each of these AR applications leverage existing smartphone technologies supporting interactions in a 3D space with 3D objects (Vogt & Shingles, 2013), to place them in the user's environment (Johnson, 2016).

With these applications, using AR equals less specialized equipment to buy and learn how to work, assuming the user has access to a smartphone and Internet capabilities. In the U.S., about 77% of Americans now have smartphones, and 9 in 10 adults access the Internet (Pew Research Center, 2018a; Pew Research Center, 2018b). Using accessible technology, AR can take objects that might be physically limited in the real world, say a sheet of paper, a toy, a model, or a book, and expand their functions within a digital reality (Martindale, 2016).

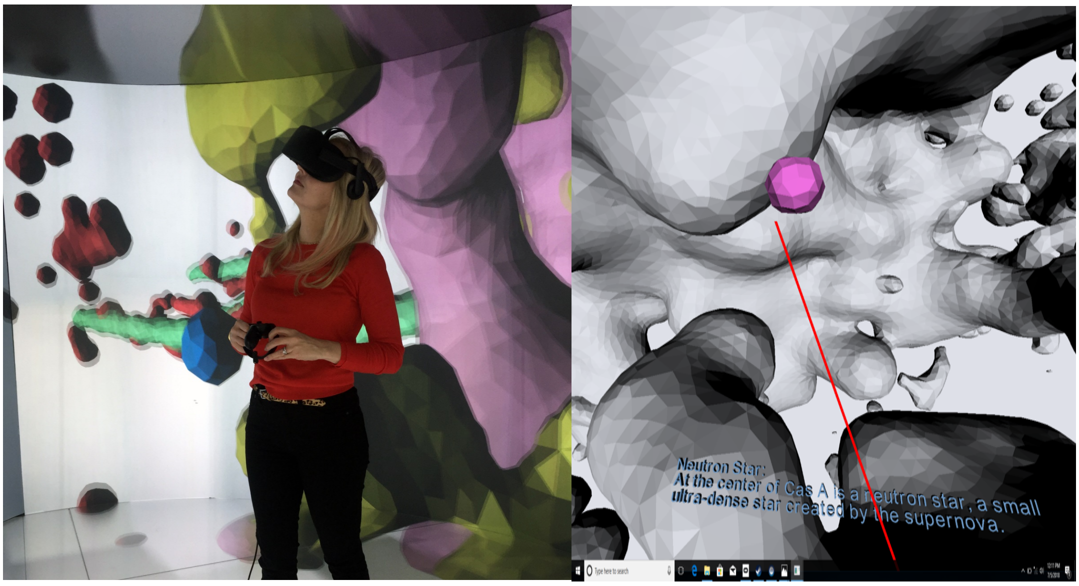
The Sol AR app, for example, through some general exploration and play, offers a simplistic view of our Sun and planets, with one important perceived benefit being that of scale, e.g., the relative distance of the planets' orbits and size of the planets. Research has demonstrated that scale is an important scientific concept for many users (L. F. Smith et al., 2011; L. F. Smith et al., 2017b), but understanding the scale of objects in astronomy can be challenging and complex. Work by Agan (2004) noted difficulties in student understanding of the distances between stars alone. The magnitude of the scales of distance between stars is dwarfed by the distances between galaxies, galaxy clusters, and beyond to the farthest reaches of the observable Universe (Arcand & Watzke, 2017), so the complexities of comprehending Universal scale should only increase with other objects. AR apps, however, might be able to help elucidate the issue of scale for the user, as they can take viewers beyond limitations of 2D representations and use the space in their environment to communicate concepts that take up quite a bit of physical (and mental) room. These applications can potentially contribute to research for STEM interventions with underserved populations of young learners by exploring participant response around scientific topics, issues of scale, or overall engagement levels.

2.2.6 AR Narrative in the VR Space

Research has shown that including contextual information improves the expert and non-expert user experience in both understanding and appreciating 2D and 3D astronomical representations across various technological platforms (L. F. Smith et al., 2010, 2015a, 2017a, 2017b). The 2010 and 2015a L. F. Smith et al. studies, for example, found the need for strong narrative and textual context when presenting astronomical images, as well as for explicit discussion of the colors and what they represent in science images. They also found that a clear sense of physical scale is helpful for comprehension, across all levels of expertise. Additionally, as stated in section 2.4.1 (3D printing), alternative types of representations, such as in the form of the 3D stills or 3D videos, can and should be used, assuming they are appropriately explained and put into context (L. F. Smith et al., 2017b).

Figure 2.7.

Cassiopeia A in Virtual Reality



Note. Left: Virtual reality (VR) application of Cas A allows the user to walk inside the debris from a massive stellar explosion and select the parts to engage with. This photo shows the author inside Brown University's YURT, or VR CAVE, during testing of the Oculus Rift application. Right: A screenshot of Cas A VR shows narrative text, where users can highlight parts of the remnant and access information. Credit: NASA/CXC/SAO/E.Jiang

Therefore, applying those findings to VR data sets seems ideal for increasing comprehension for users at all levels of expertise (Chandrashekar, 2018). With a VR-based high-energy data-driven object such as Cas A, additional context needs to be provided for non-expert users in particular. A 3D visual representation of Cas A, for example, is not what non-experts (or even some experts) might expect to see as a representation of a supernova remnant (L. F. Smith et al., 2017b), especially if the 3D visualization does not resemble a 2D space-based image with, say, a starfield and nebulous material or gas around it. With a lack of standard astronomical visual cues, providing text (or audio) based information as background could be critical for an informed user experience (Arcand et al., 2018[1]).

Due to this visual complexity of the science model for the Cas A VR application, programming responsive text alongside the VR model provides the user with a key narrative component for the overall experience, as expressed anecdotally from users during formative testing of the application (Arcand et al., 2018). The VR experience of Cas A includes descriptions for physical components of the supernova remnant, such as iron, argon, silicon etc., as well as structures like the jets and neutron stars (Arcand et al., 2018). Such features may help educators to effectively tell the life story of a star and provide resources for researchers to observe closely the changes in size, density, and shape of a star across time. Going forward, they have the potential to provide greater access to the science and the story behind the science for a variety of learners in STEM interventions.

One key to making such VR applications move beyond being just a toy or "gee-whiz" moment is to move away from positioning the application as a gimmick and provide meaningful information and content that is clearly embedded in the virtual experience (Thompson, 2016). This type of experience may be able to help learners create a sense of presence with data that, due to the very nature of the extreme

[1] It is acknowledged that a majority of this section comes from a group including the researcher; however, little other work in this specific area, with the goal of qualitative research with young learners, had been conducted to date.

distances from our home planet, the magnitude, type of wavelength or other factors, can be challenging to relate to otherwise (L. F. Smith et al., 2017a). Communication of the science and technology in unique but accessible ways for young learners may also provide additional exposure to career paths and diverse opportunities in STEM, particularly for underrepresented learners (Howard-Brown & Martinez, 2012).

2.2.7 Challenges with VR: Access Points

There are challenges with VR technologies to consider, however. These challenges include visual disconnect causing motion sickness (also known as simulator sickness), the need to incorporate an illusion of boundless movement, accessibility (both for socio-economically underserved areas, but also for physical accessibility by people who are visually impaired), as well as struggles in establishing touch-responsive features (Amer & Peralez, 2014; Disabled World, 2016; Steinicke, 2016).

Beyond possible difficulties for the individual user, in a formal or informal education environment there is the likely additional need to train educators in the use of the 3D/VR application technology – the hardware primarily, but also the software. Additionally, physical access to this technology in informal or formal learning environments might be difficult for underrepresented groups (Chandrashekar, 2018). VR experiences that are not within CAVES, such as head-mounted displays (HMDs), or virtual 3D tables, also tend to be considered as individualized experiences, which could be challenging for educators working with certain groups, particularly children (Zaharias, Michael-Grigoriou, & Chrysanthou, 2013).

2.2.8 Applications and Adaptations in Educational Settings for Non-Expert Audiences: Different Learning and/or Physical Abilities

In education settings, increasing access to VR should be done if concurrently working on ways to include multimodal access points for those with physical or learning disabilities. Such work could be done partially through the dissemination of inexpensive popup viewers such as Google Cardboard, or with 360-degree YouTube videos, that require a smartphone to drive the technology (Chandrashekar, 2018). These applications can act as a canvas for individualized VR experiences tailored to the needs of different learners (Cotabish, 2017).

Such viewer-driven experiences in VR (Chen et al., 2014) could potentially positively affect users with different learning preferences, or viewers with autism (Lahiri et al., 2015), different physical abilities, or other special needs (Tyler-Wood et al., 2015). YouTube driven 360-degree experiences could also help with formal or informal education environments both through a cost and a social participation experience. Though 360-degree videos through YouTube are not as immersive as an HMD or CAVE experience, they might provide a reasonable facsimile accommodation (Locher et al., 1999), in which the viewer becomes immersed in what is being viewed and responds as if viewing an original rather than a reproduction, or visual downgrade.

When creating virtual reality experiences of 3D astronomical data sets for expert or non-expert purposes, it is particularly important to investigate potential access points of such visually-driven technologies for blind and visually impaired (BVI) participants (Disabled World, 2016). Data sonification, for example, is the ability to use non-narrative audio to map scientific data into sound (instead of image) in order to communicate information. This technique has been applied to 2D astronomical data sets (Diaz-Merced et al., 2012; Diaz-Merced, 2013), many of which are time-lapse data sets, the detection of infrequent astronomical events, the detection of orbits that may indicate the presence of exoplanets, or the exploration of low signal-to-noise data in galaxies. Diaz-Merced (2013) researched the use of data sonification as an adjunct to data visualization and found that among the expert population of astrophysicists studied (who had no training in data sonification use), there were positive increases in their abilities to detect signals when the audio data was timed with a strong visual cue to the visual data.

There have been experiments with exploration and presentation of spatially sonified astronomical data with non-experts. For example, Tomlinson and colleagues demonstrated that a mixed visual and spatial audio program was “interesting, understandable, relatable and helpful, even to a sample audience without visual impairments” (Tomlinson et al., 2017, p. 128). Related, planetarium-based experiences focusing on the sounds of the Universe (non-spatially oriented, though in surround sound), while also providing visuals to match have received positive attention from low vision participants (R. Levine, 2018). Adding 3D printed or other similar tactile models to such experiences for blind and low vision participants has helped reach underserved audiences through multimodality (Russo, 2018).

Individualized VR headsets (such as the Oculus Rift and the HTC Vive, the two most popular VR HMDs), are equipped with audio capabilities and can be set up to play sound and also to key sound to specific regions of a three-dimensional virtual space. Adding audio capabilities such as descriptive narrations of what is being seen is a straightforward process and can be added to improve accessibility (Chandrashekar, 2018); this was successfully added to the Cas A VR experience, for example (Arcand et al., 2018). Increasing the accessibility of VR experiences by expanding only visual to include audio descriptions or potentially a form of sonified data can help render such applications compatible. For working with young stem learners in the U.S., for example, compatibility with the Americans with Disabilities Act (ADA) (ADA National Network, n.d.) and alignment with government standards, such as U.S. Section 508, which is a set of standards and guidelines for all U.S. government agencies for accessibility (United States Access Board, 2000), is important for consideration when researching potential STEM interventions.

One potential solution for greater inclusion of underrepresented young learners, therefore, could be the incorporation of the data in such additional scaffolded translations, from audio recordings of meaningful narrative descriptions, to sonification of the data set itself, to inclusion of haptic or touch-based versions of the information. Such layering of information would likely increase the total development time of any single VR application, but would also provide a multimodal experience of sound, sight, and touch in which users of different kinds of abilities would be able to participate (Belardinelli et al., 2009). Accessible technologies such as these, therefore, have the potential to inform research on STEM interventions for young learners from a variety of underrepresented communities.

2.2.9 Applications and Adaptations in Educational Settings for Non-Expert Audiences: Potential Costs and Concerns

VR and AR technologies are currently projected to have a direct impact on about 15 million students in the U.S. alone by the year 2025 (Bellini et al., 2016). The introduction of new technologies into educational spaces is, of course, not new. Merchant et al.

(2014) have noted that educators, whether formally or informally, must weigh the costs both in terms of funding and in time to learn, explore, and teach using such new mechanisms. There are, therefore, numerous questions to be answered from an instructional design standpoint, including the length and depth of VR application most conducive to student learning.

Critics of VR in educational environments have expressed concern that VR and AR emphasize more entertainment than education, or that there is a paucity of research showing actual best use cases and impacts of such technologies (Korbey, 2017). These technologies are still under considerable development so that even the definitions of what AR and VR, or even Mixed Reality, which combines aspects of each to make up the third in a trio of digital realities, are not standardized (Johnson, 2016). Maya Georgieva, co-founder of Digital Bodies, said:

> We are hearing from teachers unanimously that these experiences generate more questions and more engagement in students . . . . For children, it often takes time to create a mental model of what they are learning. Virtual reality provides them with a stepping stone—and possibly a leap—to connect the dots…science teachers are saying VR can help deepen understanding of subjects such as biology and anatomy, which require students to grasp the inner workings of cells and organs that are not visible to the human eye. (Korbey, 2017, p. 1)

It is likely that the benefits of these technologies have the potential to outweigh the costs, both in terms of educational and experiential value as well as in terms of sparking interest in science/STEM subjects, but more studies must be done in order to ensure any benefits outweigh potential costs among participants. New clear and visually interesting VR and/or AR products may help elucidate complex scientific concepts, and provide authentic student-based learning experiences through direct access points to scientific data and subject matter experts, or offer a firsthand view of scientific processes.

With current commercial trends in equipment production, and more translations of expert level, data-driven astrophysical content for VR applications being added (Baracaglia & Vogt 2020; Ferrand et al., 2016; Fluke & Barnes, 2018; Russell, 2020), it is an important time for the production of data-driven science-based content for learners

(Arcand et al., 2018; Ferrand & Warren, 2018). For example, the data that were used for analysis by scientists to discover aspects of Cas A's 3D morphology are being presented across the pipeline of data visualization techniques via emerging technologies, for non-experts to directly explore and experience without artistic enhancement (i.e., using the same version created by scientists, for scientists) (Arcand et al., 2018). Applications of the astrophysical data sets discussed in this section informed the development of the materials used in this thesis, to provide young learners with direct, immersive, and data-driven experiences in VR, with captioning and/or sound, using Oculus Rift and phone-based applications for accessibility (see Chapter 3 for further detail).

2.2.10 Underserved Audiences in STE

The literature reviewed in the previous sections has shown that it is imperative to carefully consider the intended audience when developing data-driven astronomical visualizations, whether in 2D or 3D. The next section of the literature review will discuss evidence of the importance of young female learners' participation in STEM activities, the development of spatial reasoning skills, and the presence of encouraging role models, to open potential future pathways in STEM studies. In addition, this section will establish the importance of 3D printing and VR/AR technologies when engaging with such audiences for such purposes.

There are a number of terms used to define audiences that have historically been excluded from STEM fields. Such groups have been defined as underserved audiences:

> The term “underserved” deals with the demographic status of and the services that are offered or presented to a particular group. It is a segment of the community that is not currently being served by an organization. (Williams et al., 2009, p. 1)

“Underserved” is a commonly used term, often used in a similar way to “underrepresented”. These terms will be used interchangeably in this thesis.

Identifying characteristics of historically underserved audiences, therefore, can include, in no particular order: gender, socioeconomic status, special needs/disability ethnicity/race, income, language, literacy skills, and geographic location. Whether, for example, a person identifies as female, lives in a rural area, is a person of color, is a non-native English speaker, or has a learning disability can seriously affect inclusion in STEM fields (Williams et al., 2009).

Specific to STEM learning, there are several obstacles and challenges that underrepresented groups can face. The next section will provide an overview of some of the issues facing the subgroups of underserved audiences of interest for this thesis.

2.2.10.1 Women in STEM.

The history of women's contributions to the fields of science, technology, engineering, and math is long and varied. But it often has been overlooked, and women remain underrepresented. Today, though women are in every STEM discipline, in every type of job, and represent the widest range of background and experiences, there is not yet parity in representation numbers, pay, or rank. In the U.S. alone women make up about 47% of the overall workforce. That nearly gender-equal percentage does not, however, translate into STEM fields (Bureau of Labor Statistics, 2018). To compare, in New Zealand, women make up about 48% of the total workforce, but are not near parity in STEM fields overall (Statistics New Zealand, 2015)

Women were positioned in about 26% of U.S. STEM jobs as of 2011 (Landivar, 2013), which was a significant gain over the 7% reported in 1970, but still far from parity. Women currently make up about 39% of chemists/material scientists, 16% of chemical engineers, and 12% of civil engineers. The number of women in computer science careers has, however, decreased significantly during the past 20 years, reaching 26% in 2017, down from 35% in 1990 (Bureau of Labor Statistics, 2018). Beyond the U.S., UN Women, in a report on data from 14 countries, indicated that female students graduate with a Bachelor's degree, Master's degree, and Doctoral degree in science-related fields at levels of 18%, 8%, and 2% respectively, as compared with 37%, 18% and 6% respectively for male students (Luchsinger, 2017). To narrow the scope of the representation of women in STEM as more closely related to the topics in this thesis, the areas of women in computer science and astronomy/physics are specifically addressed.

As stated above, computer science is the only STEM career path that has consistently shown a *decrease* in the number of U.S. women obtaining undergraduate degrees since 2002 (Larson, 2014; National Academies of Sciences, Engineering, and Medicine, 2020). In astronomy, the American Astronomical Society Committee on the

Status of Women in Astronomy reported that as of 2013, there were only 95 female full professors in astronomy in the U.S., versus 548 male full professors of astronomy (Schmelz et al., 2014). In 2013, Women made up about 14% of physics professors in the U.S. (Pollack, 2013). For minority women, however, the statistics tended to be much lower. In 2015, there were 83 black American women with PhDs in physics or a physics-related area of study (Pitney, 2017).

Similarly in New Zealand, to compare, though recent enrollments towards science degrees are high, at 64 percent for women, representation is heavily tilted towards health and human subject related occupations, and away from engineering, technology and physical sciences, such as astronomy (Ministry for Women, 2018). For example, women were represented at less than 25% for engineering, and about 33% for technology (Ministry for Women, 2018). As of 2013, women made up 21% of the work force in those three fields (Statistics New Zealand, 2015).

More broadly, representation in STEM careers is particularly low for women of color, where representation in such fields is below representation in the population more generally. For example, Black and Latina women were each represented at 2% in science, engineering, and similar fields, below their representation levels in the U.S. population - at 7% and 8% respectively - as of 2015 (National Academies of Sciences, Engineering, and Medicine, 2020). Overall, only 1 in 10 women of color filled the position of scientist or engineer (National Girls Collaborative Project, 2016).

2.2.10.2 Why More Women are Needed in STEM.

There are a number of factors to consider in arguing for why more women are needed in STEM, as well as issues related to their positions in STEM fields, including better job security and pay (Langdon et al., 2011), as well as other practical and even life-saving reasons.

For example, females can experience more and varied side effects from medications than males do (U.S. Government Accountability Office, 2001); yet, such medicines can be biased towards male subjects (Beerya & Zucker, 2011). Traditionally, U.S. clinical trials did not have to be conducted on both male and female human subjects, with the result of adverse drug reactions more likely to occur in females (the cause of which is still not well understood, though ongoing research points towards combinations of body size, dosage, physiology, drug metabolism, and drug clearance issues) (Soldin et al., 2011; Zopf et al., 2008).

Even after U.S. Congress passed a bill in 1993 to increase representation of women in such studies, there have been reports that a gender bias still exists in medicine in preclinical trials, clinical trials, and biomedical research (Beerya & Zucker, 2011; Kim, Tingen, & Woodruff, 2010; Levine, S., 2014), and a lack of evidence that clinical analyses are specifically including differences in the outcomes of clinical research by sex (U.S. Government Accountability Office, 2015; Hoff, 2019). The exclusion of females from the critical phase of clinical drug trials leaves female patients without the possible personal advantages of new medicines during trial states. Rather, they must wait until the medications are available to the public (Kim et al., 2010), though, it is fair to note that in being excluded, they of course did not suffer any potentially negative effects of clinical trials.

Studies, however, have shown that when heterogeneous parties are included in problem solving tasks, more comprehensive results can arise than if the parties were homogenous (Misao, 2014; Phillips et al., 2008). Therefore, it could be beneficial to include a higher diversity of researchers in fields such as biomedical engineering, where the ratio is approximately 1:6 for female to male workers in the U.S. as of 2016 (Bureau of Labor Statistics, U.S. Department of Labor, 2018).

Additionally, air bags, and related automobile features, have historically been more dangerous for women of smaller stature (as well as children) because engineers originally designed and tested airbags around the male body (Bloch, 1998; Criado-Perez, 2019). Such issues of automobile safety have not been satisfactorily resolved worldwide (Linder & Svedberg, 2018, 2019).

Furthermore, recently there has been a rise of command-based speech towards digital personal assistants that are assigned women’s names and voices. For example, “Siri, play [song name]” or “Alexa, order some paper towels” are types of commands that adults use and even many children may learn to do as they play with smart devices. This could function as a powerful socialization tool that teaches members of society where the role of women, girls, and any who identify as female, is to respond on demand or to be commanded (Lever, 2018).

Beyond representation issues, and beyond STEM jobs and outputs, lie more broad-reaching reasons for improving girls' interest in and potential prospects in STEM fields. From improving critical thinking skills (Duran & Sendag, 2012) to making up well-informed citizenry (Marincola, 2006), STEM issues affect people in the voting booth, in government, in finance, in the world as a whole. What problems need solving, for whom they're solved, and how they're solved, with and in STEM fields, is an issue in which all people should participate.

2.2.10.3 Intersectionality.

> If you're standing in the path of multiple forms of exclusion, you're likely to get hit by both. (Crenshaw, 2016, p. 1)

Crenshaw (1991), an expert and authority in civil rights, Black feminist legal theory, and race, racism, and the law, created the term "intersectionality" to define where the intersection of race and gender bias occurs. She noted that women of color cannot choose to be female one day and a minority the next. There are intragroup differences that must be considered when planning work with underrepresented groups in educational settings (Crenshaw, 1991).

In STEM fields, specifically, biases being encoded into applications and products created with artificial intelligence (AI) or machine learning algorithms, for example, can negatively affect people with darker skin. One MIT study found that facial recognition software has unusually high error rates among darker skinned females, a much higher error rate than lighter skinned females, and a slightly higher error rate than darker skinned males (Buolamwini & Gebru, 2018). An improved skin tone and better gender distributed dataset for AI training purposes was recommended, one that more closely represents the population as a solution to a highly problematic area that has greater implications in search applications and police databases (Lohr, 2018).

Similar issues have been found in physical products, such as auto-dispensing soaps that use infrared technology that do not "see" or recognize darker skin – or even more impactful products such as personal wearable health trackers and heart monitors (Fussell, 2017). Such technological errors and issues could have been avoided or at least decreased by paying greater attention to diversity and having a wider range of people in the technology and engineering fields that do not prioritize a white male body.

A study by the Girl Scout Research Institute (2012) showed that there were multiple issues facing young minority female learners who might be interested in STEM topics, both as far as exposure and as related to specific barriers. Exposure to STEM topics and STEM fields, for example, was reported as lower for both African American as well as Hispanic young females in the U.S. Caucasian female youths were more likely to be familiar with someone in a STEM career (61%), compared to African American (48%) or Hispanic (52%) female youths. Caucasian girls (70%) were also more likely to approach their parent(s) for information on career choices, compared to African American (54%) and Hispanic (54%) girls.

2.2.10.4 STEM and Low Income Students.

For low income students, there might be a significant learning gap (Neuman, 2006). In one of the few large-scale studies found that included young participants in after-school time programs, 1,600 students from grades 4 through 12 of various incomes throughout 11 states in the U.S. took part in about 160 such programs (Ayoub, 2017; PEAR Institute, 2016). Approximately 80% of the students reported positive gains in their STEM career knowledge, while 78% showed a positive change in their reported interests, and 72% reported a positive change in their perseverance and critical thinking skills. Perhaps most importantly, 73% of the students reported an increase in their personal STEM identity, or the belief that he or she can do well and succeed at STEM subjects (The PEAR Institute, 2016). However, it is useful to note that the large-scale results provided from the study did not provide statistics by gender or by the specific age group of interest for this thesis.

Between middle class and low-income children, it has been shown that the loss of access to such after-school programs may result in a 3,000-hour deficit in such extra-curricular learning and engagement by sixth grade ("The 6,000-Hour Learning Gap", 2013). Wealthier families may be able to devote up to 8 times more resources for extra-curricular engagement than families that are less well off (Kawashima-Ginsberg, 2014). Similarly, a study published in 2011 from the University of Virginia found that middle school and high-school students who engaged in such out-of-school-time activities were more likely to have interests in STEM careers as college students than those who had not participated in similar activities (Dabney et al., 2011). Activities ranged from science clubs or camps to competitions, and even reading or watching science fiction or popular science nonfiction (Dabney et al., 2011). Alternatively, a study published in 2017 (Lynch & Kim) investigating the potential for online summer supplemental STEM learning, in this case specific to mathematics, showed positive results for reported engagement levels on behalf of the students in grades 3-9 for which the online learning program and laptop were provided. However, similar results were measured for achievement levels with the experimental and control groups, and no statistical breakdown by gender was provided (Lynch & Kim, 2017).

Additionally, the study from the University of Virginia (2011) reported that young learners who noted an interest in science-related fields by eighth grade were two to three times more likely to earn a STEM degree in college (Dabney et al., 2011). Girls who reported being interested in STEM typically had had greater exposure to STEM fields as compared to girls who reported not being interested in STEM. Therefore, if girls are exposed to STEM in learning enrichment programs, their likelihood of pursuing a STEM career might also increase (Dabney et al., 2011; Maltese & Tai, 2011).

2.2.10.5 STEM and Differently Abled Learners: Blind and Visually Impaired.

There are a number of types of differently abled learners. This section will provide an additional focus on the literature regarding BVI audiences. Finding ways to increase participation for all learners in science and engineering can be a universal challenge, but it can be more challenging for students with disabilities, such as BVI students, as they are underrepresented in these disciplines (Villanueva & Di Stefano, 2017). Approximately 11% of U.S. students in undergraduate programs reported a disability in 2012, and of those 11%, about 23% were enrolled in a science or engineering degree program (National Center for Science and Engineering Statistics, 2017). This compares favorably with the overall percentage of U.S. students seeking STEM-related degrees (about 25%, National Center for Science and Engineering Statistics, 2017). Those rates split further in graduate school with 19% of students with disabilities enrolling in science or engineering related degrees as compared with 21% for those not reporting as having a disability (National Center for Science and Engineering Statistics, 2017). For employed scientists, about one in nine scientists or engineers under the age of 75 reports a disability (National Center for Science and Engineering Statistics, 2017). Comparative statistics on scientists with disabilities in New Zealand were not located online (Statistics New Zealand, 2015).

When considering the particular needs of BVI audiences, especially children, it is important to note that each individual's development greatly correlates with the specific support or interventions that person has received in critical skills (Raisamo et al., 2006). It is also important to ensure that learners who are BVI take part in the development and testing of inclusive resources through the design of interfaces that build upon their different abilities (Skorton, 2018), and draw from a diversity of approaches to data representation that enhances the toolkit of science (Schmelz, 2015). This approach broadens the framework of participation for underserved populations more generally.

Creative spaces for hands-on activities and making (such as MakerSpaces) and related settings emphasize creative participation in the learning process that increases ownership of the material through critical thought, problem solving, and the incorporation of accessible technology in group settings (Giannakos et al., 2015). It also has been shown to increase the engagement and confidence of people with disabilities (Nosek et al., 2016). Sheppard and Aldrich (2001) reported that teachers were highlighting benefits of tactile graphics in that they could help pupils think in different ways, and help get across information that could not be explained in words alone. Many STEM subjects rely heavily on visual resources that can be inaccessible to students who are blind or partially sighted unless the material is presented in an alternative format (Cryer, 2013). Those with low vision or blindness can be particularly challenged in classroom learning, especially in STEM fields where instruction relies heavily on graphically conveyed information such as charts, graphs, diagrams, engineering drawings, data-based imagery, and 3D simulations (Beck-Winchantz & Riccobono, 2008; Cryer, 2013). Finding ways to help facilitate both the presentation and analysis of information in multiple ways and through multiple senses can help users detect details that might potentially be missed by focusing on a single sensory modality. Such methods could enhance the quality of knowledge obtained from the interpretation of results for the scientific community as a whole, BVI and sighted members alike (Díaz-Merced, 2014).

As noted by Jones and Broadwell (2008), “Similar knowledge of shape of common objects and similar principles of depiction are used by both blind and sighted children when interpreting pictures” (p. 287). This similarity illustrates the importance and relevance of “universal design” (Childers et al., 2015, p. 21), which creates objects (whether digital or physical) that are accessible to everyone, regardless of ability. The approximately 60,000 blind students in the United States alone, and 500,000 U.S. youths with vision difficulties or impairments (American Printing House for the Blind, 2016) could, therefore, benefit from STEM educational programming that is specifically designed to help place them on the same footing as their sighted peers. To compare, in New Zealand, there are about 30,000 people overall who are blind or visually impaired, with about 2,700 of them youths or students (Blind Low Vision NZ, 2020).

There are other sensory programs in astronomy in recent years, with some built around sound (Quinn, 2012), others built around taste (Trotta, 2018), smell (Wenz, 2018), or touch (e.g., Christian et al., 2015). 3D prints can help serve the need for specific kinds of access incorporating modalities beyond sight. Research with BVI participants has suggested that, “the visual cortex is really multimodal or a combination of spatial and multimodal” (Jones & Broadwell, 2008, pp. 287-288). It seems reasonable that such multi-modality would be beneficial for both sighted and non-sighted participants.

The next section investigates the importance of spatial reasoning skills for young learners.

2.2.11 Spatial Reasoning Skills

Understanding spatial abilities includes looking at how individuals “mentally represent and manipulate spatial information to perform cognitive tasks” (Hegarty & Waller, 2005, p. 138). Lohman (1993) defined spatial reasoning as "the ability to generate, retain, retrieve, and transform well-structured visual images" (p. 3). Spatial reasoning skills cover both spatial visualization and spatial orientation that relate to mental rotation skills, as well as orientation as aligned to the individual’s self or perspective (Hegarty & Waller, 2005).

The ability to think about objects in multiple dimensions, whether processing 3D information about a molecule or a building or 2D information of a photograph, as well as the ability to draw conclusions about objects, such as in interpreting a blueprint or audio-based directions while navigating to a new location, are all examples of spatial skills (Dewar, 2018; Shah & Miyake, 2005; Thorndyke & Goldin, 1983). In referencing "visuospatial" or "visualspatial", Hegarty and Waller (2005), referred to:

> information that is visual in nature (initiated by stimulation of the retina by light) and has spatial properties (involving the representation of space including relationships between objects within that space), and this information can either be sensed directly or generated from memory. (p. 188)

Spatial reasoning is currently understood as a critical skillset for a majority of STEM fields (Newcombe, 2010). It has long been considered an indicator of success in technical fields, dating back to early 20th century spatial testing on mechanical skills (Shah & Miyake, 2005). Studies have shown that such skills can function as early indicators of later mathematical success (Hegarty & Waller, 2005; Verdine et al., 2014) and of science performance (Uttal et al., 2013), as well as the pursuit of STEM careers more generally (Uttal & Cohen, 2012). Students in middle school classes who can successfully complete mental rotations (such as the Tetris block rotation), for example, have a higher probability of performing well in science class as compared with those learners who cannot (Ganley et al., 2014).

Additionally, very young learners who successfully visualize spatial relationships, either mentally or physically, have been shown to become more math-advanced in elementary school (Zhang et al., 2014). There is also research suggesting that very young learners with strong spatial skills develop stronger reading skills than those without (Franceschini et al., 2012). Spatial thinking can, therefore, be an important predictor of achievement in STEM (Dewar, 2018; Newcombe, 2010; Uttal et al., 2013; Wai et al., 2009).

Another consideration is that learners who demonstrate strong confidence in their abilities of task mastery have been shown to demonstrate better spatial skills than those without confidence (Gold et al., 2018). It would be useful to further investigate if the presence of strong spatial skills is directly correlated with increased confidence in learners, which, as noted above, may also be a critical component of leading to STEM interest in girls.

STEM Focused Studies

Focused studies around spatial skills and 3D objects in learning have ranged from investigations in geometry, to engineering and molecular biology. Manipulating 3D objects such as in learning geometry has been studied (Hwang et al., 2009; Yeh, 2007) with specific attention paid to the ability to use digital models to help "bridge the gap between the mental images of humankind and external representations around the world" (Hwang & Hu, 2013, p. 309). Hwang and Hu also noted that virtual environments can combine observation and manipulation for such learners to improve spatial reasoning skills, providing hands-on digital learning tools and problem-solving activities.

Hansen et al. (2004) compared classroom-based astronomy learning via traditional teaching and content techniques with new techniques where the learners were responsible for computing individual 3D models. Their research found that the learners using the computational techniques developed a sophisticated understanding of the spatial relationships involved in the astronomical concepts. The traditional learners, however, demonstrated an improved grasp of more general astronomical facts and figures.

Martín-Gutiérrez et al. (2010) referenced a digital/virtual teaching tool using AR technology to help in training of spatial abilities for engineering students by providing learners with accessible and inexpensive digital/virtual 3D models. This particular method used a book designed with AR, along with a web cam and average consumer-grade computer. Results indicated positive impacts on spatial skills, as well as on perceptions of usefulness towards learning goals.

Gillet et al. (2004) noted that the use of 3D printed models of complex molecules has become common in molecular biology and related courses at the college level. Researchers are, however, investigating the effect of combining these physical models with emerging technology such as augmented reality. This would allow virtual 3D representations to be projected onto physical 3D prints, making the experience interactive, such that users can access different kinds of information, alternate representations, and display options. In this case, the physical model functions as an accessible, knowable interface for the enhanced computational and digital aspects. More generally, Pan et al. (2006) have demonstrated that virtual learning applications may offer useful tools for participants to learn in a quick and efficient way when interacting with virtual environments. This research, therefore, has potential implications for the study and application of the VR tools and whether the findings could be generalized to STEM and with young learners.

2.2.12 Virtual Reality and Gender

It is possible that individuals who demonstrate difficulty completing visuospatial tasks (e.g., the Tetris block-like mental rotation) are more likely to also experience motion sickness, or simulator sickness (SS), and women typically represent a higher percentage of those who experience SS (Boyd, 2000; Flanagan, May, & Dobie, 2005; Parker & Harm, 1992). Other factors being researched that may influence a higher proportion of women experiencing SS include possible hormonal factors; differences between male-female fields of view, with women typically having a larger field of view than males; and potential issues with self-reporting in the studies, wherein males could be under-reporting their side effects (Johnson, 2007). Additional research in both posture and visual acuity are also under consideration, which posits that females are more able than males to pick up greater detail in a field, which might make women more susceptible to SS (Koslucher et al., 2015). Regardless of the cause(s), such virtual environments and SS studies seem to indicate that current HMD VR systems not only pose some risk of SS, but that such systems may differentially affect females and males (Koslucher et al., 2015). Such findings, if replicated with younger audiences, might indicate that gender must be considered when designing virtual STEM interventions for young female students.

2.2.13 Spatial Skills and Gender

Individuals vary greatly in their ability to carry out spatial skills-based tasks (Thorndyke & Goldin, 1983), even within a gender group (Halpern et al., 2007). Most researchers seem to support the argument that there are differences between males and females in spatial skills, though there is not a consensus on any explanation for this (Maccoby & Jacklin, 1974; Linn & Petersen, 1985; Voyer et al., 1995; Yilmaz, 2009). Delays in the development of spatial skills in girls have been attributed to a variety of factors ranging from biological, such as hormone differences, to sociological or cultural, such as various cultural norms (Yilmaz, 2009).

Research related to sex hormones has noted that the existence of a high percentage of sex hormones in retinas, specifically, indicates the possibility that testosterone can increase a subject's ability to perform certain visual-spatial exercises such as mental rotation (Van Goozen et al., 1995). Though one investigation of female subject menstrual cycles showed spatial abilities changing during the cycle, with testosterone positively influencing spatial skills and estradiol negatively influencing such skills (Hausmann et al., 2000), another more recent analysis on the possible associations between hormone levels in female subjects and related cognitive skills in visualspatial areas cautioned against making conclusions based on small sample sizes (e.g., 12 female subjects) and tracking through only a single cycle (Leeners et al., 2017). Preliminary studies with transsexual participants in a study documented a reduction in mental rotation skills when the participant was taking hormones to transition from male to female, but that research was both incomplete and not replicated (Boyd, 2000).

Moving beyond sex hormones, according to a report by the American Association of University Women (AAUW) (Corbett & Hill, 2015), the stereotype that only boys are interested in or are good at STEM subjects can discourage very young girls from subscribing to an interest in these topics, and/or discourage families from encouraging the activities that might help prepare girls for such fields. Though infants at age 4 months have shown no gender differences in spatial skills (Slone et al., 2018), spatial skill differences by gender are evident by preschool ages (S. Levine et al., 1999).

Spatial skills have been shown to improve through targeted programs (Baenninger & Newcombe, 1995; Newcombe, 2010; Uttal et al., 2013) and in one case, to remove gender-specific differences (Quaiser-Pohl et al., 2006). Thorndyke and Goldin (1983) showed that remediation efforts can focus either on providing the individual with additional cognitive resources (e.g., by teaching effective strategies) or by altering the task to fit existing human capabilities (e.g., by providing additional sources of information).

The literature is not clear, however, on the minimal time allowances required for spatial reasoning increases, however, particularly for young female learners. Lord (1985), showed that 30-minute interactions across 14 weeks could demonstrate visuospatial skill enhancement in post-secondary science majors, but no analyses were reported by gender. Wright et al. (2008) tested improvement capabilities in mental rotation and mental paper folding for post-secondary students (ages 18-43; n = 31) across 21 consecutive days with at least 15 minutes of practice each day. That study showed that improvements in the spatial skills could be demonstrated, and that existing sex differences between the 14 male and 17 female participants could be reduced or eliminated through the interventions.

Related studies have used multiple 1-hour or 2-hour sessions, spread across four or more weeks for college age students in degree programs like engineering, design or architecture, for science majors, or for post-secondary teachers of similar topics (see, e.g., Contero et al., 2006; Dominguez, Martín-Gutierrez, Gonzalez, & Corredeaguas, 2012; Lord, 1985; Martín-Gutierrez et al., 2013; Rafi et al., 2005). One notable study (Feng, Spence, & Pratt, 2007) (*n* = 48, ages 19-30) reported improvements after 10 hours of training for women (as well as men, but to a slightly lesser extent), via video game interventions. One other study published in 1992 with young children as participants (*n* = 23, ages 8-11) described spatial reasoning skill improvements from early VR technology-based interventions, but did not discuss the time, details or testing mechanisms of the activities, nor did it investigate gender differences (Merickel, 1992).

Research results concerning gender and spatial skills development have not established whether spatial reasoning delays in females are part of the reason for smaller percentages of girls being drawn to STEM skills or being retained in STEM tracks from early on. Such may be due to cultural conditions or other societal issues, such as conscious or unconscious bias (Lavy & Sand, 2015), or not (Bach, 2016; Girl Scout Research Institute, 2012), or related to issues of confidence (Heaverlo et al., 2013; Corbett & Hill, 2015; Leslie et al., 2015; Pajares, 2005; Perez-Felkner et al., 2017; Sarsons & Xu, 2015; Stoet & Geary, 2018). It also has not been determined whether there are recommended approaches or minimum time periods for targeted programs to improve spatial skills.

2.2.14 Spatial Skills & Video Games

There is often a negative perception of how video games can affect children (and even adults), as framed in the media (Dewar, 2013), However, multiple studies have investigated the potential for positive impacts that video games might have on cognitive abilities beneficial to scientific thinking, such as spatial rotation skills and reaction times (Boot et al., 2008; Choi, & Feng, 2017; Dye, Green, & Bavelier, 2009; Feng et al., 2007; Green & Bavelier, 2007; Redick & Webster, 2014; Wu et al., 2012.). Palaus and colleagues (2017) analyzed 116 scientific studies on video games and brain health or brain functionality and found positive effects on attention and efficiency, and an increase in efficiency and size in regions of the brain related to visuospatial skills (though they also noted from the meta-analysis negative potentials in both attention and addiction issues). More specifically, Feng et al. (2007) concluded that improved spatial attentional capacity and function could be affected through interventions with interactive action-based video games such as Halo or Grand Theft Auto, which may help to address the potential gender disparity in spatial attention.

Whereas Reilly et al. (2017) partially linked girls' seemingly reduced levels in spatial abilities to perceived incompatibility of activities that build skills in spatial abilities with female gender roles, the competencies developed and tested in such interactive first-person games could potentially be integrated into formats more appealing to those who identify as female. If adolescent girls were not stereotypically discouraged from gaming as a hobby, gamified interfaces might, therefore, work as an intervention for spatial skills.

Studies on whether emerging technologies can help to improve spatial skills and interest in STEM for underserved young females are lacking. The research to date suggests that it might be feasible that a high quality, targeted program could improve spatial reasoning skills for young females. Improvements in spatial skills might lead to improved interest, confidence, or science identity, as well, as discussed in the next section.

Biases, Role Models and Identities: Additional Socio-cultural Issues in STEM

Multiple studies have shown that STEM skills are learned (Hill et al., 2010) and gender bias still has a negative impact on girls' noted interest in STEM fields from a very early age. Work from Spencer et al. (1999), for example, demonstrated the strength of stereotype threat for girls in mathematics testing among top math performers, where even the mention of gender bias in a test led to reduced performance for female participants. Group stereotypes (whether based on gender or race) "can threaten how students evaluate themselves, which then alters academic identity and intellectual performance" and can affect "members of any group about whom negative stereotypes exist" (American Psychological Association, 2006, p. 1). Gender bias not only supports the perception that science and mathematics are “for boys,” but more importantly, that stereotype threat can lead to girls’ performance anxiety and low expectations on academic tests (Doyle, 2016).

A growing body of research has shown that there are significant sociocultural roadblocks for women in both the computer science and engineering fields. These barriers can greatly hinder determination of selection and study (Cheryan et al., 2015; Ceci et al., 2009). A meta-analysis conducted by Cheryan et al. (2017) of 1,200 papers on gender gaps in computer science, engineering, and physics, pointed to three primary issues. These included a masculine culture, which included three sub-issues of incompatibility stereotypes, negative stereotypes, and lack of role models, that can lead to women feeling less welcome in those fields; less early exposure or work within those fields; and reduced self-efficacy. The researchers noted that STEM programs could benefit by addressing problematic cultural issues as well as by building awareness in girls and boys that both are equally capable of succeeding in STEM careers.

It has been shown that even something seemingly minor, such as changing out posters and other décor in a computer science classroom to be less male-centered or geeky (e.g., Star Trek, Call of Duty) and more gender-neutral (e.g., images of nature or art), can help high school girls feel more welcome and more apt to opt in, while also not discouraging boys (Cheryan et al., 2015). This issue of belonging is likely linked to STEM identity, as discussed in the next subsection.

2.2.15 Identity

As mentioned briefly in section 2.4.8.4, a personal STEM identity is the belief that one can do well and succeed at STEM subjects (Ayoub, 2017). The social aspect of the STEM identity is where participants can visualize themselves “accepted as a member of a STEM discipline or field” (Kim et al., 2018, p. 3). There may be a number of factors related to STEM identities that make it challenging, particularly for underserved groups like young women of color, to adopt such an identity for themselves (Steinke, 2017). Negotiating an identity as a girl or woman (and likely additional groups) while also adopting an identity in STEM can be challenging, though also eventually beneficial (Settles, 2014).

The challenges to reaching such an identity, however, may include not being able to picture oneself working in STEM, particularly for underrepresented groups (Chee, 2018). Additionally, the socio-cultural cues from others, such as those who seem to indicate that STEM is not cool and, therefore, is less acceptable among peers (Steinke, 2017), or that women do not belong, particularly women of color (Kim et al., 2018), can be challenging. Self-efficacy is often lower in females than males generally (Gnilka & Novakovic, 2017), and related self-efficacy issues of belonging and confidence (Settles, 2014) can therefore be difficult to navigate in formulating the STEM identity. Importantly, however, recent research has demonstrated that through interventions, STEM identity challenges can be positively influenced (Kim et al., 2018). The next two subsections briefly present two categories of biases that women in, or interested in, STEM can face.

Sections 2.2.14 and 2.2.15, therefore, each relate to Bandura's theory of self-efficacy, which concerns one's belief in one's capabilities to perform tasks in specific domains in order to bring goals to fruition (Bandura, 1997). In these two sub-sections, self-efficacy relates to the importance of both mentorship, in regards to influence from others, and identity. Self-efficacy can influence what choices and effort an individual will make to reach such goals, and also, importantly, if the individual will persist through difficulties and challenges to obtain those goals (Bandura, 1997; Rittmayer & Beier, 2008). According to Bandura, there are four major sources of self-efficacy: performance accomplishments, vicarious experience, verbal persuasion, and emotional arousal (1977, p.195). Bandura's work further states that individuals with higher states of expectation towards self-efficacy, or the belief that they will be able to achieve their goal(s), tend to be more successful in comparison with individuals with lower expectations towards their self-efficacy. This is a useful topic as success in STEM subjects requires a strong sense of one's ability to succeed in such topics, and females can have lower senses of self-efficacy towards STEM than males (Williams & George-Jackson, 2014).

2.2.16 Explicit Gender Bias

A 2011 University of Wisconsin-Milwaukee and National Science Foundation report, based on over 5,500 participants of women in engineering, stated that women who left the field of engineering were more likely to have done so because of sexist behaviors in their workplaces and feeling undermined by their managers or peers, as compared with women engineers who stayed in their field (Fouad & Singh, 2011). Women who left the field were also not as likely to report educational or advancement opportunities on the job, nor general support for a work-life balance, as compared with women who stayed (Fouad & Singh, 2011). Therefore, women tended to leave not because they were lacking in skill or knowledge, but because of work environments that were less civil or supportive for women (Doyle, 2016). This may point to a possible explicit bias, or a bias that is more consciously held and that shapes how behavior towards certain groups of people is evaluated (Handelsman & Sakraney, 2015), and that could affect perceived notions about STEM careers for those who are making decisions on which fields to pursue (Girl Scout Research Institute, 2012; Girlguiding, 2016).

2.2.17 Implicit Gender Bias

According to an American Association of University Women (AAUW) report, "women and men are exposed to the same stereotypes about women in math and science in U.S. culture and, on average, acquire the same implicit or unconscious 'science/math=male' biases by age 7 or 8" (Hill et al., 2010, p. 56). This bias is implicit, or the unconscious assumption that influences our judgment and perceptions of others (Handelsman & Sakarney, 2015), versus the more explicit bias described above. Studies have shown, for example, that many people, even scientists themselves, can maintain an unconscious belief that women are inferior in STEM fields or carry implicit assumptions regarding gender roles (see Caplar et al., 2016; Handley et al., 2015; Knobloch-Westerwick et al., 2013; Macaluso et al., 2016; Milkman et al., 2015; Moss-Racusin et al., 2012; National Research Council, 2010; Wennerås & Wold, 1997; West, et al., 2013). Such unconscious biases can affect how adults talk to children, how family members select toys for them, and how educators address them in environments for learning (Hill et al., 2010).

2.2.18 Role Models

As noted above, having a lack of visible role models in STEM fields currently underrepresented by women can be problematic. Lockwood (2006) stated that women specifically require female role models for success to feel attainable. Such a dearth of female role models has been shown to exist particularly in the media, with less representation than in reality (S. Smith et al., 2012). A worldwide study of over 4,000 women on the representation of women in film and television, for example, reported that about 90% of participants indicated female role models in the media are important, and about 60% reported female role models in the media had had influence in their own lives (Geena Davis Institute on Gender in Media, 2016). Recent reports have shown that role models positively affected the development of interest in careers for 1,600 girls and young women aged 7 to 21; whereas, the lack of such role models negatively affected the development of interest (Girlguiding, 2016). When females aged 11-21 discovered the lack of women representation in many leadership positions, 45% noted that they felt that they had less chance of success, as well (Girlguiding, 2016).

It has been known for over three decades that interventions with women scientists for adolescent female learners can positively affect female learners, and benefit adolescent male learners as well (Smith & Erb, 1986). From demonstrating higher rates of interest in the subject matter than participants who did not speak with a female scientist engineer (Girls STEAM Ahead with NASA & NASA's Universe of Learning, unpublished, 2017), to increasing the percentage that enrolled in science programs after high school (Breda et al., 2018), very short-term interventions (of approximately one hour) have been shown to produce positive results for female learners. Furthermore, exposure to role models is likely closely connected to formulating a stronger sense of STEM identity (Rosenthal et al., 2013; Young et al., 2013).

Summary

Research findings have established that females do not participate in STEM studies as much as males and are less likely than males to pursue STEM careers. This literature review has demonstrated, however, that there is some evidence that if young females participate in STEM activities, are assisted to develop spatial reasoning skills, and have encouraging role models, they are more likely to become more interested in continuing with STEM studies. In addition, 3D printing and VR/AR have been shown to be highly engaging in general; yet, evidence indicates that those areas and activities are still oriented towards or dominated by males. Therefore, a program of high quality that explicitly brings 3D printing and VR/AR to underserved young females in a focused fashion, that utilizes spatial reasoning, and is presented with positive role modeling, should lead to more positive dispositions towards STEM-related fields for these underserved females.

This thesis will focus on the potential for improving spatial reasoning skills and encouraging STEM interest in underrepresented groups of young female learners, recognizing that those who identify as female can belong to multiple sub groups of underrepresented learners, and that issues of intersectionality cannot be separated from individuals (Crenshaw, 2016). As stated at the outset of this chapter, it is recognized that among potential cultural biases, stereotype threats, and/or issues with group and personal identities, there is not any single or simple mediation, nor is the researcher suggesting young female learners need to be "fixed." The intent is to investigate potential interventions that may be implemented to help counteract cultural biases (implicit or explicit), and create such tactics or strategies towards the overall goal of improving accessibility, interest, and parity. With that said, the author restates the primary research question for this thesis as:

> What are the quantifiable effects of data-based 3D models and prints on improving spatial reasoning skills and interest in STEM fields in under-represented groups, particularly of young female learners?

The next chapter describes the researcher's methodologies used for investigating the research question. A mixed methods approach is presented, utilizing qualitative research for the initial study (Study 1) to inform the design of the quantitative research for the second study (Study 2). It also provides details of ethical procedures followed, the instruments and procedures used to collect the data, methods of analysis used, and issues related to validity, reliability, and trustworthiness.

Chapter 3. Methodology

This chapter will address the methodology that was used to investigate the quantifiable effects of data-based 3D models and prints on improving spatial reasoning skills and interest in STEM fields in under-represented groups of young female learners. This chapter begins by describing the methodological framework that was used to examine that research topic. The justification for using mixed methods, using one qualitative study and one quantitative study as the foundation for the design, will then be presented. That is followed by the research design, ethical considerations, and methods of analysis, presented separately for each study. This chapter concludes with how the qualitative and quantitative data were integrated, and discusses issues related to validity, reliability, and trustworthiness.

Pragmatism and the Mixed Methods Design

Mixed methods research is an inclusive, complementary, and creative form of research that allows the researcher to integrate more objective data collection and analyses in quantitative techniques (such as surveys) with more typically value-bound qualitative techniques (such as interviews) to provide a workable approach to exploring a research question (Johnson & Onwuegbuzie, 2004). In quantitative research, objectivity is necessary and obtainable with the goal of results that can be produced both reliably and validly; in qualitative methodologies, a researcher can prioritize relativism and humanism in the research, often utilizing rich, empathetic description. Additionally, in both quantitative and qualitative methods, researchers use techniques designed to obtain the most amount of meaning from the data that is feasible without going beyond the limitations of the data (Onwuegbuzie & Leech, 2005). Leveraging mixed methodologies, therefore, allows for a potentially more in-depth examination of a research question by combining objective techniques with the "voice" of the participants.

Thus, in this research, a mixed methods approach was used to both inform and augment the quantitative analyses with qualitative information. In particular, the qualitative data were used to assist with theory building, to add clarification for the quantitative research design, and to help interrogate and illustrate the data obtained from the quantitative data collection (Onwuegbuzie & Leech 2005). In this case, a monomethod (of either just qualitative or just quantitative design) would not have maximized the ability to investigate the research topic. Therefore, the research for this thesis was conducted in two studies. The first was a qualitative study, involving personal interviews; the second was a quantitative study, using evaluations and surveys.

The first part of this research was a qualitative study that, as stated, was conducted to inform the theoretical groundwork and design of the quantitative study, as well as to help not only explore but also make sense of the data collected in the quantitative study (Creswell, 2009). The following quantitative study formed the majority of the research to address the stated research questions. Therefore, the progression of qualitative leading to quantitative was selected because in that way, the mixed methodologies could provide an “interactive continuum” for the research (Onwuegbuzie & Leech, 2005, p. 380). It was clear that a qualitative approach for the first study would help identify the most important variables to examine in the main body of research, and provide some flexibility in investigating and framing the research, while a quantitative approach for the second study would ground the structure of the inquiry (Creswell, 2009).

Mertens (2010) outlined the use of mixed methods in addressing issues of social justice or human rights, in particular with underserved communities and underrepresented populations, as is central to the research question. As the researcher is a member of the broader community upon which this thesis is focused, her background and experiences could not practically or completely be separated from the research questions or methodologies. As such, using mixed methods was also chosen to help further reduce potential weaknesses such as biases of the researcher, and build upon complementary strengths of knowledge frameworks, experiences, and networks (Morgan, 2007).

With the use of both qualitative and quantitative approaches, pragmatism (Johnson & Onwuegbuzie, 2004) was chosen as the research paradigm for the study. Pragmatism was selected as it allows that there is a subjective reality or “real world,” although within that subjective reality there are different world views or perspectives

(Johnson & Onwuegbuzie, 2004). Pragmatism, therefore, frames the combination of those perspectives in considering the stated research questions with an eye towards “workability,” while understanding that “our values and our politics are always a part of who we are and how we act” (Morgan, 2007, p. 70). A strong value of pragmatism for this research is the rejection of having to choose between information gained in context, and universal or generalized information. Rather, pragmatism permits combining the knowledge gleaned from one method (qualitative) and using it to direct or frame the information to be collected in another method (quantitative) (Morgan, 2007).

Finally, it has also become more prevalent in research to use mixed methods as related to educational outcomes, as mixed methods can help capture both precise measurements while also capturing the social and cultural contexts specific to the educational phenomena (Ponce & Pagán-Maldonado, 2015).

Research Design

As this thesis concerns young females, especially those in underrepresented groups, it was necessary to gain perspective on possible historical reasons for young women typically being less engaged with STEM subjects than are young men. Issues concerning women in STEM have been studied previously of course (see e.g., Cvencek et al., 2011; Ganley & Lubienski, 2016; Heaverlo et al., 2013; Corbett & Hill, 2015; Leslie et al., 2015; Pajares, 2005; Perez-Felkner et al., 2017; Sarsons & Xu, 2015; Stoet & Geary, 2018), but personal interviews that aim to collect information on how early experiences could inform current practice were not found in the extant literature.

Study 1 (qualitative), therefore, was designed to address and explore those potentially important historical perspectives to, as stated, help inform the design of Study 2 (quantitative), which involved working directly with young women to investigate the research question: What are the quantifiable effects of data-based 3D models and prints on improving spatial reasoning skills and interest in STEM fields in under-represented groups, particularly of young female learners? The next section will briefly describe Study 1.

3.2.1 Study 1. Women in Science, Technology, Engineering, & Math: Investigating Obstacles, Biases, and Perceptions

Study 1 was undertaken to gain an understanding of the types of obstacles and challenges that underrepresented groups of females potentially face specific to STEM learning. Therefore, Study 1 explored the following research question: Specific to STEM fields, what are some of the obstacles and challenges that female-identifying underrepresented groups can face? Data were collected by the researcher in a series of individual interviews of women who represented a variety of underrepresented groups and who were currently working in a STEM-related career.

3.2.1.1 Perspective.

It is important to reiterate key relevant points of the literature review to clarify the perspective underpinning Study 1. It is understood that those who identify as female can belong to multiple sub groups of underrepresented learners, for example, as women of differing nationalities or ethnicities, cognitive or physical abilities, socio-economic status, geographic location, etcetera, and such issues of intersectionality cannot be separated from the individuals (Crenshaw, 1991). These identities, of being female, of being a person of color, of residing in a rural area, of being a non-native English speaker, or aligning with another identity, have the potential to seriously affect acceptance in STEM communities (Williams et al., 2009).

Women's contributions to STEM fields, though substantial, are often undersold and not often recognized (Brodérickn & Casadevall, 2019; Dutt et al., 2016; Freund et al., 2016; Moss-Racusin et a., 2012; Nittrouer et al., 2018; Sege et al., 2015). Parity has not been reached in women’s representation numbers in STEM careers, their pay, or their rank as compared to men in the same careers (Holman et al., 2018; Landivar, 2013; Moss-Racusin et al., 2012; National Science Foundation, 2018; Shen, 2013). Furthermore, representation of women in STEM fields is critical for a number of societal issues including nurturing critical thinking skills for well-informed citizens in governmental, commercial, or personal decision making (Duran & Sendag, 2012; Marincola, 2006); providing unique viewpoints and experiences (Buck et al., 2008), to improve the production of materials, goods, or services that benefit women’s health or safety (see, e.g., Beerya & Zucker, 2011; Bloch, 1998; U.S. Government Accountability Office, 2001); and improving job security and equality of pay (Langdon et al., 2011).

3.2.1.2 Participants.

Participants in Study 1 were 11 women currently active in STEM fields, aged 30-70, identified through the researcher's professional networks. The 11 participants were an ethnically diverse sample (representing one Latina, two African-American, one Indian-American participants, and seven white participants) of scientists including astronomers, a cosmologist, a planetary geologist, an astronaut, a biologist, an engineer, a technologist, and a mathematician. Eight were prominent in their fields, and four identified publicly within LGBTQIA+. Although all of the participants gave permission to use their names when reported on in this research, they are referred to in this thesis by their occupations.

The researcher had no supervisory role over any of the participants, or other coercive professional or personal relationships with them that might have made them feel obligated to agree to take part in this research.

3.2.1.3 Materials.

Based on the literature that was reviewed, as well as the knowledge and experience by the researcher as a woman in STEM, questions were developed to guide the sessions. The interviews followed a semi-structured format; but all included the following questions:

1. Please tell me about your educational background and work experience.
2. What was your career path?
3. What were the attitudes towards women in STEM fields when you were starting your career?
4. What made you decide on a STEM career? What sorts of things led you to believe that you wanted to be a scientist?
5. Next, I'd like to know whether you hesitated to pursue your STEM field. If so, why? Did anyone encourage you? Discourage you? If so, how? (note gender of encourager)

6. How many other women were pursuing or had active careers in your field when you started?
7. What might have prevented you from being successful in your chosen field? What hurdles did you need to overcome?
8. How has the climate toward women changed in your field since you started?
9. What suggestions do you have for engaging young women in STEM fields?
10. What suggestions do you have for retention of young women in STEM fields?

3.2.1.4 Procedure.

An email invitation to participate in the study was sent to 12 women in STEM careers, along with an information sheet and consent form. Out of all those asked to participate, only one did not respond. In the email invitation, the researcher offered to call the potential interviewees to discuss the project and respond to any questions prior to the interviewee giving consent. Ten of the participants noted satisfaction with email discussions and did not find it necessary for the researcher to call; one participant requested a short call to clarify the purpose of the interviews and how they would be analyzed.

Once the 11 women who responded to the original email agreed to participate, arrangements were made for a mutually agreeable time for the interviews. Each interview was conducted over the phone and lasted from 60 to 90 minutes. Due to the varied geographic locations of the participants, the interviews were conducted over an iPhone with a recording application installed. At the start of each interview, the participant was provided with a refresher on the study's purpose and an opportunity to ask questions. Each participant then orally confirmed her permission to have the interview recorded.

All interviews were transcribed by a secure digital service and reviewed by the researcher to correct for inaccuracies in the transcription process (e.g., names misspelled or garbled sounds). Participants were provided the transcriptions to edit or delete any sensitive or undesirable information and make other corrections as needed.

Two participants provided edits to the transcripts; one removed a small amount of sensitive information (specific names and dates that had been discussed), another added a few minor notes for clarity (such as a URL).

The interviews took place from March 2018 through September 2019, with the majority of the interviews occurring from March to mid 2018. Reviewing and coding the transcripts, and analyses, occurred throughout the remainder of 2018 through September 2019.

No compensation was offered or requested.

3.2.1.5 Ethics.

The University of Otago Human Ethics Committee approved this research as a Category A application (see Appendix A for the approval letter). Participants were informed of the purpose for which the researcher was collecting the information, and the uses proposed to make of it. They were informed who would receive the information and they were also informed of their rights of access to and correction of personal information. They were informed that the researcher intended to publish the results in her thesis and that it was anticipated that the results would be presented at a conference, and perhaps in professional publications or peer-reviewed journals. Participants understood that each would be forwarded a summary of the research and links to any publications once that occurred. Participants were informed they could withdraw from participation in the project without any disadvantage to themselves. As noted previously, the researcher was not in a relationship with participants such that they might feel obligated to participate, and they were assured that their participation/non participation would not impact them in any way.

3.2.1.6 Analysis.

The data were analyzed following Straus and Corbin's (1998) grounded theory approach, with an iterative method. Five iterations were used in reviewing the interviews, to accurately represent the data. As this was new research for the field, the researcher used inductive themes derived from the data, instead of deductive themes that otherwise might have come from existing research (O'Reilly, 2009). Representative quotes were selected and categorized by the interviewee's occupation (e.g., “mathematician”). An excerpt from the coding for one participant is shown Table 3.1, as an example. Excerpt coding for each participant is shown in Appendix B.

Note that the themes as shown in the left column will be discussed further in the next chapter.

Table 3.1

Study 1 Interviews - Sample of Quote of Selection for One Participant ("Astronomer")

Influencers	"How do I how do I deal with a professor who doesn't support me, who doesn't want to write me recommendation like there's no class that teaches you how to do that. . . if you don't have good mentors around you to help buffer those negative things you're just going to wash out. And so that's what I...try to focus on is kind of helping support them do the science they want to do but also giving them the interpersonal kind of the social skills to help them because you're going to face these things." "...when he's mentoring students like it's for him...it was about building the community around them so they go out and they eat. They feel this sense of...unity that they belong because there's so many microaggressions and just outward aggressions that say you shouldn't be here. You know, kind of what is said to minorities. There's this...sense you shouldn't be here and so building that sense of community you say you belong here."
Educational Experiences	"So my interest in astronomy as a career path initially started out as really wanting to be a teacher...this "weakness" that I had, not really liking math, turned into a strength."
Hurdles	"And I think sometimes when people hear that you're coming from an HBCU [Historically Black College and University] they kind of immediately assume that you have gaps in your education or maybe you're not as smart, like it's not anything in what they're saying but it's kind of an attitude - like you're here but you're only here because you're part of this special program because you needed it and that's, it - it's all these little microaggressions that begin to add up."
Attitude Changes	"I think there are some good changes that have happening I know statistics, statistics-wise was the number of women in STEM field has increased since my time. But one thing that hasn't changed much since kind of going into the STEM field is the number of minorities who are getting their master's or they're getting their Ph.D. And that hasn't changed. So it's a little discouraging."
Recommendations	"But I want to be able to explain this to other people, that real world like I think there's just so many studies that I'm sure you' read and I've read that's one of the connections to get our young women into STEM, is the 'why,' why is this important?"

3.2.1.7 Study One informing Study Two.

This study involved a qualitative piece of research conducted first to lay the groundwork to help inform the quantitative study. The quantitative study then formed the bulk of the overall research. Based on the qualitative findings (see Chapter 4 for further details of these findings), the researcher made specific changes to the research plan for the quantitative study. The first adjustment was due to participants in the qualitative study describing their own experiences towards STEM pathways at very young ages, as well as some expressing explicit concern that girls needed to be reached even before entering middle school. Therefore, the researcher lowered the bottom end of the age range for the quantitative study to include upper elementary in order to help make it more inclusive of younger participants. Additionally, the researcher made sure to provide data in different formats and coded to U.S. Section 508 standards (United States Access Board, 2000) to be more inclusive for differently abled learners as recommended by some interviewees, and in compliance with U.S. government standards, as the data were collected in the United States.

Furthermore, as role models and mentors were prioritized by each interviewee, materials incorporating stories of diverse female role models in STEM were provided as handouts and reviewed at the end of the workshops. Finally, the researcher incorporated personal stories of failure, resilience, and creativity into the introductions and wrap-up portions of the workshop (described in greater detail in the next section). These additions were a direct result of hearing such themes expressed as having importance in the qualitative study.

The next section will describe Study 2.

3.2.2 Study 2. The Potential Effects of NASA 3D Data-based Models and 3D Prints on Spatial Reasoning Skills and STEM Interest in Young Female Learners

As described in Chapter 2, spatial reasoning skills concern the ability to mentally manipulate 2- or 3-dimensional objects to visualize what the objects represent (Hegarty & Waller, 2005). Research has shown that spatial reasoning can be a critical skillset and indicator of potential success for many STEM fields (Hegarty & Waller, 2005; Shah & Miyake, 2005; Uttal & Cohen, 2012; Uttal et al., 2013; Verdine et al., 2014). Study 2, therefore, investigated the effects of a targeted program using astronomical 3D models and 3D printing, to explore whether spatial reasoning skills and interest in STEM fields would be increased for a sample of females aged 10-15.

Study 2 included working with young female learners in half day or full day workshops where participants explored working directly with NASA data through coding, 3D modeling and printing, and virtual reality through computer or digital based applications as well as supplementary paper-based activities. The workshops, along with what was measured, are described in detail in the procedure section below

3.2.2.1 Perspective.

Proficiency in spatial reasoning can be considered as an important STEM factor (Dewar, 2018; Uttal et al., 2013; Wai et al., 2009). Spatial reasoning skills have been shown to help indicate success in technical fields (Shah & Miyake, 2005), as well as functioning as an indicator of mathematical success (Hegarty & Waller, 2005; Verdine et al., 2014), science performance (Uttal et al., 2013), and STEM career pursuit (Uttal & Cohen, 2012). Students successful in spatial reasoning tests have been shown to have a greater likelihood of better performance in science classes, as compared with learners who did not test as well (Ganley et al., 2014).

Over nearly half a century, research has established differences in spatial skill performance between males and females, with females having a tendency towards delayed development (Halpern et al., 2007; Linn & Petersen, 1985; Maccoby & Jacklin, 1974; Voyer et al., 1995; Yilmaz, 2009). However, this is not well understood (Linn & Petersen, 1985; Maccoby & Jacklin, 1974; Voyeret al., 1995; Yilmaz, 2009). Possible explanations have included biological, sociological, or cultural differences as underlying the delay (Yilmaz, 2009).

More recently, and encouragingly, spatial reasoning skills have been shown to be improvable through the application of targeted programs (Gold et al., 2018; Hwang et al., 2009; Uttal et al., 2013; Yeh, 2007), through the use of virtual environment targeted approaches (Hwang & Hu, 2013). Virtual 3D modeling specifically has the potential to provide a vehicle to help users gain new perspectives that might also positively affect spatial reasoning (Amorim et al., 2015; Berra et al., 2014; Craig et al., 2013). This might be particularly effective when used in combination with physical 3D models (Takagishi & Umezu, 2017).

Research to date, however, has not focused on female learners, especially those at an age when they are on the cusp of making educational and career decisions concerning STEM fields. Therefore, Study 2 incorporated 3D environments and 3D printed models, including those developed by scientists and technologists from NASA's Chandra X-ray Observatory (Arcand et al., 2017), in a targeted program designed to study spatial reasoning skills and interest in STEM fields with young female learners.

3.2.2.2 Participants.

In Study 2, 117 upper elementary and middle school ages (range of 9-15 years) were invited to participate. All female-identifying students participating were recruited from networks with which the researcher works, namely: a local girls day camp group, a local private all-girls school, and local scouting organization. To protect anonymity, these will be referred to as Camp Group, Private School and Scout Group. Anyone who did not have signed consent forms (or interest) would still able to participate in all of the activities and would not be excluded from the program, but would not have been included in the data collection for this study. As *Table* 3.2 shows, a majority of the participants came from the all-girls school, and no one declined participation.

Table 3.2

Workshop Participants and Declines Per Location

	Number participants per location	**Number of declines per location**
Scout Group	29	0
Camp Group	29	0
Private School	59	0

3.2.2.3 Materials.

There were three instruments used in Study 2,; a demographics questionnaire, a spatial skills evaluation, and a STEM interest inventory. The full list of questions and items are provided below and in the appendices. The materials used in the workshops are also described, with screen shots shown in the appendices.

3.2.2.4 Demographics Inventory.

The demographics inventory was developed for Study 2 (see Fig 3.1). The items on the inventory included age, grade, gender, ethnicity, zip code, activity location, self-rated knowledge of STEM and hours of video games played per day. Age, grade, gender and ethnicity information, zip code and location were collected to ensure the sample groups closely represented the targeted population. Self-rating information and estimates of how many hours of video games are played per day were collected to later assist with the examination of the data in the spatial skills and inventory responses.

Figure 3.1

Demographic Inventory Screen Shot

ID: ____________

Thank you for taking part in this study!

To begin, please tell me about yourself.

1. What is your age? ___________
2. What grade are you in? ____________
3. How do you identify your gender? _____________________
4. How do you identify your ethnicity? (select all that apply)
   - Asian
   - Black/African
   - Caucasian
   - Hispanic/Latinx
   - Native American
   - Pacific Islander
   - Prefer not to answer
   - Other
5. In what ZIP code is your home located? (for example, 00544)
   ____
6. Where did you take part in this activity?
   - School or University
   - Library
   - After-school Club or Activity (e.g., Girls Who Code, Black Girls Code)
   - Museum
   - Other (please specify where) ___________________________
7. Think about your overall knowledge in science, technology, engineering, and math (STEM). Circle one of the numbers below to indicate how you would rate yourself:

   1 2 3 4 5 6 7 8 9 10

   I know almost nothing — I'm OK at these — I know a great deal

8. About how many *hours* do you play video games *each day*? _____

3.2.2.5 Spatial Skills Inventory.

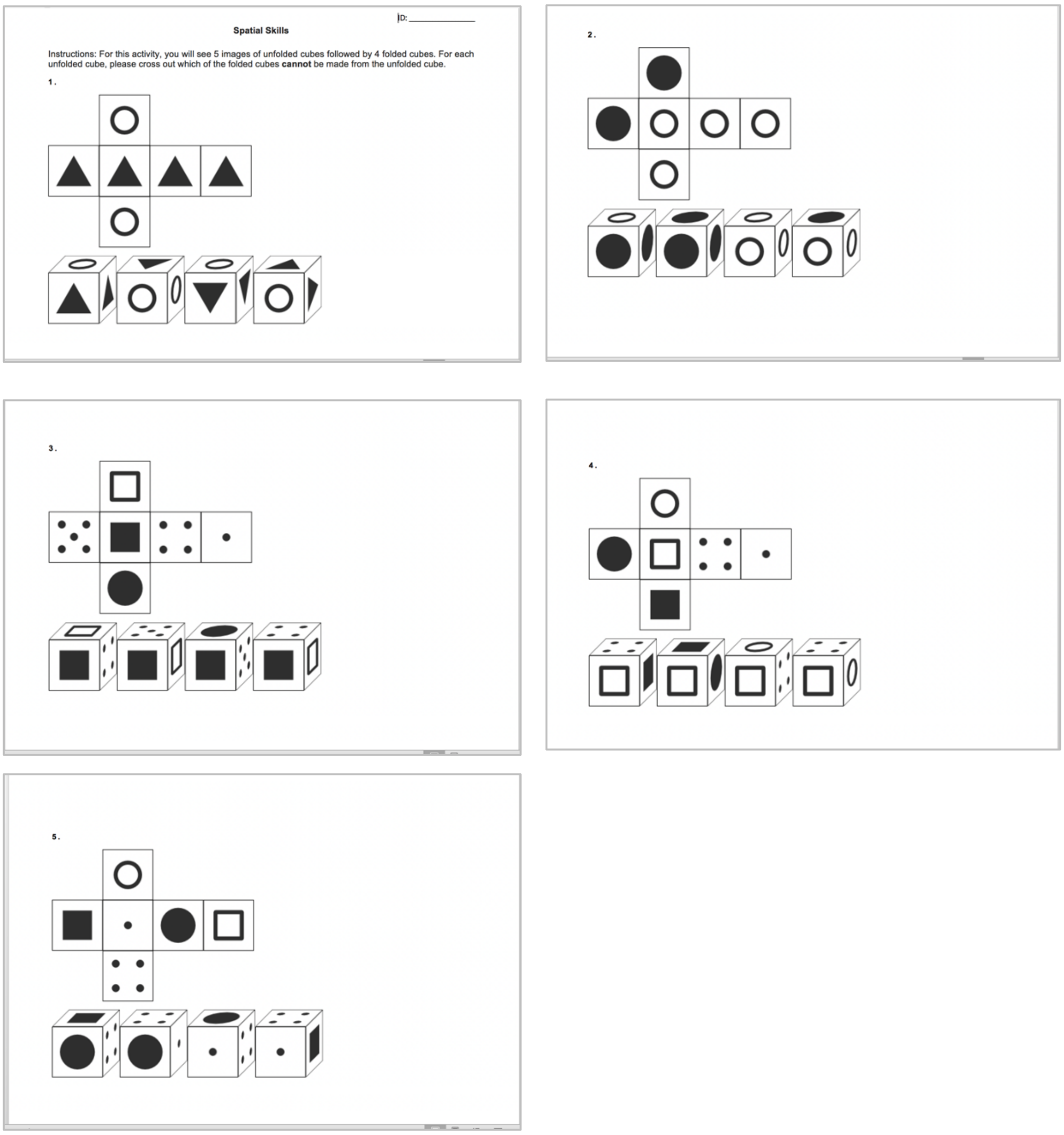
The spatial skills instrument used was the freely available "Spatial Reasoning Test | 123test.com," (123test, 2019) and is provided below as a quick-look image (full text of the inventory available in Appendix C).

In pilot testing with a small group of students (n = 4) prior to data collection, it was determined that the full evaluation of 10 items from the original instrument was too lengthy for the age group of the participants. Therefore, the total number of items on this evaluation was reduced to the first five examples for the data collection. This instrument is a long-established approach to assessing spatial reasoning skills. The reliability statistics, while not available for this instrument, were computed for the data from this study and are presented in the results chapter.

During use in the workshops, however, the researcher adapted a strategy to help assist participants who struggled with the spatial instrument, whereby an example of the folding exercise that had not been included on the instrument was reviewed as an example in front of all participants. The researcher and facilitators then followed up after this demonstration by going around to the tables to clarify what was required amongst smaller groups of participants or individuals as needed.

Figure 3.2

Quick-Look Image of the 5 Items Used from the Spatial Skills Inventory



3.2.2.6 STEM Interest Inventory.

The STEM interest inventory used was the "Instruments for Assessing Interest in STEM Content and Careers" (Tyler-Wood et al., 2010). It was used with the written permission of the authors, and has good reliability (see reliability section). The inventory comprises five opposite word pairs repeated across each topic of science, math, engineering, technology, and STEM careers (see Appendix D for the full inventory), with participants making selections across a 7-point scale. Figure 3.3 below presents the first subscale as an example.

Figure 3.3

First Subscale from STEM Interest Inventory

To me, SCIENCE is:

1.	fascinating	① ② ③ ④ ⑤ ⑥ ⑦	mundane
2.	appealing	① ② ③ ④ ⑤ ⑥ ⑦	unappealing
3.	exciting	① ② ③ ④ ⑤ ⑥ ⑦	unexciting
4.	means nothing	① ② ③ ④ ⑤ ⑥ ⑦	means a lot
5.	boring	① ② ③ ④ ⑤ ⑥ ⑦	interesting

Workshop Materials

The activities used in Study 2 applied the information gained from researching the data processing and 3D modeling pipeline as described in Chapter 2. The order of the activities was chosen to build up the participant towards a knowledge base of a topic that likely many had not had access to before the workshops, as data visualization of deep space observations is not typical course content for elementary and middle school grades in the U.S. Care was taken therefore to be sure participants did not feel like they were being dropped into a large pool of esoteric 3D data but rather to help provide the underpinnings of how that data is collected, what scientists do to the data and why, as well as "how do we know?" what the data mean. From providing an overview of the information and coding underlying space-based data, to incorporating 3D data sets and virtual reality, the following sections provide details on each activity used in the workshops.

All materials used in the workshops provided multiple modes of accessibility for participants. Virtual reality applications utilized audio tracks and closed captioning, tactile 3D prints of data sets were provided, all videos used had audio and text transcripts incorporated, images were appropriately tagged with alternative content for screen readers, and all digital files (such as PDFs) were coded to U.S. accessibility standards.

3.2.3 Binary Code: Nametag Materials

The researcher introduced binary code, what it is, and how it is used to talk to spacecrafts and other electronics as the first topic. Blank “Hello my name is” nametags and pens were provided for each of the participants as a warm-up activity. The participants used a binary code chart to convert their first name, nickname, or initials into strings of ones and zeroes (see Figure 3.4; see Appendix E for the full activity sheet). (Arcand, 2017a)

Figure 3.4.

Screenshot of First Page of Binary Code Name Tag Activity

Directions: Use the chart below to write your name in binary code on your nametag.

For example, here is "Chandra" written in binary code:

01000011 | 01101000 | 01100001 | 01101110 | 01100100 | 01110010 | 01100001

Using the chart below, can you tell what name is written here? 01011000 | 01110010 | 01100001 | 01111001

Here is a chart of uppercase and lowercase English language alphabet characters:

A	01000001	N	01001110	a	01100001	n	01101110
B	01000010	O	01001111	b	01100010	o	01101111
C	01000011	P	01010000	c	01100011	p	01110000
D	01000100	Q	01010001	d	01100100	q	01110001
E	01000101	R	01010010	e	01100101	r	01110010
F	01000110	S	01010011	f	01100110	s	01110011
G	01000111	T	01010100	g	01100111	t	01110100
H	01001000	U	01010101	h	01101000	u	01110101
I	01001001	V	01010110	i	01101001	v	01110110
J	01001010	W	01010111	j	01101010	w	01110111
K	01001011	X	01011000	k	01101011	x	01111000
L	01001100	Y	01011001	l	01101100	y	01111001
M	01001101	Z	01011010	m	01101101	z	01111010

3.2.4 Imaging

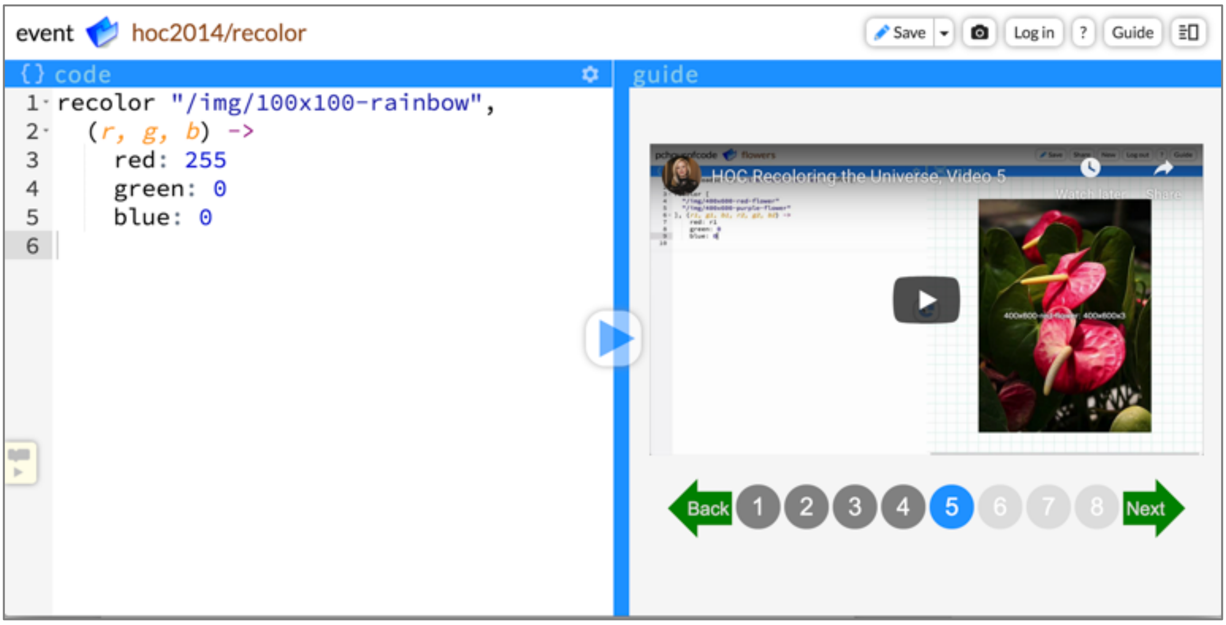
Participants were introduced to working with 2D NASA data through the application of an online browser-based tutorial - using the Pencil Code language - co-created between the researcher and Google CS Ed (computer science education) as well as the AAS (American Astronomical Society). The tutorial includes seven interactive modules with video and step-by-step instructions. In this activity, participants are guided through each step of the tutorial collectively but then complete the computer-based work as an individual or in pairs with input from facilitators as needed. The next chapter details the length of the modules completed for the imaging activity per location.

Working with data from NASA's Chandra X-ray Observatory and other telescopes, on topics from exploded stars, to star-forming regions, to the area around black holes, students learn basic coding (though no coding experience is required) and follow video tutorials to create colorized images of the Universe. The activity therefore starts the participant with an introduction to computers making red, green, and blue (RGB) colors on a screen using values between zero and 255. Next, they explore filters and using a coloring function that maps input RGB colors to output RGB colors. The third module lets the participant mash up two images using a coloring function to mix red, green, and blue light from multiple images.

In the fourth module, participants see how astronomers combine different images to create a single colored image of the leftovers from a star exploding. In the fifth module, participants explore a deep six-wavelength stack of astronomy images, and create their own unique RGB image of a star-forming region. In the sixth module, they examine the remnants of a supernova observed from Earth in the 17th century. The final module steps participants through X-ray data revealing a supermassive black hole at the center of a galaxy. The full activity sheet can be found in Appendix F (see also http://chandra.si.edu/code for further details). All of the user-created objects are saved into the participants' free accounts where they can be accessed after the workshop (Arcand, 2015).

Figure 3.5

Example of Image Processing Interface



3.2.5 3D Modeling and Printing

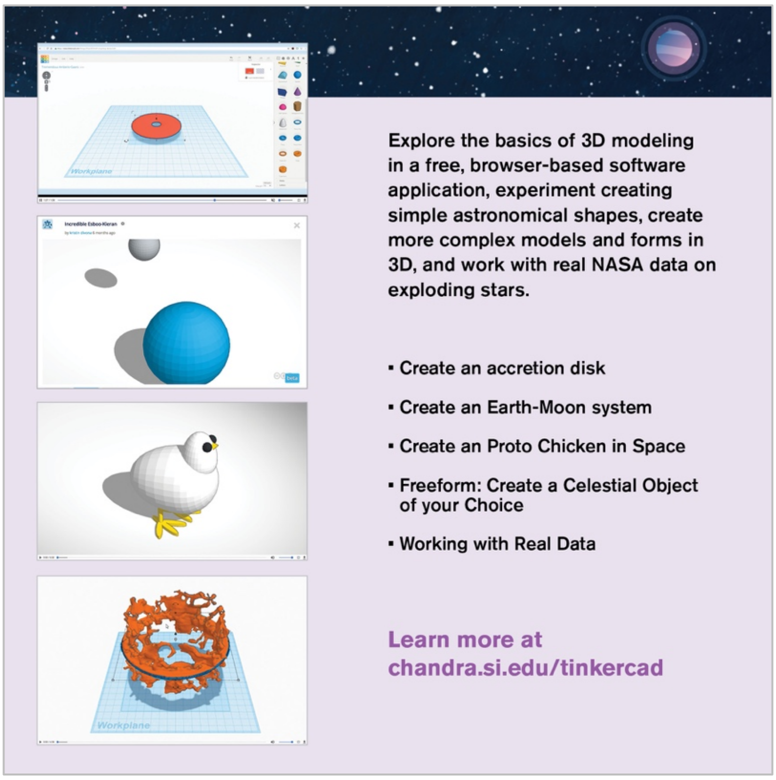
After experiencing 2D data processing, participants then learned about using astronomical data to create 3D models and prints using an online browser-based application that steps learners through five modules. The modules move participants from an introduction to working in a 3D space to advanced concepts working with actual NASA 3D data. This module utilized the TinkerCad application, free online software common in educational venues or settings. Similar to the imaging activity, in the 3D modeling activity participants are guided through each step of the tutorial collectively but then complete the computer-based work in pairs with input from facilitators as needed.

This segment assumed no prior experience in 3D modeling, and therefore, as mentioned, provided an introduction to TinkerCad commands and an overview of using a 3D workspace. The participants created multiple new 3D designs in the application, beginning with a simple accretion disk (a disk of gas and dust that can accumulate around various kinds of stars or black holes) and followed by a basic Earth-Moon system. These first two modules introduced the astronomy underpinnings of the activity while also requiring users to become familiar with shape-making, use of zoom/pan/rotate, and solid and pattern filling.

Module three launched the participants into a more complicated object, a "Proto-Chicken" that required more complex shapes, utilization of the special shape library built in to TinkerCad, and more advanced placement and overlap of items in a 3D space. The proto-chicken is typically the most time-consuming part of the unit. The fourth module gives the user free time to flex their 3D skills by free-forming any kind of celestial object using non-uniform shapes. The final module requires the loading of a real NASA 3D data set of a supernova where participants can manipulate the object to their liking. All of the objects are saved into the participants' free accounts where they can be accessed after the workshop for 3D printing. Appendix G provides the full activity sheet, and further details may be accessed at http://chandra.si.edu/tinkdercad. (Arcand, 2017c)

Figure 3.6

Sample Images from 3D Modeling Activity



3.2.6 Origami

Participants were provided with a non-computer based, hands-on activity, working with basic spatial information by folding special paper into a simple star as a non-expert origami activity. Origami provides solutions to many problems in modern science and engineering. For example, origami-inspired techniques are used to unfold stents in clogged arteries, release airbags during automobile collisions, and even unfurl the large mirror for the soon-to-be-launched James Webb Space Telescope. In astrophysics, there are instances where the expansion and unpacking of origami demonstrates what scientists witness, such as with the death of stars. Using paper provided by the researcher and a set of instructions, each participant followed along with the researcher to fold a simple star shape. During the folding session, the researcher discussed how stars unpack themselves in the supernova process. Appendix H lists the full activity sheet, and http://chandra.si.edu/origami has further details and background on the activity (Arcand, 2018a).

Figure 3.7

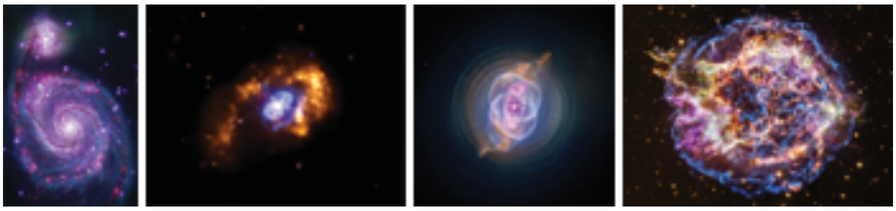
Sample Image of Folding a Simple Star in Origami

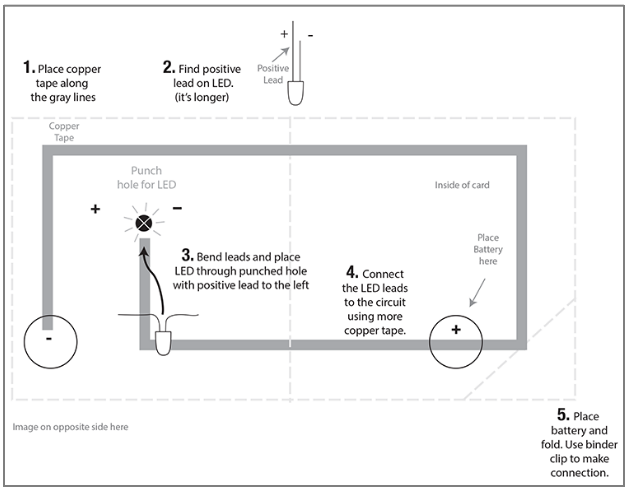
3.2.7 Paper Circuits (Light Up Exploded Stars)

Paper circuits can help learners explore the basics of electricity (energy that results from the existence of charged particles like electrons or protons) and conductivity (the degree to which a material can conduct electricity). Paper circuits function as simple low-voltage electronic circuits (a path through which electrons from a voltage or current source flow) made using paper, LED lights, a type of conductive tape such as copper, as well as a small battery for the power source. Following along with directions from the researcher and other facilitators, students used NASA data-driven images (see Figure 3.8 below) printed out on cardstock and then determined how to light up a star in the image using an LED, coin battery, copper tape and a binder clip, along with simple assembly tools of scissors and pencils. This hands-on, paper-based activity provided basic directions but encouraged inquiry and discovery to make it light up any way the participant saw fit. See Appendix I for the full activity sheet, and http://chandra.si.edu/make for further details. (Arcand, 2018b)

Figure 3.8

Sample Images from Paper Circuits



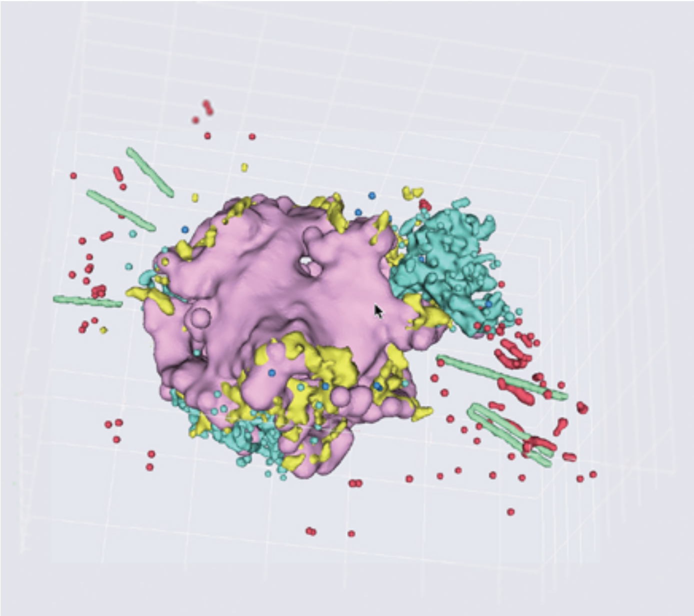


3.2.8 Virtual Reality

Virtual reality applications were provided on portable Oculus headsets for participants to have a guided tour and open play time in immersive data-driven astronomical applications. The VR applications used for the activity included the Cas A supernova remnant, SN1987 supernova changing over time, and the Galactic Center's perspective from the Milky Way's central supermassive black hole. The applications included audio and text descriptions within the experiences. For supernova 1987a and the Galactic Center, verbal descriptions of what the students were seeing were provided in person by the researcher as the models were more complex. Example VR activity simulations without headsets are available to view online at http://smithsonianeducation.org/interactives/cas-a/safari/index.html; see also http://chandra.si.edu/vr for further content and details (Arcand, 2019).

Figure 3.9

Sample Image of Cas A Inside the 3D/VR Space



Procedure

Based on a convenience sample of organizations the researcher knows and has previously worked with, permission was sought from each organization's head or principal to conduct a workshop and invite participants from that organization for inclusion in the study. Once permission was granted by the organization's head or principal, information sheets and consent forms were provided for the parents/legal caregivers, along with information sheets and consent forms for the students (see Appendix J , K, & L). These were distributed by the organization's head or principal and sent home with students. Completed forms from the parents/legal caretakers and students were returned to the organization's head or principal, prior to the workshop. The organization's head or principal delivered the forms to the researcher.

Compensation was not expected by the venue leaders in the researcher's network, nor did individual participants receive compensation; this was explained in all information sheets and consent forms. However, each organization was given free NASA handouts/literature for the students, regardless of participation levels, which was also explained.

The workshops ranged from 2.5 to 6 hours long, as determined by the usual amount of meeting time for the group involved. The workshops were held where the groups typically met (e.g., Scout Group headquarters or school meeting spaces). Participating students were randomly assigned to group A or group B to counterbalance the order for the pre- and post-conditions. Identification (ID) numbers were used to ensure that the pre- and post-evaluations were matched correctly for the participants. Therefore, this study used a controlled within groups design. Only the researcher had knowledge of the list of participants' names with their ID numbers, and destroyed that list once the data were collected. No potential participants declined participation in the workshop or to be included in the study.

Group A completed the spatial skills instrument as a pre-evaluation, engaged in the workshop, and then completed the STEM interest inventory as a post-evaluation. Group B completed the STEM interest inventory as a pre-evaluation, engaged in the workshop, and then completed the spatial skills instrument as the post-evaluation. Both Groups A and B completed the demographics inventory as part of the pre-evaluations.

The workshop activities included the following scientific data-driven activities. All activities were created and produced by the researcher and her team for NASA's Chandra X-ray Observatory over the past 5 years, particularly while working with groups of under-represented students to refine and further develop the materials. The activities were developed as ways to describe and interactively show the kind of work the researcher and others on the team do for the X-ray mission or using the astronomical data. The materials were primarily developed with funding from NASA under contract NAS8-03060, except where noted below. As part of such mission-based work, all products are required to eventually pass NASA product review, a rigorous internal quality control system from NASA to ensure scientific and educational accuracy of materials. Those products successfully reviewed by NASA are noted in the procedure description.

The half day event was conducted with the researcher and one additional female facilitator who was trained by the researcher on all activities. The schedule went as follows:

1. Welcome & pre-evaluation (15 minutes).

2. Binary Code warm-up activity (10 minutes).
3. Imaging/coding Discussion (20 minutes).
4. 3D modeling & printing exploration (15 minutes).
5. VR experience (60 minutes).
6. Origami activity and paper circuits (overlapped with the VR experience, based on ratio of VR headsets to participants) (45 minutes).
7. Post-evaluation for students with permission, open discussion time for students without permission; Debriefing and opportunity for questions; Workshop concluded (15-30 minutes).

Full-day events were conducted with the researcher and three to four additional trained female facilitators or teacher helpers. All trained facilitators were current workers in STEM fields. One assistant facilitator served at all workshop events, with additional facilitators brought in for workshop 2 (Camp group). The Private School group had a surplus of volunteer teachers to help throughout the days, and who were trained by webinar prior to the event.

Camp Group Workshop Schedule:

1. Introduction/welcome/pre-evaluation for all students (20 minutes).
2. Binary Cody warm-up activity (10 minutes).
3. Imaging hands-on activity (60 minutes).
4. 3D modeling & printing hands-on activity (60 minutes).
5. Lunch (30 minutes).
6. Origami activity and paper circuits (60 minutes).
7. VR exercise (60 minutes).
8. Post-evaluation for all students; Debriefing and opportunity for questions; Workshop concluded (30 minutes).

Private School Workshop Schedule:

1. Introduction/welcome/pre-evaluation for all students (30 minutes).
2. Binary Cody warm-up activity (10 minutes).
3. Origami (25 minutes).
4. Outdoor recess (30 minutes).
5. Imaging hands-on activity (45 minutes).

6. Paper circuits (60 minutes).
7. Lunch (45 minutes).
8. 3D modeling & printing hands-on activity (60 minutes).
9. VR exercise (45 minutes).
10. Post-evaluation for all students; Debriefing and opportunity for questions; Workshop concluded (30 minutes).

3.2.9 Procedure for Workshop Activities

1. **Introduction and warm-up.**

   Once a brief welcome was concluded, the pre-evaluation was administered to all participants after randomly establishing group A and group B. All participants took the demographics survey and then completed either the spatial instrument (Group A) or the STEM inventory (Group B). That was followed by an introduction for the workshop content which included a short talk from the researcher, adapted for the ages of the audience, on her scientific background and the telescope she works on, NASA's Chandra X-ray Observatory. The warm-up activity involved outlining how controllers talk to spacecraft that orbit beyond Earth: the data that are eventually converted into astronomical images originates as binary information (a stream of 1's and 0's that encode the information) before taking a 40,000-mile/64,000 km journey (more or less, depending on the telescope's position in its orbit at the time of the downlink) through space to one of NASA's Deep Space Network (DSN) antennas in Australia, Spain, and California (USA), where it is downloaded, translated, and worked on. This activity set the stage for the authentic data experiences used throughout the rest of the workshops. After the introduction to binary code students created binary code name tags by translating their names into a set of 1's and 0's, a NASA product-reviewed activity that the researcher developed (more information at http://chandra.si.edu/binary/; see also Appendix E).

2. **Imaging discussion or activity.**

After reviewing binary code and completing the activity, the next segment focused on discussing how two-dimensional astronomical images are created using NASA data (e.g., see Chapter 1). In the shorter workshops, this section covered the basics on how to create an image and what that information tells the scientist, followed by a question and answer session for the participants with the researcher. In the longer workshops, students completed a 40-45 minute computer-based hands-on activity using Pencil Code and videos created with the researcher and Google CS Education. The NASA product-reviewed activity takes the viewer through the mechanics of red-green-blue images and through to compositing and colorizing real NASA data to create their own image of a supernova remnant or area around a black hole for an authentic learning experience. Pre-recorded videos of the activity assisted the researcher in presenting the information while going around to each participant to ensure they were able to complete each module (more information at http://chandra.si.edu/code/; see also Appendix F).

3. **3D modeling & 3D print activity or exploration**

   As a follow-on to the 2D imaging discussion or activity, the 3D modeling and 3D print segment built on top of the previous information to bring participants into understanding the basic geometry of creating simple astronomical models. In the longer form workshops, users complete a hands-on activity on how to do basic 3D modeling using free browser-based software (Tinkercad), stepping through 3-4 sample models before loading a 3D NASA data set. The content discusses some of the spatial information of the datasets used in the previous activity. Next users discuss how to move the 3D models to 3D printers and review some of the challenges of 3D printing before handling sample 3D print objects. This is a NASA product-reviewed activity that the researcher developed. In the shorter workshop, the focus is on a brief discussion of the modeling and printing processes before the participants handle the example 3D prints for a question and answer session. Pre-recorded videos of the activity assisted the researcher in presenting the information while going around to each participant to ensure they were able to complete each module (more information at http://chandra.si.edu/tinkercad/ and http://chandra.si.edu/3dprint; see also Appendix G). The 3D modeling module's creation was supplemented with funding from NASA's Universe of Learning, based upon work supported by NASA under award number NNX16AC65A to the Space Telescope Science Institute, working in partnership with Caltech/IPAC, Center for Astrophysics | Harvard & Smithsonian, Jet Propulsion Laboratory, and Sonoma State University.

4. **VR experience.**

   Building on the 3D modeling exercise, the VR segment began with a short presentation by the researcher on creating NASA data-driven VR applications and what the use of such applications can mean for researchers such as herself before moving into a series of spatially-aware demonstrations and discussions of multiple astronomical VR data sets including two 3D supernova remnants (Cassiopeia A and Supernova 1987a) and a 3D journey of the Milky Way's galactic center around the supermassive black hole Sagittarius A* (more information at http://chandra.si.edu/vr).

5. **Origami activity and/or paper circuits.**

   The VR experience listed above was typically run as the final activity but this was dependent on the ratio of headsets to students. With more students and fewer headsets, the VR and the activity(ies) would be set up as stations for participants to cycle between. The other station activities included a simple origami activity (http://chandra.si.edu/origami; see also appendix H) and/or a paper circuits activity (http://chandra.si.edu/make/; see also appendix I), depending on the number of students and facilitators as well as the total amount of time remaining in the workshop. Both the origami and paper circuits activities are NASA product-reviewed activities that the researcher developed to help communicate some of the science concepts of the data (e.g., expansion and unpacking, or neutron stars). The paper-based modules' creation was supplemented with funding from NASA's Universe of Learning, based upon work supported by NASA under award number NNX16AC65A to the Space Telescope Science Institute, working in partnership with Caltech/IPAC, Center for Astrophysics | Harvard & Smithsonian, Jet Propulsion Laboratory, and Sonoma State University.

6. **Post-assessment and wrap-up**

   The post-evaluation assessment was run after the participants finished the activities, at the end of the event. The post-evaluation was presented along with a final open question and answer and discussion period for content-based questions, career-related questions, etc. that the students might have. Additionally, participants were provided with free NASA handouts in this segment which showcased women in STEM (see Appendix M). This included postcards and information sheets of STEM explorers like Mae Jemison (the first African-American woman to fly in space), Liu Yang (the first Chinese woman in space), Wanda Diaz (a Latina computer scientist who is also blind) and Katherine Johnson (a famous African-American mathematician). Additionally, handouts on the activities completed during their workshop (see Appendices E, F, G, H and I) were also given out so participants could reflect on their activities, refer to the content, or share the materials with their families.

3.2.10 Informal Observations

Additionally, beyond the formal instruments used as discussed above, informal observations were recorded by the researcher. Though not formal analyses, these observations of participant behaviors and comments were written down throughout the day in between modules, as well as in a summary at the conclusion of each workshop. A running list of the observations was recorded on the researcher's iPad. These observations, initially not planned for, varied by participant and location. However, as they were part of the session, it became evident that they added a layer of insight that was valuable for later reflection and application of findings.

Ethics

The University of Otago Human Ethics Committee approved this research as a Category A application (see Appendix A for the approval letter). Organisation heads or principals, parents/legal caretakers, and students were informed of the purpose for which the researcher was collecting the information and the uses proposed to make of it. They were informed who would receive the information and they were also informed of their rights of access to and correction of personal information. They were informed that the researcher intended to publish the results in her thesis and that it was anticipated that the results would be presented at a conference, and perhaps in professional publications or peer-reviewed journals. Participants understood they could request a summary of the research and links to any publications once that occurred. Participants were informed they could withdraw from participation in the project without any disadvantage to themselves. Language used in the information sheet and consent form for the student participants was adjusted for ease of comprehension.

Participation was anonymous and the data were aggregated, with no personally identifiable information stored. No ethical issues were expected, but it was acknowledged that a participant, being underage, might not fully comprehend the study itself; even with having consent from a parent/guardian. Therefore, opportunities for discussion and questions were provided both before and after each workshop as an additional safety mechanism. Participants were reminded that they could withdraw from the project at any time prior to the conclusion of the activities, without any disadvantage of any kind. No ethical issues arose with any participant in any of the organisations.

Analysis

After the workshops were completed, the data collected were digitized and entered into SPSS version 26 for analysis (IBM Corp., 2019). Frequencies and descriptive statistics were completed for the full sample and by affiliation. Next, means and standard deviations for the inventories were completed, by both full sample and pre post conditions. Then, a principle component analysis was run on the items of the STEM inventory. Reliability statistics using Cronbach's Alpha were calculated using each sub scale for the STEM inventory, and the spatial skills inventory. Correlations were also computed of video hours with affiliations, self-rating, spatial total, and inventory total for the full sample and by affiliation. Finally, multivariate analysis of variance was used to examine the research questions.

3.2.11 Validity, Reliability, and Trustworthiness

There are always threats to the conduct and interpretation of research. The researcher must be aware of such concerns in both quantitative and qualitative research (Creswell & Clark, 2007; Onweugbuzie & Johnson, 2006). In quantitative research, it is critical to address issues related to validity and reliability. In qualitative research, as Sanjari and colleagues noted, ". . . the researcher has to both evaluate what he or she observes and to interpret it" (Sanjari et al., 2014, p. 1). In this regard, trustworthiness becomes an important issue. Each of these will be discussed next.

3.2.11.1 Validity.

Validity concerns the quality of "a research study, its parts, the conclusions drawn, and the applications based on it . . ." (Onwuegbuzie & Johnson, 2006, p. 48). Validity, therefore, is about the soundness of the research design and methodology. It can relate to internal or external issues. Internal validity concerns issues related to the design of the study itself, for example, the data collection, use of controls, or not taking all variables into consideration (Onwuegbuzie, 2003). External validity concerns whether the outcomes can be generalized to additional groups, or applied to broader contexts (Onwuegbuzie, 2003).

3.2.11.2 Internal Validity.

To ensure internal validity, the materials used in the quantitative study were chosen after an extensive search of the literature to examine potential instruments that might have been used. The spatial skills evaluation and STEM interest inventory were selected as the most appropriate instruments, based on their psychometric properties, wide usage, and potential for addressing the research question. To confirm their suitability with the participants and maximize their potential in the research these were also pilot tested small group of girls (n = 8) (Arcand, unpublished). This resulted in cutting the number of items on the spatial reasoning instrument in half, as the participants became fatigued on the full set of 10 problems. Additionally, the researcher verified with the girls whether they had questions on any of the materials.

3.2.11.3 External Validity.

External validity concerns the extent to which the findings can be generalized. As with any research, caution needs to be exercised in terms of applying results to the population. Additional caution is needed given that this research was conducted with a convenience sample. Thus, the results should not be generalized to other age groups, should be used with caution with those who do not identify as female, and might not apply to those in other geographic areas or to people outside the organisations that were worked with.

The researcher used established materials with high psychometric properties, known in the field as being legitimate measures for the topic of this research. Comprehension was assured through pilot testing and reminding participants that they could ask questions along the way. These steps enhanced potential generalizability for like samples in the population, in that the instruments were appropriate and were understood by the girls in the age groups of interest.

As mentioned earlier in this section, mixed methods research combines the complementary strengths and non-overlapping weaknesses of quantitative and qualitative research (Onwuegbuzie & Johnson, 2006). There can, however, be issues of integration in mixed methods, whether the methods are parallel or sequential. Validity, then, is particularly important in mixed methods research where the goal of mixed methods is to achieve “heightened” validity and knowledge (Schoonenboom & Johnson, 2017, p. 4). For such validity, and to help ensure transparency, the researcher must institute “legitimate checks” for each step in the research design; this can be referred to as “legitimation” (Jameson-Charles, 2015, p. 22). These checks include ensuring that: a variety of strategies were used to collect the data, emerging themes obtained from the qualitative data were quantified to correctly inform the quantitative study of the research, the researcher treated the quantitative and qualitative data objectively such that any personal biases were excluded in the analyses, and data collection and findings were reviewed to confirm that the research questions were adequately addressed. All such legitimation was conducted in this research and reported on in this thesis to achieve a high level of validity.

3.2.11.4 Reliability.

Reliability concerns being able to minimize errors while increasing outcome consistency, as well as the overall soundness of the methods and application (Noble & Smith, 2015). It can be defined more specifically as “the consistency, dependability and replicability” of the research results (Zohrabi, 2013, p. 259).

The psychometric properties of the two instruments used also contributed to the reliability for this study. The STEM interest inventory, as noted, is the “Instruments for Assessing Interest in STEM Content and Careers” (Tyler-Wood et al., 2010) and is partly derived from earlier work by Novodovorsky (1993). The instrument has good reliability, with Cronbach’s Alpha = .78-.94 across the subscales. The spatial reasoning instrument is one of the scientifically validated psychological assessments available online (Verma & Bakshi, 2017) reaching over 900,000 participants in June 2019 alone (123test, 2019).

In the quantitative study, the researcher used standardized procedures, instruments, and materials, and randomly assigned girls to conditions. Because this was done across several groups, there is evidence of reliability in terms of collecting the data and obtaining results that pertain to the research question.

3.2.11.5 Trustworthiness.

Trustworthiness is a term that is often used in qualitative research, whereas generalizability or validity are used in quantitative research (Leung, 2015). It concerns the way in which researchers can reassure their audience – as well as themselves - that their "research findings are worthy of attention" (Nowell et al., 2017, p. 3). Specific to qualitative research, trustworthiness is a surrogate for validity (Onweugbuzie & Johnson, 2006; Giddings & Grant, 2009).

The researcher addressed trustworthiness in the qualitative study by sending the recorded transcribed interviews back to each participant and requesting feedback and corrections. This also helped to ensure that any possible interpretation was based on what participants actually said versus what the interviewer (and transcription process) thought was said. The researcher was additionally cautious, as the qualitative study did not include a random selection of participants, and even though she did not personally oversee or otherwise have influential relationships with any of the participants, without the check for accuracy with the interviewees, her biases might have been present in the interpretation. Therefore, the credibility of the data was enhanced through this safe-guard.

In the qualitative study, the researcher used the same questions for all participants, so that if others were to replicate the study, the questions could be used as a basis for repeating the procedure. Additionally, the researcher ensured reliability by keeping meticulous notes and records of the methodologies, investigating personal biases, and noting sampling biases (Noble & Smith, 2015).

The researcher also paid particular attention to keeping the minors' identities confidential and data in aggregated form only, closely considered and monitored her relationship with all participants, ensuring that she did not exert power or influence over them, paid attention to any potential areas of stress during the study, and meticulously detailed all data collection.

Summary

This chapter presented the methodology used for this thesis across two studies, one qualitative, and one quantitative. It addressed the issues related to mixed methodologies, as well as the pragmatism, reliability, validity, and trustworthiness. Additionally, the materials, procedures and ethics were described. The next chapter will present the results from the data.

Chapter 4. Results

This chapter begins with an overview of the research questions used to investigate the quantifiable effects of data-based 3D models on improving spatial reasoning skills and interest in STEM fields in under-represented groups of young female learners. It then presents the qualitative and quantitative results for the two studies, where the smaller qualitative study, Study 1, involved interviews with women in STEM fields, and the larger quantitative study, Study 2, involved workshops conducted with upper elementary and early middle school girls. Study 2 formed the major part of this research.

Overview of Research Questions

As described previously, this research concerns girls and young women, especially females belonging to groups that are considered underrepresented by gender, socioeconomic status, special needs/disability, ethnicity/race, income, language, literacy skills, and/or geographic location. It was, therefore, important to gain perspective on potential historical or sociological reasons for young women being less engaged with STEM subjects on average than young men (Wang & Degol, 2017). Women in STEM have been the focus of numerous studies previously (see e.g., Cvencek, et al., 2011; Ganley & Lubienski, 2016; Heaverlo et al., 2013; Corbett & Hill, 2015; Leslie et al., 2015; Pajares, 2005; Perez-Felkner et al., 2017; Sarsons & Xu, 2015; Stoet & Geary, 2018), but personal recollections have not been examined to investigate how early experiences could have informed career decisions or current practice. Therefore, Study 1 (qualitative) was designed to explore those potentially important historical perspectives. The results of this study were then used to help inform the design of Study 2 (quantitative), which involved working directly with such populations of girls and young women (see Chapter 3, 3.2.1 and 3.2.2 for detailed rationale for Study 1 and Study 2).

The research questions were:

Study 1:

Specific to STEM fields, what are some of the obstacles and challenges that female-identifying underrepresented groups can face?

Study 2:

What are the quantifiable effects of data-based 3D models and prints on spatial reasoning skills and interest in STEM fields, particularly with young female learners?

Study 1 Results

This section reports on in-depth interviews with 11 diverse female scientists in STEM fields to identify the types of obstacles and challenges that underrepresented groups of young females might face in STEM learning and STEM careers. Table 4.1 presents the demographic characteristics of the participants. Although all of the participants gave permission to use their information and names when reported on in this research in this thesis they are referred to by their occupations. Chapter 3 provides the information on permissions and ethics obtained for Study 1.

Table 4.1.

Description of Interview Participants

ID	Occupation	Education	Ethnicity	Sexual Orientation	English 1st Language	Disability	Career	Mother
1	Astronaut	PhD	Caucasian	Cishet	Y	N	Late, Prominent	Y
2	Engineer	BS	Caucasian	Cishet	Y	N	Mid/Late	Y
3	Software Developer	MS	Caucasian	LGBTQIA+	Y	N	Late, Prominent	Y
4	Technologist/Pre-Med	BS/Post-Bacc**	Indian American	LGBTQIA+	N	N	Early	Unknown
5	Mathematician	PhD	Asian American	Cishet	Y	N	Mid, Prominent	Y
6	Radio Astronomer	PhD Candidate	Caucasian	Cishet	Y	N	Mid, Prominent	Unknown
7	Science Writer	MA	Caucasian	LGBTQIA+	Y	N	Mid, Prominent	Y
8	Astronomer	MS	Black/Mixed	Cishet	Y	N	Mid	Y

9	Cosmologist	PhD	Caucasian	LGBTQIA+	Y	N	Mid, Prominent	Unknown
10	Geologist	MS	Caucasian	LGBTQIA+	Y	N	Mid, Prominent	Y
11	Computer Scientist	PhD	Hispanic/Black	--	N	Y	-- Unknown	

NOTE: * LGBTQIA+ is an abbreviation for lesbian, gay, bisexual, transgender, intersex, queer/questioning, asexual as well as other non-binary identifiers; Cishet is the combination of cisgender (identifying with gender as assigned at birth) and heterosexual (attracted to people of the opposite sex).
**Post-Bacc is a post-baccalaureate program offered in the U.S. to prepare for additional programs such as medical school.

It can be seen in Table 4.1 that in addition to being female and in a STEM field, all but three of the participants fitted with a minority group of either ethnicity, physical ability, or sexual orientation.

Of the eleven women interviewed, each attended their undergraduate programs as young women, with two having obtained a maximum of a Bachelor of Science degree (one of whom is currently enrolled in a post-bac program towards the intent of enrolling in medical school), four holding masters degrees, and five working towards their PhDs. One of the five reported being a PhD candidate/ABD (all but dissertation) and four held PhDs. Each participant proceeded into a career path after their current level of schooling was complete. At least eight of the participants are considered prominent in their fields either through direct research outputs or by reputation in their fields.

The semi-structured interview data were analyzed following Straus and Corbin's (1998) grounded theory approach, with an iterative method using comparisons to responses until all phrases within the interviews were complete. Data were reviewed through five iterations, with repeated readings of the data lensed through sifting, sorting, coding, abstracting, and checking (Ryan & Bernard, 2003). As this was a new area to be explored for the purpose of informing the literature as well as guiding the scope of the research for Study 2, the author relied on inductive themes arising from the data itself, as compared to deductive themes coming from other research (O'Reilly, 2009). Five themes emerged from the data and were defined to facilitate accuracy in identification: influencers, educational experiences, hurdles, attitude changes, and recommendations.

Table 4.2 shows the total numbers of responses by theme, as determined through the iterative process described in Chapter 3. All participants commented at least once within each of the five themes. The first theme, with the most responses, addressed the participants' influencers that had positive or negative impacts, from role models and mentors to detractors (101 responses). The second theme that emerged was educational experience, which concerned the educational background or range of educational experiences of the participants. Hurdles was the third theme that emerged from the data, pertaining to issues that needed to be overcome in the participants pursuing their careers.   The fourth theme reflected attitudes over the years towards women in STEM. The fifth theme related to participants' recommendations for engaging and retaining females in STEM fields.

Table 4.2

Number of Responses for Each of the Five Themes from the Qualitative Data

Theme	Total Collated Responses*
Influencers/Role Models	101
Educational experiences	65
Hurdles	56
Attitude changes	44
Recommendations	41

*Note, all participants responded at least once to each theme.

In the next sections, each of these themes will be discussed along with representative quotes. Each quote is identified by the participant's occupation (e.g., "Astronaut").

4.2.1 Influencers/Role Models (Positive and Negative) (101 Responses)

In their interviews, all of the participants discussed influencers, which could take the form of mentors, role models, or detractors. Although the mentors were, as might be expected, from more senior positions than the participants, some peer-to-peer or community support and influence was also discussed.

Of the mentorships discussed, five participants related information about male mentors and five of female mentors, while two did not mention the genders of their mentors. Two participants noted that the availability of female mentors was low or non-existent. Seven participants referred to specific role models, all of whom were female:

> When I thought about what astronauts looked like, I had in my mind a picture of the Mercury 7 astronauts standing in front of an airplane and they were all a bunch of old guys with no hair. And it certainly didn't say to me, this could be you. It wasn't until I went to college and Sally Ride came to talk, it just opened up that possibility of if she could do it then I could aspire to do it, too. (Astronaut)

> And . . ., you tend to look for role models. You tend to look for people who somehow are similar to you. That you, so you can put yourself in their shoes and

imagine what you might be like or how you might succeed in the future. (Mathematician)

And I remember my biology teacher in particular would never, she would never skip a beat. She would go straight to her bookcase and pull out her human sexuality textbook to answer the ninth graders' questions. And it was, they were just so awesome . . . . So I had this really strong group of science happy women in my background. (Geologist)

So when I was at - the mentor mentioned at [HBCU] who kind of took me underneath his wings. Unfortunately . . . going into my sophomore year of 2006 he passed away suddenly and he was such a huge impact. I still talk about him to this day even though it's been many years now because he was such an impact on me. (Astronomer)

When I was growing up, there weren't a lot of girls being astronauts [to look up to]. (Astronaut)

The fact that this woman [the first American woman to walk in space] who was on this huge pedestal for me was willing to take almost an hour out of her day was really meaningful to me . . .I kept saying, 'I think we should get back to the symposium,' and she would say, 'No, this is part of my job and this is really important because we need more astronauts who are qualified.' (Astronaut)

In my own judgment I'm not performing at the top of my capacity. But other, other blind folks, they tell me - we want to do science at the level you do the science. And then I think, oh this is not good, this is not good at all! (Computer Scientist)

And you know, my mom [a PhD oncology nurse] was a role model as, you know, somebody who is scientifically minded and, and you know, mathematically capable and and my sister also is very good at math and she, she's older than [I am]. So that was, you know I had those role models in my family for, for just kind of quantitative expertise and ability. (Cosmologist)

Peer-to-peer mentorships were also mentioned, as part of community building (8):

I think, the group of friends that I had at the time, a lot of us were like-minded. We were all interested in, you know, biology or some sort of an engineering field . . . I think that helped keep me on-path as well because I had good friends that, we could all study together and work together and encouraged each other throughout the process. (Engineer)

One of my ways of responding to the women in STEM issues was I formed a group called the Women in Science Forum . . . it was a group of graduate students, all the women graduate students. I guess there were, what maybe 10 maybe . . . but what, it was a quarter of the program. We would get together and ultimately our goals were to A) try to figure out how to get more role models for ourselves. Because, like I was describing before, the fraction of female faculty in the department was very small. (Mathematician)

But an incredible thing that [female researcher] did, is she intentionally hired women. Like that was part of her agenda was to have a club-like lab that was very female positive and certainly like men that worked in the lab also. But it was just a very positive, affirming vibe to it to know that this was my PI’s like life goal. (Technologist/Pre-medical Student)

And I think [like-minded group of women] has been kind of fun just because it's created another community. And cool ways to express themselves and some of the designers that we work with are also in STEM fields and they're creating things inspired by women in STEM or they're using STEM to do them like 3D printed jewelry, and things like that. (Radio Astronomer)

We are a team [of women], and that when things are hard, we’re going to turn to each other and we’re going to solve our problems together. (Astronaut)

About half of the participants (6) mentioned detractors or negativity in general, with two participants reflecting on specific persons or instances and the remaining four participants reflecting more broadly:

Have you heard of the phrase ‘racism without racists?’ It’s not like there were people who were being violent or verbally abusive or offensive or anything, more just like a general sense that there were opportunities and ways of being that other people had access to that I maybe had to work a little harder for. (Technologist/Pre-Medical Student)

> . . . the disabled woman is by herself. I find that is true. I find myself very self-reliant, and I like life. But that has, that has a huge effect . . . on your performance in daily life. Because if I would be, if I would be an abled woman, I would have a way right to do my work…and to be [seen as capable]. (Computer Scientist)

> And you know my math adviser in college was always making remarks about how I was, you know if he would see me walk into his office for a meeting and I was smiling, he would say things like, 'Oh I know, you're in love you're going to get married!' (Mathematician)

> I feel like around the observatory, the people that work I work mostly . . . tend [to view me] at a lower status level [with a master's degree] than the PhDs. There's not much question about that, except among the younger people and mostly they've used my software *Laughter*. (Software Developer)

> . . . it was a big to-do about whether I was under too much stress because I had kids and I was trying to do grad school. It became a subject of a faculty meeting . . . . I made a summary of things I had accomplished up til that point per semester, all the papers I had written, all the observing programs I had approved . . . empirical evidence . . . I think I was a little more productive than the average graduate student, but just evidence to show what she was saying was not the case. And you know [that] women with children can make it to through graduate school. *Laughter* (Mathematician)

This section demonstrated the critical importance of community to underserved audiences, whether mentor-mentee relationships or peer-to-peer networks. Positive instances of community, and particularly mentors or role models, were prioritized by a majority of interviewees as having a strong effect on their determination, success, and/or contentment with career or work circumstances. Negative influences in the community, or detractors, were either accumulated into larger conglomerations of negativity experienced over time, or conversely, were singled out in specific detailed stories that seemed to have a lasting impact on the interviewee. Additionally, such negative influences did not always come from outside the underrepresented community, but were occasionally insiders who would have presumably also experienced the biases and stereotypes of the participants during their own careers.

This outcome was taken into serious consideration for Study 2 and is, as such, discussed as related to interventions in Chapter 5.

4.2.2 Educational Experiences (65 Responses)

All participants mentioned having been interested in science since they were very young. They expressed how their interests in STEM stretched back to early childhood days (e.g., “I always loved animals and trying to figure out how things worked” (Engineer); “[I was] always looking at the sky” (Radio Astronomer); “[I enjoyed] watching *Nova*” (Mathematician); “I did a lot of reading on my own about science and physics” (Cosmologist); “I played with Lego's and I took apart my Transformers” (Geologist); and “I had always had this interest in geology and it went on and on” (Software Developer)).

The participants mentioned a range of educational experiences, both formal and informal, as well as diverse educational backgrounds. Formal education backgrounds included private schools and universities, public schools (including two public schools that specialized in STEM) and universities, and specifically Historically Black Colleges and Universities (HBCU). They took advantage of informal learning such as museums, books, television series, special programs and science fairs, all of which was part of their pathway into STEM.

Encouragement seemed an important aspect within this theme, and connects with the theme concerning role models. Most participants recalled encouragement from someone in their very young years, mostly teachers (4) or parents (3). For example, three participants mentioned looking up at the night sky with their families. Three other participants mentioned wanting to be something specific when they were little (an astronaut, doctor, or teacher), and three mentioned having parents that encouraged science and math activities at home or after school from an early age:

> I do feel again lucky to have had parents who, from day one just never questioned my ability to do anything. I mean, they were certainly very explicitly encouraging of my ability to be good in math and science. But it was, but they were just very supportive and encouraging in general. (Technologist/Pre-Medical Student).

Three participants also mentioned having family members who were scientists or PhD researchers or engineers that helped give them an insider’s perspective and additional educational opportunities or insights. One participant recalled that she felt as if she belonged in STEM even though she did not mention specific educational experiences or encouragement from someone in particular at a young age *("No one seemed to ever question me being there when I was growing up*", and [science and math] "*that was my spot*" (Science Writer). Many of these responses reflected on the role of positive influences in education. Responses included:

> When I was a kid I was the odd one outright. I was the person with no friends and especially because I was a girl and I loved, I loved playing Dungeons and Dragons. I loved video games. And that was really . . . hard . . . . So from an early age, I had a predisposition to STEM activities. I mean there was an emphasis on it at home. Of course: math is important, science is important. (Mathematician)

> . . . these teachers, as is true of a lot of private school science teachers, they just love science. They love teaching science. They love indulging kids' curiosity about science and they were just, they really encouraged me and other kids to hang out after school and ask questions. (Geologist)

> I had a really great teacher in high school for biology, which helped to cement my college major choice as biology. (Engineer)

Eight participants discussed the demographics or changing representation of their classes in either high school or college, with the majority of responses focused on the lack of equal representation in the student body, as well as a lack of equal representation in their educators, and how that had affected the culture of their classes, with some mentions that also stood out for positive or negative feelings:

> I noticed the [high school] classmates around me started to dwindle down and I'll never forget . . . I looked around the room and I was the only black woman. (Astronomer)

> When I went to college I noticed that there were very few women in my physics, math, and astrophysics classes. And that was, you know definitely eye opening to me at that point. It was a very small major at that point; you know there weren't that many students in these classes but I think there was only one other woman

who was in most of the classes with me . . . say there were ten students in the class, there was the two of us. (Science Writer)

> The library is where I used to do my problem sets. And the math library, not the general library because I used to want, you know look up stuff in books that were only in the math library and I would be there pretty late and it wasn't, it didn't take me so long to realize that the women's bathroom closed at 5 o'clock because the only women in the building were the secretaries and they locked up the bathroom before they left . . . . And the first time I realized this, I had to walk in the snow to go to the bathroom and then come back to the library. (Mathematician)

> . . . When I went to [Ivy league University] it was all guys doing research except [a female researcher] was there, not doing what I did. She worked on asteroids, then somebody else was, also the same age . . . . So she was around but I don't remember any other women doing science really except her. There probably were one or two in astronomy at [Ivy League University] but not very many. And then we came back to [Elite Technical University], the first year or two, not so many women, but [when] we started, we had women, a few women that came through . . . (Software Developer)

> Yeah at [Ivy League school] it was very clear that mechanical was more guys than girls. It was better than electrical and chemical and then worse like civil and industrial like those other ones were better . . . and . . . just the one female teacher that I had. (Radio Astronomer)

> And what was amazing about [my female scientist's] lab is that those, she's one of a handful of like female faculty at [Ivy League school] that have labs. Like honestly, I think [Ivy League University] could really work on its representation in terms of having female science faculty . . . . I only maybe had one female biology professor my entire time at [Ivy League University]. (Technologist/Pre-Medical Student)

Only one of the 11 participants, the geologist, had a markedly positive experience in this area of representation across her educational program:

> And you know just there were a lot of other cool women [in my grad school program], so it was a good mix of students pretty much 50/50 and so it was, I don't

> know if I've been, if I have particularly good judgment which is, or if I had good luck I'm sure it's a mixture of a little bit of both. But I, I always have managed to land in environments that are not toxic. (Geologist)

These quotes highlighted the importance of educational experiences, both formal and informal, and how they affected career development for the participants. They also reinforced the importance of encouragement for young women towards education in STEM from trusted sources in their lives that have a say on education, such as parents, teachers, or caregivers, with the positive influence they can exert, and particularly starting from an early age. The potential impact of such results on interventions will be discussed in the next chapter.

4.2.3 Hurdles (56 Responses)

In their interviews, all participants discussed hurdles that they faced in their careers. These largely focused on personal issues of motherhood (3), policy issues (4), or biases against gender, disability, sexuality, race, or educational level (10).

All of the women provided examples of discrimination in some form in either education (5) or career-related situations (4). Most examples seemingly fell between microaggressions (3) and unconscious biases (5). Four of the participants mentioned they did not recognize biases until later:

> My advisor challenged me a lot to reflect on my own experiences, and to come to terms with it frankly because . . . when I was in elementary school [and] high school I think I was just oblivious to the way I was being treated. (Mathematician)

One of the participants mentioned that they did not yet, at the time, have the vocabulary to process their experiences in reference to broader experiences they would later understand:

> I'm sure there were microaggressions that I experienced all the time as a kid and I definitely have some memories of these. But what really made it difficult for me to understand is that it wasn't really until college that I had the, like the liberal arts vocabulary to talk about maybe what was happening. (Technologist/Pre-medical Student).

Participants' reflections indicated the range of hurdles experienced:

For a lot of women, myself included, after getting married and starting a job, it's hard to go back and get a graduate degree. I think that's probably the main hurdle, and then if you start a family, that could be an additional hurdle, just your time that you are available to invest. (Engineer)

And so a lot of the problem is, is people you know having their own biases and their own sort of attitudes that, that make it, make it unpleasant for people who don't fit a certain mold. (Cosmologist)

. . . like what about payscale? It's one thing to have like 50 percent of their staff being women but if they all make like 75 percent of the pay that a man at that same level would make, that's certainly not equity. (Technologist/Pre-Medical Student)

I'm Hispanic, Afro, Afro Puerto Rican proudly . . . . I have a physical disability and I'm a woman . . . and I think . . . if I would be a sighted woman in a room, how will it be? I would have lots more chances because when people talk to me they don't see the scientist. Once I lost my sight . . . the biggest shock was to notice that I didn't have access to the same amount and quality of information that I had when I was sighted. I couldn't understand the professors . . . they were just pointing at things on the blackboard. (Computer Scientist)

And the problem was that as people retire they were replaced with PhDs. And all the PhDs that had been hired have been guys. Because relatively few women have been involved with just, this pipeline kind of stuff. (Software Developer)

I think sometimes when people hear that you're coming from an HBCU they kind of immediately assume that you have gaps in your education or maybe you're not as smart, like it's not anything in what they're saying but it's kind of an attitude - like you're here but you're only here because you're part of this special program because you needed it and that's it - it's all these little microaggressions that begin to add up. (Astronomer)

Additionally, there were four specific incidences concerning a participant experiencing a burden of difference, in having to either explain or over-compensate for some difference in ethnicity, sexuality, ability, or educational level. The following quotes exemplify this additional pressure mentioned:

> I think the burden comes from having to compensate. Yeah that sometimes you get . . . cognitively tired. Right. Right. For having to compensate so much. You know most of the time I do not . . . most of the time, I think - why do I have to interrupt this person to explain? Sometimes I just stay at the back of the room. (Computer Scientist)

> It's just, it's this constant feeling of you're constantly having to prove yourself, that you deserve to sit at the table. (Astronomer)

This theme of hurdles therefore, helps demonstrate the types of issues underrepresented groups in STEM face, and particularly, as related to intersectionality, how those issues can be compounded when women identify with multiple groups. Encouragement and interventions to help address such biases and burdens will be discussed in the next chapter.

4.2.4 Attitude Changes (44 Responses)

All participants discussed attitude changes, and nine specifically agreed that attitudes towards women in STEM had improved in most fields. Five participants spoke on how not enough change has occurred to support women (as well as people who are non-binary, which is not a focus of this thesis) in STEM:

> The issues that I thought would be taken care of to some degree by now: the underrepresentation of women, you know the percentages that are extremely low…they haven't moved the needle very much. I'm in my mid 40s now and I remember hearing about these issues when I was a very young person . . . and that's depressing. I think what has changed, especially in the past couple years, is that there is more awareness, certainly of issues like sexual harassment. (Science Writer)

> Growing up in the 80s and 90s, there was a general understanding that getting more women into sciences is a good thing. There needed to be opportunities made and sexism was real . . . . Then somewhere in the early 2000s, I started to perceive that people thought women were getting an unfair advantage. So, there

was starting to be this kind of backlash where people would say, 'Oh you know you'll definitely get a job. Everybody's trying to hire women.' (Cosmologist)

Well that you know it shows, the experience shows the duality. You know you ask the question - have we seen progress over the time at least in my professional lifetime. We have, but there is still the underlying culture that I don't think will change until that generation moves on. (Mathematician)

And I think that my favorite, favorite aspect of this trend is like really just we're getting young girls and boys involved in this idea of equality and equity and like women's rights because it's, I think for me . . . because I keep coming back to what's polarizing about it. I see like this if the movement could just figure out how this how to express itself in a way that isn't polarizing. (Technologist/Pre-medical Student)

And the sexual harassment piece very much ties into the underrepresentation side of it. There's sort of, you know I think there's a better understanding of how two - those are two sides of the same coin. So, you know, and I think that in the past six months, that our society has become much more aware of sexual harassment outside of science too. (Science Writer)

The first time I remember noticing that my gender mattered was when I was working as a . . . basically a reporter for our website and interviewing scientists at meetings when I suddenly started realizing that some of the scientists were sort of creepy. There's a couple leering faces I remember in particular but I also remember thinking that, since they - they tended to underestimate my intelligence or grasp of the material, those same people and so they tended to have looser lips in terms of telling me things that maybe they shouldn't have. (Geologist)

I feel like kids start to develop a sense of if they are 'good at math and science' right around the same age that they start to develop opinions about their abilities as artists. And I'm just like, 'You're 6, you've never even had hot sauce. So how do you know that you don't like math?' So, I wonder what signals a child has been receiving…what has changed (Technologist/Pre-medical Student)

Expanding upon that, another grouping of five women mentioned that although representation had improved somewhat for women, it was not nearly enough change in specific subsets of underrepresented people:

> I think there are some good changes that have happening. I know statistics, statistics-wise was the number of women in STEM field has increased since my time. But one thing that hasn't changed much since kind of going into the STEM field is the number of minorities who are getting their masters or they're getting their PhD. And that hasn't changed. So, it's a little discouraging. (Astronomer)

> Even though, even though [all] the people that I know, all of the people that I know in the field that have jobs, that have permanent jobs, and have severe disabilities . . . the most I'm just talking about two, no not even three right. (Computer Scientist)

Though positive attitude changes were remarked upon by participants, the lack of enough substantial change was made clear. Underrepresentation in STEM for women remains a serious issue, particularly when compounded by additional underrepresented identities. The emphasis on negative stereotype impacts, and potential backlash by perceived unfair advantages is also important to consider for interventions with such groups, as discussed in Chapter 5.

4.2.5 Recommendations (41 Responses)

In giving recommendations for engaging or retaining young women in STEM fields, the participants commented on the need for positivity. They stressed the importance of not focusing solely on negative stories and negative aspects, with the understanding that such negativity might discourage even greater numbers of talented individuals away from STEM fields. "I want them not to be scared - as we are not scared, right?" (Computer Scientist)

Ten participants commented on the importance of changing policies or cultures to help retain more underrepresented groups in STEM:

> All these things, science can be just you know brutal. Oh, you know, the I just worked 60 hours in a lab and 20 more on writing papers kind of thing, or the telescope or whatever people who publish first and most win. So, you know, if

> that's the only measure of success then a woman who is taking care of her kid or kids or you know a parent or whatever is going to be at a disadvantage. So, it's retaining people, it just has to be a good quality of work/life. (Science Writer)

> I think that in all of these areas of bias and privilege and stuff it is really, it's the responsibility of the people who are in a position of greater privilege or power to work on making that change. You know, so I think that men need to speak up more against sexism. You know, white people need to speak up more against racism. People who are able bodied need to speak up more against ableism . . . (Cosmologist)

> All of the advice is being given to women to tell them how to change, but it's equally important to get existing culture to change to be more welcoming to women and other underrepresented groups. (Geologist)

> The recognition of the emotional labor that women can do in the communities and organizations that they're a part of. Like, the kindness, the office vibes, like thinking about how to say something - considering other people's feelings and like the group dynamics offered by being sensitive to personality types. Like, all of those things are so difficult to, to quantify but have to be recognized and valued. And I think women take on a lot about work. (Technologist/Pre-medical Student)

> Any kind of policy issue, you need the simultaneous grassroots activity with policy changes at the top. (Mathematician)

Other recommendations included mentorship and community (3) (relating to the first theme), as well as the potential for creating new communities in younger STEM fields (1):

> So, finding mentors and then finding community. So, and hopefully - if you're lucky you can find community in your own department. But if you can't, there are other places to find community. There's social media, there are - you know, make sure that you are not isolated. (Geologist)

> Planetary science: my theory about women in science is that when there's a new field, that's when there's not as much of an 'old boy network' maybe or that's the way it's been, and women can get into it. (Software Developer)

Being cognizant of representation was also a strong message throughout many of the interviews, and in particular for women of color and people who are differently abled:

> When I'm doing outreach events sometimes a young African-American is like, 'Oh your hair is so beautiful!' Others comment on what I'm wearing. I asked a colleague, 'I don't know why they do that . . . it always catches me off guard. I want to talk about this cool infrared demonstration I'm doing. Thank you for complimenting me, but let's focus on this.' But she said, 'It's because they see themselves in you.' (Astronomer)

> This idea of equality and equity . . . if the movement could just figure out how this how to express itself in a way that isn't polarizing. Then maybe more people would understand but it's not trying to be . . . . It's not trying to recreate another system where we would then for example put men down, like that doesn't, that doesn't make any sense . . . . I think it's to have men talk to other people about it and to explain why they don't feel necessarily like threatened by it, and it's of course a shame that like women of color's voices can be so easily dismissed in the world that we live in. (Technologist/Pre-medical Student)

> Now . . . people with disabilities, we are different among each other, as abled people are different among themselves. We are completely different. (Computer Scientist)

From focusing on life-long learning, to helping to enact positive change for others, to ensuring that negative stories and situations not be the sole focus of any single issue of working on under-representations in STEM, setting a positive stage for further work, further change, in STEM fields was strongly encouraged:

> If space is where you want to go and what you want to do, then you can do that . . . . And I'm hoping that you realize that if real people can go to this amazing, fantastic place and be astronauts - real people like me - then real people like you can do whatever you want to do as well. (Astronaut)

> I think that there are ways to use the same language of . . . STEM, of math and economics to talk about how feminism and equality makes sense. (Technologist/Pre-medical Student)

> As you go on . . . there's always going to be more things to learn. And as long as you figure out how you learn, how you figure things out, whether you like to write them down . . . whatever way is the way you learn, that's how you are going to get the skills that are required (Astronaut)

> And you know just there were a lot of other cool women [in my grad school program], so it was a good mix of students pretty much 50/50 and so it was, I don't know if I've been, if I have particularly good judgment which is, or if I had good luck I'm sure it's a mixture of a little bit of both. But I, I always have managed to land in environments that are not toxic. (Geologist)

These recommendations are discussed as supporting the literature in the next chapter, and were also taken into consideration for the design of Study 2 as described next.

4.2.6 Impact of Study 1 on Study 2

From the five overall themes mentioned in the above sections, multiple takeaways were applied to Study 2, such as access to role models and mentors. One additional point was an expression of concern that girls need to be engaged with and encouraged in STEM fields even before entering middle school. All participants but two reviewed their own movement towards STEM pathways as starting at very young ages (as early as kindergarten). Even more, a few participants (3) specifically mentioned they had seen, experienced, or heard of girls "opting out" of STEM topics, or feeling discouraged from STEM topics while still in elementary school. Additionally, it was clear from these interviewees that importance needs to be placed on the broader STEM community as a whole need to help ensure STEM materials and outputs are accessible for differently abled learners.

Just over half of the interviewees (6) commented on the importance of discussing personal stories of failure, resilience, and creativity when communicating about STEM careers, to help dispel the "genius" stigma often associated with such fields. For example, the astronomer noted that, “It was a huge misconception that I had, [STEM] was just these geniuses. They were really smart, things just came to them quickly, and that wasn't the case with me.” Closely related to that was the need to help dispel the idea of perfection in STEM, a particular concern for interviewees, and importantly for those who identified with other underrepresented subgroups. For example:

> The [positive] fact, that you see other people potentially talking about both successes and failures, because that’s the other half of that, seeing that, is that you know things that they’re not good at or not doing perfect, they're not on the *one true path* . . . Which is going to affect women and minorities. (Radio Astronomer)

> I made a mistake . . . and I really just had to say, ‘Hey, ground, that was me, I did that.’ And then I think the hardest thing was just saying, ‘Okay, where were we, let’s start again.’ (Astronaut)

Study 1, therefore, not only helped to inform the literature in this area, but also helped construct the design and implementation of the workshops in Study 2. The following concepts, therefore, were directly incorporated into the design of Study 2: (a) that girls should be targeted in elementary school, which led to the researcher targeting ages 9 through 12 for the workshops rather than ages 11 through 13; (b) that all the materials used in the workshops were coded to U.S. government accessibility standards, with consideration of Universal Design for inclusivity; (c) that personal stories of failure, resilience, and creativity were incorporated into each workshop, as a result of interviewees expressing the importance of these being included; (d) that materials showcasing diverse women in STEM were provided and reviewed in the workshops, as related to the need for more role models; and (e) that current, diverse women in STEM were trained as assistant facilitators for the workshops, also in response to the importance of role models and mentors. See Chapter 5 for additional details discussing these programmatic adjustments.

The next section will detail the results of the Study 2, including the overall discussion of the three workshop events, participant demographics, and the data analyses used to examine the materials used and to investigate the research question for Study 2.

Study 2 Results

To explore the research question for Study 2, What are the quantifiable effects of data based 3D models and prints on spatial reasoning skills and interest in STEM fields, particularly with young female learners?, the researcher conducted the following three sets of workshops, as detailed in Chapter 3, for the quantitative study. Study 2 was conducted over four days in three separate locations in February, July, and October of 2019. The data from Study 2 were comprised of surveys administered to the participants, using a randomized pre-post design. For the workshops in Study 2, all participants granted permission for the data being collected to be incorporated into this thesis (see Chapter 3 for additional information on ethics and permissions, and schedules for the activities for each workshop). The following sections provide additional detail on each of the workshops.

4.2.7 Workshop 1

The first workshop, conducted on Thursday, February 28, 2019 from 5:30-8:30pm, was a special program offered at a local Scout Group headquarters for n = 29 4^{th}, 5^{th}, and 6^{th} grade girls (aged 9-11), as part of events being organized worldwide in support of the International Astronomical Union (IAU)'s celebrations for Women and Girls in Astronomy. The free program had been advertised as "Celebrate the International Day of Women and Girls in Science!" in the local Scout Group program guide (online and in print). Participants, with their parents/caregivers, self-selected to register individually or participate as representatives from a grouping of Scouts. Capacity was set at 30 students. Thirty students registered and 29 students attended. The event ran for about 2.5 hours formally with about 30 minutes of additional informal time at the beginning of the workshop when participants began showing up in staggered numbers.

The 29 participants spent the entirety of the workshop in one large room together, grouped into five tables of approximately six participants per table. Chrome books and Internet were provided by the organization, with the rest of the materials supplied by the researcher. Two facilitators were on hand for the workshop, this researcher as lead facilitator, and a female assistant trained by the researcher as a second facilitator. The second facilitator was experienced, having been trained by the researcher on the digital materials, and having assisted with demonstrating workshop activities and approaches over other multiple in-person session events during 2018. One Scout Group headquarters employee remained outside of the room but nearby for assistance with logistics as needed, and multiple parents stayed in the next room to wait. On this day, poor weather was a factor. Though all but one of the girls who registered for the event showed up, 14 girls had to leave early, as their parents were concerned for their personal safety regarding driving home in the recently fallen snow. This negatively affected the total number of post-evaluations for this group and reduced the total number of completed pre-post sets of data for this group to 15.

4.2.8 Workshop 2

The second workshop was conducted as a full day workshop organized with the Camp Group for a special summer-long day-camp program for local socio-economically disadvantaged girls. Participation had been planned for n = 50, but as the summer program progressed, almost half had dropped out of that program and/or showed up less frequently for the Camp Group's programs. Therefore, for this workshop, there were 29 participants. This event for girls aged 11-12 was organized as a sponsored field trip titled, "A Virtual Trip to the Stars with NASA," the last one of five field trips of the program that summer. They were bussed to a local college on Thursday, July 25, 2019 from 9:30am-3:30pm. Two students had to leave the event early for personal reasons, bringing the total of completed pre-post sets of data to 27.

Participants spent the day moving between one large meeting room and two nearby smaller computer labs equipped with desktop PC computers and high-speed Internet. The remaining materials provided were supplied by the researcher. Five facilitators in total were on hand for the workshop, with this researcher as lead facilitator and four female volunteers, including two women of color, trained by the researcher as assistant facilitators. One woman was an assistant facilitator at all three of the workshops for Study 2. Training for the assistant facilitators had occurred by reviewing the online materials and assisting with demonstrating workshop activities and approaches over multiple in-person session events during 2018. Four Camp Group chaperones also remained on site to assist with logistics, such as helping with bagged lunches and restroom breaks.

4.2.9 Workshops 3 and 4

The third and fourth workshops took place at a local private girls' school equipped with a full "STEAM" (science, technology, education, art and math) center for 59 girls, who comprised their entire 4th, 5th, and 6th grade classes (aged 9-11). On Thursday, October 10, (n = 16) 4th and (n = 17) 5th grade girls participated, and on Friday October 11, 2019, (n = 26) 6th grade girls participated. Organized in part to celebrate Ada Lovelace day, the workshop, "NASA Runs on Coding" was conducted from 8:30am-3pm each day. One 6th grade student had to leave early for personal reasons, bringing the total of completed pre-post sets of data to 58.

Participants spent the day moving between one large meeting room and one nearby smaller computer lab (as well as a lunch room and outdoors for recess). Both the meeting and computer rooms were equipped with PC laptops and high-speed Internet, as well as one of the school's 3D printers, provided by the technology department, to run during the event in the meeting room. The remaining materials provided were supplied by the researcher.

Two facilitators were on hand for Workshop 3, with this researcher as lead facilitator, and with a female volunteer trained by the researcher as an assistant facilitator that had served at each workshop. Six teacher chaperones cycled through the rooms during the two days to assist with the workshop as needed and help with any logistics, such as overseeing outdoor recess and leading students to lunch. A month prior to Workshop 3, the researcher led a 60-minute online webinar for teacher training so the educators would be comfortable with the material offered during the workshops and be able to incorporate content extensions or supplements, or answer questions from the students, in the days before and after the workshops.

Statistical Analyses

4.2.10 Descriptive Data

To begin, frequencies on the data were run for each variable in the study to obtain the descriptive statistics associated with the total sample of n = 100. For each variable, the researcher looked at the frequency, mean, median, and standard deviation as applicable to each variable, and examined the minimum and maximum values to ensure that the data remained within expected value ranges. In two instances, data for a variable had been mis-entered; these were corrected after locating the correct information from the hard copy.

Basic demographic information was collected from the participants during the pre-evaluation phase. Results for the full sample, and broken down by affiliation, is provided in Table 4.3, with the means and standard deviations across age, self-rating, and video hours for both the full group as well as by affiliation is provided in Table 4.4.

Table 4.3

Demographic Data for the Full Sample and by Affiliation

Item	Group	*n*	Percent
Affiliation	Scout Group	15	15
	Camp Group	27	27
	Private School	58	58
Pre-Post Group			
Full Group	Spatial/Inventory	55	55
	Inventory/Spatial	45	45
Scout Group	Spatial/Inventory	7	46.7
	Inventory/Spatial	8	53.3
Camp Group	Spatial/Inventory	16	59.3
	Inventory/Spatial	11	40.7
Private School	Spatial/Inventory	32	55.2
	Inventory/Spatial	26	44.8
Age			
Full Group	9	21	21
	10	25	25
	11	38	38
	12	16	16
Scout Group	9	6	40
	10	8	53.3
	11	1	6.7
	12	--	--
Camp Group	9	--	--

Item	Group	*n*	Percent
	10	4	14.8
	11	9	33.3
	12	14	51.9
Private School	9	15	25.9
	10	13	22.4
	11	28	48.3
	12	2	3.4
Grade			
	4	27	27
Full Group	5	25	25
	6	32	32
	7	16	16
Scout Group	4	11	73.3
	5	4	26.7
	6	--	--
	7	--	--
Camp Group	4	--	--
	5	4	14.8
	6	7	25.9
	7	16	59.3
Private School	4	16	27.6
	5	17	29.3
	6	25	43.1
	7	--	--
Gender	Female	99	99
	Nonbinary	1	1
Ethnicity			
Full Group	Caucasian	45	45
	Black/African	11	11
	Hispanic/Latina	9	9
	Other	30	30
	Prefer NtA	5	5

Item	Group	*n*	Percent
Scout Group	Caucasian	11	73.3
	Black/African	--	--
	Hispanic/Latina	--	--
	Other	2	13.3
	Prefer NtA	2	13.3
Camp Group	Caucasian	--	--
	Black/African	8	29.6
	Hispanic/Latina	8	29.6
	Other	10	37
	Prefer NtA	1	3.7
Private School	Caucasian	34	58.6
	Black/African	3	5.2
	Hispanic/Latina	1	1.7
	Other	18	31
	Prefer NtA	2	3.4
Self-rating			
Full Group	1	2	2
	2	--	--
	3	1	1
	4	6	6
	5	21	21
	6	19	19
	7	20	20
	8	18	18
	9	7	7
	10	6	6
Scout Group	1	--	--
	2	--	--
	3	--	--
	4	2	13.3
	5	3	20
	6	1	6.7

Item	Group	*n*	Percent
	7	2	13.3
	8	2	13.3
	9	3	20
	10	2	13.3
Camp Group	1	--	--
	2	--	--
	3	1	3.7
	4	1	3.7
	5	8	29.6
	6	7	25.9
	7	7	25.9
	8	3	11.1
	9	--	--
	10	--	--
Private School	1	2	3.4
	2	--	--
	3	--	--
	4	3	5.2
	5	10	17.2
	6	11	19
	7	11	19
	8	13	22.4
	9	4	6.9
	10	4	6.9
Video Hours			
Full Group	0	48	48
	1	24	24
	2	14	14
	3	6	6
	4	2	2
	5	2	2
	6	1	1

Item	Group	*n*	Percent
	7	2	2
	8	1	1
Scout Group	0	5	33.3
	1	5	33.3
	2	3	20
	3	1	6.7
	4	1	6.7
	5	--	--
	6	--	--
	7	--	--
	8	--	--
Camp Group	0	6	22.2
	1	10	37
	2	5	18.5
	3	1	3.7
	4	1	3.7
	5	1	3.7
	6	1	3.7
	7	1	3.7
	8	1	3.7
Private School	0	37	63.8
	1	9	15.5
	2	6	10.3
	3	4	6.9
	4	--	--
	5	1	1.7
	6	--	--
	7	1	1.7
	8	--	--

Table 4.4

Means and Standard Deviations for Age, Self-rating, and Video Hours for Full Group, and by Affiliation

Item	Mean	Standard Deviation
Age		
Full Group	10.49	1
Scout Group	9.67	0.62
Camp Group	11.37	0.74
Private School	10.29	0.9
Self-rating		
Full Group	6.55	1.81
Scout Group	7.07	2.12
Camp Group	6	1.24
Private School	6.67	1.91
Video Hours		
Full Group	1.16	1.68
Scout Group	1.2	1.21
Camp Group	1.96	2.19
Private School	0.78	1.38

As shown in Tables 4.3 and 4.4, participants in the full group were fairly evenly spread across age and grade, in a narrow band from ages 9 to 12 and grades 4 to 7. Participants identified as female with one exception, who self-identified as non-binary. In the full sample, of those who responded to the item asking for ethnicity, 45% of the participants (n = 45) self-identified as Caucasian, 30% (n = 30) as mixed race, 11% (n = 11) as Black, and 9% (n = 9) as Latina. The remaining five participants did not respond to this item. In terms of affiliation, the Camp Group was the only group comprised completely of girls of color (with one participant who chose not to respond to this item).

There were slightly more participants in the spatial inventory pre-STEM inventory post sample (*n* = 55) than the STEM inventory pre-spatial inventory post sample (*n* = 45). This was mostly a result of some participants having to leave early who were in the STEM inventory post-condition, as well as a result of the distribution of the instruments to groups with odd numbers of participants.

All participants (*n* = 100) were asked to rate themselves on their overall knowledge in STEM topics. On a scale of 1 (low) to 10 (high), the mean rating for the full sample was 6.55 (*SD* = 1.81). Roughly one third of the participants (*n* = 30) rated themselves between 1 to 5, just over one third rated themselves at 6 or 7 (*n* = 39), and the final third rated themselves at the highest levels of 8 to10 (*n* = 31). This indicated a fairly wide range of self-reported STEM information for the sample, with the average rating approaching 7 (see Table 4.4).

When examined by affiliation, self-reported overall STEM knowledge for the Camp Group participants was *M* = 6.00 (*SD* = 1.24); for the Scout Group, *M* = 7.07 (*SD* = 2.12); and for Private School, *M* = 6.67 (*SD* = 1.91), thus setting the Camp Group participants somewhat below the other two groups in terms of their self-reported STEM knowledge. A one-way analysis of variance determined that these differences were not statistically significant, $F(2, 97) = 2.03$, *ns*. Finally, the majority of participants (*n* = 86; 86%) reported spending 0-2 hours playing video games per day (*M* = 1.16, *SD* = 1.68). This was reported similarly across affiliations. However, as there was some confusion vocalized by the girls and noted by the researcher as to what "counted" as playing a video game during the evaluation, this variable was only used in a correlational analysis and not in the primary analyses for investigating the research question. This will be discussed further in Chapter 5.

The scores for the spatial and STEM inventories are presented in Table 4.5. The total score for the spatial inventory, based on 0 (lowest possible score) to 5 (highest possible score) for the full group was *M* = 2.89 (*SD* = 1.60*).* For the the STEM inventory, based on 25 (lowest possible score) to 175 (highest possible score) the mean was 121.08 *(SD* = 35.50*).* By affiliation, Private School had the highest values for the spatial score totals (*M* = 3.47, *SD* = 1.23), followed by the Camp Group (*M* = 2.78, *SD* = 1.60), and then the Scout Group (*M* = 0.87, *SD* = 1.19). For the STEM inventory score totals, Private School placed the highest again (*M* = 130.76, *SD* = 33.97), followed by the Scout Group (*M* = 114.40, *SD* = 32.92), and then the Camp Group (*M* = 104.00, *SD* = 33.88).

Table 4.5

Scores for the Spatial Skills and STEM Inventories for the Full Sample and by Pre Post Conditions Within Affiliation

Item	Group	*n*	Mean	*SD*
Spatial Total Score	Full Group	100	2.89	1.6
	Scout Group	15	0.87	1.19
	Camp Group	27	2.78	1.6
	Private School	58	3.47	1.23
Inventory Total Score	Full Group	100	121.08	35.5
	Scout Group	15	114.4	32.92
	Camp Group	27	104	33.88
	Private School	58	130.76	33.97
Spatial Pre	Full Group	55	3.24	1.48
	Scout Group	7	1.14	1.35
	Camp Group	16	3.06	1.77
	Private School	32	3.78	0.79
Spatial Post	Full Group	45	2.47	1.66
	Scout Group	8	0.63	1.06
	Camp Group	11	2.36	1.29
	Private School	26	3.08	1.55
Inventory Pre	Full Group	45	116.24	43.28

Item	Group	*n*	Mean	*SD*
	Scout Group	8	105.63	40.88
	Camp Group	11	89	42.04
	Private School	26	131.04	39.14
Inventory Post	Full Group	55	125.04	27.36
	Scout Group	7	124.43	18.94
	Camp Group	16	114.31	23.08
	Private School	32	130.53	29.77

4.2.11 Principal Component Analysis

Next, a Principal Component Analysis with a direct oblimin rotation was run on the items of the STEM inventory to examine their factor structure (see Table 4.6). A direct oblimin rotation was chosen as any anticipated underlying factors could be correlated, and this allowed for such correlation among factors. As Table 4.6 shows, the structure matched what was expected for the inventory, with the items for each subscale loading into an individual factor, aligning with the published results (Tyler-Wood et al., 2010). Based on this analysis, the items for each category were combined into their expected subscales.

Table 4.6

Principal Component Analysis of the "Instruments for Assessing Interest in STEM Content and Careers" (Tyler-Wood et al., 2010)

	Component					
Item	1	2	3	4	5	Communalities
Science Boring	**.865**	.225	-.371	.363	-.451	.800
Science Appealing	**.847**	.241	-.178	.437	-.411	.754
Science Fascinating	**.840**	.299	-.322	.354	-.545	.550
Science Nothing	**.818**	.148	-.484	.385	-.365	.747

	Component					
Item	1	2	3	4	5	Communalities
Science Exciting	**.718**	.145	-.284	.402	-.173	.792
Math Boring	.045	**.869**	-.267	.051	-.237	.799
Math Appealing	.119	**.940**	-.130	.118	-.106	.899
Math Fascinating	.200	**.948**	-.182	.206	-.188	.905
Math Nothing	.375	**.634**	-.458	.305	-.477	.609
Math Exciting	.268	**.917**	-.145	.089	-.187	.860
Technology Boring	.450	.248	**-.866**	.267	-.178	.803
Technology Appealing	.266	.214	**-.886**	.247	-.293	.797
Technology Fascinating	.209	.194	**-.878**	.248	-.383	.822
Technology Nothing	.362	.156	**-.877**	.248	-.103	.801
Technology Exciting	.238	.239	**-.798**	.236	-.135	.651
Engineering Boring	.539	.212	-.192	**.905**	-.284	.875
Engineering Appealing	.282	.085	-.266	**.845**	-.430	.747
Engineering Fascinating	.215	.145	-.296	**.849**	-.468	.791
Engineering Nothing	.498	.111	-.269	**.792**	-.218	.689
Engineering Exciting	.375	.201	-.216	**.922**	-.410	.858
Career Boring	.422	.228	-.096	.552	**-.771**	.702
Career Appealing	.354	.230	-.364	.337	**-.899**	.840
Career Fascinating	.528	.282	-.325	.525	**-.784**	.733
Career Nothing	.471	.282	-.093	.527	**-.606**	.541
Career Exciting	.566	.246	-.260	.503	**-.782**	.734
Factor Name	Science	Math	Technology	Engineering	Career	
Eigenvalues	9.801	3.321	2.801	1.829	1.346	

	Component					
Item	1	2	3	4	5	Communalities
Variance Explained %	39.206	13.283	11.202		7.317	5.385

Each subscale was then examined in terms of reliabilities, using Cronbach's Alpha. Results are provided in Table 4.7, along with the published reliabilities for the inventory (Tyler-Wood et al., 2010). As shown, in each case the data from the participants on the STEM inventory subscales were the same or similar to the published coefficient alphas. Reliabilities were calculated for the Spatial inventory, also shown in Table 4.7 below. The value reported is generally considered to be at the minimum level of acceptability (Cortina, 1993). As there were no published values for this inventory, no comparison could be made to previous data, however.

Table 4.7

Reliability Statistics using Cronbach's Alpha for STEM Inventory Subscales and Spatial Skills Inventory (5 Items each)

Subscale	Cronbach's Alpha	Published Cronbach's Alpha
Science	.91	.84
Math	.91	.88
Engineering	.90	.92
Technology	.91	.91
Career	.89	.93
Spatial	.70	--

Having established that the reliabilities of the inventories meant that the scales were viable, the researcher proceeded with analyses using the total scores for the Spatial and STEM inventories. First, correlations were computed to examine the relationships of hours playing video games with self-rating of STEM knowledge, the Spatial total scores, and the STEM inventory total score. The purpose of this correlational analysis was to investigate the extent of any relationship among these variables that might help inform STEM identity. The correlations were done first for the full sample and then by affiliation (see Tables 4.8 and 4.9).

For the full sample, video hours were negatively correlated with self-rating of STEM knowledge, r (98) = -.26, p < .01 and the STEM inventory total score, r (98) = -.29, p < .01, thus suggesting that more hours playing video games were related to lower values for self-rating of STEM knowledge and the STEM inventory total score. Also of note is the positive correlation, r (98) = .33, p < .01 between perception of self-rating of STEM knowledge and the STEM inventory total score.

Table 4.8

Correlation of Video Hours with Self-rating, Spatial Total, and Inventory Total for Full Sample

Variable	Video Hours	Self-rating	Spatial Total	Inventory Total
Full Sample (n = 100)				
Video Hours	1			
Self-rating	-.262**	1		
Spatial Total	.033	.052	1	
Inventory Total	-.289**	.328**	.130	1

NOTE. * Correlation is significant at p <. 05
** Correlation is significant at p <. 01

When the correlation analysis was rerun by affiliation (Table 4.9), only the results for Private School yielded significant relationships. For the full sample, video hours were negatively correlated with self-rating of STEM knowledge, r (56) = -.47, p < .01, and the STEM inventory total score r (56) = -.29, p = .02, suggesting that more hours playing video games were related to lower values for self-rating of STEM knowledge and the STEM inventory total score. Again, for the full sample there was also a positive correlation, r (56) = .45, p < .01, between self-rating of STEM knowledge and the STEM inventory total score for the Private School sample.

Table 4.9

Correlation of with Video Hours, Self-rating, Spatial Total, and Inventory Total by Affiliation

Variable	Video Hours	Self-rating	Spatial Total	Inventory Total
Scout Group (*n* = 15)				
Video Hours	1			
Self-rating	.162	1		
Spatial Total	-.080	.061	1	
Inventory Total	.102	.121	-.390	1
Camp Group(*n* = 27)				
Video Hours	1			
Self-rating	.014	1		
Spatial Total	.261	.155	1	
Inventory Total	-.206	.046	.089	1
Private School (*n* = 58)				
Video Hours	1			
Self-rating	-.474**	1		
Spatial Total	.032	.111	1	
Inventory Total	-.290*	.445**	.100	1

NOTE. * Correlation is significant at p <. 05
** Correlation is significant at p <. 01

4.2.12 Multivariate Analysis of Variance (MANOVA) Results

These analyses laid the groundwork to allow the examination of research question for Study 2 concerning the quantifiable effects of databased 3D models of on under-represented populations in STEM. As this analysis involved two input or independent variables, and two output or dependent variables, a multivariate analysis of variance (MANOVA) was used. The independent variables in the MANOVA were the three affiliations (Scout Group, Camp Group, and Private School) and two levels of the order of the presentation of the inventories (Spatial inventory pre and STEM inventory post or STEM inventory pre and Spatial inventory post). The two dependent variables were the total scores for the Spatial and STEM inventories. Self-rating of STEM knowledge was used as a covariate to eliminate the possibility of any potential relationship between perceptions of preexisting knowledge and the dependent variables, especially the STEM inventory. Therefore, using this covariate essentially equalized the baseline going in to the study in terms of where the participants thought they were in terms of ability, so as not to obscure any potential effects.

The results of the MANOVA (see Table 4.10) yielded two significant findings. Affiliation was significant, $F(4, 186) = 12.66$, $p < .001$, Partial *Eta* Squared = .214., as the pre-post condition, $F(2, 92) = 4.11$, $p = .019$, Partial *Eta* Squared = .082. There was no interaction effect of affiliation by pre-post condition, $F(4, 186) = .710$, $p = .586$, *ns*.

Pillai's trace, which is considered a robust test statistic (Glen, 2016), is reported here, although it is noted that all four test statistics yielded the same level of significance for affiliation and pre-post condition. Partial Eta squared, a measurement of the variance accounted for, is reported as an estimate of effect size.

Table 4.10

Results of Multivariate Analysis of Variance

Effect	Value	*F*	Hypothesis *df*	Error *df*	Sig.	Partial Eta Squared
Intercept						
Pillai's Trace	.363	26.26	2	92	<.001	.363
Wilks' Lambda	.637	26.26	2	92	<.001	.363
Hotelling's Trace	.571	26.26	2	92	<.001	.363
Roy's Largest Root	.571	26.26	2	92	<.001	.363
Self-rating						
Pillai's Trace	.110	5.69	2	92	.005	.110

Effect	Value	*F*	Hypothesis *df*	Error *df*	Sig.	Partial Eta Squared
Wilks' Lambda	.890	5.69	2	92	.005	.110
Hotelling's Trace	.124	5.69	2	92	.005	.110
Roy's Largest Root	.124	5.69	2	92	.005	.110
Affiliation						
Pillai's Trace	.428	12.66	4	186	<.001	.363
Wilks' Lambda	.596	13.58	4	184	<.001	.363
Hotelling's Trace	.637	14.50	4	182	<.001	.363
Roy's Largest Root	.566	26.32	2	93	<.001	.363
Pre Post Condition						
Pillai's Trace	.082	4.11	2	92	.019	.082
Wilks' Lambda	. 918	4.11	2	92	.019	.082
Hotelling's Trace	.089	4.11	2	92	.019	.082
Roy's Largest Root	.089	4.11	2	92	.019	.082
Affiliation*Pre Post						
Pillai's Trace	.030	.71	4	186	.586	.015
Wilks' Lambda	.970	.71	4	184	.586	.015
Hotelling's Trace	.031	.71	4	182	590	.015
Roy's Largest Root	.030	1.41	2	93		.015

4.2.13 Univariate Results

The univariate results are shown next on Table 4.11. For two significant main effects, for affiliation for the Spatial inventory, $F(2, 93) = 22.96$, $p < .001$, Partial *Eta* Squared = .331. For affiliation for the STEM inventory, $F(2, 93) = 6.10$, $p = .003$, Partial *Eta* Squared = .116. For pre-post condition for the Spatial inventory, $F(1, 93) = 4.34$, $p = .040$, Partial *Eta* Squared = .045. For pre-post condition for the STEM inventory, $F(1, 93) = 3.67$, $p = .058$, Partial *Eta* Squared = .038. The descriptive statistics for the multivariate test are shown previously on Table 4.10, and are presented graphically in Figures 4.1 and 4.2 below.

Table 4.11

Results of Univariate Analysis of Variance Between-subjects Effects

Source	Dependent Variable	Type III Sum of Squares	*df*	Mean Square	*F*	Sig.	Partial *Eta* Squared
Affiliation	Spatial Total	78.14	2	39.36	22.96	<.001	0.331
	Inventory Total	12464.33	2	6232.17	6.1	0.003	0.116
Pre Post	Spatial Total	7.44	1	7.438	4.34	0.04	0.045
Condition	Inventory Total	3751.09	1	3751.09	3.67	0.058	0.038
Affiliation *	Spatial Total	0.14	2	0.067	0.04	0.961	0.001
Pre Post	Inventory Total	2879.38	2	1439.69	1.41	0.25	0.029
Condition							
Error	Spatial Total	159.39	93	1.71			
	Inventory Total	95069.43	93	1022.25			
Total	Spatial Total	1089	100				
	Inventory Total	1590788	100				
Corrected	Spatial Total	253.79	99				
Total	Inventory Total	124751.36	99				

Figure 4.1. shows the mean pre-post scores for the Spatial inventory, with separate lines for each affiliation. It can be seen that all three groups did less well on average in the post-evaluation condition, and that the participants from the Camp Group were well below the other two groups.

Figure 4.1

Mean Pre-Post Scores for Spatial Inventory

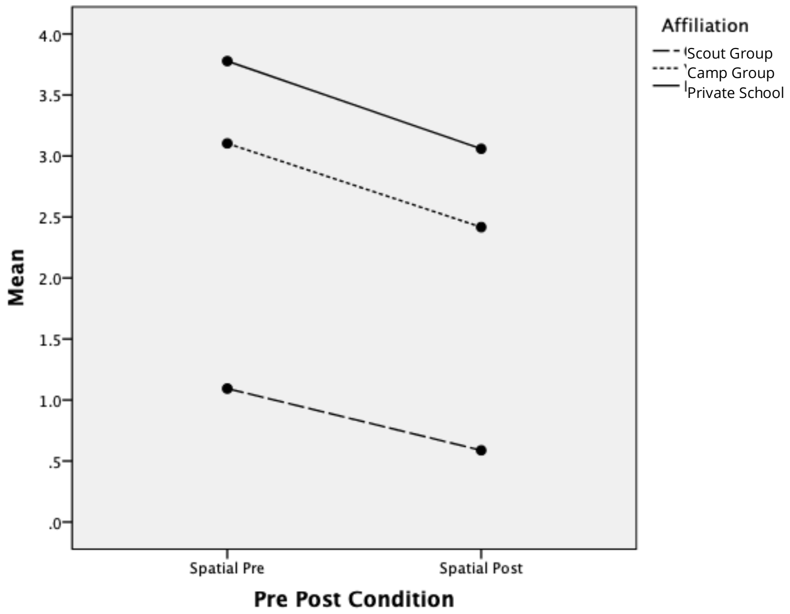
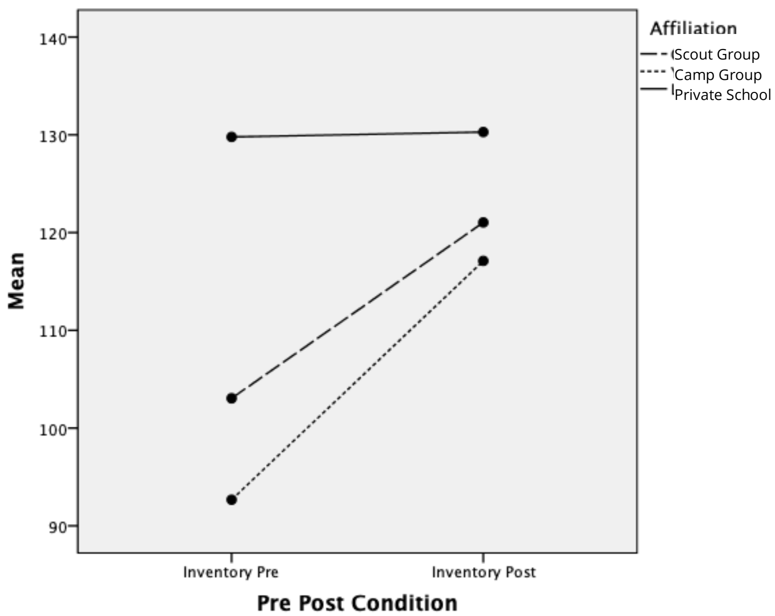


Figure 4.2. shows the mean pre-post scores for the STEM inventory, with separate lines for each affiliation. It can be seen that the Private School participants did not exhibit much change from pre- to post, but the other two groups increased nearly 20 points for the Scout Group and 25 points for the Camp Group participants.

Figure 4.2

Mean Pre-Post Scores for STEM Inventory



4.2.14 Informal Observations

Finally, although not included as formal analyses, informal observations were recorded by the researcher after each workshop. This included general observations on student participation, vocalizations and energy levels, comments made by the participants to the researcher throughout the day, questions or concerns raised during the activities, as well as summations from the students at the end-of-day wrap up sessions.

Participant comments throughout the workshops, for example, included such notes as: "Will you be my BFF?", "I want to do this when I grow up," "I didn't know I could do this," "This was the best day ever," and "I didn't know I could walk around a black hole." The Camp group related the highest number of comments like this directly to the researcher, and the Scouts group was the least vocal to the researcher (which could have been due to the shorter length of time spent with the researcher for the Scouts, and the slightly early dispersal due to the weather).

Informal question and answer sessions after the workshop activities resulted in discussions around which activities the girls enjoyed the best, what concepts they learned, and what issues they were curious about. One common theme expressed across all three groups was particular enjoyment of the VR, and to a slightly lesser extent, the 3D printing (which was also backed up through the recorded observations of the activities themselves), though the girls spoke positively about each activity as a whole. Questions relating to the researcher's career were numerous, but particularly from the Private School, ranging from curiosity of what field of study was majored in, to how the researcher got a job on a NASA mission, to specific questions on the types of work the researcher currently does. Finally, science-based questions were another common theme across all the groups, with the highest frequency in the Private School group (which also had the longest time of the workshops). These questions ranged from specific context questions as related to the VR activities, and particularly black holes, to questions on broader topics such as aliens.

As noted previously, the highest levels of confusion with the spatial instrument – and to a slightly lesser extent, the STEM inventory and demographics – were expressed to the researcher by the Camp group, followed by the Scout Group, followed by the Private School, though all groups related notable levels of confusion and frustration.

The Private School group participants worked with each other to help fellow students complete the spatial instrument. This issue is discussed in the next chapter.

Summary

This chapter presented the results from the qualitative and quantitative studies as they pertained to the research questions on the obstacles and challenges that female-identifying underrepresented groups can face and the potential quantifiable effects of 3D data on spatial reasoning skills and interest in STEM fields of such learners. The qualitative study, designed to investigate the STEM pathways of a diverse group of women currently active in their fields, and to solicit actionable thoughts with regard to how to improve those pathways for young females today, was then applied to the design of the quantitative study.

Statistical analyses from the quantitative study will be discussed in Chapter 5. For example, disadvantaged groups experienced gains in STEM interest and confidence from the workshops, and the more privileged group remained effectively constant (already high). Further, positive impact on spatial reasoning skills for this sample was not significant but contributes a useful data point for the literature. The next chapter provides a summary of the thesis and main findings, a discussion of the analyzed data and results, contributions to the literature, limitations of the studies, and reflections and suggestions for future research.

Chapter 5. Discussion

The previous chapter presented the data, analyses, and results from the two studies of this thesis. Chapter 5 provides a summary of the thesis and main findings, discusses the findings, and presents the contributions to the literature, as well as the limitations of the studies. It concludes with reflections and suggestions for future research.

Thesis Summary

Research to date has not focussed on the development of STEM interests and spatial reasoning skills of young female learners, particularly at the time when such young learners are forming potential identities in or with STEM and beginning to think about educational and career-related decisions. In this thesis, a targeted program was designed to gauge, investigate, and increase spatial reasoning skills and interest in STEM fields for females in upper elementary and middle school years. The program used unique, data-based models and emerging technologies grounded in cutting-edge astrophysics research, along with a few more familiar activities such as origami, to engage the participants and get them thinking about the possibilities for further study or future work in areas related to STEM. The program was carried out across formal and informal learning environments with different demographical groups.

Therefore, the goal for the targeted program that was developed was to explore its effects on spatial reasoning abilities and interest in STEM fields for young females across a variety of venue types and with a particular lens towards working with young female learners who were primarily from underrepresented groups.

As the focus of this research was on young females, particularly in groups considered underrepresented in STEM fields with regard to socioeconomic status, special needs/disability, ethnicity/race, income, language, literacy skills, and/or geographic location, it was critical to gain perspective on possible historical or sociological reasons why young women throughout the “pipeline” (student progress from school to college and into career (Ewell et al., 2006)) typically have been less engaged in STEM subjects as compared to young men. Larger swaths of underrepresented populations in STEM - such as women – also switch from STEM fields to non-STEM fields during undergraduate educations than more traditionally typical STEM populations (Anderson & Kim, 2006; Chen, 2013; Hill, Corbett, & St. Rose, 2010). Although the literature includes research on the roles of women in STEM-related fields (see e.g., Cvencek et al., 2011; Ganley & Lubienski, 2016; Heaverlo et al., 2013; Corbett & Hill, 2015; Leslie et al., 2015; Pajares, 2005; Perez-Felkner et al., 2017; Sarsons & Xu, 2015; Stoet & Geary, 2018), personal recollections have not been examined in light of how that information might inform current practice as it relates to promoting STEM with young female learners. A qualitative study, therefore, (Study 1) was designed to explore such potentially important historical perspectives, with adult female participants who represented diverse groups both in terms of STEM careers and personal attributes. Their perspectives then helped inform the development of the quantitative study (Study 2), which involved working directly with young female learners using the targeted program.

There were two research questions, one for each study. These were:

Study 1:

Specific to STEM fields, what are some of the obstacles and challenges that female-identifying underrepresented groups can face?

Study 2:

What are the quantifiable effects of data-based 3D models and prints on spatial reasoning skills and interest in STEM fields, particularly with young female learners?

Importance of the Topic

As addressed in Chapters 1 and 2, there are numerous reasons why gender parity in STEM is of import to achieve. Firstly, practical issues such as equal opportunity and pay, along with good job security for women in STEM pathways, are key, especially as career opportunities in STEM fields increase (Langdon et al., 2011). Such financial security can be important for the economic viability of a family (see Anderson, 2016), and particularly as single-mother families increase (U.S. Census Bureau, 2016). More importantly, in terms of education, developing the strong critical thinking skills (Duran & Sendag, 2012) that are part of STEM subjects are vital in today's world. Women tend to make many of the decisions on matters related to health and wellbeing not only for themselves but also for their families (Marincola, 2006). Their personal consumer choices, voting behaviors, investments, and other decisions affect wider economics, politics, finance, and other areas. This argues for women to be well versed in skills, especially those associated with critical thinking and reasoning, associated with STEM fields.

As presented in Chapter 2, applications in artificial intelligence, health diagnostics and medications, engineering, and other fields, as well as how research is conducted, by whom and for whom, matters. A lack of parity can have serious consequences on the populations who are left behind. Therefore, the loss – or absence – of women in STEM has quantifiable effects on economies, as well as effects on the "systems we create", from the scientific policy established by governments, to the consumer products people use on a daily basis (Reilly et al., 2019; Wade & Zaringhalam, 2019, para.4).

More specifically, STEM interest and spatial reasoning skills were prioritized in this research. Mental manipulation and understanding of 2D or 3D objects has been posited as an important STEM skill, helping to indicate future mathematical success (Hegarty & Waller, 2005; Verdine et al., 2014), science performance (Uttal et al., 2013), and potential pursuit of STEM careers (Uttal & Cohen, 2012). Middle school students with good mental rotation skills particularly tend to perform well in their science classes (Ganley et al., 2014). And Rafi et al. (2005) noted that early childhood activities involving paper folding, unfolding, and other manipulations make important contributions towards enhancing spatial skills.

Research has indicated that differences in spatial reasoning between male and female learners often show reduced or delayed development in females (Linn & Petersen, 1985; Maccoby & Jacklin, 1974; Voyer et al., 1995; Yilmaz, 2009). A meta-analysis of gender differences across 14 studies published between 1975 and 1992 supported that claim, with females shown to be at a statistically significant disadvantage in mental rotation skills in each of the studies (Masters & Sanders, 1993). Recent research has emerged indicating that such spatial skills can be improved through interventions (Gold et al., 2018; Hwang et al., 2009; Uttal et al., 2013; Yeh, 2007), and likely through interventions in virtual environments (Hwang & Hu, 2013). Those findings underpinned the motivation for the research conducted for this thesis.

Some literature has suggested an optimal age for spatial skills development would be in early middle school years, that is, ages 11-12 (Ben-Chaim, 1989). Yet, no definitive research was found on the lower limits of total time needed for such interventions, nor specific research particularly targeting underserved young female learners. The research in this thesis set out to explore such variables.

STEM interest is typically a critical component of developing a STEM identity, and can be intertwined with issues of confidence and self-efficacy for young female learners. Research has shown that by as young as kindergarten age, young girls believe boys are more brilliant and suited to highly intellectual activities over girls (Bian et al., 2017). It follows that negative stereotypes and implicit biases, particularly as unconsciously reinforced by parents, caretakers, and educators, can affect girls' self-perception in STEM topics (Levine, M., et al., 2015). Any such lack of confidence in themselves as participants in STEM, or more generally feeling inadequate, can lead to feelings associated with what has been characterized as imposter syndrome (Heaverlo et al., 2013), which affects adult women (and men) in STEM, and particularly affects minoritized populations (Byars-Winston & Dahlberg, 2019).

Younger women and underrepresented groups may find that if they are not fitting a more typical STEM profile by middle school, then STEM might not look to be a viable or feasible career path for them (Hill, 2019). Furthermore, there is an often referenced "STEM pipeline" which, perhaps inadvertently, asserts a linear path from childhood interest in STEM, straight through to taking STEM courses at university, to finding work in a STEM career (The STEM Pipeline, 2015). In fact, this pipeline applies to only about 50% of STEM workers, and further can serve to discourage diversification of the STEM workforce population (Cannady et al., 2014) by unintentionally propounding a one size fits all.

This section has reviewed the context for and importance of the topic addressed in this thesis. It argued for progress to be made assisting young females to develop skills related to STEM areas through targeted programs, and engendering enthusiasm for STEM career options. The next section will describe the main findings from the two studies conducted for this thesis.

Main Findings

This section details the main findings of Study 1 and Study 2 of this thesis. The findings of Study 1 will also be discussed as to how these findings had an impact on the workshop design of Study 2.

5.2.1 Study 1

Study 1 was a qualitative investigation involving in-depth interviews with 11 diverse adult females in various STEM fields, many of whom affiliated with additional underrepresented groups. It was designed to explore their educational and career pathways, and to solicit their thoughts with regard to how to improve those pathways for young females today. The literature found to date did not contain qualitative research that investigated personal recollections of diverse women in STEM, in particular in terms of how those recollections could be applied to understanding the needs of underrepresented young female learners. This study helps to address that void.

Although the demographics of the women interviewed in Study 1 represented a variety of age groups and career stages, most participants were in a mid or early-career stage, with the majority of the participants in their 30s to 40s. The memories were described as being still quite fresh for the participants. So, it is reasonable to posit that the time that had elapsed for many of the interviewees as they discussed the experiences that either helped or harmed them in their STEM career paths was short enough to be helpful for modern implications.

The results from Study 1 were directly applied to the design of Study 2 to enhance the interventions for underrepresented young female learners in STEM. As such, the researcher incorporated multiple suggestions from the Study 1 (qualitative study) into Study 2 (quantitative study). These were (a) there was a high degree of participant concern in the qualitative study that girls should be targeted prior to entering middle school. Acting on this, the researcher expanded the originally intended age range for the quantitative study to include upper elementary participants instead of limiting it to middle grades participants, thereby making it more inclusive of younger ages; (b) the researcher verified or improved the accessibility of all the materials used based on U.S.

government accessibility standards, taking aspects of Universal Design (Luna, n.d.) into consideration, in order to be inclusive for differently abled learners; (c) the researcher incorporated personal stories of failure, resilience, and creativity into the introductions and wrap-up portions of each workshop, as a direct result of interviewees expressing the importance of these to dispel ideas of scientists being born and not made, and the need to increase self-efficacy in STEM areas; (d) as role models and mentors were prioritized by each interviewee, materials incorporating stories of diverse women in STEM were provided as handouts and reviewed at the end of the workshops; (e) women actively working in STEM fields were incorporated as facilitators or volunteer assistant facilitators for the workshops, in response to findings from Study 1 underlining the importance of such inclusion.

The analysis of the interview data yielded five themes, including the highest number of responses in the theme of influencers (whether role models, mentors or detractors), as well as four additional themes of learning experiences, hurdles or difficulties, attitude changes towards women in STEM, and recommendations for engaging and retaining females in STEM. In addition, the participants in Study 1 clearly noted that though we have seen improvements in attitudes towards and in opportunities for women in STEM over past decades, equity is not yet in sight, and this lack of equity is particularly egregious for women in under-represented communities**.**

There were three primary findings from Study 1 that directly addressed the research question and also affected Study 2 in terms of design of and approaches used in the workshops. The first primary finding addressed the critical role of having a good mentor, role model, or support system in place along the girls' pathway (whether in school, at home, or during activities). The second primary finding stressed the need to work with and engage females in STEM activities and subjects when they are as young as possible, preferably while in primary/elementary school. The third primary finding emphasized the importance of young girls believing in themselves. The interviewees' responses could be interpreted as a call for developing a sense of STEM self-efficacy in young females. These three primary findings will be discussed in turn.

5.2.1.1 First Primary Finding from Study 1 – The Critical Role of Mentors, Role Models, and Support Systems.

The first main finding of Study 1 is the importance of positive influencers in the capacity of mentors, role models, and similar peer or community systems of support for women in STEM. As the most discussed topic by the participants overall, it stood out in importance, with every participant mentioning it multiple times (just over 100 coded responses in total). This issue is a key component that relates to the research question regarding how to moderate the obstacles and challenges that female-identifying underrepresented groups can face. Furthermore, as a result of Study 1, materials incorporating stories of diverse women in STEM were included in each workshop for Study 2. In addition to the researcher, several diverse women in STEM were incorporated as volunteer assistant facilitators for each workshop in Study 2. These facilitators not only assisted with the administration of the workshops; by their presence they brought to life the importance of such diversity and inclusion as stressed by the participants in Study 1.

5.2.1.2 You Can't Be What You Can't See.

The underlying meanings of American astronaut Sally Ride's often-quoted statement, "You can't be what you can't see," (Sally Ride, 2012, para. 2) can be applied directly to opinions expressed by the participants of Study 1. That is, multiple participants remarked upon the effects that being the only woman in the room, or among dwindling numbers of women and other underrepresented minorities in STEM, could have towards feelings of belonging, awareness of biases, and having a lack of the network or community support for STEM. This idea of being able to see oneself in a STEM field relates to formulating a STEM identity, or a construct in which one can see oneself - and be seen - as being competent in STEM, as possessing skills and having opportunities to function professionally in STEM fields, and as being recognized, both by their self and others, as a STEM worker (Byars-Winston & Dahlberg, 2019). The interviewees emphasized the need for role models and mentors, as well as peer support, in their career paths, and stressed the importance of having these from as early an age as possible. This finding from Study 1 supported the extant literature that has demonstrated the positive impact of mentorship and role models (Asgari et al., 2010; M.

Bruce & Bridgeland, 2014; Dasgupta, 2011), particularly on underrepresented populations (Anderson & Kim, 2006; Byars-Winston et al., 2015; Ensher & Murphy, 1997; Estrada et al., 2010; Huang, Taddese, & Walter, 2000; Lewis et al., 2016; Lisberg & Woods, 2018; Zambrana, et al., 2015), and specifically for women in STEM (Dennehy & Dasguptaa, 2017; Marx & Roman 2002; National Academies of Sciences, Engineering, and Medicine, 2020; Stout et al., 2011).

This finding also supported the need to continue the numerous STEM initiatives that involve aspects of mentorship or role modeling for students, particularly for underrepresented students such as females and people of color, in programs that are at various universities. Programs in the U.S. that include mentorship are currently being run by organizations such as Million Women Mentors, US2020, and AmeriCorps (Kupersmidt et al. (2018). However, the finding in this thesis suggests that by the time most current programs get underway, it could be too late to accomplish all that might be done for younger female learners. Therefore, this finding extends the literature as it currently exists to underscore the importance of the early timing for these mentorship programs.

With over 100 reflections coded on the importance of mentorship and role modeling, all of the women interviewed described direct relationships between their experiences and their career paths. They spoke of the importance of having such experiences and role models for young female learners. In terms of informing Study 2, the importance of this finding shaped the researcher's plan to provide authentic learning experiences for the student participants by placing them directly in contact with active women researchers and workers in STEM as facilitators for the workshops, and in particular, including women of color for the group that would have the highest percentage of girls of color (Camp group). The researcher also incorporated the reflections on role models in the giveaways provided for the participants and educators. These giveaways included a series of postcards and information sheets of women in STEM across diverse groups, from Mae Jemison (the first African-American woman to fly in space) and Liu Yang (the first Chinese woman in space) to Wanda Diaz (a Latina computer scientist who is also blind) and Katherine Johnson (a famous African-American mathematician), as shown in Chapter 3, to permit additional exploration of other women researchers in STEM.

5.2.1.3 Second Primary Finding from Study 1 – Engagement in STEM at a Young Age.

The need for engagement in STEM at ages younger than middle school is the second main finding of Study 1. Participants related numerous instances of being activated, encouraged, or geared towards STEM fields from a very young age (mentions were as early as kindergarten age), while simultaneously discussing how they knew of girls opting out of STEM subjects before and during middle school; many noting that they thought it due to societal biases and influences. This issue is a key component that relates to the research question regarding the obstacles and challenges that female-identifying underrepresented groups can face, particularly as it relates to reaching girls before decisions are made to avoid STEM fields.

This finding supports the literature to date (see e.g., Bystydzienski et al., 2015; Hirsch et al., 2011; Milgram, 2011; Sadler et al., 2012; Shapiro & Williams, 2012), that girls need to be encouraged towards STEM areas – including assisted from any perceived discouragement they might face, through actions of unconscious bias or more explicit stereotyping – well before they enter postsecondary education. In a large study by Microsoft (2017), 11,500 girls across 12 European countries reported that young female learners lose interest in STEM by age 15. A recent meta-analysis (Miller et al., 2018) examined studies of children in the U.S. who were asked to draw scientists. This analysis indicated that kindergarten girls often drew women scientists (at 70%), but after that age, more of the highly-stereotyped white, male, lone genius (typically with crazy hair and glasses) appeared progressively with each year, with high school years drawings showing women scientists only 25% of the time (Miller et al., 2018). Additional literature has also demonstrated that intrinsic motivation in academics - or the desire to participate in an activity for the journey or for the challenge versus for an external reward or credit (Dhami, 2019) - decreases between grades three and eight (Lepper et al., 2005). Earlier ages, therefore, before middle grades and high school, might indeed be key times to reach young female learners before motivation levels change, before biases are heavily entrenched, and before negative stereotypes are further reinforced, affecting girls' interest levels, self-efficacy, and engagement related to formulating STEM identities. As a result of this finding from Study 1, the lower age limit was expanded for Study 2, for the workshops to include girls in upper elementary, instead of just middle school (ages 9-12 instead of 11-13).

In terms of conducting workshops in STEM with young females, much of the literature reviewed to date had a strong focus on middle school interventions (see Dare, 2015; Frye et al, 2018; Kager, 2015; Levine, M. et al., 2015; Mann et al., 2014; Ogle et al., 2017; Wang & Frye, 2019, and the following section). Educators, parents, and caretakers can consider beginning potential interventions at younger ages than middle school, while emphasizing access to authentic learning experiences, positive role models, and mentorship programs.

How young? is an important question to consider for future and broader research on encouraging girls' interest and success in STEM, and one that Study 1 results can inform. Beyond this thesis, the recommendation to lower the ages for interventions could have a major impact on the numerous programs currently being targeted towards middle and high school girls. This is not to say there is no value in working with those audiences (the researcher strongly believes there is, and the literature cited previously provides evidence of its efficacy) but that additional work should be considered, and might be a key factor for younger participants before reaching the critical middle school stage. This thesis, therefore, makes an important contribution to expanding what parents, educators, museum communities and other professionals might consider when developing interest, confidence, or self-efficacy in STEM topics for young female learners, particularly those who might be in other historically disadvantaged groups.

5.2.1.4 Third Primary Finding from Study 1 – The Importance of Young Girls Believing in Themselves.

The importance of self-efficacy, or believing in oneself and one's abilities, for young female learners in STEM was a third primary finding of Study 1. Numerous discussions with the interviewees related to self-efficacy ranged from confidence building and coping mechanisms, to dispelling the genius and myths of being perfect as necessary steps for building a STEM identity. These issues are being grouped under one larger umbrella of self-efficacy.

The issue of believing in oneself is also a key component that relates to the research question regarding the obstacles and challenges that female-identifying underrepresented groups can face, specifically in regard to combatting socio-cultural biases towards women in STEM. Dare (2015), for example, reported that unequal gender balances in STEM fields such as physics are not due to differences in intrinsic aptitudes, but instead seem to draw partially from girls' increasingly negative self-assessments, among other issues as stated in Chapter 2 around cultural conditioning and stereotypes. Correspondingly, though there is literature showing the judgments associated with STEM fields are not always perceived to be a good fit with many middle school girls' identities, there is also literature that such judgments can potentially be overcome (Kager, 2015). It is important, therefore, to study the factors that can positively affect such perceptions, and at critical periods of time, to create more impactful interventions. Study 1 supports the literature on the importance of self-efficacy for underrepresented group in STEM fields as further discussed in the following sections.

5.2.1.5 Scientists Are Made, Not Born.

A key finding from Study 1 related to the ideas of the STEM genius and the importance of emphasizing to young female learners that, "scientists are made, not born" (Burke & Mattis, 2007, p. 4). This issue, as stressed by the interviewees, supports findings from the literature. The Scientista Foundation, a large collective of U.S. women pursuing STEM degrees at various high-education institutions, for example, links the concepts outlined by Gladwell (2008) cleverly synthesized this difference in a popular piece between experts and non-experts in sports, music, and other fields, with the expert being differentiated not by innate ability but by thousands of hours of practice (Mathews, 2013). Furthermore literature by Ericsson et al. (2007) go into greater detail studying and elucidating the concept of genius being made, not born, providing evidence through case studies. Interestingly, one involved upsetting the notion that females had subpar spatial thinking, for which the case study demonstrated that three sisters became top ranking female chess players through a regimented education program.

Further aligning this result from Study 1 to STEM topics, neuroscience studies such as that by Minati and Sigala (2013) have shown that virtuosos in certain fields, such as mathematics, can be explained by hard work and not special innate abilities (as demonstrated by using fMRI scans of a brain during math calculations). The idea that the experientially driven, therefore, can trump perceived genetic predisposition, was a key concern that Study 1 participants thought needed to be brought to light for younger learners in STEM. Applications of how this was incorporated in the interventions are discussed in sections 4.2.6 and 5.3.1 for Study 2.

Numerous STEM-based interventions for middle school girls, as described in the next few paragraphs, including efforts in engineering, science topics such as chemistry, non-science topics such as fashion, community development, confidence building, and providing role models, have demonstrated some effects on issues of self-efficacy in STEM, seeing oneself in STEM, or at least understanding the potential career options in STEM. Efforts relating concrete skills and strategies to topics that relate to participants' everyday lives have been shown to improve self-efficacy in STEM by helping to overcome the negative perceptions of STEM fields that may emerge during early adolescence (Ogle et al., 2017). Hands-on activities across STEM fields have demonstrated the practical applications of science and how they relate to day-to-day life, while also increasing their interest in school subjects and careers in STEM (M. Levine et al., 2015). Engineering-based camps have been shown to increase engagement with STEM topics and increase interest in attending college by including interactive lab activities to build confidence, and including female role models such as teachers, local STEM professionals, and high school girls serving as peer mentors who had previously participated in the camp (Frye et al., 2018). Results from Study 1 therefore, support this literature while also extending it in terms of shifting the age range downward to include younger females.

Additionally, interventions geared toward specific, proven "gender-responsive strategies" have been shown to be helpful for at-risk populations of middle school girls (Mann et al., 2014, p. 124). Creating communities of support that provide role models and convey care can also help vulnerable, underserved girls to develop self-confidence and healthy coping strategies that can benefit them as they aim to improve academically in middle school (Mann et al., 2014). Specific teaching strategies have also been investigated to sustain and increase middle school girls' interest as well as confidence in STEM topics by encouraging girls' responsibility and challenging them within a supportive environment to help inspire engagement while providing linkages between classroom activities and the broader world (Heaverlo et al., 2013). The findings from Study 1 both support and extend these results from the literature, through opening the door to increase notably younger females' confidence (younger than middle school) to engage in STEM areas. The findings from Study 1 accomplish this through emphasizing role models and mentorship, particularly for additionally underrepresented populations; exposure towards and encouragement in careers and research topics in STEM fields; and stressing the learning journey that STEM workers are a part of, where STEM status can be earned and not awarded through circumstances of birth.

Finally, the importance of talking about imperfection was raised by several interviewees in Study 1, often intertwined with the problem of the genius stereotype mentioned above. Dispelling the genius myth was seen as a potential way to combat the culturally prevalent idea that one must be a mental giant to flourish in STEM fields, something they noted could be holding back young female and particularly underrepresented learners. This agrees with previous findings in the literature (see e.g., Bian et al., 2018; Chestnut et al., 2018; Cimpian & Leslie, 2017; Leslie et al., 2015). But related to this, perfectionism was referenced in the interviews, along with the issue of having to show up and constantly be the best so as to best represent your group. This finding also supports the concepts of "fending off the stereotype" as discussed in Block et al. (2011, p. 575), and Klinger (1977), as well as the issue of "I'll show you that women can do science" as discussed in Rice, et al. (2013, p. 291). The latter issue, of having to constantly best represent a specific group, was a strong concern for those who identified with other underrepresented groups, and also aligned with higher stress levels they experienced. This was an issue previously noted in Rice et al. (2015).

Using the findings from Study 1 with regard to genius and perfectionism to help address these assumptions and stereotypes in STEM, the researcher incorporated stories of failure from her own work, such as failing a genetics class and talking about 3D prints that did not work out, and also noted her personal struggles in the summary discussion at the end of the 3D workshops. This tactic seemed to help raise excellent questions during the open question and answer session at the end of the workshops. It should be noted however, that in the private school location, one of the head teachers when thanking the researcher at the conclusion of the wrap-up session, referred to her as being overly “humble” and “sweet.” This, though kindly meant, had followed the researcher’s discussion of failure, and could perhaps have tainted the point of the discussion on struggle. This type of misplaced response helps to both exemplify responses to women in STEM and has the potential to undermine some of the efforts in working to breakdown stereotypes in STEM.

5.2.1.6 Secondary Findings from Study 1.

Besides the primary findings from Study 1, another point emphasized in some participant interviews regarded barriers for differently-abled learners. Interviewees gave strong recommendations to ensure STEM materials and outputs or formats were created with accessibility in mind, and for aiming to work with all learners when possible, not just creating special materials for a special event of differently-abled learners. This concern aligned well to one of the areas of interest of the researcher herself, and materials were chosen that had multiple methods of accessibility. For example, audio tracks and captioning were provided in the virtual reality applications, tactile 3D prints of data sets were produced, audio and text transcripts of all videos used in the modules were incorporated, images were appropriately tagged for screen readers, and all digital files (PDFs) were coded to U.S. accessibility standards.

This suggestion and approach aligns with the literature on Universal Design (UD) – a set of principles for designing materials that can be used by everyone (Luna, n.d.) – methodologies, as outlined in the literature, as well as more general literature on inclusivity and accessibility, particularly for STEM students, and the applicability for UD on improving learning outcomes for all students (see, e.g., Basham & Marino, 2013; Izzo & Bauer, 2015; Ralabate, 2011; Schreffler et al., 2019; Tharp et al., 2012). An important take away of this issue for teachers, other education related professionals, and parents or caretakers is that if a student with different needs, one who is blind or visually impaired or had cognitive differences, for example, were participating in activities - particularly if unexpectedly - facilitators following UD would be prepared and have materials suitable to the student’s learning needs.

Furthermore, another secondary finding from Study 1 concerned women who identified with additional underserved communities besides gender intimating a hierarchy of burden. This was expressed such that race, ethnicity, or disability, for example, could outweigh gender as far as amount of biases and stereotypes that must be fought in STEM fields. The concerns of being a person with a disability in STEM, a person of color in STEM, or a person who is transgender in STEM (though note that the one transgender woman in the study transitioned later in life, after having an established career as a male, so the conversation with her often focused more heavily on her position as a non-PhD functioning in a STEM research environment of PhD scientists), could weigh heavier than those who identified as white, able-bodied, cishet females.

This study does not claim to show that there is a hierarchy of oppression; rather that the participants of this study noted certain identities could cost more for them in terms of needing to overcome cultural biases and stereotypes, and handling additional pressures related to their workload, as described in the next paragraph. This is an important cultural challenge to consider for female-identifying groups in STEM overall, and awareness of such could perhaps have implications as to how interventions are designed and conducted with such underrepresented female learners in the future.

Related to this finding is the cognitive load some participants mentioned of being “other” (in other terms, an “outsider within” (Rios & Stewart, 2014, p. 295), in their field, workplace, or career: that they were often expected to help inform, educate or sway others who are not marginalized, that they felt pressure to be the best for their underrepresented group and could not fail (relating back to the perfectionism discussed in the previous section), or that they were often placed in positions of having to do more or work harder to represent their underserved community because of expectations being placed upon them, for example, being asked to serve on more committees or provide talks on diversity, or serve more often as mentors. These types of “performance pressures” (Settles, 2014, para. 3) and burdens have been noted for women in STEM more broadly, so it is to be understood that this pressure and burden could greatly increase if the person also identifies with another marginalized group. It is useful to take such issues into consideration when working with any underrepresented communities in STEM. This finding agrees with and further helps support the literature (see e.g., Charles et al., 2009; Davidson, 2007; Figueroa & Hurtado, 2013; Poirier et al., 2009;

Prescod-Weinstein, 2019; Rios & Stewart, 2014). It is important to take into consideration such obstacles and challenges that underrepresented female groups face in STEM, and when working with such populations, to develop interventions, evaluation instruments, and materials with those considerations in mind. As discussed in Chapter 2, such identities in various groups cannot be separated out from the individuals (Crenshaw, 1991), and should be considered as a whole to inform the intervention design as well as the targeted outcomes. This issue of identities was taken into consideration in designing Study 2, for example, in the inclusion of diverse women as facilitators and in materials showcasing role models.

Study 1 results also broadly agreed that recruitment for girls in STEM is only one side of the coin. Completing higher-education in STEM topics, therefore, is seen as just half of the marathon, if once one gets into the STEM-based career, the environment one must then function in is poor for women in STEM. Historically, women in STEM have, as noted in Chapter 3, received less support and recognition throughout their careers (Broderickn & Casadevall, 2019; Dutt et al., 2016; Freund et al., 2016; Moss-Racusin et al., 2012; Nittrouer et al., 2018; Sege et al., 2015). Parity has certainly not been reached for women in STEM careers, whether considering numerical representation, income levels, or seniority as compared to men in similar STEM fields and stages, and most particularly for women of color (Holman et al., 2018; Landivar, 2013; Moss-Racusin et al., 2012; National Science Foundation, 2018; Shen, 2013). Though beyond the scope of implementation for Study 2, this issue was an additional finding from Study 1 that supports the extant literature on issues of retention for women in STEM and further reflects on the notable challenges and obstacles that female-identifying groups in STEM face.

5.2.1.7 Summary and Significance of Study 1.

As noted, Study 1 was largely developed to help fill a void around a lack of research on how personal recollections of diverse women in STEM could be applicable to the development of interventions with underrepresented young female learners to encourage engagement with STEM areas. Using the results of Study 1 to directly inform the design of Study 2, therefore, contributed to the literature both by reporting on the recollections of the women in STEM and also, more importantly for this thesis, by shaping the design of Study 2 in terms of targeted age groups, materials included, how dialogue was conducted, and consideration regarding issues of accessibility.

In summary, three main findings resulted from Study 1 that expand and support the extant literature. These were: (a) bringing awareness to the crucial nature of mentorship and support systems for underrepresented groups in STEM; (b) the critical role of building self-efficacy and awareness around issues as related to STEM careers, including breaking down common stereotypes of “the genius” or being perfect; and (c) helping underrepresented learners create STEM identities or view STEM as an interesting and viable pathway when younger than middle school age, before many start to be discouraged or otherwise feel the need to opt-out. That these diverse women in STEM with successful careers across career stages considered it important to reach beyond high school and middle school age girls to elementary school age girls is an important message that extends the literature found to date and perhaps holds the key to successfully changing the current culture for these young learners to ensure that opportunities in STEM fields remain in their sights.

Other findings from Study 1 that supported the literature included: (a) women who identified with additional underserved communities besides gender currently worked under additional performance pressures, and existed as an outsider-within in the STEM community; (b) approaching the creation and dissemination of STEM materials with a UD methodology can benefit all learners, in any situation and can help participants who are differently-abled feel less “other;” and (c) for women and girls in STEM, recruitment is only one side of the coin, with retention being the other side, wherein policy issues to effect change in the STEM culture must not be neglected in favor of trying to just push more through the broken, leaky, or otherwise defective pipeline.

The main findings from Study 1 are significant for several reasons. As the interviewees noted, there is work to be done to help negate cultural and other biases and encourage young female learners to continue to move towards and within STEM related pathways, as well as help them thrive in, and throughout, those pathways. Providing role models and mentorship is of critical importance. Reaching out to girls when they are young, in middle school but also younger, could be an important way to broaden many current interventions to help set young females on a STEM pathway and give them tools for potential success. Helping to combat stereotypes and biases for such underserved groups in STEM, including discussing the genius and the perfectionist fallacies, recognizing the burdens and pressures on additionally underrepresented groups, and providing materials that are universally accessible, is also important to build confidence, self-efficacy and self-identities in STEM.

Finally, it is important, as stated in Chapter 2, that this study, and indeed, this thesis, is not about "fixing young females" but rather should be viewed as helping identify how the STEM community can assist underserved populations in overcoming negative implicit or explicit biases and discouragements, building confidence and self-envisioning in STEM, and further developing or acquiring the skills needed for STEM topics that might be overlooked or delayed due to cultural conditioning and stereotyping.

5.2.1.8 Limitations.

As with any research, there were limitations to this study. The limitations for Study 1 were the small sample size (n = 11) and that the distribution of participants came from a convenience sample who agreed to volunteer for participation from within the researcher's own larger professional network within the U.S. That meant the sample chosen was comprised of primarily space-related scientists and researchers, mostly in their 30s and 40s, many in a mid-career stage. Any researcher biases resulting from being in a similar demographic might have been overlooked in the analysis of the interviewees' responses. Also, the method of individual interviews might have been a limitation in terms of what might have been discussed or emphasized had the interviews been conducted in a focus group.

5.2.1.9 Practical Considerations and Recommendations.

To improve the potential results in future applications, the researcher recommends repeating the interview with a different, larger sample size, spread geographically in locations beyond the U.S., and spread further across career trajectory with a better balance of early career and advanced career women. The benefits of adding more participants would be to gain more information, viewpoints, and perspectives that could be analyzed and applied.

Researchers might consider conducting in-person focus groups in which the participants could compare and contrast their thoughts in a dynamic and responsive environment. Such settings, where participants can listen to others and expand their own responses based on feedback and inputs, might uncover additional experiences, perspectives, and potential approaches for future studies. Additionally, expanding such studies to obtain the viewpoint of participants who are non-binary, as well as males in STEM, either in single-sex groups and/or in mixed groups, would be ideal for expanding this research. This thesis focused on women in STEM, but it is important to consider and include perspectives and concerns from other marginalized groups - particularly people who are non-binary, for whom there is not much research in this area to date, but who can report higher levels of discomfort as well as harassing behavior aimed at them in their STEM jobs (Gibney, 2019).

Adding a cohort of male professionals in STEM to future studies who might be working through unconscious biases or stereotypes, and who might also be potential allies to help support issues facing young women in STEM, could help further inform future work. Male STEM researchers who are in a majority racial or ethnic group may contribute insight from what can be thought of as a position of privilege (Etchells et al., 2017), and as such could help strategically leverage that potential advantage as an ally (O'Donnell, 2019) for issues outside of their own experiences. It is also important to capture future data around males of color in STEM who are in marginalized groups themselves. Males who are Black or Hispanic in STEM in the U.S., for example, are underrepresented and report facing discrimination in the work force (Funk & Parker, 2018). Recent reports have shown that the representation of African Americans in topics like physics and astronomy can be improved through supportive environments, both culturally and financially (American Institute of Physics, 2020). Further developments of this research could consider other such underrepresented populations.

In summary, although Study 1 was a small-scale and exploratory qualitative study, the results were important in their own right, and could potentially be built upon, including for other underrepresented groups, through future research and expanded qualitative studies.

5.2.2 Study 2

In investigating the research question for Study 2, the primary finding was that disadvantaged groups experienced significant gains in STEM interest and confidence from the 3D workshops, while the results for the more privileged group remained relatively constant. A second important finding was that a single session under 6 hours of intervention tasks involving 3D spatial and related hands-on activities in STEM was not enough to have a positive impact on spatial reasoning skills for this sample. A third finding was that to determine whether early interest in STEM has been engendered, choosing cognitively appropriate measures that are sensitive to inequalities is essential when working with younger and underserved populations in STEM. These major findings, as well as additional minor findings, are discussed in the following sections.

5.2.2.1 First Primary Finding from Study 2 – Significant Growth in STEM Inventory for Disadvantaged Groups.

As reported in the previous chapter, the mean pre post scores for the STEM inventory showed that the Private School participants did not exhibit much change from the pre- to post evaluations, but the Scout and Camp groups did, with a statistically significant increase of almost 20 points for the Scout Group and 25 points for the Camp Group participants. It might seem counterintuitive at first to find that the more privileged audience remained relatively stable in their STEM inventory total scores, especially given that the participants' behavior and observed and recorded comments during and after the 3D workshops were highly positive. However, it is useful here to note that the private school is a leader in STEAM (adding an A to STEM for art and design, or creativity and critical thought (Fogarty & Arcand, 2020)) learning, with a very well-equipped facility with 3D printers, robotics and coding programs, and an excellent staff-to-learner ratio. As such, these participants attended a resource-rich private school, and there STEAM/learning exposure levels were high, while many, though not all, participants provided zip codes of often wealthier communities, in general. This group of participants came in to the workshops strong in STEM interest, and left just as strong. For this group, the workshops may have been more about reinforcing and providing practical examples of STEM topics, STEM careers, STEM role models, etc., rather than being novel or even revelatory regarding pathways STEM could provide for them.

The significant positive growth for the Camp group firstly, and Scout group secondly, in the STEM inventory, however, gets to the core of the research question. The Camp group overall was the most socio-economically disadvantaged group of the three audience samples, as determined by the participants' home zip codes deriving from typically low-earning income areas. The participants in the program are considered potentially at-risk youth. Besides signing up for the overall summer camp program and agreeing to attend the specific STEM 3D workshop, Camp participants had less individual agency in selecting a day-long STEM activity, as the Camp program directors selected the summer itinerary. This group, however, exhibited the most growth in the STEM inventory overall. As such, it is an example of the potential benefits of even short term (single day) STEM engagement on STEM interest for less socio-economically advantaged groups, and perhaps provides additional evidence regarding reaching groups who are not necessarily self-selecting for STEM activities already.

Next in STEM inventory improvement, the Scout group had more variable individual agency than the Camp group, in that some students selected to attend the workshop by themselves while others came as part of their chapter's decision to attend. Overall, the Scout group participants came from mostly and generally middle-class income zip code districts, and was less diverse than either of the other workshop groups. Being members of an out-of-school group likely provided these participants with access to external enrichment programs, but still this half-day, night time program saw a quantifiable effect on the growth of their STEM interests.

5.2.2.2 Second Primary Finding from Study 2 – Lack of Impact of Spatial Reasoning Skills.

Although it was hoped that the 3D data manipulation activities in Study 2 would yield improvement in spatial reasoning skills from the pre to post groups, ultimately perhaps it was not surprising to see no statistical improvement in the spatial reasoning evaluation. Current literature was not clear on the minimal baseline of interventions required to effect positive change in spatial reasoning skills, and specifically not for this age, gender, and schooling level, although research with older learners tended toward multiple steps of interventions spread over time (see e.g., Contero et al., 2006; Dominguez et al., 2012; Feng et al., 2007; Martín-Gutierrez et al., 2013; Rafi et al., 2005;

Wright et al., 2008). The literature, therefore, lacks a baseline for understanding spatial reasoning intervention impacts, particularly for the age and gender groups that participated in this study.

This thesis, then, adds to the overall literature on spatial skills improvement for young female learners, that single, relatively short interventions (6 hours or less) with spatial skills related activities are likely not enough to effect demonstrably positive change. However, the researcher noted that effective spatial skills testing instruments for such demographic groups must be greatly reconsidered in approach and methodology before reaching any conclusions in this area, as discussed in detail in following sections.

It was, however, surprising to see a decrease in the spatial reasoning skills between pre- and post statuses, particularly as STEM interest went up as a whole in Study 2. It is possible that the participants were suffering from frustration with the spatial instrument used (see the next subsections critiquing the evaluation instruments chosen), test fatigue or more broad fatigue from hours of STEM work in a space beyond their more typical daily schedule, or, in the case of the Scouts group, from a late activity after a school day and with the disruption of some classmates leaving early due to poor weather. STEM education program evaluation fatigue has been remarked upon generally in U.S. projects (Malyn-Smith et al., 2013). Another more specific study on cognitive fatigue during administration of standardized tests showed that, in Danish public schools as the school day progresses, test scores tended to lower each hour by 0.9 of a standard deviation (Sievertsen et al., 2016). Such results might help explain why there was a decrease in spatial skills demonstrated even during the short Scout event, which was conducted in the evening, ending at 8:00 p.m., and with the younger students (ages 9 and 10).

It is important, therefore, to reflect on the methodology at this point. There was a disparity, and difficulty in completion, the survey instruments across the three groups, with the workshops for the Camp and Scout groups having the most difficulty. The spatial task was the more challenging for this age group as a whole, and the STEM inventory instrument also presented some difficulties for the students. Minor interventions were required for the participants to be able to complete the pre- and post-evaluations. Future research might be improved by the development of evaluations that are more appropriate for this age group and skill set. This is discussed in the next section.

5.2.2.3 Third Primary Finding from Study 2 – The Importance of Appropriate Instruments for Specific Demographics.

5.2.2.3.1 Spatial Skills Instrument.

As mentioned in Chapter 4, the researcher found it necessary to talk through an example of the mental rotation exercise – not one included on the handout – to the participants, often with much confusion around it even with the demonstration. The researcher and assistant facilitators needed to go around and repeat directions for the evaluation for all groups, but needed to provide noticeably more assistance for the Camp group, followed by slightly less assistance for the Scout group, followed by the least amount for the Private School (though reiterating here that all groups needed assistance).

It seemed to the researcher that the participants went into the first spatial exercise on the instrument with more confidence after the initial demonstration, but then continued to struggle progressively as the evaluation went on. The researcher noted frustration and fatigue with the spatial skills instrument, with some participants even giving up before achieving completion, particularly in the Camp and Scout groups. Even after the researcher had already reduced the folding exercise to five questions instead of the original 10 after initial informal formative assessments, it still proved to be very challenging for this age group. It would be useful to compare this type of data from these participants with similarly aged groups across different demographics, including of other genders (male and non-binary).

As noted in Chapter 2, males often outperform females in spatial skills testing such as in mental rotation tests (Moè, 2009). Research from Moè (2009) and Moè and Pazzaglia (2010), however, demonstrated that improvements could be made on mental rotation testing for female and male participants (n = 152, aged 15 - 22) with attitude-based interventions. Overall, for female performance, providing positive information on gender before testing (e.g., telling subjects women tend to outperform men) led to improved test results, whereas for males, discussion of task difficulty before testing led to improved results (Moè, 2009). A second study (n = 120, mean age 17.02), further suggested that discussions of effort involved (“anyone can succeed in this task by putting in effort”) can help affect positive achievement, improving performance, in mental rotation tests (Moè & Pazzaglia, 2010, p.464). The research suggested, then, that female improvement in spatial skills testing could be directed through targeted encouragement leading to increased self-efficacy. This technique could potentially be applied to future spatial instrument assessments to see if it expands results beyond mental rotation testing, to again, help better capture the crucial data necessary for investigating spatial reasoning skills in young female-identifying populations, and particularly those that identify with other groups.

5.2.2.3.2 STEM Inventory Instrument.

The STEM inventory instrument was also problematic during the study. In each of the workshops, the visual boxing of the STEM inventory questions by topic (science, technology, etc.) led many of the younger participants to believe they only needed to select one condition per topic. Others were confused by the switching of the sides for the positive and negative terms. While this is done purposefully to discourage automatic fill-ins without consideration, it was slightly more challenging for the age group in this study. The researcher and assistant facilitators needed to re-explain and clarify the directions multiple times, asking participants to complete the rest of the questions in each topical box. Overall, though, this instrument was not as problematic as the spatial skills instrument discussed previously.

The Camp group had the most difficulty understanding how to complete both the spatial and inventory instruments, with the Scout group coming in next after that. These two groups needed more assistance and reminders to fill out the whole sheet for the inventory, instead of completing just one row, for example. The Private School participants, however, tended to socialize their spatial instruments, and to some minor extent their STEM inventories as well – unprompted by the researcher – seemingly trying as a collective not to leave fellow students behind. In all of the workshops, the participants were divided among multiple round tables throughout the room, with each table hosting about four or five girls. For the Private School groups, if one of the girls seemed to be struggling at any given table, whether through some combination of noticeable sighs, clicking of pen, resting head on hand, or vocalizing frustration or confusion, the participant would either talk to her fellow table-mates or one of them might proactively reach out to her and help explain what the folding exercise was about. This could, perhaps, be partly due to the type of community learning that emphasizes responsibility, stewardship, and similar qualities that the Private School stresses for its students and might provide an example of how supportive environments can benefit young female learners in STEM learning.

The observed issues support the literature that argues for "culturally and contextually responsive" instruments in STEM interventions, and particularly those that target underrepresented audiences in STEM (Malyn-Smith et al., 2013, p.2). Understanding the needs of the specific demographic groups being evaluated, and being sensitive to the perspectives and experiences they may have, should be considered during instrument development, but also during instrument deployment where a real-time, flexible response could be practiced to guide the evaluation process (Malyn-Smith et al., 2013; National Academies of Sciences, Engineering, and Medicine, 2018; University of Birmingham, 2020). As noted earlier, cognitive fatigue could have been a factor in post-evaluation performance. It is also possible that the instruments resembled "high-stakes testing" during formal education, which can be stressful to learners (Malyn-Smith et al., 2013, p.2). Less frustrating and obtrusive instruments might be better situated for collecting such data for informal STEM engagements (Allen & Peterman, 2019), and particularly for the younger female-identifying learners that this thesis targeted. This result also extends the literature of current assessment instruments, however, helping to show that additional research is required to refine existing instruments or develop more learner-specific methodologies that could better capture spatial reasoning skill data or STEM interest data for younger female learners (ages 9-12) and particularly for socio-economically disadvantaged group subsets within that demographic, who might otherwise experience frustration with existing instruments. In sum, the findings from this thesis highlight the importance of using or creating age appropriate, and level of learning appropriate ways to be able to evaluate progress.

5.2.2.3.3 Demographics Questions.

There were minor issues with the demographics questionnaire. Some of the youngest students were unsure what their zip code was; they were advised to skip the question. A couple of the participants were unsure what the question on identifying gender meant, and that was clarified by the facilitators who were helping out.

A much more common question that arose from the participants, particularly in the workshop within the Private School, was that they wanted to know what qualified as a video game. The participants asking the question at first did not seem to consider phone-based games as video games, as compared to console-based games like those on an X-box. For example, the researcher was asked multiple times if Candy Crush "counted as a video game." There seemed to be some sort of preconceived notion that just "serious" games would be considered, such as Halo, Fortnite, or even Minecraft. In conversations, the girls did not seem to think that the "fun apps," as one of them called them (such as Candy Crush, Tetris-like apps, Two Dots, and other more graphical games or puzzle-based games), and which many of them play periodically throughout the day, counted as proper video games. This raises a question about the language used in such inventories to investigate a (seemingly-simple) question on video game usage, and how understanding of the question evolves over time between generations.

Additionally, as there are strong male participant percentages, as well as masculine stereotypes, around the gaming community, and there have been numerous gender-based difficulties with gamer identities noted in the literature (see e.g., Cassell & Jenkins, 2000; Hefflinger, 2008; Kafai, Heeter, Denner, Sun, 2008; Royse et al., 2007; Shaw, 2012; Williams et al., 2009), and in the media (see e.g., "gamergate" in Penny, 2019, Warzel, 2019), this is a potential point for future research around possible relationships between gamer, gender, and STEM identities. In hindsight, the researcher should have addressed the issue specific to the video game question on the demographics survey by adding an open field asking what games the students play, not just hours, and by providing examples of games and apps. This might have captured better data on this topic. This is recommended for future research.

Beyond the problems with the instruments, there were a few other external issues with the time of year for the first workshop. As described, due to snowy weather conditions, some of the Camp group had to leave early, which may also have disrupted the remaining students. In addition, there were two different lengths of time for full day workshops versus the short workshop, which might have brought some inconsistency to the data. However, the participants in the shorter workshop demonstrated similar levels of increase in the STEM inventory. As such, it is not clear whether the extra time provided in the full day events is always necessary.

5.2.2.4 Secondary Findings from Study 2.

As noted in the results chapter, there was a significant positive correlation between perception of STEM knowledge and total career score in STEM inventory. This correlation suggests support for the literature regarding self-efficacy and interests in middle school populations (see, e.g., Blotnicky et al., 2018; Fouad, & Smith, 1996; Simpkins et al., 2006), and also was reflected in comments from participants in Study 1 regarding their self-efficacy (e.g., "You have to really kind of prove yourself, like I'm here, I'm here because I'm good. Physics was hard but what appealed to me about physics was that I could finally apply this math [that] seems so abstract . . . . And so when I started to see the physical applications of the physics and how you can you know do rotations of velocity and all of these different things you can learn with physics and then how it applies to astronomy like it was a big thing" (Astronomer); "I'm not saying I'm the smartest person in the room always but I also feel like I belong in the room and I can make it work with the smartest people." (Science Writer). However, it is important to remember that correlational findings do not imply causation. As such, although for this sample as girls' perceptions of their STEM knowledge increased, there was a tendency for their career aspirations also to increase. An alternative explanation for this result is that perhaps young female learners are drawn towards areas of perceived strength or self-efficacy.

Positive attitudes by students towards VR technologies in education has been established for some time (see Mikropoulos et al., 1998). Mantovani (2001) noted the potential for learners' visualization, making concrete what might seem abstract through other methods of display or interactions, and important for learning that which cannot be easily experienced in the real world. Additionally, as described in the literature, VR has the potential to offer avenues of adaptation, collaboration, and evaluation

(Mantovani, 2001). 3D visualization, therefore, is understood to be an immersive environment that can help solve the "problem of looking at two-dimensional images and requiring students to understand relationships three-dimensionally" (Bengfort, 2020, para. 12). In the case of the workshops presented in this thesis, traditional, or physical, and computer-based, or 3D, materials for data manipulation were combined so they could work "in concert" (Paranandi, 2002, p. 333) to enrich the learning process and build up to the direct 3D modeling and VR application work, which capped off the final third of the workshops. The observed highly positive response to the 3D/VR segment of Study 2, therefore, aligns with the literature that supports the use of VR as an educational tool (see e.g., Chen, 2006; Pantelidis, 2009), and simultaneously recognizes that much deeper research is required to identify and understand the models and techniques used. Findings from this research suggest that these techniques need to be examined and adapted to facilitate assessment of evaluative methods specific to younger age groups.

The results from Study 2 may also support the literature that VR applications that provide immersive experiences for meaning-making can lead to increased motivation and engagement levels in students (Pantelidis, 1995, 2009; Winn, 1993). In observing the participants in Study 2, engagement levels notably increased during the 3D and VR parts of the workshops, and particularly the VR. The most positively remarked upon part of the workshops involved the 3D and VR activities, as well. In these activities, the participants were tasked with manipulating, working with, and generally "playing" with NASA 3D models of exploded stars. The number of content-related participant questions (versus how-to or logistical questions) asked during these segments were dramatically higher in each of the three workshops, and the complexity of questions increased greatly from those with regard the other activities. The energy or physical activity levels as well as volume levels went up most during the VR segment, as participants could not be passive learners and needed to engage physically. In each workshop participants asked, over multiple instances, for more time with the VR applications. Though this result was observational and not quantified in this study, based on this, future programs that involve interactions with middle school girls might want to include more 3D and VR- or AR- or XR- related materials, aligning to current safety standards of a maximum of 15 minutes of VR with 10 minutes of rest afterwards

(Hicks, 2018). The benefit of having multiple students sharing devices in such workshops provides a natural time span in groups of these sizes. The results from Study 2, therefore, provide observational evidence that the 3D and VR applications were particularly motivating for the participants, supporting the existing literature on this topic and extending it to the age groups in the study.

Future research might closely investigate what works and what does not with these types of VR environments for similar audiences. Future targeted programs could consider including more of the type of direct-from-the-science visualizations that were used in the program, which are well suited to VR/AR/MR (combined as XR or "extended reality") environments, in that it is not as limiting to scale and dimension of the data sets. User experiences are not boxed in by the size of the laptop or phone screen, but instead are able to experience the data in less restrained ways (see Pantelidis, 1995, 2009). It is also useful to note that VR, and by extension XR, enables a learner-paced experience, and can be particularly helpful for students who are differently-abled. This supports findings reported by Pantelidis (1995, 2009), and also aligns with the outcome from Study 1 that emphasized the importance of accessible materials universally designed for all learners.

Study 2 helped show the effectiveness of starting young for developing STEM interest. Creating hands-on activities, through a combination of digital and "real world" programs, was beneficial for this audience and their resulting STEM interest levels. A few months after the third workshop, for example, when the researcher was speaking about her observatory with the Private School's parent association, multiple parents approached the researcher to speak of their daughter's positive experiences in the workshops, with one stating, "My daughter said this was the best program she had ever done at school." Comments like these, expressed anecdotally to the researcher, helped demonstrate that the program, including the data manipulations they were able to do, was something the participants seemed to feel that no one else had access to, that they were special participants getting a unique behind-the-scenes look at the actual research being done today. This might have contributed to their lasting enthusiasm.

Additional observational recordings from the workshops demonstrated a particularly high engagement level from the Camp group. From the students who remarked how they "didn't know" about something to the demonstrative statements on the material affecting what they wanted to be when they grew up, to the heartfelt comments directed at the researcher personally, the attitude was very high and the energy very motivating. Similar positive comments were recorded at the other two workshops, but the students at the Camp event were either more energized or motivated, or perhaps more outgoing in vocalizing those comments directly to the researcher.

5.2.2.5 Limitations.

For Study 2, the researcher acknowledges specific limitations related to choices made about the study design, including access to only a small portion of the total U.S. geographic area, and a moderate sized database of only 100 participants in a limited age range. Additional limitations of the research include total exposure time, that is, the workshops being single-day events instead of multiple sessions across longer intervals of time. The researcher further acknowledges the unexpected limitations identified previously, regarding issues with a weather hazard for the first workshop group, and with the frustration around the test instruments across the workshop groups. This research also should not be generalized to different underserved populations, such as those with specific physical disabilities, or other underserved groups not included in the research population of this thesis. That there was only one large group of socio-economically underserved female learners in the sample is a clear limitation. Additionally, that there was not a population of male learners to compare results between is another limitation of the study.

Practical Considerations, Recommendations and Future Directions

The overarching recommendation from this research is that interventions to engage young females with STEM topics need to begin early, and can be particularly effective for underserved groups. For privileged groups who have excellent access to resources already, the issue might be less about changing attitudes or opening opportunities, and more about providing challenges beyond those already available, or helping them to visualize themselves more clearly within those STEM pathways. For other groups without such access and advantage, and for whom there is some interest and potential, there is great potential for improving STEM engagement.

More, therefore, needs to be done in engaging young females in STEM areas, especially for the girls who are not positioned at the higher end of the spectrum of privilege. Similar STEM interventions as these, particularly when they are available to young female learners in upper elementary and middle school, are needed. These interventions should include access to mentors or role models, access to authentic, hands-on experiences, access to universally designed materials, and other activities as described in this thesis, and as might be expanded upon through further research. Future studies could consider a greater, more explicit comparison between the short duration and longer duration workshops, and consider comparisons with young male learners.

If Study 2 were replicated with a different sample, there are a few recommendations to consider. One possibility would be to consider conducting it with smaller groups across a larger total quantity of participants and across multiple sessions (increasing exposure times), as well as across a larger geographic distribution. Additionally, specifically targeting different underserved populations, such as female learners who are blind or visually impaired or who have different cognitive abilities, would be useful to expand the research. More facilitators for larger groups could be beneficial, for both assistance with instruments and activities, but also for more direct or one-on-one experience with women researchers and workers in STEM. And, as noted, more age-appropriate and potentially “embedded assessments” (Allen & Peterman, 2019, p.24) for the pre-post evaluations, that are more consistent with the overall activities, and less test-like may help. Greater consideration should be taken to research how to reduce possible cognitive fatigue, perhaps through different, shorter instruments, simpler or more engaging instruments, moving any post evaluation slightly earlier in the sessions, taking more breaks with snacks before evaluations, and/or starting events earlier in the day when possible. Additionally, the researcher suggests adding specific questions to target collecting quantifiable data on learning gains, engagement, and motivation levels of the learners.

Additionally, there are other areas where potential progress might be made in order to help positively influence STEM efficacy in less advantaged learners outside of such interventions, or in concert with them. For example, empirical studies on guidance counseling programs have demonstrated the effectiveness of such programs on improving student self-efficacy and helping inform decision making towards higher education and career paths, notably for underserved populations (Falco, 2016). These have been shown to be particularly valuable when guidance counselors are not overburdened with caseloads or in greatly underfunded situations (see e.g., Berger, 2013; A. M. Bruce, et al., 2012; Cholewa, Burkhardt, Hull, 2015; Bryan et al., 2011; Davis et al., 2013; Goodman-Scott, 2013; Goodman-Scott et al., 2018; Lapan et al., 2012; Leon et al., 2011; Salina, et al., 2013; Wilkerson et al., 2013). Working with schools and guidance counselors to develop interventions might assist the counselors while potentially reaching and impacting more students. School guidance counselors could potentially help fill a gap in the community support system towards STEM careers (Byars-Winston, 2014), which was also shown to be a priority in Study 1, and is a notable need for underrepresented groups. Such potential impact might be especially true if offered beginning at a young age, so students have a sense of direction in STEM before seeking educational or career advice in their teen years.

In considering similar research, using a longitudinal design, with workshops or other related programmatic events conducted at intervals over the course of a school year, or potentially over a summer break, could demonstrate what happens to both interests and spatial skills over time. Participating schools and government agencies or NGOs, however, would need to be lobbied to direct such effort and money to undertake such a longitudinal study.

Though the researcher had carefully considered the instruments and done brief formative testing with them, in practice the instruments were less successful than was anticipated with this demographic. Testing the instruments on their own, and not in a setting where the participants were excited about the activities to come or possibly experiencing fatigue, might have contributed to the researcher not anticipating the challenges the instruments would present. It is feasible that the difficulties posed by such evaluations can be reduced with different instruments, perhaps created with both the participants' needs combined with the workshop activities in mind. One major recommendation, therefore, is to develop more targeted evaluations for similar groups of young underserved female populations. For example, the origami exercise used in the workshop was responded to positively by many students during the sessions. It is possible then that the activity itself could be turned into a spatial skills assessment with written observations by the researcher and a pre-post evaluation. Such a folding exercise done “in the real world” using their hands, versus exclusively on paper with mental rotation skills, would require participants to engage in folding, but using skills that are kinesthetic and directly related to the workshop activities. In is acknowledged that although such a technique might be different from the mental rotation task used in the workshops, it might be more engaging for this targeted age group, and perhaps more informative, versus the instrument used in the workshops.

For example, providing a set of instructions for participants to independently fold a star or a fish, or other object, where participants have to engage spatially, might provide a better evaluation of their spatial skills while being enjoyable and feeling less like a test. Devising the pre-post scenario with such an instrument would then include asking participants questions such as: have they done origami previously, if so how much have they done; self-rank their skills in folding, how easy or enjoyable was it; how long did it take (with a stop watch to record time)? And then the researcher would rate the quality of the product on a simple 3-point scale, taking into consideration any potential cognitive or mobility issues that participant might have. Such a technique of incorporating the instrument into the hands-on activities that feel more playful or fun might also help produce less frustration or testing fatigue for the participants. To avoid issues with reading ability being a confound for younger groups, the facilitators could read the instructions aloud for the participants.

For the STEM inventory, a similar technique might be employed. A survey might be used to ask participants: What do you think a scientist does? Do scientists have fun? How much would you like to be a scientist?   A pre-post evaluation design using such an evaluation might reveal whether the young learners have a sense of what STEM scientists do and how much the intervention affects the extent to which they want to be in a STEM field in the future. As with the paper folding, a handful of such questions might help capture their perceptions, rather than feeling like another test. Of course, any new instrument would need to be evaluated and tested for validity and reliability, using experts to examine content validity, pilot studies for comparisons with other instruments to examine concurrent validity, known group studies to determine if the constructs have been addressed appropriately, and pilot testing with purposefully chosen groups on final versions of the instruments.

Conclusion

This thesis set out to examine the effects of data-based 3D models and prints on spatial reasoning skills and interest in STEM, in particular for young female learners from underrepresented groups. The results indicate that although there is work to be done to engage young female leaners with STEM topics, the potential benefits are well worth the effort.

In particular, this thesis investigated the development of STEM interests and spatial reasoning skills of young female learners at times when such young learners are forming potential identities in or with STEM. To do that, targeted programs were designed for use with females from different demographical groups, in upper elementary and middle school years, carried out across formal and informal learning environments, and led by female researchers in STEM. By interviewing and then applying the results from a series of recollections from diverse career women in STEM fields, the researcher aimed to strategically leverage the collective knowledge specific to the obstacles and challenges that female-identifying underrepresented groups can face, in order to guide and improve the interventions.

The findings showed that such interventions that utilize real world data manipulations and 3D applications as part of hands-on activities can be particularly effective for females from underserved groups who are in upper elementary and middle school. An important finding from the study that extends the extant literature is that audiences younger than middle school should be encouraged to participate in STEM activities and interventions. This thesis also adds to existing literature on how to determine the potential improvement of spatial reasoning skills. Namely, interventions shorter than 6 hours in duration for young female learners, or that are done in only one session, may not be enough to effect demonstrably positive change in such skills. However, the researcher underscores that another important contribution from this thesis is noting is the difficulty the participants had with the spatial skills instruments used, and to a lesser extent the STEM inventory assessment. Further instrument development that is specialized for these age groups and learning levels, and that is a less obtrusive part of the intervention is encouraged. Additional observational research should be conducted around the use of 3D-VR in such educational settings for similar audiences contributes towards increases in learning gains, engagement, and motivation, as well as provides accessible resources to help promote inclusivity to differently abled learners in STEM.

Further, this research demonstrated that young female learners both want to do STEM activities that provide authentic experiences manipulating actual observational data such as the NASA data used in Study 2, and they are excited when they can do such STEM activities with women researchers. There is, however, a difference that needs additional investigation, between groups having privilege and those with no or less privilege. In comparison with socio-economically disadvantaged female learners, more privileged female learners might start off higher in interest levels, but then leave just as high, which is also encouraging for potential STEM identities and pathways for the ages of the participants in this research. Still, investing in younger and underserved populations in STEM, which is critical to help reach parity, must be researched via rigorously tested measures for age and cognitive appropriateness.

Going forward, this thesis holds promise for helping to engage girls in STEM research. This can be accomplished through mentorship and support systems for underrepresented groups in STEM, breaking down common stereotypes of “the genius” or perfectionism is important for female learners, and with interventions for underrepresented learners beginning before middle school age. Additionally, it should be noted that women who identify with underserved communities in addition to gender work under a hierarchy of burden, in terms of additional performance pressures, that the community should prioritize STEM materials with a Universal Design methodology to benefit all learners, and that policy issues must be addressed in the STEM community as a whole to benefit all learners and practitioners.

As a researcher (or mommy-scientist as my young daughter’s 5th grade friend said) in data representation and 3D modeling, the availability of the cutting-edge data sets in

3D used in this study that are able to be converted into 3D prints and VR or AR applications is currently expanding at a rapid rate. There have been significant improvements in quantity and platform reach even since the data for this thesis were collected. Such scientific and technological advancements are leading to a larger, expanded pipeline of spatial data modeled into 3D that can potentially further enhance authentic learning experiences for all learners in STEM topics, but particularly for underrepresented learners. These also could inform the development of the spatial reasoning skills that are so important for STEM. Using 3D data is not a novelty, but rather a tool for learning, with great potential for disseminating scientific knowledge to help diversify the potential influx of future researchers. However, it is crucial to recognize that the data and the technology are only one small part of bringing the Universe down to Earth for underrepresented young female learners. It is the people, and the community support structures, that can help drive the most far-reaching, out-of-this-world impact.

References

123test (2019). *About 123test*. https://www.123test.com/about_123test/

3D.si.edu. (2013). *Explorer view: Cassiopeia A supernova remnant*. https://3d.si.edu/explorer/casa-supernova-remnant

AbouHashem, Y., Dayal, M., Savanah, S. & Štrkalj, G. (2015). The application of 3D printing in anatomy education. *Medical Education Online*, *20*(1), Article 29847. https://doi.org/10.3402/meo.v20.29847

ADA National Network. (n.d.). *What is the Americans with Disabilities Act (ADA)?* https://adata.org/learn-about-ada

Agan, L. (2004). Stellar ideas: Exploring students' understanding of stars. *Astronomy Education Review*, *3*(1), 77-97. https://doi.org/10.3847/aer2004008

Allen, S. & Peterman, K. (2019). Evaluating informal STEM education: Issues and challenges in context. In A. C. Fu, A. Kannan, & R. J. Shavelson (Eds.), *Evaluation in informal science, technology, engineering, and mathematics education* (Iss.161, pp. 17-33). New Directions for Evaluation. https://doi.org/10.1002/ev.20354

Amazon.com. (2018a). *AUPALLA Google Cardboard v2 Christmas version 3D virtual reality glasses best Christmas gift support Pokémon GO in future*. https://www.amazon.ca/AUPALLA-Cardboard-Christmas-Version-Virtual/dp/B01LZA1EKZ

Amazon.com. (2018b). *Oculus Rift - Virtual reality headset.* https://www.amazon.com/Oculus-Rift-Virtual-Reality-Headset pc/dp/B00VF0IXEY/ref=sr_1_4?s=electronics&ie=UTF8&qid=1521395894&sr=1-4&keywords=oculus+rift

Amer, A., & Peralez, P. (2014, October 10-13). Affordable altered perspectives: Making augmented and virtual reality technology accessible. *IEEE Global Humanitarian*

Technology Conference, San Jose, CA, pp. 603-60. https://doi.org/10.1109/GHTC.2014.6970345

American Institute of Physics (AIP) National Task Force to Elevate African American Representation in Undergraduate Physics & Astronomy (TEAM-UP). (2020). *The time is now: Systemic changes to increase African Americans with bachelor's degrees in physics and astronomy*. American Institute of Physics. https://www.aip.org/sites/default/files/aipcorp/files/teamup-full-report.pdf

American Printing House for the Blind. (Fiscal Year 2016). *Annual report of research and development activities*. https://www.aph.org/files/research/ar2016/ar2016.html

American Psychological Association. (2006). *Stereotype threat widens achievement gap.* http://www.apa.org/research/action/stereotype.aspx.

Amorim, J., Travnik, I., & Sousa, B. (2015). Simplified three-dimensional model provides anatomical insights in lizards' caudal autotomy as printed illustration. *Anais da Academia Brasileira de Ciências*, *87*(1), 63-70. http://www.scielo.br/pdf/aabc/v87n1/0001-3765-aabc-201520130298.pdf

Andersen, R. (2012, April 19). How big data is changing astronomy (again). *The Atlantic*. https://www.theatlantic.com/technology/archive/2012/04/how-big-data-is-changing-astronomy-again/255917/

Anderson, E., & Kim, D. (2006). *Increasing the success of minority students in science and technology*. American Council on Education. https://www.acenet.edu/Documents/Increasing-the-Success-of-Minority-Students-in-Science-and-Technology-2006.pdf

Anderson, J. 2016. *Quick Figures: Breadwinner mothers by race/ethnicity and state*. (Research Report NO. #Q054. Washington, DC: Institute for Women's Policy Research. https://iwpr.org/publications/breadwinner-mothers-by-raceethnicity-and-state/

Arcand, K. (unpublished). Preliminary pilot testing of STEM instruments.

Arcand, K., Edmonds, P., & Watzke, M. (2017) *The tale of Supernova 1987a*. https://chandra.si.edu/deadstar/sn1987a.html

Arcand, K. & Watzke, M. (2016). *3D printing the X-ray universe*. http://chandra.si.edu/3dprint

Arcand, K., & Watzke, M. (2015a). *Light: The visible spectrum and beyond*. New York, NY: Black Dog & Leventhal Publishers Inc.

Arcand, K., & Watzke, M. (2015b). Reaching new heights for women and X-ray astronomy. In S. Charman-Anderson (Ed.), *More passion for science: Journeys into the unknown* (1st ed., pp. 375-395). https://findingada.com/shop/more-passion-for-science-journeys-into-the-unknown/

Arcand, K.K. (2015). *Recoloring the Universe*. http://chandra.si.edu/code

Arcand, K. K. (2016, October 7). Women in astronomy & computer science: There's still work to do #WiSTEMspotlight [Blog post]. https://www.digital-science.com/blog/guest/women-\astronomy-computer-science-theres-still-work-wistemspotlight/

Arcand, K. K. (2017a). *How to talk to a spacecraft*. https://chandra.si.edu/binary/

Arcand, K. K. (2017b). [*Preliminary data analysis of a recent 3D printed workshop*]. Unpublished raw data.

Arcand, K. K. (2017c). *Universe in 3D: modeling and printing cosmic objects*. http://chandra.si.edu/tinkercad/

Arcand, K. K. (2018a). *Origami Universe*. https://chandra.si.edu/origami/

Arcand, K. K. (2018b). *A Universe of making and doing*. https://chandra.si.edu/make

Arcand, K. K. (2019). *Walking among the stars*. https://chandra.si.edu/vr

Arcand, K. K., Edmonds, P. & Watzke, M. (2019). *A black hole primer with Chandra*. https://chandra.si.edu/blackhole

Arcand, K. K., Jiang, E., Price, S., Watzke, M., Sgouros, T., & Edmonds, P. (2018). Walking through an exploded star: Rendering supernova remnant Cassiopeia A into virtual reality. *Communicating Astronomy with the Public Journal*, *1*(24), 17-24. https://www.capjournal.org/issues/24/24_17.php

Arcand, K. K., Jubett, A., Watzke, M., Price, S., Williamson, K., & Edmonds, P. (2019). *Touching the stars: Improving NASA 3D printed data sets with blind and visually impaired audiences*. Manuscript submitted for publication.

Arcand, K. K., & Watzke, M. (2017). *Magnitude: The scale of the Universe*. New York, NY: Black Dog & Leventhal Publishers Inc.

Arcand, K., & Watzke, M. (2019) *Tycho's supernova remnant*. https://chandra.si.edu/deadstar/tycho.html

Arcand, K. K., Watzke, M., DePasquale, J., Edmonds, P., & DiVona, K. (2017). Bringing cosmic objects down to Earth: An overview of 3D modeling and printing in astronomy. *Communicating Astronomy with the Public Journal*, *1*(22), 14-20. https://www.capjournal.org/issues/22/22_14.pdfs

Arcand, K. K., Watzke, M., Rector, T., Levay, Z. G., DePasquale, J., & Smarr, O. (2013). Processing color in astronomical imagery. *Studies in Media and Communication*, *1*(2), 25-34. https://doi.org/10.11114/smc.v1i2.198

Arcand, K. K., Watzke, M., Rector, T., Levay, Z. G., DePasquale, J., & Smarr, O. (2016). Processing color in astronomical imagery. In K. Kuc & J. Zylinska (Eds.), *Photomediations: A reader* (1st ed., pp. 75-92). London, England: Open Humanities Press. http://openhumanitiespress.org/books/download/Kuc-Zylinska_2016_Photomediations-A-Reader.pdf

Arcand, K. K., Watzke, M., Smith, L., & Smith, J. K. (2010). Surveying Aesthetics & Astronomy: A project exploring the public's perception of astronomy images and the science within. *Communicating Astronomy with the Public Journal*, *1*(10), 13-16. https://www.capjournal.org/issues/10/10_13.php

Asgari, S., Dasgupta, N., & Cote, N. G. (2010). When does contact with successful ingroup members change self-stereotypes? A longitudinal study comparing the effect of quantity vs. quality of contact with successful individuals. *Social Psychology, 41*(3), 203-211. https://doi.org/10.1027/1864-9335/a000028

Autodesk.com. (2018). Maya | Computer animation & modeling software | Autodesk. https://www.autodesk.com/products/maya/overview

Ayoub, C. (2017, May 1). After-school STEM programs need our help [Blog post]. https://amysmartgirls.com/afterschool-stem-programs-need-our-help-86a7d7d8b35b

Azuma, R. T. (1997). A survey of augmented reality. *Presence, 6*(4), 355-385. https://doi.org/10.1162/pres.1997.6.4.355

Bach, D. (2016, October 12). Why do some STEM fields have fewer women than others? UW study may have the answer. *UW News*. http://www.washington.edu/news/2016/10/12/why-do-some-stem-fields-have-fewer-women-than-others-uw-study-may-have-the-answer/

Baenninger, M., & Newcombe N. (1995). Environmental input to the development of sex-related differences in spatial and mathematical ability. *Learning and Individual Differences, 59*(3), 363-379. https://doi.org/10.1016/1041-6080(95)90007-1

Bandura, A. (1977). *Self-efficacy: Toward a unifying theory of behavioral change.* Psychological Review, 84(2), 191-215.

Bandura, A. (1997). *Self-efficacy: The exercise of control* (10th ed.). W. H. Freeman and Company.

Baracaglia, E. & Vogt, F. P. A. (2020). E0102-VR: Exploring the scientific potential of Virtual Reality for observational astrophysics. *Astronomy & Computing, 30*, Article 100352. https://doi.org/10.1016/j.ascom.2019.100352

Basham, J. D., & Marino, M. T. (2013). Understanding STEM education and supporting students through Universal Design for Learning. *Teaching Exceptional Children,* *45*(4), 8-15. https://kucrl.ku.edu/sites/kucrl.ku.edu/files/images/general/Handouts/UDL_STEM.pdf

Bauer, M., Prusti, T., Brown, A., Vallenari, A., Clementini, G., & Jansen, F. (2016, 14 September). Gaia's billion star map hints at treasures to come. *ESA Gaia*. https://www.esa.int/Our_Activities/Space_Science/Gaia/Gaia_s_billionstar_map_hints_at_treasures_to_come

Beck-Winchantz, B., & Riccobono, M. A. (2008). Advancing participation of blind students in science, technology, engineering, and math. *Advances in Space Research*, *42*(11), 1855- 1858. https://www.sciencedirect.com/science/article/pii/S0273117707005960

Beerya, A. K., & Zucker, I. (2011). Sex bias in neuroscience and biomedical research. *Neuroscience & Biobehavioral Reviews*, *35*(3), 565-572. http://www.sciencedirect.com/science/article/pii/S0149763410001156

Belardinelli, M. O., Federici, S., Delogu, F., & Palmiero, M. (2009, July 19-24). Sonification of spatial information: Audio-Tactile exploration strategies by normal and blind subjects. In C. Stephanidis (Ed.), *Lecture Notes in Computer Science: Vol 5615. Universal Access in Human-Computer Interaction. Intelligent and Ubiquitous Interaction Environments, UAHCI 2009.* Springer, Berlin, Heidelberg https://doi.org/10.1007/978-3-642-02710-9_62

Bellini, H., Chen, W., Sugiyama, M., Shin, M., Alam, S., & Takayama, D. (2016). *Profiles in innovation - Virtual & augmented reality: Understanding the race for the next computing platform*.: http://www.goldmansachs.com/our-thinking/pages/technology-driving-innovation-folder/virtual-and-augmented-reality/report.pdf

Ben-Chaim, D. (1989). Adolescents' ability to communicate spatial information: Analyzing and effecting students' performance, *Educational Studies in Mathematics, 20*, 121–146.

Bengfort, J. (2020, February 17). Virtual reality advances bring new possibilities to higher education. EdTech. https://edtechmagazine.com/higher/article/2020/02/virtual-reality-advances-bring-new-possibilities-higher-education

Berger, C. (2013). Bringing out the brilliance: A counseling intervention for underachieving students. *Professional School Counseling, 17(*1), 86-96. https://doi.org/10.1177/2156759X0001700102

Bergwerf, H. (2018). *MolView*. http://molview.org/

Berra, F., Felletti, F., & Zucali, M. (2014). 3D geological modelling and education: Teaching geological cross sections with a 3D modelling software to improve spatial thinking skills in geoscience students. *Rendiconti online della Società Geologica Italiana*, *30*(3), 5-11. https://www.researchgate.net/publication/260436805_3D_geological_modelling_and_education_Teaching_geological_cross_sections_with_a_3D_modelling_software_to_improve_spatial_thinking_skills_in_geoscience_students

Bian, L., Leslie, S.-J., & Cimpian, A. (2017). Gender stereotypes about intellectual ability emerge early and influence children's interests. *Science*, *355*(6323), 389-391. https://doi.org/10.1126/science.aah6524

Bian, L., Leslie, S.-J., Murphy, M. C., Cimpian, A. (2018). Messages about brilliance undermine women's interest in educational and professional opportunities. *Journal of Experimental Social Psychology, 76,* 404-420. https://doi.org/10.1016/j.jesp.2017.11.006

Bigg, C., & Vanhoutte, K. (2017). Spectacular astronomy. *Early Popular Visual Culture*, *15*(2), 115-124. https://doi.org/10.1080/17460654.2017.1319037

BioDigital: 3D human visualization platform for anatomy and disease. (2018). https://www.biodigital.com/

Blind Low Vision NZ. (2020). *Blindness and low vision in New Zealand - Latest statistics.* https://blindlowvision.org.nz/information/statistic-and-research/#sta

Bloch, B. (1998). *The tragedy of airbag fatalities to children and short drivers, and how to reduce the hazards*. http://www.autosafetyexpert.com/Assets/Docs/article-airbagdefects.pdf

Block, C. J., Koch, S. M., Liberman, B. E., Merriweather, T. J., & Roberson, L. (2011). Contending with stereotype threat at work: A model of long-term responses. *The Counseling Psychologist, 39*(4), 570–600. https://doi.org/10.1177/0011000010382459

Blotnicky, K. A., Franz-Odendaal, T., French, F., & Joy, P. (2018). A study of the correlation between STEM career knowledge, mathematics self-efficacy, career interests, and career activities on the likelihood of pursuing a STEM career among middle school students. *International Journal of STEM Education*, *5*, Article 22. https://doi.org/10.1186/s40594-018-0118-3

Boot, W. R., Kramer, A. F., Simons, D. J., Fabiani, M., & Gratton, G. (2008). The effects of video game playing on attention, memory, and executive control. *Acta Psychologica, 129*(3), 387-398. https://doi.org/10.1016/j.actpsy.2008.09.005

Borkin, M. (2010). *IIC/AstroMed*. http://wayback.archive-it.org/org-935/20170105143005/http://am.iic.harvard.edu/

Borkin, M., Goodman, A. Halle, M., & Alan, D. (2007). Application of medical imaging software to 3D visualization of astronomical data. In R. A. Shaw, F. Hill, & D. J. Bell (Eds.), *Astronomical Data Analysis Software and Systems XVI ASP Conference Series, Vol. 376* (pp. 621-624). San Francisco, CA: Astronomical Society of the Pacific.

Borovoy, A. (2017, July 28). 5-Minute film Festival: Teaching with 360-degree videos. *Edutopia*. https://www.edutopia.org/article/5-minute-film-festival-teaching-360-degree-videos-amy-borovoy

Boyd, D. (2000). *Depth cues in virtual reality and real world: Understanding individual differences in depth perception by studying shape-from-shading and motion parallax*. An honors thesis submitted for a Bachelor of the Arts Degree in the Department of Computer Science at Brown University (undergraduate thesis). Brown University, Providence, RI.

Breda, T., Grenet, J., Monnet, M., & Van Effenterre, C. (2018). *Can female role models reduce the gender gap in science? Evidence from classroom interventions in French high schools*. (PSE Working Papers No. 2018-06).: https://halshs.archives-ouvertes.fr/halshs-01713068/document

Brieber, D., Nadal, M., Leder, H., & Rosenberg, R. (2014). Art in time and space: Context modulates the relation between art experience and viewing time. *PLoS ONE, 9(*6). https://doi.org/10.1371/journal.pone.0099019

Broderick, N. A. & Casadevall, A. (2019). Meta-research: Disequilibrium in gender ratios among authors who contributed equally. *eLife, 8*. https://doi.org/10.7554/eLife.36399

Bruce, A. M., Getch, Y. Q., & Ziomek-Daigle, J. (2009). Closing the gap: A group counseling approach to improve test performance of African-American students. *Professional School Counseling, 12*(6), 450-457. https://doi.org/10.1177/2156759X0901200603

Bruce, M., & Bridgeland, J. (2014). The mentoring effect: Young people's perspectives on the outcomes and availability of mentoring. Civic Enterprises with Hart Research Associates for MENTOR: The National Mentoring Partnership. https://www.mentoring.org/new-site/wp-content/uploads/2015/09/The_Mentoring_Effect_Full_Report.pdf

Bryan, J., Moore-Thomas, C., Day-Vines, N. L., & Holcomb-McCoy, C. (2011). School counselors as social capital: The effects of high school college counseling on college application rates. *Journal of Counseling and Development, 89*(2), 190-199. https://doi.org/10.1002/j.1556-6678.2011.tb00077.x

Buck, G. A., Plano Clark, V. L., Leslie-Pelecky, D., Lu, Y., & Cerda-Lizarraga, P. (2008). Examining the cognitive processes used by adolescent girls and women scientists in identifying science role models: A feminist approach. *Science Education*, *92*(4), 688-707. https://doi.org/10. 1002/sce.20257

Bureau of Labor Statistics. (2018). *Occupational outlook handbook, biomedical engineers*. https://www.bls.gov/ooh/architecture-and-engineering/biomedical-engineers.htm

Burns, M. (2016, May 3). Harnessing the power of YouTube in the classroom [Blog post]. https://www.edutopia.org/blog/harnessing-power-youtube-in- classroom-monica-burns

Buolamwini, J., & Gebru, T. (2018). Gender shades: Intersectional accuracy disparities in commercial gender classification. *Proceedings of Machine Learning Research*, *81*, 1-15. http://proceedings.mlr.press/v81/buolamwini18a/buolamwini18a.pdf

Burke, R. J. & Mattis, M. C. (2007). *Women and minorities in science, technology, engineering and math: Upping the numbers*. Northhampton, MA: Edward Elgar Publishing.

Byars-Winston, A. (2014). Toward a framework for multicultural STEM-focused career interventions. *The Career Development Quarterly*, *62*, 340-357.

Byars-Winston, A. M., Branchaw, J., Pfund, C., Leverett, P., & Newton, J. (2015). Culturally diverse undergraduate researchers' academic outcomes and perceptions of their research mentoring relationships. *International Journal of Science Education, 37*(15), 2533-2554. http://doi.org/10.1080/09500693.2015.1085133

Byars-Winston, A., & Dahlberg, M. L. (Eds). (2019). *The science of effective mentorship in STEM*. Washington, DC: The National Academies Press. https://doi.org/10.17226/25568

Bystydzienski, J. M., Eisenhart, M., & Bruning, M. (2015), High school is not too late: Developing girls' interest and engagement in engineering careers. *The Career Development Quarterly, 6*3(1), 88-95. https://doi.org/10.1002/j.2161-0045.2015.00097.x

Cannady, M. A., Greenwald, E., & Harris, K. N. (2014). Problematizing the STEM pipeline metaphor: Is the STEM pipeline metaphor serving our students and the STEM workforce? *Science Education*, *98*(3), 443-460. https://doi.org/10.1002/sce.21108

Caplar, N., Tacchella, S., & Birrer, S. (2016). Quantitative evaluation of gender bias in astronomical publications from citation counts. *Nature Astronomy, 1*(6). https://doi.org/10.1038/s41550-017-0141

Capraro, K. & NASA JPL (2014). *Block Island*. https://nasa3d.arc.nasa.gov/detail/block-island

Carey, J., & Dimmitt, C. (2012). School counseling and student outcomes: Summary of six statewide studies. *Professional School Counseling, 16*(2), 146-153. https://doi.org/10.1177/2156759X0001600204

Cassell, J., & Jenkins, H. (Eds.). (2000). *From Barbie to Mortal Kombat: Gender and computer games*. The MIT Press. (Original work published 1998).

Ceci, S. J., Williams, W. M., & Barnett, S. M. (2009). Women's underrepresentation in science: Sociocultural and biological considerations. *Psychological Bulletin*, *135*(2), 218-261. https://doi.org/10.1037/a0014412

CesiumJS (2018). *An open source JavaScript library for world-class 3D globes and maps.* https://cesiumjs.org/

Chandrashekar, S. (2018, May 17). *GAAD: How virtual reality can transform the way people with disabilities learn*. Desire2Learn. https://www.d2l.com/corporate/blog/gaad-virtual-reality-people-disabilities-learn/

Chandra X-ray Observatory. (2009, January 6). Cassiopeia A: 3-D model: A star from the inside out. *Chandra Photo Album*. http://chandra.si.edu/photo/2009/casa2/

Charles, C. Z., Fischer, M. J., Mooney, M. A., & Massey, D. S. (2009). Affirmative-action programs for minority students: Right in theory, wrong in practice. *Chronicle of Higher Education, 55*(29), Article A29.

Chee, C. (2018). *Building STEM identity*. Presentation at 2015 Winter NSF EPSCoR PD/PA/EOD Meeting, Honolulu, HI. https://www.nsf.gov/od/oia/programs/epscor/presentations/PDPA_Winter_2015/STEM_ID.pdf

Chen, C. J. (2006). The design, development and evaluation of a virtual reality based learning environment. *Australasian Journal of Educational Technology*, *22*(1), 39-63. https://doi.org/10.14742/ajet.1306

Chen, X. (2013). *STEM Attrition: College Students' Paths Into and Out of STEM Fields* (NCES 2014-001). National Center for Education Statistics, Institute of Education Sciences, U.S. Department of Education. Washington, DC. https://nces.ed.gov/pubs2014/2014001rev.pdf

Chen, J. A., Metcalf, S. J., & Tutwiler, M. S. (2014). Motivation and beliefs about the nature of scientific knowledge within an immersive virtual ecosystems environment. *Contemporary Educational Psychology*, *39*(2), 112-123. https://doi.org/10.1016/j.cedpsych.2014.02.004

Cheryan, S., Master, A., & Meltzoff, A. N. (2015). Cultural stereotypes as gatekeepers: Increasing girls' interest in computer science and engineering by diversifying stereotypes. *Frontiers in Psychology*, *6*(49), 1-8. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4323745/

Cheryan, S., Ziegler, S. A., Montoya, A. K., & Jiang, L. (2017). Why are some STEM fields more gender balanced than others? *Psychological Bulletin*, *143*(1), 1-35. https://doi.org/10.1037/bul0000052

Childers, G., Watson, K., Jones, M. G., Williamson, K., & Hotette, V. (2015). Touching the stars: Making astronomy accessible for students with visual impairments. *Science Scope*, *38*(9), 20-26. https://www.uky.edu/~jwi229/saas/Childers_etal_2015.pdf

Choi, H., & Feng, J. (2017). Using video games to improve spatial skills. In R. Zhang & M. Gardner (Eds.), *Handbook of research on serious games for educational applications* (pp. 93-114). Hershey, PA: IGI Global. https://doi.org/10.4018/978-1-5225-0513-6.ch005

Cholewa, B., Burkhardt, C., Hull, M. (2015). Are school counselors impacting underrepresented students' thinking about postsecondary education? A nationally representative study. *Professional School Counseling*, *19*(1), 144-154. https://doi.org/10.5330/1096-2409-19.1.144

Christensen, N. L. (2011). *Multimessenger astronomy*. Paper presented at 46th Rencontres de Moriond and GPhyS Colloquium on Gravitational Waves and Experimental Gravity, La Thuile, Italy. https://arxiv.org/abs/1105.5843

Christian, C. A, Nota, A., Greenfield, P., Grice, N., & Shaheen, N. (2015). You can touch these! Creating 3D tactile representations of Hubble Space Telescope images. *Journal and Review of Astronomy Education and Outreach*, *3*, B33-48.

Cimpian, A. & Leslie, S. J. (2017) The brilliance trap: How a misplaced emphasis on genius subtly discourages women and African-Americans from certain academic fields. *Scientific Am*erican, *317*, 60-65.

Chestnut, E. K., Lei, R. F., Leslie, S.-J., & Cimpian, A. (2018). The myth that only brilliant people are good at math and its implications for diversity. *Education Science*s, *8*(2), Article 65. https://doi.org/10.3390/educsci8020065

Clark, T. (2014). 2014 American Ingenuity Awards: How Palmer Luckey Created Oculus Rift. *Smithsonian Magazine*. https://www.smithsonianmag.com/innovation/how-palmer-luckey-created-oculus-rift-180953049/?preview=&page=2 .

Clements, D., Sato, S., & Fonseca, A. (2016). Cosmic sculpture: A new way to visualise the cosmic microwave background. *European Journal of Physics*, *38*(1). https://doi.org/10.1088/0143-0807/38/1/015601

Comins, N. (2001). *Heavenly errors: Misconceptions about the real nature of the Universe*. New York, NY: Columbia University Press. http://www.jstor.org/stable/10.7312/comi11644

ComputerScience.org (2020) *The Current State of Women in Computer Science.* https://www.computerscience.org/resources/women-in-computer-science/

Contero, M., Naya, F., Company, P., & Saorin, J. L. (2006). Learning support tools for developing spatial abilities in engineering design. *International Journal of Engineering Education, 22*(3), 470-477.

Corbett, C., & Hill, C. (2015). *Solving the equation: The variables for women's success in engineering and computing*.: https://files.eric.ed.gov/fulltext/ED580805.pdf

Cortina, J. M. (1993). What is coefficient alpha? An examination of theory and applications. *Journal of Applied Psychology*, *78*(1), 98-104.

Cotabish, A. (2017, December 12). Utilizing YouTube for immersive VR science learning [Blog post]. https://edexcellence.net/articles/utilizing-youtube-for-immersive-vr-science-learning

Courtois, H., Pomarède, D., Tully, R., Hoffman, Y., & Courtois, D. (2013). Cosmography of the local Universe. *The Astronomical Journal*, *146*(3), 69-82. https://doi.org/10.1088/0004-6256/146/3/69

Craig, P., Michel, L., & Bateman, R. (2013). A survey of educational uses of molecular visualization freeware. *Biochemistry and Molecular Biology Education*, *41*(3), 193-205. https://doi.org/10.1002/bmb.20693

Crenshaw, K. (1991). Mapping the margins: Intersectionality, identity politics, and violence against women of color. *Stanford Law Review*, *43*(6), 1241-1299. https://doi.org/10.2307/1229039

Crenshaw, K. (2016). *Kimberlé Crenshaw: The urgency of intersectionality*. https://en.tiny.ted.com/talks/kimberle_crenshaw_the_urgency_of_intersectionality

Creswell, J. W. (2009). *Research design: Qualitative, quantitative and mixed methods approaches* (3rd ed.). Thousand Oaks, CA: SAGE Publications.

Creswell, J. W., & Plano Clark, V. L. (2007). *Designing and conducting mixed methods research*. Thousand Oaks, CA: SAGE Publications.

Criado-Perez, C. (2019, February 23). The deadly truth about a world built for men - from stab vests to car crashes. *The Guardian*. https://www.theguardian.com/lifeandstyle/2019/feb/23/truth-world-built-for-men-car-crashes

Cryer, H. (2013). *Teaching STEM subjects to blind and partially sighted learners*. https://www.rnib.org.uk/knowledge-and-research-hub/research-reports/education-research/stem

Cvencek, D., Meltzoff, A., & Greenwald, A. (2011). Math-gender stereotypes in elementary school children. *Child Development*, *82*(3), 766-779. https://doi.org/10.1111/j.1467-8624.2010.01529.x

Dabney, K., Tai, R. H., Almarode, J. T., Miller-Friedman, J. L., Sonnert, G., Sadler, P. M., & Hazari, Z. (2011). Out of school time science activities and their association with career interest in STEM. *International Journal of Science Education, Part B*, *2*(1), 63-79. https://doi.org/10.1080/21548455.2011.629455

Dare, E. (2015). U*nderstanding middle school students' perceptions of physics using girl-friendly and integrated STEM strategies: A gender study* (Doctoral thesis). Available from ProQuest Dissertation & Theses database. Full Text (3727776)

Dasgupta, N. (2011). Ingroup experts and peers as social vaccines who inoculate the self-concept: The stereotype inoculation model. *Psychological Inquiry, 22*(4), 231-246. https://doi.org/10.1080/1047840X.2011.607313

Davidson, M. A. (2007). *Understanding the burdens of race at a predominantly white university: The experiences of underrepresented students in an introductory statistics course*. (Doctoral dissertation, The Ohio State University). https://iase-web.org/documents/dissertations/07.Davidson.Dissertation.pdf

Davis, P., Davis, M. P., & Mobley, J. A. (2013). The school counselor's role in addressing the Advanced Placement equity and excellence gap for African American students. *Professional School Counseling*, *17*(1), 32-39. https://doi.org/10.1177/2156759X0001700104

DeLaney, T., Rudnick, L., Stage, M. D., Smith, J. D., Isensee, K., Rho, J.,& Houck, J. C. (2010). The three-dimensional structure of Cassiopeia A. *The Astrophysical Journal*, *725*(2), 2038-2058. https://doi.org/10.1088/0004-637X/725/2/2038

Dennehy, T. C., & Dasgupta, N. (2017). Female peer mentors early in college increase women's positive academic experiences and retention in engineering. *Proceedings of the National Academy of Sciences of the United States of America*, *114*(23), 5964-5969. https://doi.org/10.1073/pnas.1613117114

DePasquale, J., Arcand, K. K, & Edmonds, P. (2015). High energy vision: Processing X-rays. *Studies in Media and Communication*, *3*(2), 62-71. https://doi.org/10.11114/smc.v3i2.913

Devitt, J. (2012, August 8). New 3D map of massive galaxies and black holes offers clues to dark matter, dark energy. *NYU*. http://www.nyu.edu/about/news-publications/news/2012/august/new-3d-map-of-massive-galaxies-and-black-holes-offers-clues-to-dark-matter-dark-energy.html

Dewar, G. (2018). *Spatial intelligence: What is it, and how can we enhance it?* https://www.parentingscience.com/spatial-intelligence.html

Dewar, G. (2013). *The beneficial effects of video games on the visual mind: Do action video games sharpen visual-spatial skills?* https://www.parentingscience.com/ beneficial-effects-of-video-games.html

Dhami, H. (2019, June 27). Intrinsic motivation in the classroom: The ultimate guide. Top Hat. https://tophat.com/blog/intrinsic-motivation/

Díaz-Merced, W. (2014, September 22). Making astronomy accessible for the visually impaired [Blog post]. https://blogs.scientificamerican.com/voices/making-astronomy-accessible-for-the-visually-impaired/

Diaz-Merced, W. L., Candey, R. M., Brickhouse, N., Schneps, M., Mannone, J. C., Brewster, S., & Kolenberg, K. (2012). Sonification of astronomical data. *Proceedings of the International Astronomical Union*, *7*(S285), 133-136. https://doi.org/10.1017/S1743921312000440

Diaz-Merced, W. L. (2013). *Sound for the exploration of space physics data* (Doctoral thesis, University of Glasgow, Scotland). http://theses.gla.ac.uk/5804/

Diemer, B., & Facio, I. (2017). The Fabric of the Universe: Exploring the cosmic web in 3D prints and woven textiles. Public*ations of the Astronomical Society of the Pacific* *129*(975), 1-10. doi:10.1088/1538-3873/aa6a46

Disabled World (2019, March 14). *Disability and virtual reality technologies*. https://www.disabled-world.com/assistivedevices/computer/vr-tech.php

Dominguez, M. G., Martín-Gutierrez, J., Gonzalez, C. R., & Corredeaguas, C. M. M. (2012). Methodologies and tools to improve spatial ability. Procedia - Social and Behavioral Sciences, 51, 736-744. https://doi.org/10.1016/j.sbspro.2012.08.233

Doyle, M. (2016, March 10). The truth about why boys and girls need STEM Toys. *The Good Men Project*. https://goodmenproject.com/gender-sexuality/the-truth-about-why-boys-and-girls-need-stem-toys-dg/

Dredge, S. (2015, 19 November). Why YouTube is the new children's TV… and why it matters. *The Guardian*. https://www.theguardian.com/technology/2015/nov/19/youtube-is-the-new-childrens-tv-heres-why-that-matters

Duran, M., & Sendag, S. (2012). A preliminary investigation into critical thinking skills of urban high school students: Role of an IT/STEM program. *Creative Education*, *3*(2), 241-250. https://doi.org/10.4236/ce.2012.32038

Dutt, K., Pfaff, D.L., Bernstein, A. F., Dillard, J. S., & Block, C. J. (2016). Gender differences in recommendation letters for postdoctoral fellowships in geoscience. *Nature Geoscience, 9,* 805-808. https://doi.org/10.1038/ngeo2819

Dyches, P. (2018, March 20). New 'AR' mobile app features 3-d NASA spacecraft. *NASA*. https://www.nasa.gov/feature/jpl/new-ar-mobile-app-features-3-d-nasa-spacecraft/

Dye, M. W., Green, C. S., & Bavelier, D. (2009). The development of attention skills in action video game players. *Neuropsychologia, 47*(8-9), 1780-1789. https://doi.org/10.1016/j.neuropsychologia.2009.02.002

Edgerton Jr, S. Y. (1984). Galileo, Florentine "disegno," and the "strange spottednesse" of the Moon. *Art Journal*, *44*(3), 225-232. https://doi.org/10.1080/00043249.1984.10792550

Ellison, D. (2014). *Moon nearside farside*. https://nasa3d.arc.nasa.gov/detail/moon-nearside-farside

Ensher, E. A., & Murphy, S. E. (1997). Effects of race, gender, perceived similarity, and contact on mentor relationships. *Journal of Vocational Behavior*, *50*, 460-481. https://pdfs.semanticscholar.org/0980/182528dd53c79bd22597726b8820bb7d5342.pdf

Ericsson, K. A., Prietula, M. J., & Cokely, E. T. (2007, July-August). The making of an expert. *Harvard Business Review*. https://hbr.org/2007/07/the-making-of-an-expert

Eriksson, U., Linder, C., Airey, J., & Redfors, A. (2014). Who needs 3D when the Universe is flat? *Science Education*, *98(*3), 412- 442. https://doi.org/10.1002/sce.21109

Estrada, M., Hernandez, P. R., Schultz, P. W., & Herrera, J. (2018). A longitudinal study of how quality mentorship and research experience integrate underrepresented minorities into STEM careers. *CBE—Life Sciences Education, 17*(1), 1-13. https://doi.org/10.1187/cbe.17-04-0066

Etchells, M. J., Deuermeyer, E., Liles, V., Meister, S., Suarez, M. I., & Chalklen, W. L. (2017). White male privilege: An intersectional deconstruction. *Journal of Ethnic and Cultural Studies, 4*(2), 13-27. http://www.ejecs.org/index.php/JECS/article/view/78/pdf

Everett-Green, R. (2013, May 11). A 3-D machine that prints skin? How burn care could be revolutionized. *The Globe and Mail*. http://www.theglobeandmail.com/life/health-and-fitness/health/a-3-d-machine-that-prints-skin-how-burn-care-could-be-revolutionized/article7540819/

Ewell, P. T., Jones, D. P., & Kelly, P. J. (2006, May). *Conceptualizing and researching the education pipeline*. The National Center for Public Policy and Higher Education, Higher Education Policy Institute. http://www.higheredinfo.org/analyses/Pipeline%20Article.pdf

Faisal, A. (2017). Computer science: Visionary of virtual reality. *Nature*, *551*(7680), 298-299. https://www.nature.com/articles/551298a

Falco, L. D. (2016). The school counselor and STEM career development. *Journal of Career Development*, 44(4), 359-374. https://doi.org/10.1177/0894845316656445

Farr, W. M., Hut, P., Ames, J., & Johnson, A. (2009). *An experiment in using virtual worlds for scientific visualization on self-gravitating systems.* https://arxiv.org/ftp/arxiv/papers/0905/0905.1066.pdf

Feng, J., Spence, I., & Pratt, J. (2007). Playing an action video game reduces gender differences in spatial cognition. *Psychological Science*, *18*(10), 850-855. https://doi.org/10.1111/j.1467-9280.2007.01990.x

Ferrand, G., English, J., & Irani, P. (2016, May-June). *3D visualization of astronomy data cubes using immersive displays*. Paper presented at the CASCA Conference, Winnipeg, Manitoba. http://hci.cs.umanitoba.ca/assets/publication_files/Gilles.pdf

Ferrand, G., & Warren, D. (2018). Engaging the public with supernova and supernova remnant research using virtual reality. *Communicating Astronomy with the Public Journal*, *1*(24), 25-31. https://www.capjournal.org/issues/24/24_25.ph

Figueroa, T., & Hurtado, S. (2013, November). *Underrepresented racial and/or ethnic minority (URM) graduate students in STEM disciplines: A critical approach to understanding graduate school experiences and obstacles to degree progression*. Paper presented at the Annual meeting for the Association for the Study of Higher Education, St. Louis, MO, USA. https://heri.ucla.edu/nih/downloads/ASHE2013-URM-Grad-Students-in-STEM.pdf

Flanagan, M., May, J., & Dobie, T. (2005). Sex differences in tolerance to visually-induced motion sickness. *Aviation, Space, and Environmental Medicine*, *76*(7), 642–646.

Fluke, C. J., & Barnes, D. G. (2016). The ultimate display. In N. P. F. Lorent & K. Shortridge (Eds.), *Proceedings of* the Astronomical Data Analysis Software & Systems Conference (*ADASS XXV)*, Sydney, Australia (pp. 473-476). San Francisco, CA: Astronomical Society of the Pacific. https://arxiv.org/abs/1601.03459v1

Fogarty, S., & Arcand, K. (2020, January 10). Making the case for STEAM, not STEM. *Providence Business News*. https://pbn.com/making-the-case-for-steam-not-stem/?bypass=5e174943d326a

Fouad, N. A., & Smith, P. L. (1996). A test of a social cognitive model for middle school students: Math and science. *Journal of Counseling Psychology, 43*(3), 338–346. https://doi.org/10.1037/0022-0167.43.3.338

Fouad, N., & Singh, R. (2011). *Stemming the tide: Why women leave engineering*. https://www.energy.gov/sites/prod/files/NSF_Stemming%20the%20Tide%20Why%20Women%20Leave%20Engineering.pdf

Franceschini, S., Gori, S., Ruffino, M., Pedrolli, K., & Facoetti, A. (2012). A causal link between visual spatial attention and reading acquisition. *Current Biology, 22*(9), 814-819. https://doi.org/10.1016/j.cub.2012.03.013

Freund, K. M., Raj, A., Kaplan, S. E., Terrin, N., Breeze, J. L., Urech, T. H., & Carr, P. L. (2016). Inequities in academic compensation by gender: A follow-up to the National Faculty Survey cohort study. *Academic Medicine, 91*(8), 1068-1073. https://doi.org/10.1097/ACM.0000000000001250

Frye, M., Wang, C., Nair, S. C., & Burns, Y. C. (2018, April 29). *miniGEMS STEAM and programming camp for middle school girls.* Paper presented at the 2018 ASEE CoNECD - The Collaborative Network for Engineering and Computing Diversity Conference, Crystal City, VA. https://www.researchgate.net/publication/337090255_miniGEMS_STEAM_and_Programming_Camp_for_Middle_School_Girls_miniGEMS_STEAM_and_Programming_Camp_for_Middle_School_Girls_This_paper_provides_an_overview_of_a_STEAM_Camp_for_middle_school_girls_from_Tit

Funk, C., & Parker, K. (2018, January 9). *4. Blacks in STEM jobs are especially concerned about diversity and discrimination in the workplace*. https://www.pewsocialtrends.org/2018/01/09/blacks-in-stem-jobs-are-especially-concerned-about-diversity-and-discrimination-in-the-workplace/

Fussell, S. (2017). Why can't this soap dispenser identify dark skin? [Blog post]. https://gizmodo.com/why-cant-this-soap-dispenser-identify-dark-skin-1797931773

Gaensler, B. (2011). *Extreme cosmos: A guided tour of the fastest, brightest, hottest, heaviest, oldest, and most amazing aspects of our Universe* (Reprint). New York, NY: TarcherPerigee.

Ganley, C., & Lubienski, S. (2016). Mathematics confidence, interest, and performance: Examining gender patterns and reciprocal relations. *Learning and Individual Differences*, *47*, 182-193. https://doi.org/10.1016/j.lindif.2016.01.002

Ganley, C., Vasilyeva, M., & Dulaney, A. (2014). Spatial ability mediates the gender difference in middle school students' science performance. *Child Development*, *85*(4), 1419-1432. https://doi.org/10.1111/cdev.12230

Garcia-Betances, R., Arredondo Waldmeyer, M. T., Fico, G., & Cabrera-Umpierrez, M. F. (2015). A succinct overview of virtual reality technology use in Alzheimer's disease. *Frontiers in Aging Neuroscience, 7*(80). https://doi.org/10.3389/fnagi.2015.00080

Geena Davis Institute on Gender in Media. (2016, February 25). *Female characters in film and TV motivate women to be more ambitious, more successful, and have even given them the courage to break out of abusive relationships.* https://seejane.org/wp-content/uploads/female-characters-in-film-and-tv-motivate-women-to-be-more-ambitious-more-successful-and-have-even-given-them-the-courage-to-break-out-of-abusive-relationships.pdf

Giannakos, M. N., Divitini, M., Iversen, O. S., & Koulouris, P. (2015). *Make2Learn: Fostering engagement and creativity in learning through making*. Paper presented at the Entertainment Computing - ICEC 2015, 14th International Conference, Trondheim, Norway. https://pdfs.semanticscholar.org/f49e/5a61e32ef23f84c544497c86302261f45898.pdf

Gibney, E. (2019, June 27). Discrimination drives many LGBTQ+ scientists to think about quitting. *Nature*, *571*, 16-17. https://doi.org/10.1038/d41586-019-02013-9

Giddings, L.S. & Grant, B.M. (2009). From Rigour to Trustworthiness: Validating Mixed Methods. In Mixed Methods Research for Nursing and the Health Sciences (eds S. Andrew and E.J. Halcomb). doi:10.1002/9781444316490.ch7

Gillet, A., Sanner, M., Stoffler, D., Goodsell, D., & Olson, A. (2004). *Augmented reality with tangible auto-fabricated models for molecular biology applications*. Paper presented at the 15th IEEE Visualization Conference, Houston, Texas. https://doi.org/10.1109/VISUAL.2004.7

Girlguiding. (2016). *Girls' attitudes survey*. https://www.girlguiding.org.uk/globalassets/docs-and-resources/research-and-campaigns/girls-attitudes-survey-2016.pdf

Girl Scout Research Institute. (2012). *Generation STEM: What girls say about science, technology, engineering, and math*. https://www.girlscouts.org/content/dam/girlscouts-gsusa/forms-and-documents/about-girl-scouts/research/generation_stem_full_report.pdf

Gladwell, M. (2008). *Outliers: The story of success*. New York, NY: Little, Brown and Company.

Glen, S. (2016, October 9). *Pillai's Trace*. https://www.statisticshowto.datasciencecentral.com/pillais-trace/.

Globe at Night (n.d.) What is Light Pollution? *Learning*. https://www.globeatnight.org/light-pollution.php

Gnilka, P. B., & Novakovic, A. (2017). Gender differences in STEM students' perfectionism, career search self-efficacy, and perception of career barriers. *Journal of Counseling & Development*, *95*(1), 56-66. https://doi.org/10.1002/jcad.12117

Gold, A., Pendergast, P., Ormand, C., Budd, D., Stempien, J., Mueller, K., & Kravitz, K. (2018). Spatial skills in undergraduate students—Influence of gender, motivation, academic training, and childhood play. *Geosphere*, *14*(2), 668-683. https://doi.org/10.1130/ges01494.1

Good, A. (2017). *Take a walk on Mars -- In your own living room*. https://www.jpl.nasa.gov/news/news.php?feature=6978

Goodman, A., Rosolowsky, E. W., Borkin, M. A. Foster, J. B., Halle, M. Kauffmann, J., & Pineda, J. E. (2009). A role for self-gravity at multiple length scales in the process of star formation. *Nature*, *457*, 63-66. https://doi.org/10.1038/nature07609

Goodman-Scott, E. (2013). Maximizing school counselors' efforts by implementing school-wide positive behavioral interventions and supports: A case study from the field. Professional School Counseling, *17*(1), 111-119. https://doi.org/10.1177/2156759X0001700106

Goodman-Scott, E., Sink, C., Cholewa, B., & Burgess, M. (2018). An ecological view of school counselor ratios and student academic outcomes: A national investigation. *Journal of Counseling and Development*, *96*(10), 388-398. https://doi.org/10.1002/jcad.12221

Green, C. S., & Bavelier, D. (2007). Action-video-game experience alters the spatial resolution of vision. *Psychological Science, 18*(1), 88-94. https://doi.org/10.1111/j.1467-9280.2007.01853.x

Grice, N., Christian, C., Nota, A., & Greenfield, P. (2015). 3D Printing technology: A unique way of making Hubble Space Telescope images accessible to non-visual learners. *JBIR: Journal of Blindness Innovation and Research*, *5*(1). https://nfb.org/images/nfb/publications/jbir/jbir15/jbir050101.html

Griffith, A. (2010). Persistence of women and minorities in STEM field majors: Is it the school that matters? *Economics of Education Review*, 29(6), 911-922 https://doi.org/10.1016/j.econedurev.2010.06.010

Gwinner, K., Oberst, J., Jaumann, R., & Neukum, G. (2014). *Gale Crater*. https://nasa3d.arc.nasa.gov/detail/gale-crater

Hall, S., Grant, G., Arora, D., Karaksha, A., McFarland, A., Lohning, A., & Anoopkumar-Dukie, S. (2017). A pilot study assessing the value of 3D printed molecular modelling tools for pharmacy student education. *Currents in Pharmacy Teaching and Learning 9*(4), 723-728. https://doi.org/10.1016/j.cptl.2017.03.029

Halpern, D. F., Benbow, C. P., Geary, D. C., Gur, R. C., Hyde, J. S., & Gernsbacher, M. A. (2007). The science of sex differences in science and mathematics. *Psychological Science in the Public Interest: A Journal of the American Psychological Society*, *8*(1), 1-51. https://doi.org./10.1111/j.1529-1006.2007.00032.x

Handelsman, J., & Sakraney, N. (2015). *Implicit bias*. https://obamawhitehouse.archives.gov/sites/default/files/microsites/ostp/bias_9-14-15_final.pdf.

Handley, I., Brown, E., Moss-Racusin, C., & Smith, J. (2015). Quality of evidence revealing subtle gender biases in science is in the eye of the beholder. *Proceedings of The National Academy of Sciences*, *112*(43), 13201-13206. https://doi.org/10.1073/pnas.1510649112

Hansen, J., Barnett, M., MaKinster, J., & Keating, T. (2004). The impact of three-dimensional computational modeling on student understanding of astronomy concepts: A qualitative analysis. *International Journal of Science Education*, *26*(13), 1555-1575. doi:10.1080/0950069042000167376

Harold, J., Lorenzoni, I., Shipley, T. F., & Coventry, K. R. (2016). Cognitive and psychological science insights to improve climate change data visualization. *Nature Climate Change, 6*, 1080-1089. https://doi.org/10.1038/nclimate3162

Hausmann, M., Slabbekoorn, D., Van Goozen, S., Cohen-Kettenis, P., & Güntürkün, O. (2000). Sex hormones affect spatial abilities during the menstrual cycle. *Behavioral Neuroscience*, *114*(6), 1245-1250. https://doi.org/10.1037//0735-7044.114.6.1245

Heaverlo, C., Cooper, R., & Laanan, F. S. (2013). STEM development: Predictors for 6th-12th grade girls' interest and confidence in science and math. *Journal of Women and Minorities in Science and Engineering*, *19*(2), 121-142. https://doi.org/10.1615/JWomenMinorScienEng.2013006464

Hefflinger, M (2008) Survey: Average U.S. Gamer Age is 35; 40% are Women. at: http://www.dmwmedia.com/news/2008/07/17/survey:-average-u.s.-gamer-age-35;-40%25-are-women

Hegarty, M., & Waller, D. (2005). Individual differences in spatial abilities. In P. Shah & A. Miyake (Eds.), *The Cambridge handbook of visuospatial thinking* (pp. 121-169). New York, NY: Cambridge University Press.

Hicks, M. (2018, December 10). *When is it safe to buy kids a VR headset?* TechRadar. https://www.techradar.com/how-to/when-is-it-safe-to-buy-kids-a-vr-headset

Hill, C., Corbett, C., & St. Rose, A. (2010). *Why so few? Women in science, technology, engineering, and mathematics*. https://www.aauw.org/files/2013/02/Why-So-Few-Women-in-Science-Technology-Engineering-and-Mathematics.pdf

Hill, W. L. (2019, October 2). The myth of the STEM pipeline. *Inside Higher Ed.* https://www.insidehighered.com/views/2019/10/02/negative-consequences-pipeline-metaphor-stem-fields-opinion

Hinode Science Center at NAOJ. (2018, July 9). VR app "Excursion to the Sun" has been released! http://hinode.nao.ac.jp/en/news/notice/vr-app-excursion-to-the-sun-has-been-released/

Hirsch, L., Berliner-Heyman, S., Cano, R., Kimmel, H., & Carpinelli, J. (2011). Middle school girls' perceptions of engineers before and after a female only summer enrichment program. Proceedings - Frontiers in Education Conference. 10.1109/FIE.2011.6142990.

Hoff, C. (2019, February 16). *Taking on gender bias in clinical trials*. National Women's Health Network. https://nwhn.org/taking-on-gender-bias-in-clinical-trials/

Holman, L., Stuart-Fox, D., & Hauser, C.E. (2018). The gender gap in science: How long until women are equally represented? *PLoS Biology, 16*(4). https://doi.org/10.1371/journal.pbio.2004956

Howard-Brown, B., & Martinez, D. (2012). *Engaging diverse learners through the provision of STEM education opportunities*. http://www.sedl.org/secc/resources/briefs/diverse_learners_STEM/

Howell, E. (2017, November 13). You can visit real alien planets in VR thanks to this awesome new simulation. *Space.com*. https://www.space.com/38749-visit-six-real-exoplanets-with-virtual-reality.html

Huchra, J. & Geller, M. (1998). CfA Redshift Survey. http://tdc-www.harvard.edu/zcat/

Hughes, A.M. (2014, January). The 2013 CWSA demographics survey: Portrait of a generation of women in astronomy. *Status: A Report on Women in Astronomy*, 1-9. https://cswa.aas.org/status/Status_2014_Jan_links-corrected.pdf

Huang, G., Taddese, N., & Walter, E. (2000). *Entry and persistence of women and minorities in college science and engineering education* (NCES 2000-601). National Center for Education Statistics, U.S. Department of Education. https://files.eric.ed.gov/fulltext/ED566411.pdf

Hung, Y., Vetivelu, A., Hird, M. A., Yan, M., Tam, F., Graham, S. J., Cusimano, M., & Schweizer, T. A. (2014). Using fMRI virtual-reality technology to predict driving ability after brain damage: A preliminary report. *Neuroscience Letters*, *558*, 41-46. https://doi.org/10.1016/j.neulet.2013.10.065

Hwang, W. Y., Su, J. H., Huang, Y. M., & Dong, J. J. (2009). A study of multi-representation of geometry problem-solving with virtual manipulatives and whiteboard system. *Educational Technology & Society*, *12*(3), 229-247. https://www.researchgate.net/publication/220374659_A_Study_of_Multi-Representation_of_Geometry_Problem_Solving_with_Virtual_Manipulatives_and_Whiteboard_System

Hwang, W. Y., Hu, S.-S. (2013). Analysis of peer learning behaviors using multiple representations in virtual reality and their impacts on geometry problem solving. *Computers & Education, 62*, 308-319. https://doi.org/10.1016/j.compedu.2012.10.005

IBM Corp. Released 2019. IBM SPSS Statistics for Windows, Version 25.0. Armonk, NY: IBM Corp.

Information Today. (2009). *Nature publishes PDF with 3D interactive images*. http://newsbreaks.infotoday.com/wndReader.asp?ArticleId=52126

Isenberg, T. (2011). Position paper: Touch interaction in scientific visualization. In P. Isenberg, S. Carpendale, T. Hesselman, T. Isenberg, & B. Lee (Eds.), *Proceedings of the workshop on data exploration on interactive surfaces DEXIS 2011* (pp. 24-27). Le Chesnay, France: INRIA.

Izzo, M. V., & Bauer, W. M. (2015). Universal Design for Learning: Enhancing achievement and employment of STEM students with disabilities. *Universal Access in the Information Society, 14*(1), 17-27. https://doi.org/10.1007/s10209-013-0332-1

Jameson-Charles, M. (2015, March 12-13). *Legitimation (validity) in mixed methods research.* Paper presented at the Inaugural Mixed Methods International Research Association Regional Conference in the Caribbean, Mona, Jamaica. https://www.researchgate.net/publication/274324307_Legitimation_validity_in_Mixed_Methods_Research

Jenkins, A. (20 June 2019). The fall and rise of VR: The struggle to make virtual reality get real. *Fortune*. https://fortune.com/longform/virtual-reality-struggle-hope-vr/

Jensen, K. (2017, February 15). Meet VRML: How people made VR websites in the 90s. *PCMag*. https://www.pcmag.com/article/351339/meet-vrml-how-people-made-vr-websites-in-the-90s

Jittivadhna, K., Ruenwongsa, P., & Panijpan, B. (2010). Beyond textbook illustrations: Hand-held models of ordered DNA and protein structures as 3D supplements to enhance student learning of helical biopolymers. *Biochemistry and Molecular Biology Education*, *38*(6), 359-364. https://doi.org/10.1002/bmb.20427

Jones, M. G., & Broadwell, B. (2008). Visualization without vision: Students with visual impairment. In J. K. Gilbert, M. Reiner, & M. Nakhleh (Eds.), *Visualization: Theory and practice in science education* (pp. 283-294). Dordrecht, Netherlands: Springer.

Johnson, D. M. (2007). *Simulator sickness research summary*. http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.214.8179&rep=rep1&type=pdf

Johnson, E. (2016, July 13). What are the differences among virtual, augmented and mixed reality? *Recode*. https://www.recode.net/2015/7/27/11615046/whats-the-difference-between-virtual-augmented-and-mixed-reality

Johnson, R. B., & Onwuegbuzie, A. J. (2004). Mixed methods research: A research paradigm whose time has come. *Educational Researcher, 33*(7), 14-26. https://doi.org/10.3102/0013189X033007014

Juarez, A., Schonenberg, B., & Bartneck, C. (2010). Implementing a low-cost CAVE system using the CryEngine2. *Entertainment Computing*, *1*(3-4), 157-164. http://www.bartneck.de/publications/2010/caveCryEngine/

Kager, E., (2015). Effects of participation in a STEM camp on STEM attitudes and anticipated career choices of middle school girls: A mixed methods study (Doctoral dissertation). Available from ProQuest Dissertation & Theses: Full Text (10145051)

Kafai, Y. B., Heeter, C., Denner, J., Sun, J. Y. (Eds.). (2008). Beyond Barbie and Mortal Kombat: New perspectives on gender and gaming. The MIT Press.

Kawashima-Ginsberg, K. (2014). *Harry, Hermione, Ron and Neville– Portraits of American teenagers' extracurricular involvement, and implications for educational interventions*. Circle Working Paper No. 80. https://civicyouth.org/wp-content/uploads/2014/03/WP_80_KawashimaGinsberg.pdf

Khine, M. S., & Salehm, M. (Eds.). (2011). *Models and modeling: Cognitive tools for scientific enquiry*. Dordrecht, Netherlands: Springer Netherlands. http://www.springer.com/us/book/9789400704480

Family Zone. (2016). Kids under 8yo spend 65% of their online time on YouTube. [Blog post]. https://www.familyzone.com/anz/families/blog/what-kids-did-online-2016

Kim, A., Sinatra, G., & Seyranian, V. (2018). Developing a STEM identity among young women: A social identity perspective. *Review of Educational Research*, *88*(4), 589-625. https://doi.org/10.3102/0034654318779957

Kim, A., Tingen, C., & Woodruff, T. (2010). Sex bias in trials and treatment must end. *Nature*, *465*(7299), 688-689. https://doi.org/10.1038/465688a

Kim, R. (2018). *Asteroid Vesta*. https://nasa3d.arc.nasa.gov/detail/asteroid-vesta

Kiniry, L. (2017, December 29). How augmented reality is helping raise awareness about one of Armenia's most endangered species. *Smithsonian Magazine*. https://www.smithsonianmag.com/travel/how-augmented-reality-helping-raise-awareness-about-one-armenias-most-endangered-species-1-180967670/

Klettner, A. (2013, 31 January). Foster & Partners designs 3D printed lunar base. *Building Design (bd)*. http://www.bdonline.co.uk/5049632.article?origin=BDbreakingnews

Klinger, E. (1977). Meaning and void: Inner experiences and the incentives in people's lives. Minneapolis, MN: University of Minnesota Press.

Knobloch-Westerwick, S., Glynn, C. J., & Huge, M. (2013). The Matilda effect in science communication: An experiment on gender bias in publication quality perceptions and collaboration interest. *Science Communication, 35*(5), 603-625. https://doi.org/10.1177/1075547012472684

Korbey, H. (2017). Will virtual reality drive deeper learning? | Edutopia. https://www.edutopia.org/article/virtual-reality-drive-deeper-learning-holly-korbey

Koslucher, F., Haaland, E., & Stoffregen, T. (2015). Sex differences in visual performance and postural sway precede sex differences in visually induced motion sickness. *Experimental Brain Research*, *234*(1), 313-322. doi:10.1007/s00221-015-4462-y

Kupersmidt, J., Stelter, R., Garringer, M., & Bourgoin, J. (2018). STEM Mentoring. Supplement to the Elements of Effective Practice for Mentoring: Research-informed recommendations for youth mentoring programs with a science, technology, engineering, or mathematics focus. MENTOR: The National Mentoring

Partnership. https://www.mentoring.org/new-site/wp-content/uploads/2018/10/STEM-Supplement-to-EEP.pdf

Lahiri, U., Bekele, E., Dohrmann, E., Warren, Z., & Sarkar, N. (2015). A physiologically informed virtual reality based social communication system for individuals with autism. *Journal of Autism and Developmental Disorders*, *45*(4), 919-931. https://doi.org/10.1007/s10803-014-2240-5

Landau, J., Groscurth, G. R., Wright, L., & Condit, C. M. (2008). Visualizing nanotechnology: The impact on lay American audience associations with nanotechnology. *Public Understanding of Science, 18*(3), 325-337. https://doi.org/10.1177/0963662507080551

Landivar, L. (2013). Disparities in STEM employment by sex, race, and Hispanic origin. https://www.census.gov/prod/2013pubs/acs-24.pdf

Langdon, D., McKittrick, G., Beede, D., Khan, B., & Doms, M. (2011). *STEM: Good jobs now and for the future*. http://www.esa.doc.gov/sites/default/files/stemfinalyjuly14_1.pdf

Lapan, R. T., Gysbers, N. C., Bragg, S., & Pierce, M. E. (2012). Missouri professional school counselors: Ratios matter, especially in high-poverty schools. *Professional School Counseling*, *16*(2), 108-116. https://doi.org/10.1177/2156759X0001600207

Larson, S. (2014, September 2). Why so few women are studying computer science. *ReadWrite*. http://readwrite.com/2014/09/02/women-in-computer-science-why-so-few/

Lavy, V., & Sand, E. (2015). *On the origins of gender human capital gaps: Short and long term consequences of teachers' stereotypical biases*. (National Bureau of Economic Research, Working Paper No. 20909). http://www.nber.org/papers/w20909

Leeners, B., Kruger, T., Geraedts, K., Tronci, E., Mancini, T., & Ille, F., ... Hengartner M. P. (2017). Lack of associations between female hormone levels and visuospatial working memory, divided attention and cognitive bias across two consecutive menstrual cycles. *Frontiers in Behavioral Neuroscience*, *11*, 120. https://doi.org/10.3389/fnbeh.2017.00120

Lepper, M. R., Corpus, J. H., & Iyengar, S. S. (2005). Intrinsic and extrinsic motivational orientations in the classroom: Age differences and academic correlates. *Journal of Educational Psychology,* 97(2), 184-196. https://doi.org/10.1037/0022-0663.97.2.184

Leslie, S.-J., Cimpian, A., Meyer, M., & Freeland, E. (2015 January 16). Expectations of brilliance underlie gender distributions across academic disciplines*. Science, 347*(6219), 262-265. https://doi.org/10.1126/science.1261375

Leon, A., Villares, E., Brigman, G., Webb, L, & Peluso, P. (2011). Closing the achievement gap of Latina/Latino students: A school counseling response. *Counseling Outcome Research and Evaluation, 2*(1), 73-86. https://doi.org/10.1177/2150137811400731

Leung, L. (2015). Validity, reliability, and generalizability in qualitative research. *Journal of Family Medicine and Primary Care*, *4*(3), 324-327. https://doi.org/10.4103/2249-4863.161306

Levine, M., Serio, N., Radaram, B., Chauduri, S., & Talbert, W. (2015). Addressing the STEM gender gap by designing and implementing an educational outreach chemistry camp for middle school girls. *Journal of Chemical Education, 92*(10), 1639-1644. https://doi.org/10.1021/ed500945g

Levine, R. (2018, January 24). U of T astrophysicist-musician helps blind, partially sighted experience the cosmos with musical planetarium show. *U of T News*. https://www.utoronto.ca/news/u-t-astrophysicist-musician-helps-blind-partially-sighted-experience-cosmos-musical-planetarium

Levine, S. (2014, June 14). New bill aims to end bias against women in clinical trials. *HuffPost*. https://www.huffingtonpost.com/2014/06/24/research-for-all-act_n_5525757.html

Levine, S., Huttenlocher, J., Taylor, A., & Langrock, A. (1999). Early sex differences in spatial skill. *Developmental Psychology*, *3*5(4), 940-949. https://doi.org/10.1037/0012-1649.35.4.940

Lever, E. (2018). *I was a human Siri*. http://nymag.com/selectall/smarthome/i-was-a-human-siri-french-virtual-assistant.html

Lewis, V., Martina, C. A., McDermott, M. P., Trief, P. M., Goodman, S. R., Morse, G. D., LaGuardia, J. G., Sharp, D., Ryan, R. M. (2016). A randomized controlled trial of mentoring interventions for underrepresented minorities. *Academic Medicine, 91*(7), 994-1001. https://doi.org/10.1097/ACM.0000000000001056

Linder, A., & Svedberg, W. (2018, May 16-18). *Occupant safety assessment in European regulatory tests: Review of occupant models, gaps and suggestions for bridging any gaps.* Paper presented at the 18th International Conference Road Safety on Five Continents (RS5C 2018), Jeju Island, North Korea.

Linder, A., & Svedberg, W. (2019). Review of average sized male female occupant models in European regulatory safety assessment tests and European laws: Gaps and bridging suggestions. *Accident Analysis and Prevention*, *127*, 156-162. https://doi.org/10.1016/j.aap.2019.02.030

Linn, M., & Petersen, A. C. (1985). Emergence and characterization of sex differences in spatial ability: A meta-analysis. *Child Development*, *56*(6), 1479-1498. https://doi.org/10.2307/1130467

Lisberg, A., & Woods, B. (2018). Mentorship, mindset and learning strategies: An integrative approach to increasing underrepresented minority student retention in a STEM undergraduate program. *Journal of STEM Education, 19*(3), 14-19.

Locher, P., Krupinski, E.A., Melo-Thoms, C., & Nodine, C.F. (2007). Visual interest in pictorial art during an aesthetic experience. *Spatial Vision, 21*(1-2), 55-77. https://doi.org/10.1163/156856807782753868

Locher, P., Smith, L. F., & Smith, J. K. (1999). Original paintings versus slide and computer reproductions: A comparison of viewer responses. *Empirical Studies of the Arts, 17*, 121-129.

Lockwood, P. (2006). “Someone like me can be successful”: Do college students need same-gender role models? *Psychology of Women Quarterly*, *30*(1), 36-46. https://doi.org/10.1111/j.1471-6402.2006.00260.x

Lohman, D. F. (1993, July 21). *Spatial ability and g*. Paper presented at the first Spearman Seminar, University of Plymouth, England.

Lohr, S. (2018). *Facial recognition is accurate, if you're a white guy*. https://www.nytimes.com/2018/02/09/technology/facial-recognition-race-artificial-intelligence.html

Lord, T. R. (1985). Enhancing the visuo-spatial aptitude of students. *Journal of Research in Science Teaching*, *22*(5), 395-405. https://doi.org/10.1002/tea.3660220503

Luchsinger, G. (2017). *UN Women annual report 2016-2017*. http://annualreport.unwomen.org/en/2017

Luna, C. (n.d.). *Universal Design techniques*. Clark College. http://www.clark.edu/tlc/technology/universaldesign.php

Lynch, M. & Edgerton, S. Y. Jr. (1987). Aesthetics and digital image processing: Representational craft in contemporary astronomy. The Sociological Review, 35(1), 184-220. https://doi.org/10.1111/j.1467-954X.1987.tb00087.x

Lynch, K., & Kim, J. S. (2017). Effects of a summer mathematics intervention for low-income children: A randomized experiment. *Educational Evaluation and Policy Analysis, 39*(1), 31-53. https://doi.org/10.3102/0162373716662339

Macaluso, B., Larivière, V., Sugimoto, T., & Sugimoto, C. R. (2016). Is science built on the shoulders of women? A study of gender differences in contributorship. *Academic Medicine*, *91*(8), 1136-1142. https:/doi.org/10.1097/ACM.0000000000001261

Maccoby, E. E., & Jacklin, C. N. (1974). *The psychology of sex differences*. Stanford, CA: Stanford University Press.

Madura, T. I. (2017). A case study in astronomical 3-D printing: The mysterious Eta Carinae. *Publications of the Astronomical Society of the Pacific*, *129*(975). https://doi.org./10.1088/1538-3873/129/975/058011

Madura, T., Clementel, N., Gull, T., Kruip, C., & Paardekooper, J. (2015). 3D printing meets computational astrophysics: Deciphering the structure of η Carinae's inner colliding winds. *Monthly Notices of the Royal Astronomical Society*, *449*(4), 3780-3794. https://doi.org/10.1093/mnras/stv422

Maltese, A. V., & Tai, R. H. (2011). Pipeline persistence: Examining the association of educational experiences with earned degrees in STEM among US students. *Science Education*, *95*(5), 877-907. https://doi.org/10.1002/sce.20441

Malyn-Smith, J., Cedrone, D., Na'im, A., & Supel, J. (2013). *A program director's guide to evaluating STEM education programs: Lessons learned from local, state, and national initiatives.* ITEST Learning Resource Center, Education Development Center, Massachusetts Department of Higher Education, UMass Donahue Institute. http://stelar.edc.org/sites/stelar.edc.org/files/A_Program_Directors_Guide_to_Evaluating_STEM_Eduation_Programs_links_updated.pdf

Mann, A., Gonzalez, R., Thompson, A., Molteni, M., Allain, R., Dreyfuss, E., & Hasan, M. (2013, August 9). 3-D cosmic map helps you wrap your brain around the Universe's weirdness. *Wired*. https://www.wired.com/2013/08/3-d-cosmic-map-distance/

Mann, M. J., Smith, M. L., & Kristjansson, A. L. (2014). Improving academic self-efficacy, school connectedness, and identity in struggling middle school girls: A preliminary study of the REAL girls program. *Health Education & Behavior, 42*(1), https://doi.org/10.1177/1090198114543005

Mantovani, F. (2001). VR learning: Potential and challenges for the use of 3D environments in education and training. In G. Riva & C. Galimberti (Eds.), *Towards cyberpsychology: Mind, cognitions and society in the Internet age* (pp. 207-226). IOS Press. https://www.semanticscholar.org/paper/VR-Learning-%3A-Potential-and-Challenges-for-the-Use-Mantovani/c7f8d19850f4a88655fe81caea89912dcad66241

Marincola, E. (2006). Why is public science education important? *Journal of Translational Medicine*, *4*(7). https://doi.org/10.1186/1479-5876-4-7

Martín-Gutiérrez, J., Saorín, J. L., Contero, M., Alcañiz, M., Pérez-López, D. C., & Ortega, M. (2010). Design and validation of an augmented book for spatial abilities development in engineering students. *Computers and Graphics*, *34*(1), 77-91. https://doi.org/10.1016/j.cag.2009.11.003

Martín-Gutierrez, J., Navarro Trujillo, R. E., & Acosta-Gonzalez, M. M. (2013). Augmented reality application assistant for spatial ability training. HMD vs computer screen use study. *Procedia - Social and Behavioral Sciences*, *93*, 49-53. https://doi.org/10.1016/j.sbspro.2013.09.150

Martindale, J. (2016). *Get real! How augmented reality toys could make VR feel like a gimmick.* https://www.digitaltrends.com/virtual-reality/augmented-reality-toys-future-of-play/

Marx, D. M., & Roman, J. S. (2002). Female role models: Protecting women's math test performance. *Personality and Social Psychology Bulletin, 28*(9), 1183-1193. https://doi.org/10.1177/01461672022812004

Masters, M.S. & Sanders B. (1993). Is the gender difference in mental rotation disappearing? *Behavior Genetics 23*, 337– 341.

Mathews, C. (2013, October 10). *Physicists are made, not born.* The Scientista Foundation. http://www.scientistafoundation.com/women-in-science-news/physicists-are-made-not-born

McLeod, A. F., Dale, J. E., Ginsburg, A., Ercolano, B., Gritschneder, M., Ramsay, S., & Testi, L. (2015). The Pillars of Creation revisited with MUSE: Gas kinematics and high-mass stellar feedback tracked by optical spectroscopy. *MNRAS*, *450*(1), 1057-1076. https://doi.org/10.1093/mnras/stv680

McLeod, A., & Hook, R. (2015, April 30). The Pillars of Creation revealed in 3D - New study suggests that iconic structures more aptly named the Pillars of Destruction. *European Southern Observatory*. http://www.eso.org/public/news/eso1518/

Merchant, Z., Goetz, E. T., Cifuentes, L., Keeney-Kennicutt, W., & Davis, T. J. (2014). Effectiveness of virtual reality-based instruction on students' learning outcomes in K-12 and higher education: A meta-analysis. *Computers & Education 70*, 29-40. https://doi.org/10.1016/j.compedu.2013.07.033

Merickel, M. L. (1992). A study of the relationship between virtual reality (perceived realism) and the ability of children to create, manipulate, and utilize mental images for spatially related problem solving. (ED352942). ERIC. https://files.eric.ed.gov/fulltext/ED352942.pdf

Mertens, D. M. (2010). Divergence and mixed methods. *Journal of Mixed Methods Research, 4*(1), 3-5. https://doi.org/10.1177/1558689809358406

Meyers, J.D. (2013). *Observatories across the electromagnetic spectrum*. https://imagine.gsfc.nasa.gov/science/toolbox/emspectrum_observatories1.html

Microsoft (2017). Why Europe's girls aren't studying STEM. Microsoft Corporation. https://news.microsoft.com/uploads/2017/03/ms_stem_whitepaper.pdf

Mikropoulos, T. A., Chalkidis, A., Katskikis, A., & Emvalotis, A. (1998). Students' attitudes towards educational virtual environments. Education and Information Technologies, 3(2), 137-148. https://doi.org/10.1023/A:1009687025419

Milisavljevic, D., & Fesen, R. A. (2015). The bubble-like interior of the core-collapse supernova remnant Cassiopeia A. *Science*, *347*(6221), 526-530. https://doi.org/10.1126/science.1261949

Milgram, D. (2011). How to recruit women and girls to the science, technology, engineering, and math (STEM) classroom. *Technology and Engineering Teacher, 71*(3), 4-11. https://www.iteea.org/File.aspx?id=137394&v=340d4cae

Milkman, K., Akinola, M., & Chugh, D. (2015). What happens before? A field experiment exploring how pay and representation differentially shape bias on the pathway into organizations. *Journal of Applied Psychology*, *100*(6), 1678-1712. https://doi.org/10.1037/apl0000022

Miller, D. I., Nolla, K. M., Eagly, A. H. & Uttal, D. H. (2018). The development of children's gender-science stereotypes: A meta-analysis of 5 decades of U.S. draw-a-scientist studies. *Child Development, 89*(6), 1943-1955. https://doi.org/10.1111/cdev.13039

Minati, L., & Sigala, N. (2013). Effective connectivity reveals strategy differences in an expert calculator. *PLoS ONE*, *8*(9), Article e73746. https://doi.org/10.1371/journal.pone.0073746

Ministry for Women. (2018, July 20). *Women in innovation*. https://women.govt.nz/council/information/women-innovation

Misao, H. (2014). Group problem solving performance by members of homogeneous and heterogeneous groups. *Japanese Journal of Experimental Social Psychology*, *54*(1), 55-67. https://doi.org/10.2130/jjesp.1217

Moè, A., & Pazzaglia, F. (2010). Beyond genetics in mental rotation test performance: The power of effort attribution. *Learning and Individual Differences, 20*(5), 464-468. https://doi.org/10.1016/j.lindif.2010.03.004

Moè, A. (2009). Are males always better than females in mental rotation? Exploring a gender belief explanation. *Learning and Individual Differences*, *19*(1), 21-27. https://doi.org/10.1016/j.lindif.2008.02.002

Morgan, D. L. (2007). Paradigms lost and pragmatism regained: Methodological implications of combining qualitative and quantitative methods. *Journal of Mixed Methods Research, 1*(1), 48-76. https://doi.org/10.1177/2345678906292462

Morris, C. (1 Dec 2016). *10 industries rushing to embrace virtual reality.* CNBC. https://www.cnbc.com/2016/12/01/10-industries-rushing-to-embrace-virtual-reality-.html

Moss-Racusin, C., Dovidio, J., Brescoll, V., Graham, M., & Handelsman, J. (2012). Science faculty's subtle gender biases favor male students. *Proceedings of the National Academy of Sciences*, *109*(41), 16474-16479. https://doi.org/10.1073/pnas.1211286109

Murphy, B. (2018, January 9). Virtual reality taking the dummies out of medical simulation. [Blog post]. https://wire.ama-assn.org/education/virtual-reality-taking-dummies-out-medical-simulation

National Academies of Science, Engineering, and Medicine. (2018). *English learners in STEM subjects: Transforming schools, classrooms, and lives*. https://doi.org/10.17226/25182

National Academies of Sciences, Engineering, and Medicine. (2020). *Promising practices for addressing the underrepresentation of women in science, engineering, and medicine: Opening doors*. The National Academies Press. https://doi.org/10.17226/25585

National Center for Science and Engineering Statistics. (2011). *Women, minorities, and persons with disabilities in science and engineering - NCSES - US National Science Foundation (NSF)*. https://www.nsf.gov/statistics/wmpd/archives/wmpd_2011.zip

National Center for Science and Engineering Statistics. (2017). *Women, Minorities, and Persons with Disabilities in Science and Engineering - NCSES - US National Science Foundation (NSF)*. https://www.nsf.gov/statistics/2017/nsf17310/downloads.cfm

National Girls Collaborative Project. (2016, August). *The state of girls and women in STEM*. https://ngcproject.org/sites/default/files/ngcp_the_state_of_girls_and_women_in_stem_2016_final.pdf.

National Girls Collaborative Project. (2020). Statistics https://ngcproject.org/statistics

National Research Council (2010). Gender differences at critical transitions in the careers of science, engineering, and mathematics faculty. The National Academies Press. https://doi.org/10.17226/12062

National Science Foundation (2018). *Science & engineering indicators 2018*. https://nsf.gov/statistics/2018/nsb20181/

Neuman, S. B. (2006). The knowledge gap: Implications for early education. In D. Dickinson & S. B. Neuman (Eds.), *Handbook of early literacy research* (Vol. 2, pp. 29–40). New York, NY: Guilford.

Newcombe, N. S. (2010). Picture this: Increasing math and science learning by improving spatial thinking. *American Educator*, *34*(2), 29-35. https://www.aft.org/sites/default/files/periodicals/Newcombe.pdf

Nicholson-Cole, S.A. (2005). Representing climate change futures: A critique on the use of images for visual communication. *Computers, Environment, and Urban Systems, 29*(3), 255-273. https://doi.org/10.1016/j.compenvurbsys.2004.05.002

Nittrouer, C. L., Hebl, M. R., Ashburn-Nardo, L., Trump-Steele, R. C. E., Lane, D. M., & Valian, V. (2018). Gender disparities in colloquium speakers at top universities. *Proceedings of the National Academies of Sciences of the United States, 115*(1), 104-108. https://doi.org/10.1073/Pnas.1708414115

Noble, H. & Smith, J. (2015). Issues of validity and reliability in qualitative research. *Evidence-Based Nursing, 18*, 34-35. https://doi.org/10.1136/eb-2015-102054

Noonan, R. (2017). *Women in STEM: 2017 update*. U.S. Department of Commerce Economics and Statistics Administration, Office of the Chief Economist website: https://www.commerce.gov/sites/default/files/migrated/reports/women-in-stem-2017-update.pdf

Nosek, M. A., Robinson-Whelen, S., Hughes, R. B., & Nosek, T. M. (2016). An Internet-based virtual reality intervention for enhancing self-esteem in women with disabilities: Results of a feasibility study. *Rehabilitation Psychology, 61*(4), 358-370. https://doi.org/10.1037/rep0000107

Novodvorsky, I. (1993). *Development of an instrument to assess attitudes toward science*. (Doctorial Dissertation, The University of Arizona, 1993) Dissertation Abstracts International, 54, 4054.

Nowell, L. S., Norris, J. M., White, D. E., & Moules, N. J. (2017). Thematic analysis: Striving to meet the trustworthiness criteria. *International Journal of Qualitative Methods, 16*(1), 1-13. https://doi.org/10.1177/1609406917733847

O'Donnell, G. (2019, August 19). *STEM fields need male allies to advocate for greater gender equity*. Insight into Diversity. https://www.insightintodiversity.com/stem-fields-need-male-allies-to-advocate-for-greater-gender-equity/

Ogle, J. P., Hyllegard, K. H., Rambo-Hernandez, K. E., & Park, J. (2017). Building middle school girls' self-efficacy, knowledge, and interest in math and science through the integration of fashion and STEM. *Journal of Family & Consumer Sciences, 109*(4), 33-40. https://doi.org/10.14307/JFCS109.4.33

O'Neill, S.J., Smith, N. (2014). Climate change and visual imagery. *WIREs Climate Change, 5*(1), 73-87. https://doi.org/10.1002/wcc.249

O'Reilly, K. (2009). *Key concepts in ethnography*. https://doi.org/10.4135/9781446268308

Onwuegbuzie, A. J. (2003). Expanding the framework of internal and external validity in quantitative research. *Research in the Schools*, *10*, 71-90.

Onwuegbuzie, A. J., & Johnson, R. B. (2006). The validity issue in mixed research. *Research in the Schools, 13*(1), 48-63. http://www.msera.org/publications-rits.html

Onwuegbuzie, A. J., & Leech, N. L. (2005). On becoming a pragmatic researcher: The importance of combining quantitative and qualitative research methodologies. *International Journal of Social Research Methodology*, *8*(5), 375-387. https://doi.org/10.1080/13645570500402447

Orlando, S., Miceli, M., Pumo, M. L., Bocchino, F. (2016). Modeling SNR Cassiopeia A from the supernova explosion to its current age: The role of post-explosion anisotropies of ejecta. *The Astrophysical Journal*, *822*(1). https://doi.org/10.3847/0004-637X/822/1/22

Pajares, F. (2005). Gender differences in mathematics self-efficacy beliefs. In A. M. Gallagher & J. C. Kaufman (Eds.), *Gender differences in mathematics: An integrative psychological approach* (pp. 294–315). Boston, MA: Cambridge University Press.

Palaus, M., Marron, E. M., Viejo-Sobera, R., Redolar-Ripoll, D. (2017). Neural basis of video gaming: A systematic review. *Frontiers in Human Neuroscience*; 11. doi: 10.3389/fnhum.2017.00248

Pan, Z., Cheok, A. D., Yang, H., Zhu, J., & Shi, J. (2006). Virtual reality and mixed reality for virtual learning environments. *Computers and Graphics, 30*(1), 20-28. https://doi.org/10.1016/j.cag.2005.10.004

Pantelidis, V. S. (1995). Reasons to use virtual reality in education. *VR in the Schools*, 1(1), 9.

Pantelidis, V. S. (2009). Reasons to use virtual reality in education and training courses and a model to determine when to use virtual reality. *Themes in Science and Technology Education*, 2, 1-2, 59-70. https://www.timtechconsults.com/images/ttcvreducation%20.pdf

Paranandi, M. (2002). An inquiry into computers in design: When cardboard met computer. In Proceedings of the 7th International Conference on Computer-Aided Architectural Design Research in Asia (pp. 329-337). Multimedia University Malaysia. https://cumincad.architexturez.net/system/files/pdf/bb35.content.pdf

Parker, D. E., & Harm, D. L. (1992). Mental rotation: A key to mitigation of motion sickness in the virtual environment? *Presence*, *1*(3), 329-333.

PEAR Institute at Harvard University and McLean Hospital, & IMMAP: Institute for Measurement, Methodology, Analysis & Policy at Texas Tech University. (2017). *Afterschool learning is a powerful STEM solution* [Fact sheet]. http://stemreadyamerica.org/wp-content/uploads/2017/02/AfterschoolSTEMEvaluation_Overview_Final.pdf

Penny, L (2019, September, 6). Gaming's #MeToo Moment and the tyranny of male fragility. Wired. https://www.wired.com/story/videogames-industry-metoo-moment-male-fragility/

Penny, M. R., Cao, Z. J., Patel, B., dos Santos, B. S., Asquith, C. R. M., Szulc, B. R., Rao, Z. X., Muwaffak, Z., Malkinson, J. P., Hilton, S. T. (2017). Three-dimensional printing of a scalable molecular model and orbital kit for organic chemistry teaching and learning. *Journal of Chemical Education*, *94*(9). 1265-1271. https://doi.org/10.1021/acs.jchemed.6b00953

Perez-Felkner, L., Nix, S., & Thomas, K. (2017). Gendered pathways: How mathematics ability beliefs shape secondary and postsecondary course and degree field choices. *Frontiers in Psychology*, *8*. doi:10.3389/fpsyg.2017.00386

Pew Research Center. (2018a). *Internet/broadband fact sheet*. http://www.pewinternet.org/fact-sheet/internet-broadband/

Pew Research Center. (2018b). *Mobile fact sheet*. http://www.pewinternet.org/fact-sheet/mobile/

Phillips, B.J. (2000). The impact of verbal anchoring on consumer response to image ads. *Journal of Advertising, 29*(1), 15-24. https://doi.org/10.1080/00913367.2000.10673600

Phillips, K., Liljenquist, K., & Neale, M. (2008). Is the pain worth the gain? The advantages and liabilities of agreeing with socially distinct newcomers. *Personality and Social Psychology Bulletin*, *35*(3), 336-350. https://doi.org/10.1177/0146167208328062

Pitney, N. (2017, December 6). Meet the 63rd Black woman in American history with a physics Ph.D. *The Huffington Post*. http://www.huffingtonpost.com/2015/06/24/chanda-prescod-weinstein_n_7574020.html

Poirier, J. M., Tanenbaum, C., Storey, C., Kirshtein, R., & Rodriguez, C. (2009). *The road to the STEM professoriate for underrepresented minorities: A review of the literature*. American Institutes for Research. https://www.air.org/sites/default/files/downloads/report/AGEP_Lit_Review_10-26-09_0.pdf

Pollack, E. (2013, October 3). Why are there still so few women in science? *The New York Times Magazine*. https://www.nytimes.com/2013/10/06/magazine/why-are-there-still-so-few-women-in-science.html

Ponce, O. A. & Pagán-Maldonado, N. (2015). Mixed methods research in education: Capturing the complexity of the profession. *International Journal of Educational Excellence, 1*(1), 111-135. https://doi.org/10.18562/ijee.2015.0005

Prescod-Weinstein, C. (2019, October 11). Are we pressuring students to choose a hostile STEM*? Inside Higher Ed*. https://www.insidehighered.com/advice/2019/10/11/do-minority-and-other-students-feel-pressured-stem-fields-opinion

Quaiser-Pohl, C., Geiser, C., & Lehmann, W. (2006). The relationship between computer-game preference, gender, and mental-rotation ability. *Personality and Individual Differences, 40*(3), 609–619. https://doi.org/10.1016/j.paid.2005.07.015

Quinn, M. (2012). “Walk on the sun”: An interactive image sonification exhibit. *AI & Society*, *7*(2), 303-305. https://doi.org/10.1007/s00146-011-0355-1

Rafi, A., Anuar, K., Samad, A., Hayati, M., & Mahadzir, M. (2005). Improving spatial ability using a Web-based Virtual Environment (WbVE). *Automation in Construction*, *14*(6), 707-715. https://doi.org/10.1016/j.autcon.2004.12.003

Raisamo, R., Hippula, A., Patomaki, S., Tuominen, E., Pasto, V., & Hasu, M. (2006). Testing usability of multimodal applications with visually impaired children. *IEEE MultiMedia*, *13*(3), 70-76. https://ieeexplore.ieee.org/document/1667979/

Ralabate, P. K. (2011, August 30). *Universal Design for Learning: Meeting the needs of all students.* American Speech-Language Hearing Association. https://pdfs.semanticscholar.org/71fd/94aa72184d4e5c673bfd5c5b9f86e3468cc3.pdf

Rector, T., Arcand, K., & Watzke, M. (2015). *Coloring the universe*. (1st ed.). Fairbanks, AK: University of Alaska Press.

Rector, T., Levay, Z., Frattare, L., Arcand, K. K., & Watzke, M. (2017). The aesthetics of astrophysics: How to make appealing color-composite images that convey the science. *Publications of the Astronomical Society of the Pacific*, 129(975). https://doi.org/10.1088/1538-3873/aa5457

Rector, T., Levay, Z., Frattare, L., English, J., & Pu'uohau-Pummill, K. (2007). Image-processing techniques for the creation of presentation-quality astronomical images. *The Astronomical Journal*, *133*(2). http://iopscience.iop.org/article/10.1086/510117/meta

Redick, T. S., & Webster, S. B. (2014). Videogame interventions and spatial ability interactions. *Frontiers in Human Neuroscience, 8*, 183. https://doi.org/10.3389/fnhum.2014.00183

Reddy, F. (2015, January 15). *Unprecedented look into superstar Eta Carinae.* NASA. https://www.nasa.gov/content/goddard/nasa-observatories-take-an-unprecedented-look-into-superstar-eta-carinae

Reilly, D., Neumann, D. L., & Andrews, G. (2017). Gender differences in spatial ability: Implications for STEM education and approaches to reducing the gender gap for parents and educators. In. M. S. Khine (Ed.), Visual-Spatial ability: Transforming research into practice (pp. 195-224). Switzerland: Springer International. https://doi.org/10.1007/978-3-319-44385-0_10

Reilly, E. D., Awad, G. H., Kelly, M. M., & Rochlen, A. B. (2019). The relationship among stigma consciousness, perfectionism, and mental health in engaging and retaining STEM women. *Journal of Career Development, 46*(4), 440-454. https://doi.org/10.1177/0894845318784745

Rennie, J. (2014, July 17). Passion and 3D printers reinvent STEM learning [Blog post]. http://blogs.plos.org/retort/2014/07/17/passion-3d-printers-can-reinvent-stem-learning

Rice, K. G., Ray, M. E., Davis, D. E., DeBlaere, C., & Ashby, J.S. (2015). Perfectionism and longitudinal patterns of stress for STEM majors: Implications for academic performance. *Journal of Counseling Psychology, 62*(4), 718-731. https://doi.org/10.1037/cou0000097

Rice, K. G., Lopez, F. G., Richardson, C. M. E., & Stinson, J. M. (2013). Perfectionism moderates stereotype threat effects on STEM majors' academic performance. *Journal of Counseling Psychology, 60*(2), https://doi.org/10.1037/a0032052

Rios, D., & Stewart, A. J. (2014). Insider and outsider-within standpoints: The experiences of diverse faculty in science and engineering fields. *Journal of Women and Minorities in Science and Engineering*, *21*(4), 295-322. https://doi.org/10.1615/JWomenMinorScienEng.2015010375

Rittmayer, A.D., Beier, M.E., (2008). Overview: Self-efficacy in STEM. SWE-AWE CASEE Overviews, *1*(12).

Rosenthal, L., Levy, S., London, B., Lobel, M., & Bazile, C. (2013). In pursuit of the MD: The impact of role models, identity compatibility, and belonging among undergraduate women. *Sex Roles*, *68*(7-8), 464-473. https://doi.org/10.1007/s11199-012-0257-9

Royse, P., Lee, J., Undrahbuyan, B., Hopson, M., & Consalvo, M. (2007). Women and games: Technologies of the gendered self. *New Media & Society, 9*(4), 555-576. https://doi.org/10.1177/1461444807080322

Russell, C. (2020, April 13). *Traveling to Our Galactic Center Through Virtual Reality* [Blog post]. https://chandra.si.edu/blog/node/755

Russell, C. M. P. (2018, January 8-12). *360-degree videos: A new visualization technique for astrophysical simulations, applied to the Galactic Center.* Paper presented at American Astronomical Society, AAS Meeting #231, National Harbor, MD. http://adsabs.harvard.edu/abs/2018AAS...23131101R

Russo, M. (2018, June 13-15). *Our musical universe*. Presentation at the AstroViz Conference at Caltech, Pasadena, CA.

Ryan, G. W., & Bernard, H. R. (2003). Techniques to identify themes in qualitative data. *Field Methods, 15*(1), 85-109.

Sadler, P. M., Sonnert, G., Hazari, Z., & Tai, R. (2012). Stability and volatility of STEM career interest in high school: A gender study. *Science Education, 96*(3), 411-427. https://doi.org/10.1002/sce.21007

Salina, C., Girtz, S., Eppinga, J., Martinez, D., Blumer Kilian, D., Lozano, E., Martinez, A., Crowe, D., De La Barrera, M., Mendez, M., & Shines, T. (2013). All hands on deck: A comprehensive, results-driven counseling model. *Professional School Counseling, 17*(1), 63-75. https://doi.org/10.1177/2156759X0001700112

Sally Ride . (2012, September). *Harvard Business Review*. https://hbr.org/2012/09/sally-ride

Sanjari, M., Bahramnezhad, F., Fomani, F. K., Shoghi, M., & Cheraghi, M. A. (2014). *Journal of Medical Ethics and History of Medicine*, *7*, 14. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4263394/

Sarsons, H., Xu, G. (2015) *Confidence men? Gender and confidence: Evidence among top economists*. (Working Paper). https://scholar.harvard.edu/sarsons/publications/confidence-men-gender-and-confidence-evidence-among-top-economists

Schhneider, B., Martinez, S., & Ownes, A. (2006). Barriers to educational opportunities for Hispanics in the United States. In M. Tienda & F. Mitchell (Eds.), *National Research Council (US) Panel on Hispanics in the United States. Hispanics and the future of America* (pp. 179-227). Washington, DC: National Academies Press. https://www.ncbi.nlm.nih.gov/books/NBK19909/

Schmelz, J. (2015, March 10). The normalcy curve [Blog post]. http://womeninastronomy.blogspot.com/2015/03/the-normalcy-curve.html

Schmelz, J., Montgomery, M., Trouille, L., Morrison, N., Bertschinger, E., & Charbonneau, D., Gehrels, N., Hughes, M., Kirkpatrick, J., Murphy, N., Zellner, N., Johnson, J., & Simpson, C., (2014). *Annual report on the Committee on the Status of Women in Astronomy for 2013-2014*. https://cswa.aas.org/AnnualReports/CSWA_Ann_Rep_2014.pdf

Schoonenboom, J. & Johnson, R. B. (2017). How to construct a mixed methods research design. Kölner Zeitschrift für Soziologie und Sozialpsychologie, *69*(2), 107–131. https://doi.org/10.1007/s11577-017-0454-1

Schreffler, J., Vasquez, E., III, Chini, J., & James, W. (2019). Universal Design for Learning in postsecondary STEM education for students with disabilities: A systematic literature review. *International Journal of STEM Education*, *6*, Article 8. https://doi.org/10.1186/s40594-019-0161-8

Sege, R., Nykiel-Bub., L., Selk, S. (2015). Sex differences in institutional support for junior biomedical researchers. *Journal of the American Medical Association, 314*(11), 1175-1177. https://doi.org/10.1001/jama.2015.8517

Settles, I. H. (2014, October). *Women in STEM: Challenges and determinants of success and well-being*. American Psychological Association. https://www.apa.org/science/about/psa/2014/10/women-stem

Shah, P. & Miyake, A. (2005). Preface. In P. Shah & A. Miyake (Eds.), *The Cambridge handbook of visuospatial thinking* (pp. 9-14). New York, NY: Cambridge University Press.

Shaw, A. (2012). Do you identify as a gamer? Gender, race, sexuality, and gamer identity. *New Media & Society*, 14(1), 7-27. https://doi.org/10.1177/1461444811410394

Shapiro, J. R., & Williams, A. M. (2012). The role of stereotype threats in undermining girls' and women's performance and interest in STEM fields. Sex Roles, 66, 175-183. https://link.springer.com/article/10.1007/s11199-011-0051-0

Sheltzer, J. M. & Smith, J. C. (2014). Elite male faculty in the life sciences employ fewer women. *Proceedings of the National Academies of Sciences of the United States of America, 111*(28), 10107–10112. https://doi.org/10.1073/pnas.1403334111

Shen, H. (2013). Mind the Gender Gap. *Nature*, 495 (7439), 22–24. https://www.nature.com/news/inequality-quantified-mind-the-gender-gap-1.12550

Sheppard, L., & Aldrich, F. K. (2001). Tactile graphics in school education: perspectives from teachers. British Journal of Visual Impairment, 19(3), 93–97. https://doi.org/10.1177/026461960101900303

Sicart, M. (2017). Reality has always been augmented: Play and the promises of Pokemon GO. *Mobile Media & Communication*, *5*(1), 30-33. https://pure.itu.dk/ws/files/82437858/MMC_Reality_has_always_been_augmented_Play_and_the_promises_of_Pok_mon_GO.pdf

Sievertsen, H. H., Gino, F., & Piovesan, M. (2016). Cognitive fatigue influences students' performance on standardized tests. *Proceedings of the National Academy of Sciences of the United States of America, 113*(10), 2621–2624. doi:10.1073/pnas.1516947113

Simpkins, S. D., Davis-Kean, P. E., & Eccles, J. S. (2006). Math and science motivation: a longitudinal examination of the links between choices and beliefs. *Developmental Psychology, 42*(1), 70. https://doi.org/10.1037/0012-1649.42.1.70

Skorton, D. J. (2018, 12 March). Access + ability: Designing with people, not for them. *Torch*. https://torch.si.edu/2018/03/access-ability-designing-with-people-not-for-them/

Slone, L., Moore, D., & Johnson, S. (2018). Object exploration facilitates 4-month-olds' mental rotation performance. *PLOS ONE*, *13*(8). https://doi.org/10.1371/journal.pone.0200468

Smith, A., & Anderson, M. (2018). *Social media use in 2018*. http://www.pewinternet.org/2018/03/01/social-media-use-in-2018

Smith, L. F., Arcand, K. K., Smith, J. K., Smith, R. K., & Bookbinder, J. (2015). Is that real? Understanding astronomical images. *Journal of Media and Communication Studies*, *7*(5), 88-100. doi:10.5897/JMCS2015.0446

Smith, L. F., Smith, J. K, Arcand, K. K, Smith, R. K, & Bookbinder, J. (2015). Aesthetics and astronomy: How labels affect understanding and appreciating deep space images. *Curator, 58*(3), 282-297. https://doi.org/10.1111/cura.12114

Smith, L. F., Arcand, K. K., Smith, B. K., Smith, R. K., Bookbinder, J., & Smith, J. K. (2017a). Black holes and vacuum cleaners: Using metaphor, relevance, and inquiry in labels for space images. *Psychology of Aesthetics, Creativity, and the Arts 11*(3), 359-374. https://doi.org/10.1037/aca0000130

Smith, L. F., Arcand, K. K., Smith, B. K., Smith, R. K., Bookbinder, J., & Smith, J. K. (2017b). Capturing the many faces of an exploded star: Communicating complex and evolving astronomical data. *JCOM Science Communication Journal, 16*(5), 1-23. https://doi.org/10.22323/2.16050202

Smith, L. F., Smith, J. K., Arcand, K. K., Smith, R. K., Bookbinder, J., & Keach, K. (2011). Aesthetics and astronomy: Studying the public's perception and understanding of non-traditional imagery from space. *Science Communication*, *33*, 201-238. https://doi.org/10.1177/1075547010379579

Smith, L. F., Smith, J. K., & Tinio, P. P. L. (2017). Time spent viewing art and reading labels. Psychology of Aesthetics, Creativity, and the Arts, 11(1), 77-85. https://doi.org/10.1037/aca0000049

Smith, J. K., & Smith, L. F. (2001). Spending time on art. Empirical Studies of the Arts, 19, 229-236. https://doi.org/10.2190/5MQM-59JH-X21R-JN5J

Smith, S., Choueiti, M., Prescott, A., & Pieper, K. (2012). *Gender roles & occupations: Look at character attributes and job-related aspirations in film and television*. https://seejane.org/wp-content/uploads/key-findings-gender-roles-2013.pdf

Smith, W., & Erb, T. (1986). Effect of women science career role models on early adolescents' attitudes toward scientists and women in science. *Journal of Research In Science Teaching*, *23*(8), 667-676. https://doi.org/10.1002/tea.3660230802

Soldin, O. P., Chung, S. H., & Mattison, D. H. (2011). Sex differences in drug disposition. *Journal of Biomedicine and Biotechnology*, 2011(187103). https://doi.org/10.1155/2011/187103

Spencer, S. J., Steele, C. M., & Quinn, D. M. (1999). Stereotype threat and women's math performance. *Journal of Experimental Social Psychology*, *35*(1), 4-28. https://doi.org/10.1006/jesp.1998.1373

Statistics New Zealand (2015). Women at work: 1991-2013. http://archive.stats.govt.nz/browse_for_stats/people_and_communities/Women/women-occupation.aspx

Steffen, W., & Koning, N. (2015, April 28). Constraints on the constraints for 3D reconstruction. *3D Astrophysics*.

https://3dastrophysics.wordpress.com/2015/04/28/constraints-on-the-constraints-for-3d-reconstruction/

Steffen, W., Koning, N., Wenger, S., Morisset, C., Magnor, M. (2011). Shape: A 3D modeling tool for astrophysics. *IEEE Transactions on Visualization and Computer Graphics, 17*(4), 454-465. https://doi.org/10.1109/TVCG.2010.62

Steffen, W., Teodoro, M., Madura, T. I., Groh, J. H., Gull, T. R., Mehner, A., Corcoran, M. F., Damineli, A., & Hamaguchi, K. (2014). The three-dimensional structure of the Eta Carinae Homunculus. *MNRAS*, *442*(4), 3316-3328. https://doi.org/10.1093/mnras/stu1088

Stein, J. (2015, August 6). Why virtual reality is about to change the world. *Time*. http://time.com/3987022/why-virtual-reality-is-about-to-change-the-world/

Steinicke, F. (2016). *Being really virtual: Immersive natives and the future of virtual*. Cham, Switzerland: Springer International Publishing.

Steinke, J. (2017). Adolescent girls' STEM identity formation and media images of STEM professionals: Considering the influence of contextual cues. *Frontiers in Psychology*, *8*. https://doi.org/10.3389/fpsyg.2017.00716

Stoet, G., & Geary, D. (2018). The gender-equality paradox in science, technology, engineering, and mathematics education. *Psychological Science*, *29*(4), 581-593. https://doi.org/10.1177/0956797617741719

Strauss, A. L., & Corbin, J. M. (1998). *Basics of qualitative research: Techniques and procedures for developing grounded theory.* Thousand Oaks, CA: SAGE Publications.

Stout, J. G., Dasgupta, N., Hunsinger, M., & McManus, M. A. (2011). STEMing the tide: Using ingroup experts to inoculate women's self-concept in science, technology, engineering, and mathematics (STEM). *Journal of Personality and Social Psychology, 100*(2), 255-270. https://doi.org/10.1037/a0021385

Takagishi, K., & Umezu, S. (2017). Development of the improving process for the 3D printed structure. *Scientific Reports, 7*. https://doi.org/10.1038/srep39852

Temkin, A. (n.d.). *MoMA | Vincent van Gogh. The Starry Night. 1889*. https://www.moma.org/learn/moma_learning/vincent-van-gogh-the-starry-night-1889

Than, K. (2006, June 5). Ancient rock art depicts exploding star. *Space.com*. https://www.space.com/2458-ancient-rock-art-depicts-exploding-star.html

Tharp, K. W., Howarton, R., Wirtanen, D., Rodriguez, G., & Ding, X. D. (2012, July 16-17). Applied Universal Design for Learning in STEM education. Paper presented at the ASQ Advancing the STEM Agenda in Education, the Workplace and Society, Menomonie, WI, USA. http://rube.asq.org/edu/2012/06/best-practices/applied-universal-design-for-learning-in-stem-education.pdf

The STEM Pipeline. (2015). *Inside Higher Ed*. https://www.bu.edu/stem/files/2015/02/The-STEM-Pipeline-booklet1.3-36.pdf

The 6,000-Hour Learning Gap | ExpandED Schools. (2013). https://www.expandedschools.org/policy-documents/6000-hour-learning-gap#sthash.Y7Swjtss.dpbs

Thomas, J., & Cook, K. (Eds.). (2005). *Illuminating the path: The research and development agenda for visual analytics* https://www.hsdl.org/?abstract&did=485291

Thompson, J. (2016). The flawed, bright future of virtual reality and content marketing [Blog post]. https://www.outbrain.com/blog/virtual-reality-and-content-marketing/

Thorndyke P. W., & Goldin S. E. (1983). Spatial learning and reasoning skill. In H. L. Pick, & L. P. Acredolo (Eds.), *Spatial orientation* (pp. 195-217). Boston, MA: Springer.

Thumbworks. (2018). Augmented reality solar system [Mobile Application Software]. https://itunes.apple.com/us/app/ augmented-reality-solar-system/id1262856697?mt=8

Tomlinson, B. J., Winters, R. M., Latina, C., Bhat, S., Rane, M., & Walker, B. N. (2017, June 20-23). *Solar system sonification: Exploring earth and its neighbors through sound*.

Paper resented at the 23rd International Conference on Auditory Display, State College, PA. http://hdl.handle.net/1853/58359

Trotta, R. (2018). The hands-on universe: Making sense of the universe with all your senses. *Communicating Astronomy with the Public Journal*, *1*(23), 20-25. https://www.capjournal.org/issues/23/23_20.pdf

Tucker, W. H. (2017). *Chandra's cosmos: Dark matter, black holes, and other wonders revealed by NASA's premier X-ray observatory.* Washington, DC: Smithsonian Books.

Tucker, W. H., & Tucker, K. (2001). *Revealing the universe: The making of the Chandra X-ray Observatory*. Cambridge, MA: Harvard University Press.

Tyler-Wood, T., Estes, M., Christensen, R., Knezek, G., & Gibson, D. (2015). SimSchool: An opportunity for using serious gaming for training teachers in rural areas. *Rural Special Education Quarterly, 34*(3), 17-20. https://www.questia.com/library/journal/1P3-3855958731/simschool-an-opportunity-for-using-serious-gaming

Tyler-Wood, T., Knezek, G., & Christensen, R. (2010). Instruments for Assessing Interest in STEM Content and Careers. *Journal of Technology and Teacher Education*. 18.

United States Access Board. (2000). *Section 508 standards for electronic and information technology*. https://www.access-board.gov/guidelines-and-standards/communications-and-it/about-the-section-508-standards/section-508-standards

United States Census Bureau. (2016, November 17). *The majority of children live with two parents, Census Bureau reports* (Release No. CB16-192) [Press release]. https://www.census.gov/newsroom/press-releases/2016/cb16-192.html

University of Birmingham. (2020). Evaluating your STEM intervention or activity. https://www.birmingham.ac.uk/university/colleges/eps/STEM/activities/pedagogic/evaluating.aspx

U.S. Government Accountability Office. (2001). *Most drugs withdrawn in recent years had greater health risks for women*.: http://www.gao.gov/products/GAO-01-286R

U.S. Government Accountability Office (2015). Better oversight needed to help ensure continued progress including women in health research (GAO-16-13). https://www.gao.gov/products/GAO-16-13

U.S. Senate. (2017). *Fair Access to Science and Technology Research Act*. Washington, DC: United States Government.

USA Today. (2018). 3 2 1 Launch [Mobile application software]. https://www.321launchapp.com

Uttal, D. H., & Cohen, C.A. (2012). Spatial thinking and STEM education: When, why, and how? In B. H. Ross (Ed.), *The psychology of learning and motivation* (Vol. 52, pp. 148-178). San Diego, CA: Academic Press.

Uttal, D. H., Meadow, N. G., Tipton, E., Hand, L. L., Alden, A., Warren, C., & Newcombe, N. S. (2013). The malleability of spatial skills: A meta-analysis of training studies. *Psychological Bulletin*, *139*(2), 352-402. https://doi.org/10.1037/a0028446

Van Goozen, S. H., Cohen-Kettenis, P. T., Gooren, L. J., Frijda, N. H., & Van de Poll, N. E. (1995). Gender differences in behaviour: Activating effects of cross-sex hormones. *Psychoneuroendocrinology*, *20*(4), 343-363. https://doi.org/10.1016/0306-4530(94)00076-X

Van Helden, A. (1977). The invention of the telescope. *Transactions of the American Philosophical Society, 67*(4), 1-67. https://doi.org/10.2307/1006276

Verdine, B. N., Golinkoff, R. M., Hirsh-Pasek, K., Newcombe, N. S., Filipowicz, A. T., & Chang, A. (2014). Deconstructing building blocks: Preschoolers' spatial assembly performance relates to early mathematical skills. *Child Development*, *85*(3), 1062-1076. https://doi.org/10.1111/cdev.12165

Verma, E. & Bakshi, R. (2017). Information and communication technologies: Assisting youth in making productive career preferences. *International Journal of Research Culture Society, 1*(8), 240-243. https://ijrcs.org/wp-content/uploads/201710049.pdf

Villanueva, I. & Di Stefano, M. (2017). Narrative inquiry on the teaching of STEM to blind high school students. *Education Sciences, 7*(4), Article 89. https://doi.org/10.3390/educsci7040089

Viotti, M., Arcand, K., Joyner, E., Day, B., Craig, J., & Law, E. (2019). *NASA Visualization Working Group white paper: STEM visualization audiences*. NASA Science Mission Directorate: SciAct Visualization Working Group, Washington, DC.

Virtual Reality 101 (2016). https://www.cnet.com/special-reports/vr101/

Vogt, F. P. A., & Shingles, L. J. (2013). Augmented reality in astrophysics. *Astrophysics and Space Science*, *347*(1), 47-60. https://doi.org/10.1007/s10509-013-1499-x

Voyer, D., Voyer, S., & Bryden, M. P. (1995). Magnitude of sex differences in spatial abilities: A meta-analysis and consideration of critical variables. *Psychological Bulletin*, 117(2), 250-270.

Wade, J., & Zaringhalam, M. (2019, August 6). Why we need to keep talking about equality in physics. *Physics World*. https://physicsworld.com/a/why-we-need-to-keep-talking-about-equality-in-physics/

Wai, J., Lubinski, D., & Bendow, C. P. (2009). Spatial ability for STEM domains: Aligning over 50 years of cumulative psychological knowledge solidifies its importance. *Journal of Educational Psychology*, *101*, 817-835.

Waldrop, M. M. (2015, July 15). Why we are teaching science wrong, and how to make it right. *Nature, 523*(7560), 272-274. https://doi.org/10.1038/523272a

Wang, C., & Frye, M. (2019). miniGEMS 2018 summer camp evaluation: Empowering middle school girls in STEAM. Paper presented at the. IEEE Integrated STEM Education Conference, Princeton, NJ. https://doi.org/10.1109/ISECon.2019.8881981

Wang, M. T., & Degol, J. L. (2017). Gender gap in science, technology, engineering, and mathematics (STEM): Current knowledge, implications for practice, policy, and future directions. *Educational Psychology Review, 29*(1), 119-140. https://doi.org/10.1007/s10648-015-9355-x

Warzel, C. (2019, August 15). How an online mob created a playbook for a culture war. *The New York Times*. https://www.nytimes.com/interactive/2019/08/15/opinion/what-is-gamergate.html

Watzke, M. (2013, November 15). Exploring the third dimension of Cassiopeia A [Blog post]. http://chandra.si.edu/blog/node/464

Watzke, M., & Edmonds, P. (2013, November 15). *Cassiopeia A: Exploring the Third Dimension of Cassiopeia A.* Chandra X-ray Observatory. https://chandra.si.edu/photo/2013/casa/

Watzke, M., & Edmonds, P. (2017, September 18). V745 Sco: *Two stars, three dimensions, and oodles of energy*. Chandra X-ray Observatory. http://chandra.si.edu/photo/2017/v745/

Watzke, M., & Edmonds, P. (2018, January 10). *Galactic Center: Scientists take viewers to the center of the Milky Way*. Chandra X-ray Observatory. http://chandra.si.edu/photo/2018/gcenter360/

Wennerås, C., & Wold, A. (1997). Nepotism and sexism in peer-review. *Nature*, *387*(6631), 341-343. https://doi.org/10.1038/387341a0

Wenz, J. (2018, July 6) Making scents of outer space. *Astronomy Magazine*. http://www.astronomy.com/news/2018/07/outer-space-smells

Werthessen, P. (2016, June 2). Is your visualization gender neutral? [Blog post]. https://blog.qlik.com/is-your-visualization-gender-neutral

West, J. D., Jacquet, J., King, M. M., Correll, S. J., & Bergstrom C. T. (2013). The role of gender in scholarly authorship. *PLoS ONE, 8*(7). https://doi.org/10.1371/journal.pone.0066212

Whitaker, E. A. (1978). Galileo's lunar observations and the dating of the composition of 'Sidereus Nuncius'. *Journal for the History of Astronomy*, *9*, 155-169. https://doi.org/10.1177/002182867800900301

White, R. L., Accomazzi, A., Berriman, G. B., Fabbiano, G., Madore, B. F., Mazzarella, J. M., Rots, A., Smale, A.P., Storrie-Lombardi, L., & Winkelman, S. (2009). The high impact of astronomical data archives. *White Paper - astro2010: The Astronomy and Astrophysics Decadal Survey.* http://adsabs.harvard.edu/abs/2009astro2010P..64W

Wilkerson, K., Perusse, R., & Hughes, A. (2013). Comprehensive school counseling programs and student achievement outcomes: A comparative analysis of RAMP versus non-RAMP schools. *Professional School Counseling, 16*(3), 172-184. https://doi.org/10.1177/2156759X1701600302

Wilkes, B. & Tucker, W. (Eds.). (2019). The Chandra X-ray Observatory: Exploring the high energy Universe. IOP Publishing. https://doi.org/10.1088/2514-3433/ab43dc

Williams, B., Bonnett, E., Jackson, C., & Smith, D. (2009). *Working with underserved and at-risk audiences*. Virginia Cooperative Extension. https://pubs.ext.vt.edu/382/382-512/382-512.html

Williams, D., Consalvo, M., Caplan, S., & Yee, N. (2009). Looking for gender: Gender roles and behaviors among online gamers. *Journal of Communication*, *59*(4), 700-725. https://doi.org/10.1111/j.1460-2466.2009.01453.x

Williams, M.M., & George-Jackson, C. (2014). Using and Doing Science: Gender, Self Efficacy, and Science Identity of Undergraduate Students in STEM. *Journal of Women and Minorities in Science and Engineering.* 20 https://doi.org/10.1615/JWomenMinorScienEng.2014004477

Winn, W. (1993). *A conceptual basis for educational applications of virtual reality* (Technical Report TR-93-9). Human Interface Technology Laboratory, University of Washington. http://www.hitl.washington.edu/publications/r-93-9/

Wright, R., Thompson, W. L., Ganis, G., Newcombe, N. S., & Kosslyn, S. M. (2008). Training generalized spatial skills. *Psychonomic Bulletin & Review*, *15*(4), 763-771. https://doi.org/10.3758/pbr.15.4.763

World Health Organization. (2017). *Vision impairment and blindness*. http://www.who.int/news-room/fact-sheets/detail/blindness-and-visual-impairment

Wu, S., Cheng, C.K., Feng, J., D'Angelo, L., Alain, C., & Spence, I. (2012). Playing a first-person shooter video game induces neuroplastic change. *Journal of Cognitive Neuroscience, 24*(6), 1286-1293. https://doi.org/10.1162/jocn_a_00192

Xiao, Y., Kavanau, C., Bertin, L., & Kaplan, E. (2011). The biological basis of a universal constraint on color naming: Cone contrasts and the two-way categorization of colors. *PLoS ONE*, *6*(9). https://doi.org/10.1371/journal.pone.0024994

Yeh, A. J. C. (2007). *Knowledge construction of 3D geometry in virtual reality microworlds*. (Doctoral thesis). Queensland University of Technology, Brisbane, Australia.

Yilmaz, H. (2009). On the development and measurement of spatial ability. *International Electronic Journal of Elementary Education*, *1*(2), 83-96. https://eric.ed.gov/?id=EJ1052049

Young, D., Rudman, L., Buettner, H., & McLean, M. (2013). The influence of female role models on women's implicit science cognitions. *Psychology of Women Quarterly*, *37*(3), 283-292. https://doi.org/10.1177/0361684313482109

YURT | Center for Computation and Visualization. (n.d.). https://web1.ccv.brown.edu/viz-yurt

Zaharias, P., Michael-Grigoriou, D., & Chrysanthou, Y. (2013). Learning through multi-touch interfaces in museum exhibitions: An empirical investigation. *Educational Technology & Society*, *16*(3), 374-384. https://www.researchgate.net/publication/256364429_Learning_through_Multi-touch_Interfaces_in_Museum_Exhibits_An_Empirical_Investigation

Zambrana, R. E., Ray, R., Espino, M. M., Castro, C., Cohen, B. D., & Eliason, J. (2015). “Don’t leave us behind”: The importance of mentoring for underrepresented minority faculty. *American Educational Research Journal, 52*(1), 40-72. https://doi.org/10.3102/0002831214563063

Zhang, X., Koponen, T., Räsänen, P., Aunola, K., Lerkkanen, M. K., & Nurmi, J. E. (2014). Linguistic and spatial skills predict early arithmetic development via counting sequence knowledge. *Child Development*, *85*(3),1091-1107. https://doi.org/10.1111/cdev.12173

Zohrabi, M. (2013). Mixed method research: Instruments, validity, reliability and reporting findings. *Theory and Practice in Language Studies, 3*(2), 254-262. https://doi.org/10.4304/tpls.3.2.254-262

Zopf, Y., Rabe, C., Neubert, A., Gaßmann, K., Rascher, W., & Hahn, E., Brune, K., & Dormann, H. (2008). Women encounter ADRs more often than do men. *European Journal of Clinical Pharmacology*, *64*(10), 999-1004. https://doi.org/10.1007/s00228-008-0494-6

Appendices

Appendix A. Ethics Approval Letters

18/018

UNIVERSITY of OTAGO
Te Whare Wānanga o Otāgo
NEW ZEALAND

Academic Services
Manager, Academic Committees, Mr Gary Witte

27 February 2018

Professor L Smith
College of Education
Division of Humanities
145 Union Street East

Dear Professor Smith,

I am again writing to you concerning your proposal entitled "**Women in Science, Technology, Engineering & Math: Investigating obstacles, biases, and perceptions**", Ethics Committee reference number **18/018**.

Thank you for your email of today with response attached addressing the issues raised by the Committee.

On the basis of this response, I am pleased to confirm that the proposal now has full ethical approval to proceed.

Approval is for up to three years from the date of this letter. If this project has not been completed within three years from the date of this letter, re-approval must be requested. If the nature, consent, location, procedures or personnel of your approved application change, please advise me in writing.

Upon approval, it is expected that all members of the research team are made aware of what the standard conditions of ethical approval covers. This includes the date ethical approval expires, as well as the process regarding applying for amendments to the research.

The Human Ethics Committee asks for a Final Report to be provided upon completion of the study. The Final Report template can be found on the Human Ethics Web Page

http://www.otago.ac.nz/council/committees/committees/HumanEthicsCommittees.html

Yours sincerely,

Gary Witte

Mr Gary Witte
Manager, Academic Committees
Tel: 479 8256
Email: gary.witte@otago.ac.nz

c.c. Dr K Pratt   College of Education

19/006

Academic Services
Manager, Academic Committees, Mr Gary Witte

1 February 2019

Professor L Smith
College of Education
Division of Humanities
145 Union Street East

Dear Professor Smith,

I am writing to let you know that, at its recent meeting, the Ethics Committee considered your proposal entitled "**Putting the stars within reach: The potential effects of NASA 3D data-based models and 3D prints on spatial reasoning skills and STEM interest in young female learners**".

As a result of that consideration, the current status of your proposal is:- **Approved**

For your future reference, the Ethics Committee's reference code for this project is:- **19/006**.

The comments and views expressed by the Ethics Committee concerning your proposal are as follows:-

While approving the application, the Committee would be grateful if you would respond to the following:

Permission from participating organisations (Question 10)

Please provide evidence of permission from the participating organisations, once these become available.

Study population (Question 14)

The Committee noted that the study population will be drawn from female-identifying students aged 11-15. The Committee asks whether you have considered allowing all those who participate in the science networks the opportunity to take part and then compare the results with the chosen study population?

Information Sheet

The Committee thought that the Information Sheet was lengthy and suggests that it is simplified.

Please provide the Committee with copies of the updated documents, if changes have been necessary.

---------- Forwarded message ----------
From: **Jo Farron de Diaz** <jo.farrondediaz@otago.ac.nz>
Date: Tuesday, February 5, 2019
Subject: Human Ethics Application 19/006
To: "Lisa F. Smith" <lisa.smith@otago.ac.nz>
Cc: Kim Arcand <kimberlykowal@me.com>, Keryn Pratt <keryn.pratt@otago.ac.nz>

Hi Lisa,

Many thanks for your reply and your response to the comments made by the Committee.

Thanks also for noting that you will forward the permissions on once you have them.

Kind regards,

Jo

Jo Farron de Diaz
Senior Administrator

Academic Committees Office

Te Tari kā Komiti Mātauraka

Academic Services
University of Otago
PO Box 56, Dunedin 9054

---------- Forwarded message ----------
From: **Lisa F. Smith** <lisa.smith@otago.ac.nz>
Date: Monday, February 4, 2019
Subject: Human Ethics Application 19/006
To: Jo Farron de Diaz <jo.farrondediaz@otago.ac.nz>
Cc: Kim Arcand <kimberlykowal@me.com>, Keryn Pratt <keryn.pratt@otago.ac.nz>

Dear Jo,

Many thanks for this! I've written to Kim. She will forward the permissions from the participating organisations to me. Once I have them all, I'll forward them to you.

Kim considered doing gender comparisons; it's a good idea. However, Kim's focus is on engaging young females in STEM careers. The organisations with which she is working are primarily all-female in their membership. There is a rich literature and tradition in encouraging young males in STEM careers, and Kim will be able to compare her findings to those extant data in her thesis.

Regarding the information sheets, we feel that the information on them is necessary to satisfy full disclosure about the study, especially given that the participants are minor-aged females. Also, as the study will be conducted in the USA, we feel that we'd rather err on the side of caution with providing detail.

If you have any questions, please let me know!

Kind regards,
Lisa

Appendix B. Selected Quotes from Coded Interviews

Note that the number following each theme heading equals the number of comments for that topic overall. The number after each participant in this appendix indicates the number of quotes given by that person per theme.

Influencers/Role Models (Positive & Negative) – Purple (101)

- **Radio Astronomer: 10**
- **Computer Scientist: 9**
- **Engineer: 7**
- **Astronomer: 12**
- **Geologist: 5**
- **Mathematician: 10**
- **Cosmologist: 10**
- **Software Developer: 20**
- **Technologist/Pre-medical Student: 7**
- **Science Writer: 8**
- **Astronaut: 3**

"When I thought about what astronauts looked like, I had in my mind a picture of the Mercury 7 astronauts standing in front of an airplane and they were all a bunch of old guys with no hair. And it certainly didn't say to me, this could be you. It wasn't until I went to college and Sally Ride came to talk, it just opened up that possibility of if she could do it then I could aspire to do it, too." (Astronaut)

"Have you heard of the phrase "racism without racists?" It's not like there were people who were being violent or verbally abusive or offensive or anything, more just like a general sense that there were opportunities and ways of being that other people had access to that I maybe had to work a little harder for." (Technologist/Pre-Medical Student)

"… the disabled woman is by herself. I find that is true. I find myself very self-reliant, and I like life. But that has, that has a huge effect…on your performance in daily life. Because if I would be, if I would be an abled woman, I would have a way right to do my work…and to be [seen as capable]. (Computer Scientist)

"Like however we choose to quantify representation, or do we see women equally represented. And then going beyond, like what about payscale? It's one thing to have like 50 percent of their staff being women but if they all make like 75 percent of the pay that a man at that same level would make, that's certainly not equity." (Technologist/Pre-medical Student)

"Planetary science: my theory about women in science is that when there's a new field, that's when there's not as much of an 'old boy network' maybe or that's the way it's been, and women can get into it." (Software Developer)

"...communication you know public affairs, science visualization, I think you'll find a higher percentage of women because I think a lot of my personal theory is that a lot of women are turned off by the, some of the traditional paths to a scientific career, they find it sort of the way feels a little more accepting and welcoming." (Science Writer)

Educational Experiences (65 total)

- **Radio Astronomer: 6**
- **Computer Scientist: 9**
- **Engineer: 1**
- **Astronomer: 10**
- **Geologist: 5**
- **Mathematician: 6**
- **Cosmologist: 4**

- **Software Developer: 11**
- **Technologist/Pre-medical Student: 7**
- **Science Writer: 4**
- **Astronaut: 2**

"I feel like kids start to develop a sense of if they are "good at math and science" right around the same age that they start to develop opinions about their abilities as artists. And I'm just like, 'You're 6, you've never even had hot sauce. So how do you know that you don't like math?' So, I wonder what signals a child has been receiving…what has changed" (Technologist/Pre-medical Student)
"I noticed the classmates around me started to dwindle down and I'll never forget…I looked around the room and I was the only black woman." (Astronomer)

"So it really was an astronaut thing originally. First it was like just looking at the night sky, and always loving it. And it was like I want to *go* to space…so I think that's where engineering came in...I did just really like the idea of how things work. Yeah very tactile." (Radio Astronomer)
"...at that time being so, being so young, right? In my, in my late 20s and being, having such, such a young mind. I wouldn't dare to tell the professor you can't continue on this you'll explain what you were pointing out? You know... that this is the way it goes right. You put this equation here when you're if you're listening to me I'm tapping on a table. ...so what you hear is the chalk on the blackboard." (Computer Scientist)

"...in the cumulative experiences that I've had, both in education and you know in my own research and policy told me that if you want people to participate, you need to flow the information through a diverse set of networks because...graduate students talk to graduate students. Women have their own networks and...tend to talk to women although you know you are for, you know you're collaborating with men a lot of the time. And one of the things, to get to the point I wanted language in the call about diversity." (Mathematician)

"...you go to [elite technical university] and all of a sudden you're surrounded by people that are smarter than you are. And that's a big *thing*. I thought I was pretty smart. Maybe not." (Software Developer)

"When I went to college I noticed that there were very few women in my physics, math, and astrophysics classes. And that was, you know definitely eye opening to me at that point. It was a very small major at that point, you know there weren't that many students in these classes but I think there was only one other woman who was in most of the classes with me...say there were ten students in the class, there was the two of us." (Science Writer)

Hurdles – Red (56)

- **Radio Astronomer: 4**
- **Computer Scientist: 11**
- **Engineer: 3**
- **Astronomer: 10**
- **Geologist: 1**
- **Mathematician: 8**
- **Cosmologist: 5**
- **Software Developer: 7**
- **Technologist/Pre-medical Student: 3**
- **Science Writer: 2**
- **Astronaut: 2**

"For a lot of women, myself included, after getting married and starting a job, it's hard to go back and get a graduate degree. I think that's probably the main hurdle, and then if you start a family, that could be an additional hurdle, just your time that you are available to invest." (Engineer)

"I'm Hispanic, Afro, Afro Puerto Rican proudly...I have a physical disability and I'm a woman…and I think…if I would be a sighted woman in a room, how will it be? I would have lots more chances because when people talk to me they don't see the scientist. Once I lost my sight…the biggest shock was to notice that I didn't have access to the same amount and quality of information that I had when I was sighted. I couldn't understand the professors…they were just pointing at things on the blackboard." (Computer Scientist)

"I think the burden comes from having to compensate. Yeah that sometimes you get… cognitively tired. Right. Right. For having to compensate so much. You know most of the time I do not...most of the time, I think - why do I have to interrupt this person to explain? Sometimes I just stay at the back of the room." (Computer Scientist)

"Because I need to understand the connection, so...switching and going off of this pathway felt lonely because I didn't realize that there were places like [science institute] that had whole departments doing outreach. I just, in school I always heard it kind of being something on the side that you did...like you still were working but you kind of did it on the side occasionally going to a school. I didn't know it was a full time job." (Astronomer)

"And so a lot of the problem is, is people you know having their own biases and their own sort of attitudes that, that make it, make it unpleasant for people who don't fit a certain mold." (Cosmologist)

Attitude Changes – Orange (44)

- **Radio Astronomer: 3**
- **Computer Scientist: 3**
- **Engineer: 3**
- **Astronomer: 5**
- **Geologist: 2**
- **Mathematician: 8**
- **Cosmologist: 5**
- **Software Developer: 5**
- **Technologist/Pre-medical Student: 3**
- **Science Writer: 5**
- **Astronaut: 2**

"The issues that I thought would be taken care of to some degree by now: the underrepresentation of women, you know the percentages that are extremely low…they haven't moved the needle very much. I'm in my mid 40s now and I remember hearing about these issues when I was a very young person…and that's depressing. I think what has changed, especially in the past couple years, is that there is more awareness, certainly of issues like sexual harassment." (Science Writer)

"Growing up in the 80s and 90s, there was a general understanding that getting more women into sciences is a good thing. There needed to be opportunities made and sexism was real …Then somewhere in the early 2000s, I started to perceive that people thought women were getting an unfair advantage. So, there was starting to be this kind of backlash where people would say, 'Oh you know you'll definitely get a job. Everybody's trying to hire women.' (Cosmologist)

"I think acceptance for women continues to grow. I still see preferential treatment given to men sometimes. Often, I think female leaders are harder on the women and the male leaders are all, attitude of you know they have to work incredibly hard to get where they are so they're not going to make it easier for you…I think it's also dependent on the area where you are, I think there's a lot of differences in academia versus industry." (Engineer)

"When I was growing up, there weren't a lot of girls being astronauts [to look up to]." (Astronaut)

"I think there are some good changes that have happening I know statistics, statistics-wise was the number of women in STEM field has increased since my time. But one thing that hasn't changed much since kind of going into the STEM field is the number of minorities who are getting their master's or they're getting their Ph.D. And that hasn't changed. So it's a little discouraging." (Astronomer)

"Well that you know it shows, the experience shows the duality. You know you ask the question - have we seen progress over the time at least in my professional lifetime. We *have*, but there is still the underlying culture that I don't think will change until that generation moves on. Yeah." (Mathematician)

"And I think that my favorite favorite aspect of this trend is like really just we're getting young girls *and* boys involved in this idea of equality and equity and like women's rights because it's, I think for me... because I keep coming back to what's polarizing about it. I see like this if the movement could just figure out how this how to express itself in a way that isn't polarizing." (Technologist/Pre-medical Student)

"And the sexual harassment piece very much ties into the underrepresentation side of it. There's sort of, you know I think there's a better understanding of how two - those are two sides of the same coin. So you know and I think that in the past six months, that our society has become much more aware of sexual harassment outside of science too." (Science Writer)

Recommendations – Pink (41)

- **Radio Astronomer: 5**
- **Computer Scientist: 6**
- **Engineer: 1**
- **Astronomer: 6**
- **Geologist: 3**
- **Mathematician: 3**
- **Cosmologist: 3**
- **Software Developer: 3**
- **Technologist/Pre-medical Student: 6**
- **Science Writer: 4**
- **Astronaut: 1**

"I want them not to be scared - as we are not scared, right?" (Computer Scientist)

"When I'm doing outreach events sometimes a young African-American is like, 'Oh your hair is so beautiful!' Others comment on what I'm wearing. I asked a colleague, 'I don't know why they do that…it always catches me off guard. I want to talk about this cool infrared demonstration I'm doing. Thank you for complimenting me, but let's focus on this.' But she said, 'It's because they see themselves in you.'" (Astronomer)

"All these things, science can be just you know brutal. Oh you know I just worked 60 hours in a lab and 20 more on writing papers kind of thing, or the telescope or whatever people who publish first and most win. So you know if that's the only measure of success then a woman who is taking care of her kid or kids or you know a parent or whatever is going to be at a disadvantage. So it's retaining people, it just has to be a good quality of work/life." (Science Writer)

"But I want to be able to explain this to other people, that real world like I think there's just so many studies that I'm sure you've read and I've read that's one of the connections to get our young women into STEM, is the 'why,' why is this important?" (Astronomer)

"I think that there are ways to use the same language of…STEM, of math and economics to talk about how feminism and equality makes sense." (Technologist/Pre-medical Student)

"Yes so I think that, I think that in all of these areas of bias and privilege and stuff it is really, it's the responsibility of the people who are in a position of greater privilege or power to work on making that change. You know, so I think that men need to speak up more against sexism. You know, white people need to speak up more against racism. People who are able bodied need to speak up more against ableism…" (Cosmologist)

"And the Ph.D. to faculty pipeline is fiction. And I felt really excluded because they were basically saying if you didn't have a Ph.D. you weren't professional and there were a few of us in the audience who didn't have Ph.Ds who were doing serious work." (Software Developer)

Radio Astronomer Interview Transcript - Excerpts from Each Theme

"So it really was an astronaut thing originally. First it was like just looking at the night sky, and always loving it. And it was like I want to *go* to space…so I think that's where engineering came in...I did just really like the idea of how things work. Yeah very tactile."

"And so I think it's much more…since I got to [Ivy League university] and since I started doing a lot more sort of scicomm and also just working with a lot more peer scientists in other fields that I've become much more aware of the hurdles, the stigmatism, the sexism all of these things…so I feel like I do have a position where I can advocate for grad students and undergrads, especially women and minorities."

"But strangely enough during my entire career I really didn't feel marginalized - does that makes sense - I feel like I kind of lucked into a couple situations where I had some of amazing female mentors. So at [Ivy League university] there were just some really great people both, both boys and girls like in my classes and all the engineering homework and everything else. A lot of teamwork and problem sets. But my junior year when we got into the stick of the subject there was one female tenured professor in the engineering department...and she, just in the last couple of years she's won a national award."

"...going back to the fact that there's so many amazing women in the field now that young early career ones, I think between us we're also trying to work in our little departments or in our other networks and groups, to both informally and formally try and help with retention...also potentially you know having informal interactions with women."

"So I think my big thing that I realized is when we talk about all these things about you know the percentage of women in the field, what I kind of feel needs to be focused on more is the person - like sort of equal access to everyone. In the sense that I don't feel like the field needs to be 50/50. Every field needs to be 50/50 or every field needs to match exactly but everybody should have the choice, like it should - the opportunity for it to be 50/50 should totally be there. Like every woman should feel that they have the option…and then also working from inside STEM to make sure that the culture is such that it doesn't push them back out once they get in."

"One of the things, so one thing I do for what's in an area that I can control is for the public nights, I always try to make sure that whoever's helping with the Q and A, whether the teachers go around doing the Q&A themselves or one of the grad students or something else that they really try and call on a woman or a kid first."

"And I think *[fashion start-up company]* has been kind of fun just because it's created another community. And cool ways to express themselves and some of the designers that we work with are also in STEM fields and they're creating things inspired by women in STEM or they're using STEM to do them like 3D printed jewelry, and things like that."

"And also I personally find some times that fashion is just another outreach too as well."

Computer Scientist Interview Transcript - Excerpts from Each Theme

“And, so in my Ph.D. I focused on the way...first to test, if a multimodality...it pertains to ...if multi, multi-modal perception was an option. I couldn’t ever find any, any literature that, that could tell me evidence, why multimodal perception or multisense reality was not being used in this field to go explore and explore the information. And, so I first decided to test if, it is useful or is it not…and also took a sample of data and analyzed.”

“...at that time being so, being so young, right? In my, in my late 20s and being, having such, such a young mind. I wouldn't dare to tell the professor you can't continue on this you'll explain what you were pointing out? You know... that this is the way it goes right. You put this equation here when you're if you're listening to me I'm tapping on a table. ...so what you hear is the chalk on the blackboard.”

“So my, my work at the…the [name], the [name] School for the Blind is that. What, what, what I'm trying to…what I'm doing is teaching them the concepts, right?...I use energy as the thread…because they can listen to energy, they can clap. They can shout very loud. They can relate potential and kinetic energy to different things in the world. And also, to…events in the sky...to be able to teach them properly in order to be able to ease the transition... from school level to University, from University to the professional field. They need to have something that they can use when they get to those levels.”

“So then it, that was quite traumatic to me. When, when asking for a...people to read. Right, even classmates to read for me they, they would react…Their reaction was not positive at having to read a paper that had too many equations. And, how would I know that the paper was plagued with equations? Right. I have no way to know, see.”

“The access to the databases is zero. It’s non-existent…so they also do not respond to our requests to work for accessibility…they did not respond, when we talked with different projects about the accessibility because we wanted to use the information. It's not only that we want to use the information, I have the *right*! Right. I'm a taxpayer and I'm *paying* for that information to be posted in an accessible way. And I don't have to wait any extra time to access my information.”

“Now it is particularly is difficult for, for anyone to get a job and it is particularly difficult if you have a disability because people don't focus on how you will…not in the mathematics, not on the theoretical analysis. No, it is on how, the way that you will perform: the physical ways…Like, how will you get it done in a…timely manner right?”

“But what happens is that…80 percent of the astronomers with severe disabilities that I know...they got trained, they got trained to do research…and they are doing...Education and People Outreach. It hasn't been their choice. See, and…if, if, if a number of years go by and they don't generate it’s going to be really difficult for them to recuperate. Right. So where is the metric of productivity?”

“I think the burden comes from having to compensate. Yeah that sometimes you get… cognitively tired. Right. Right. For having to compensate so much. You know most of the time I do not...most of the time, I think - why do I have to interrupt this person to explain? Sometimes I just stay at the back of the room.”

“In a year, for me to generate 3 peer reviewed papers. That is not doable. Right, right. Right now the access to information does not allow me to handle my background. The amount of knowledge needed in order to generate, a strong peer reviewed paper in my field. Not even, not even to generate a discussion.”

“It goes ok until we get to that point, and I think my, my digital footprint is too strong. As soon as they, as soon as they realize that something is happening, they step back. So it’s not…because they don't have the experience analyzing the solar wind. I mean, how am I going to build the experience if no one allows me to do research, right?"

"… the disabled woman is by herself. I find that is true. I find myself very self-reliant, and I like life. But that has, that has a huge effect…on your performance in daily life. Because if I would be, if I would be an abled woman, I would have a way right to do my work…and to be [seen as capable]."

"I get really surprised because I think that I'm…as I, as I told you that I'm in my own judgment I'm not performing at the top of my capacity. But other, other blind folks, they tell me - we want to do science at the level you do the science. And then I think, oh this is not good, this is not good at all!"

"For me, even if I had all all A's or all hundreds in my classes I wouldn't have been chosen to go to special programs. Right. Why, why, why do we - why do we keep in this stupidity, the massive stupidity of only choosing people that have all aces? That is a *massive*, massive stupidity - it's going to change."

"We want to do an assessment of the field, regarding the sciences in equality of participation. Equality of participation, and access to power and decision making in...in the science of astronomy as a case study."

"Now when, when I, when I'm doing my bachelor's degree, and I'm losing my sight. My confidence was not where it is right now. Right now even, even if I'm unemployed if I notice that something is happening I will...tell the person…you can't continue talking about this subject unless you explain fully what you're talking about. You have to use descriptors, and - I will, I will ask questions right? I will also provide some guidance… because the people there just aren't used…to that level of inclusion."

"Now...people with disabilities, we are different among each other, as abled people are different among themselves. We are completely different. Aim is to create something that will allow me in a…in a flexible manner to personalize. To use my perceptual style is not only to accommodate, it's to support and enhance the ways the person has to perform at their, at their own maximum."

Engineer Interview Transcript - Excerpts from Each Theme

"And I've always been detail-oriented, and just wanting to know *why* and the *how* of how things work. So the scientific method of experimentation and fact-based knowledge has just always appealed to me."

"So anyone in STEM has obviously had to work hard and had a rigorous society and getting some of the 'old guard' if you will to listen to your point of view, it was often a challenge."

"I don't think it was that women were being necessarily diminished or held back…that was the job that they really wanted to do was held at the bench kind of work they didn't want to lead a research team. That just wasn't what they wanted to do. They wanted to do the more day-to-day like working hands-on kind of a path. For some people, other people, there's different reasons why it is for them but that was something I saw more often than the reverse."

"But I think having a mentor and, and having a network of women that you can rely on and people who have that experience where you can ask questions and just gain from their knowledge base, I think that's probably something that's huge for women and probably for men as well but I think women even more so because they are so underrepresented, trying to find someone that you can identify with, that may have some similar experiences to you, is really beneficial."

"The mentors earlier on tended to be more male, simply because of availability: there were a lot of males who were in the more senior roles. The people who were serving as the mentees, much larger percentage of females than males…as time progressed the table kind of flipped around where the women were serving more as the mentors, which is kind of what's going on right about now and then the level where the mentees are, it's definitely more of a mix. In I would say a fairly short amount of time...changed to a much more even distribution."

"I think acceptance for women continues to grow. I still see preferential treatment given to men sometimes. Often, I think female leaders are harder on the women and the male leaders are all, attitude of you know they have to work incredibly hard to get where they are so they're not going to make it easier for you…I think it's also dependent on the area where you are, I think there's a lot of differences in academia versus industry."

"I guess for men and for women that there's just not a lot of glamour in becoming you know a chemist or engineer or something and the possibilities for what careers are available I think are often poorly communicated to students. Like, what can you actually *do* with a degree in STEM. Like what would your day to day job look like, and how could that evolve over time? So really what you can really *do* with your knowledge I think would make a big difference in trying to attract people, men *and* women, into the STEM field."

Astronomer Interview Transcript - Excerpts from Each Theme

"So my interest in astronomy as a career path initially started out as really wanting to be a teacher...this weakness that I had, not really liking math, turned into a strength."

"How do - I how do I deal with a professor who doesn't support me, who doesn't want to write me recommendation like there's no class that teaches you how to do that. And if you don't have good mentors around you to help buffer those negative things you're just going to wash out. And so that's what I...try to focus on is kind of helping support them do the science they want to do but also giving them the interpersonal kind of the social skills to help them because you're going to face these things." "...when he's mentoring students like it's for him...it was about building the community around them so they go out and they eat. They feel this sense of...unity that they belong because there's so many microaggressions and just outward aggressions that say you shouldn't be here. You know, kind of what is said to minorities. There's this...sense you shouldn't be here and so building that sense of community you say you belong here."

"And I think sometimes when people hear that you're coming from an HBCU they kind of immediately assume that you have gaps in your education or maybe you're not as smart, like it's not anything in what they're saying but it's kind of an attitude - like you're here but you're only here because you're part of this special program because you needed it and that's, it - it's all these little microaggressions that begin to add up."

"Because I need to understand the connection, so...switching and going off of this pathway felt lonely…I didn't realize that there were places like [research institution] that had whole departments doing outreach. I just, in school I always heard it kind of being something on the side that you did...like you still were working but you kind of did it on the side occasionally going to a school. I didn't know it was a full time job."

"I think there are some good changes that have happening I know statistics, statistics-wise was the number of women in STEM field has increased since my time. But one thing that hasn't changed much since kind of going into the STEM field is the number of minorities who are getting their master's or they're getting their Ph.D. And that hasn't changed. So it's a little discouraging."

"But I want to be able to explain this to other people, that real world like I think there's just so many studies that I'm sure you've read and I've read that's one of the connections to get our young women into STEM, is the 'why,' why is this important?"

“I hate that there's this constant I wish in the STEM field we could really get out of this path of this is the end-all, be-all Ph.D. because there are people like you, there are people like me, there are people all across the country who are doing EPO, are in the EPO field that are in the field and are worth - what they're doing is worthwhile and they're changing lives.”

Geologist Interview Transcript - Excerpts from Each Theme

“Yeah but I liked also geology and I just fell in love with when I first took the college class. I never took it when I was in high school but I, I took a first fall semester of freshman year in college because it was the one major area of science I'd never taken a class in. And just the combination of the science aspect and the art and storytelling aspect of geology just was wonderful. And at [university] the department was well known for sucking in majors from other departments like history and English and art and so it was, it was just a fun very, very imagination kind of focused science where you did - you did have data and you did you know you did approach it scientifically but you also had to start spin, you had to spin a good story to connect all the little bits of data together. And there was all that writing and everything was super fun.”

“You know so it's it's hard for me to judge because as like I said I never really felt any particular barriers because of my gender. The first time I remember noticing that my gender mattered was when I was working as a basically a reporter for our website and interviewing scientists at meetings when I suddenly started realizing that some of the scientists were sort of creepy. There's a couple leering faces I remember in particular…”

“And so then when I got to college, my first geology course was taught by the only woman professor in the department, a woman [name] who was just amazing. She was charismatic, tough but she also she, she was tough in a way that she would battle *for* her students and also force you to do better and stuff like that. She, she's the same adviser who helps connect me with grad schools and stuff…”

“I just say that mentors are really important, and having multiple mentors is important, you know not just your adviser your adviser is not the only person. If you're at a department there are going to be tons and tons of people around you who have useful things to teach you...at the same time you're not entitled to their time. So you need to ask for help in a respectful way, and maybe offer something in return….”

“I mean I know a lot of women who have experienced really career damaging events, and I think a huge problem is how tiny our field is. And so if you're in a particular subspecialty there is just no way for you to get away from people with you with whom you have a conflict of one kind or another. Because there's only so many people who have a certain expertise. And so until there is, until there are consequences for the particularly bad actors it's going to continue damaging the women in the field.”

“So finding mentors and then finding community. So, and hopefully - if you're lucky you can find community in your own department. But if you can't, there are other places to find community. There's social media, there are - you know make sure that you are not isolated to find people that you can hang out with, that you can take time off with…”

Mathematician Interview Transcript - Excerpts from Each Theme

“...in the cumulative experiences that I've had, both in education and you know in my own research and policy told me that if you want people to participate, you need to flow the information through a diverse set of networks because...graduate students talk to graduate students. Women have their own networks and...tend to talk to women although you know you are for, you know you're collaborating with men a lot of the time. And one of the things, to get to the point I wanted language in the call about diversity.”

“I needed to be in the shop, in our shop huge create a turbine to create something that could could show how this would work with two fish tanks when on a higher temperature went on a lower temperature and I heard later on that the guy who ran the shop was eventually fired because he was making a you know, he was inappropriate with students but you know he was I guess being inappropriate with me and I never recognized it…”

“And the math library, not the general library because I used to want, you know look up stuff in books that were only in the math library and I would be there pretty late and it wasn't, it didn't take me so long to realize that the women's bathroom closed at 5 o'clock because the only women in the building were the secretaries and they locked up the bathroom before they left because they made it nicer...and the first time I realized this, I had to walk in the snow to go to the bathroom and then come back to the library.”

“The crazy thing is, that the people looked up to were the people who were the hardest on me...that caused me to ask whether or not I wanted to stay in research because there was some...it was a big to-do about whether I was under too much stress because I had kids and I was trying to do grad school. It became a subject of a faculty meeting, and the person who was raising these concerns was this woman faculty member.”

“One of my ways of responding to the women in STEM issues was I formed a group called the [name of a women in science group]. And the idea behind this group, I mean it was a group of graduate students, all the women graduate students. I guess there were, what maybe 10…but what, it was a quarter of the program. We would get together and ultimately our goals were to...try to figure out how to get more role models for ourselves….to suggest women scientists to come and give colloquium.”

“Well that you know it shows, the experience shows the duality. You know you ask the question - have we seen progress over the time at least in my professional lifetime. We *have*, but there is still the underlying culture that I don't think will change until that generation moves on. Yeah.”

“I've seen in my life even as a mother, so for instance I had a long conversation with my son who is a senior in high school now….when the Google manifesto [Damore] came out. I had never had a conversation with him about issues in women in science but he had heard about it and read the news coverage of it. And then I asked him what he was doing to help address the issues and he's like what me? What have I got to do with it?”

Cosmologist Interview Transcript - Excerpts from Each Theme

“And then I did a whole bunch of other research in college so yes I started early and I am really out of it and a lot of it was you know you know I was, I was fortunate to have some connections with the science community through my mom and also through the, the place where my school was located. So it was it wasn't, it wasn’t just like you know my own initiative. But, but I did, I did take advantage of the opportunities. So you know it was, it was a combination of luck and just being really really keen.”

“And so a lot of the problem is, is people you know having their own biases and their own sort of attitudes that, that make it, make it unpleasant for people who don't fit a certain mold.”

“The main one was a few years ago there was, there was a space mission called [name]. They were landing a probe on a comet and around the time of the probe landing on the comet, there was a press conference and during that press conference...One of the project's scientists was wearing a t shirt covered in like scantily clad cartoon women and several people, including myself, on Twitter said you know - this is inappropriate...not something somebody should be wearing for an event like this. It's not encouraging to women in science and the backlash for [it] was just incredible.”

“When I was a kid and, and also you know when I started getting involved in the stuff I was I was often the only girl around but I was also the youngest person around and so there was, you know I was kind of there was a lot of other it was just… yeah you know, I kind of saw myself as a singular figure in some ways…I wasn't looking for community per se, in that sense I was just trying to like you know keep up with what was going on around me."

"I talk to a lot of women in physics these days, young women who say that, you know their classmates make disparaging remarks about girls in science or something like that. And that was not something that happened to me when I was an undergrad, or if it did I didn't notice."

"So there are there are aspects of the career track which because of the sort of societal norms we have around relationships and the raising of children do disproportionately disadvantage women in that career space. And I think that, you know is kind of bad for everybody if you float around the world in temporary jobs making very little money for, you know until you're in your mid to late 30s."

"Yes so I think that, I think that in all of these areas of bias and privilege and stuff it is really, it's the responsibility of the people who are in a position of greater privilege or power to work on making that change. You know, so I think that men need to speak up more against sexism. You know, white people need to speak up more against racism. People who are able bodied need to speak up more against ableism…"

Software Developer Interview Transcript - Excerpts from Each Theme

"We learned probability and I took an extra course in the evening on architecture…as far as spatial reasoning goes, that probably helped me as much as anything I ever did."

"...you go to [elite technical university] and all of a sudden you're surrounded by people that are smarter than you are. And that's a big *thing*. I thought I was pretty smart. Maybe not."

"And I had to do. Basically I did all the spatial work. So all I had were images and I had to figure out what I was looking at on Mars. And the spectrograph slid out and I wrote it and I wrote it up in the spectrum processing pipeline, which strangely enough is what I still do. Broad spectrum processing pipeline."

"So, all the time I was at [elite technical university] working, I, I started writing papers. So I had quite a few publications, so I was doing science and I didn't want to go back to grad school and stop doing science…so I never did. I tried to take a course once and I just couldn't do it because I didn't have time I had too much other stuff to do yeah. And so I never, I'm the only person I think that worked in that lab that didn't go get a Ph.D."

"I sort of hit a limit of things I could really do well. And I also didn't do really well in math and so I sort of had a crisis. I thought maybe I was going to be a teacher or something and not the physicist and I switched fields, to my second choice which was Planetary Exploration and took a bunch of courses in that and really got into it."

"I've talked to software people who feel like there's really just a caste system between scientists and the astronomers...what I do is astronomy in software and that's how I've made my reputation. So it's like not a thing that people can follow in the footsteps of because I was in the right place at the right time."

"And sometimes it's a problem, like I can't go talk to the legislature about rights because I have never suffered. And my therapist says I'm just immune to microaggression. But to me, that's not exactly true but I'm mostly immune to it. I mean I don't have problems with microaggression because I'm a bicyclist, which is where I get the most aggression. And I'm not an aggressive bicyclist, I mean I'm a nice bicyclist, I try real hard to be anyway."

“Planetary science: my theory about women in science is that when there's a new field, that's when there's not as much of an ‘old boy network’ maybe or that's the way it’s been, and women can get into it.”

“And then there were a bunch of, there were sort of other women at other places that graduated in that group. And I, I was pretty narrow, a lot of them have done pretty well. So I felt pretty, like I had a bunch of, I regard them now as role models...I think I’ve hung around where there are, women have been well represented. They've been well represented in my circle, right.”

“I mean it's I'm not always conscious of it yet, trying to be - figuring out when, when things are happening to me. In the rest of my life I tend to hang out with other women mostly. So...that's not totally true. But it's it's more true than not. And so I don't have lots of encounters where I feel like I'm being overridden.”

“And the problem was that as people retire they were replaced with Ph.Ds. And all the Ph.Ds. that had been hired have been guys. Because relatively few women have been involved with just, th- this pipe, pipeline kind of stuff.”

“I'm on the Program Organizing Committee for the [technical astronomy software system name] conferences and where there are 20 percent women. So it sort of matches astronomy as a whole…we're really trying for diversity and trying to include a fair number not equal, we can’t get equal men and women but we're trying to keep the levels of all the invited speakers to be a little bit higher than the percentage of women at the conference. Sort to try to push things upward a little bit.”

“As trans persona, I felt really lucky in that all the different communities I'm part of have treated me well. And I don't know whether that's because it’s, I think it's a combination of the kind of community they are and how I'm a part of it…all sorts of things, so people were really receptive. And it's partly because they were good people and partly because I was really involved and I was actively doing stuff.”
“I think about it a lot. I mean I think about how things got to be how I got to be where I am, why things are the way they are. In general it's like beyond just professional stuff. But in other parts of my life, why are some places real accepting? Why am *I* accepted? I mean I feel lucky because I can get along with almost anybody, and I think that makes me a good spokesperson.”

“I like got to use, I had developed a philosophy and how code should be and how it should be shareable and usable and readable and all sorts of things. And I put that all to work on this package because I did, I have a…a sort of self defined job.”
“I think what’s happened is that we've overproduced Ph.Ds. By a lot - it’s not by a little bit, it’s by a lot.”

“And the Ph.D. to faculty pipeline is fiction. And I felt really excluded because they were basically saying if you didn’t have a Ph.D. you weren’t professional and there were a few of us in the audience who didn't have Ph.Ds who were doing serious work.”

“And I think there are lots of ways you can be involved. This is my problem with the Inclusive Astronomy…it’s discriminating against a lot of people who might not get Ph.D.s but can contribute, and you're losing, what you really want is people that can contribute to the field. And that's the goal. Like make astronomy *inclusive* you want to make astronomy inclusive you don’t wanna just make an inclusive pipeline that puts people into data science.”

Technologist/Pre-medical Student Interview Transcript - Excerpts from Each Theme

“There were a lot of books in my house that had a lot of science content in them. These are things that, again I didn't realize until I got to college. That not everyone had the same childhood like...Some people grew up privileged but their families didn't value education and that's a different circumstance for example."

"...I think that statistic right there can speak to why it was difficult for me to have like female mentors in STEM at [Ivy League university], because they weren't there."

"And what was amazing about [female scientist's] lab is that...she's one of the she's one of a handful of like female faculty at [Ivy League university] that have labs, like honestly I think [Ivy League university] could really work on its representation in terms of having female science faculty."

"Like however we choose to quantify representation, or do we see women equally represented. And then going beyond, like what about payscale? It's one thing to have like 50 percent of their staff being women but if they all make like 75 percent of the pay that a man at that same level would make, that's certainly not equity."

"And all of the institutions that I have been a part of whether it was my high school or [Ivy League university or [private high school], I think have had really incredible politics and even if there have been moments of discomfort what's been really meaningful to me is that in all of these communities there's been a way to, to come together and to process these incidents and to be stronger and more aware as a result of that."

"And I think that my favorite favorite aspect of this trend is like really just we're getting young girls *and* boys involved in this idea of equality and equity and like women's rights because it's, I think for me... because I keep coming back to what's polarizing about it. I see like this if the movement could just figure out how this how to express itself in a way that isn't polarizing."

"But I think that's why it's maybe one of the most important things but just the, the recognition of the emotional labor that women can do in the communities and organizations that they're a part of. Like, the kindness, the office vibes, like thinking about *how* to say something - considering other people's feelings and like the group dynamics offered by being sensitive to personality types."

"And I think that like early education is really formative in that sense, and having really strong positive associations with science from a young age is probably one of the best things that a young girl can be given and I think that's one of the reasons why I love spaces like the [name] Lab. And I did love seeing girls get excited to make a connection between, you know two different topics or something."

"I think that there are ways to use the same language of of of STEM, of math and economics to talk about how feminism and equality makes sense."

Science Writer Interview Transcript - Excerpts from Each Theme

"When I went to college I noticed that there were very few women in my physics, math, and astrophysics classes. And that was, you know definitely eye opening to me at that point. It was a very small major at that point, you know there weren't that many students in these classes but I think there was only one other woman who was in most of the classes with me...say there were ten students in the class, there was the two of us."

"...communication you know public affairs, science visualization, I think you'll find a higher percentage of women because I think a lot of my personal theory is that a lot of women are turned off by the, some of the traditional paths to a scientific career, they find it sort of the way feels a little more accepting and welcoming."

"I found sort of equivalent colleagues that I relied on, you know as a sort of small group of people that does what I ended up doing and were responsible for, you know the public face of a multibillion dollar mission...I definitely found those were people that I could call to because they were spread out throughout the country and in the world."

"You know I don't think that there's something that has kept me from doing something that I wanted to do, because I am doing what I want to do. I think the only thing that has prevented me from doing more sort of macro opportunities of finding you know, you know funding and like minded people in addition to you that like to do what you want…"

"My former boss, my first boss, you know worked on a private hall space for women...so I knew that there was always issues. I mean it was never an overt thing necessarily but it was definitely you know there not for me directly but for...the community as a whole."

"And the sexual harassment piece very much ties into the underrepresentation side of it. There's sort of, you know I think there's a better understanding of how two - those are two sides of the same coin. So you know and I think that in the past six months, that our society has become much more aware of sexual harassment outside of science too."

"You know something has to be done about the perception of science as a whole and a perception of girls and women and their relationship to science. And I just have to go with and I think with a general thought process that science is some sort of specialized other thing separate from people's day to day lives. It truly isn't and I think that people including women and girls are able to understand that science is absolutely integrated into every day and every moment that we're out."

"All these things, science can be just you know brutal. Oh you know I just worked 60 hours in a lab and 20 more on writing papers kind of thing, or the telescope or whatever people who publish first and most win. So you know if that's the only measure of success then a woman who is taking care of her kid or kids or you know a parent or whatever is going to be at a disadvantage. So it's retaining people, it just has to be a good quality of work/life."

Astronaut Interview Transcript - Excerpts from Each Theme

"As you go on… there's always going to be more things to learn. And as long as you figure out how *you* learn, how *you* figure things out whether you like to write them down … whatever way is the way *you* learn, that's how you are going to get the skills that are required.

"I loved being a chemist, and there's a lot of different parts of that, as you're learning. And learning is really the key. And something that you might assume is that if you're a chemist, well you're just good at *all* kinds of science, and *all* kinds of math. But there's other kinds of science, like physics, that - there's a certain logic to… and when I think about those things, I get them, but I have to think about them hard, and I have to kind of think about them in steps… in other words, it's not all that intuitive for me."

"I made a mistake… and I really just had to say, "Hey, ground, that was me, I did that." And then I think the hardest thing was just saying, "Okay, where were we, let's start again"
"What I'm most proud of is that, you know, I was worried about that, I was nervous. And I realized that, as long as I had done my *best* to prepare, then no one could ask anything more than that of me….then on the day I did my best, to do a good job, I didn't *have* to be nervous, and I didn't have to think about how much it cost, or what if I made a mistake."

"We are a team [of women], and that when things are hard, we're going to turn to each other and we're going to solve our problems together.""When I thought about what astronauts looked like, I had in my mind a picture of the Mercury 7 astronauts standing in front of an airplane and they were all a bunch of old guys with no hair. And it certainly didn't say to me, this could be you. It wasn't until I went to college and Sally Ride came to talk, it just opened up that possibility of if she could do it then I could aspire to do it, too.

The fact that this woman [the first American woman to walk in space] who was on this huge pedestal for me was willing to take almost an hour out of her day was really meaningful to me…I kept saying, 'I think we should get back to the symposium,' and she would say, 'no, this is part of my job and this is really important because we need more astronauts who are qualified.'
"When I was growing up, there weren't a lot of girls being astronauts [to look up to]."

"If space is where you want to go and what you want to do, then you can do that...And I'm hoping that you realize that if real people can go to this amazing, fantastic place and be astronauts - real people like me - then real people like you can do *whatever* you want to do as well."

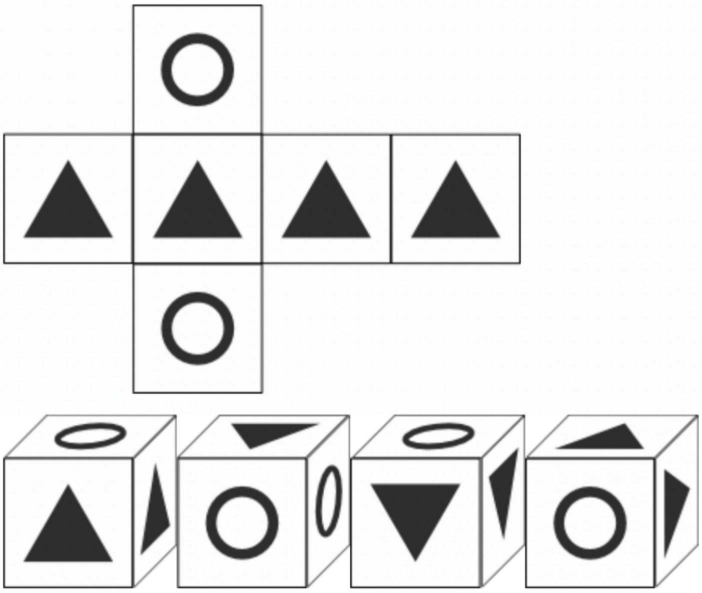
Appendix C. Spatial Skills

ID: _______________

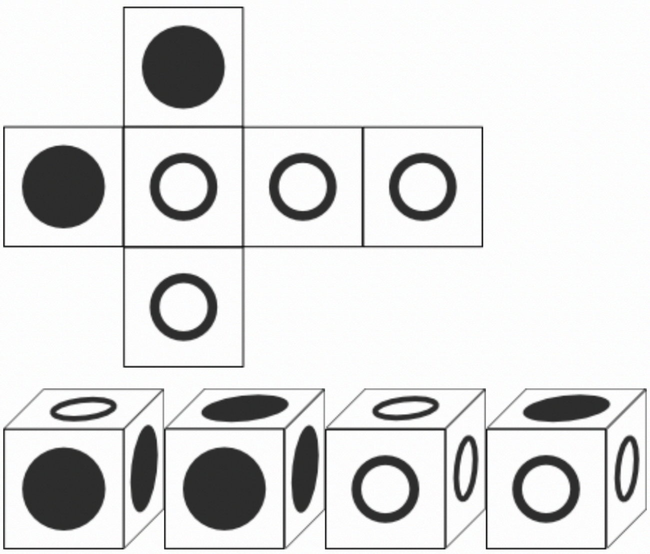
Spatial Skills

Instructions: For this activity, you will see 5 images of unfolded cubes followed by 4 folded cubes. For each unfolded cube, please cross out which of the folded cubes **cannot** be made from the unfolded cube.

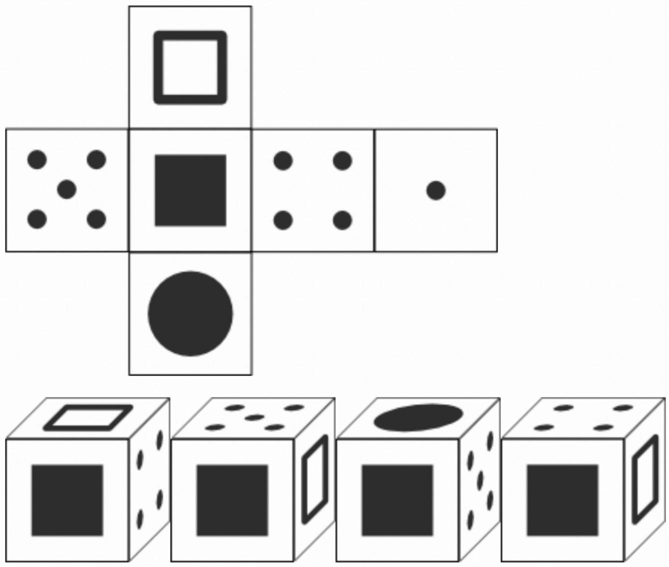
1.



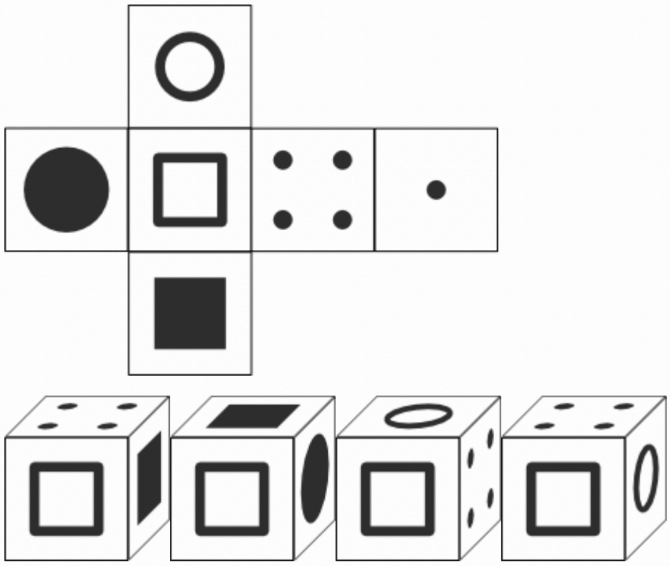
2.



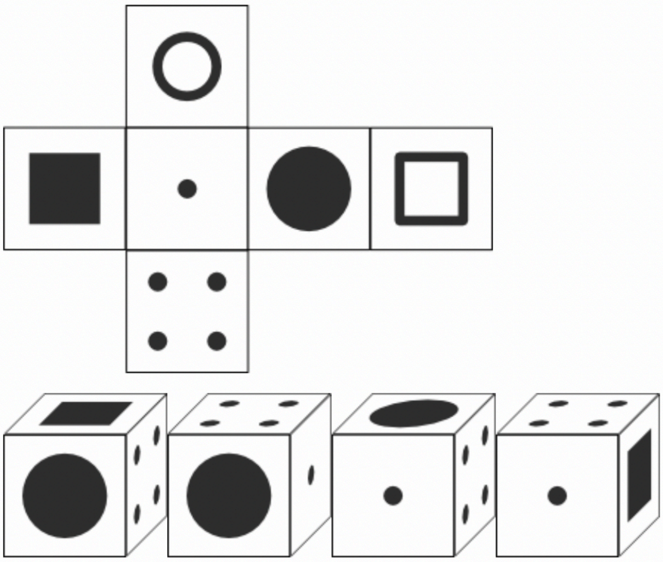
3.



4.



5.



Appendix D. STEM Interest Inventory

ID: ______________

STEM Interest Inventory

Instructions:
Below are pairs of words with circles between them. For each pair of words (**all 25 questions**), please color in the circle that best indicates how you feel.

There are no right or wrong answers. Just give your first reaction on each!

To me, SCIENCE is:

1.	fascinating	① ② ③ ④ ⑤ ⑥ ⑦	mundane
2.	appealing	① ② ③ ④ ⑤ ⑥ ⑦	unappealing
3.	exciting	① ② ③ ④ ⑤ ⑥ ⑦	unexciting
4.	means nothing	① ② ③ ④ ⑤ ⑥ ⑦	means a lot
5.	boring	① ② ③ ④ ⑤ ⑥ ⑦	interesting

To me, MATH is:

1.	boring	① ② ③ ④ ⑤ ⑥ ⑦	interesting
2.	appealing	① ② ③ ④ ⑤ ⑥ ⑦	unappealing
3.	fascinating	① ② ③ ④ ⑤ ⑥ ⑦	mundane
4.	exciting	① ② ③ ④ ⑤ ⑥ ⑦	unexciting
5.	means nothing	① ② ③ ④ ⑤ ⑥ ⑦	means a lot

To me, ENGINEERING is:

1.	appealing	① ② ③ ④ ⑤ ⑥ ⑦	unappealing
2.	fascinating	① ② ③ ④ ⑤ ⑥ ⑦	mundane
3.	means nothing	① ② ③ ④ ⑤ ⑥ ⑦	means a lot
4.	exciting	① ② ③ ④ ⑤ ⑥ ⑦	unexciting
5.	boring	① ② ③ ④ ⑤ ⑥ ⑦	interesting

To me, TECHNOLOGY is:

1.	appealing	① ② ③ ④ ⑤ ⑥ ⑦	unappealing
2.	means nothing	① ② ③ ④ ⑤ ⑥ ⑦	means a lot
3.	boring	① ② ③ ④ ⑤ ⑥ ⑦	interesting
4.	exciting	① ② ③ ④ ⑤ ⑥ ⑦	unexciting
5.	fascinating	① ② ③ ④ ⑤ ⑥ ⑦	mundane

To me, a CAREER in science, technology, engineering, or mathematics (is):

1.	means nothing	① ② ③ ④ ⑤ ⑥ ⑦	means a lot
2.	boring	① ② ③ ④ ⑤ ⑥ ⑦	interesting
3.	exciting	① ② ③ ④ ⑤ ⑥ ⑦	unexciting
4.	fascinating	① ② ③ ④ ⑤ ⑥ ⑦	mundane
5.	appealing	① ② ③ ④ ⑤ ⑥ ⑦	unappealing

Thank you for taking part in this survey!

Appendix E. Binary Code Nametag

HOW TO TALK TO A SPACECRAFT: BINARY CODE

National Aeronautics and Space Administration

A STREAM OF 1'S AND 0'S

Images from NASA's Chandra X-ray Observatory – a telescope in orbit around the Earth that looks at objects in space in a special type of light called X-rays —can be fascinating, informative, and beautiful. These images show our Universe in a way we could never see directly with human eyes. But the information that is eventually converted into images actually arrives at the Chandra X-ray Center in Cambridge (USA) as a stream of 1's and 0's that only a computer could understand. Fortunately, many people have worked hard to develop steps to process the data using software and technical know-how to convert them into something that humans can use and admire.

The Goldstone Deep Space Communications Complex, located in the Mojave Desert in California, is one of three complexes that comprise NASA's Deep Space Network (DSN).

The digital pipeline of data starts with the Chandra spacecraft that travels around our planet in a big oval that takes Chandra about a third of the way to the Moon at its farthest point from Earth. The data that Chandra records are encoded into the form of 1's and 0's, or "binary data", in order to start its journey. This 40,000-mile or about 64,000 km journey (more or less, depending on Chandra's position in its orbit at the time of the downlink) through space takes the data to one of NASA's Deep Space Network (DSN) antennas in Australia, Spain, and California (USA), where it is downloaded.

You can think of this data as a river flowing from the mountains (telescopes in space) down to the valleys (the DSN here on Earth). Once the data enters the DSN, they are streamed to NASA's Jet Propulsion Laboratory (JPL) in California, where it goes into a pool with all the other data collected by the Deep Space Network from the many NASA telescopes in space. It can another take another couple of days for Chandra's data to show up at its end point (the Chandra X-ray Center) after that.

These data can then be diverted for different purposes, much like a river whose water is channeled into various streams. Once the Chandra data stream arrives at the Chandra X-ray Center, computer processes separate it further for examination by experts who work there. Some people look at data on the instruments aboard Chandra while others make sure the parts of the spacecraft are working correctly.

Software and processing are used to create "Quick Look" versions that can take the form of a rough image. These "Quick Look" data let people at the Chandra X-ray Center know whether the telescope has looked at the correct object in the sky that it was intended to and to make sure the telescope was functioning as it should.

Meanwhile, other scientists and computer analysts begin crunching the data. This involves figuring out exactly where

www.nasa.gov chandra.si.edu

Find more coding-related activities at chandra.si.edu/code

Here is a chart of uppercase and lowercase English language alphabet characters:

A	01000001	N	01001110	a	01100001	n	01101110
B	01000010	O	01001111	b	01100010	o	01101111
C	01000011	P	01010000	c	01100011	p	01110000
D	01000100	Q	01010001	d	01100100	q	01110001
E	01000101	R	01010010	e	01100101	r	01110010
F	01000110	S	01010011	f	01100110	s	01110011
G	01000111	T	01010100	g	01100111	t	01110100
H	01001000	U	01010101	h	01101000	u	01110101
I	01001001	V	01010110	i	01101001	v	01110110
J	01001010	W	01010111	j	01101010	w	01110111
K	01001011	X	01011000	k	01101011	x	01111000
L	01001100	Y	01011001	l	01101100	y	01111001
M	01001101	Z	01011010	m	01101101	z	01111010

Can you tell what name is written here below?

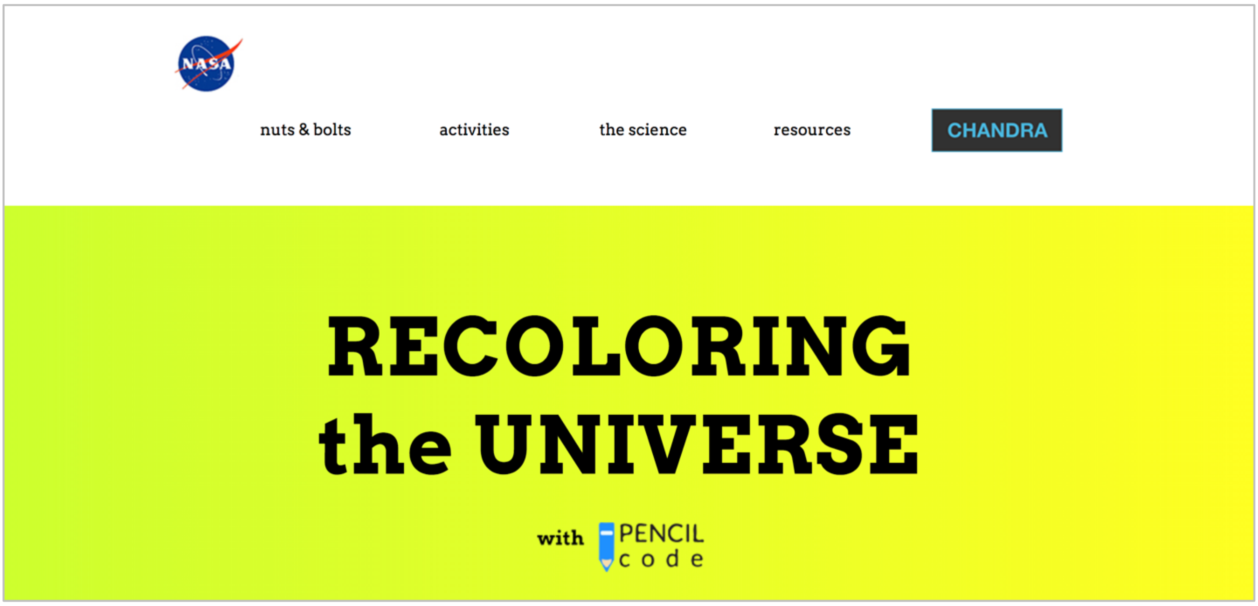
01011000 | 01110010 | 01100001 | 01111001

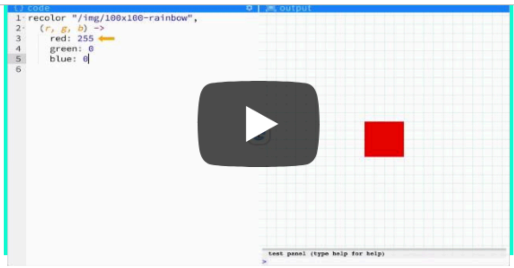
____

Hello
my name is

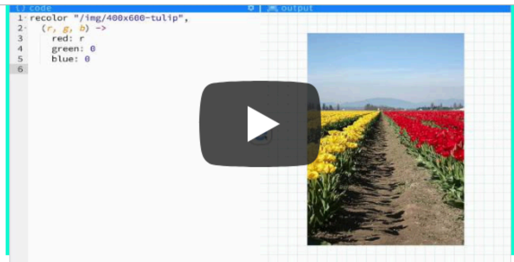
Use the chart to write your name in binary code on your nametag.

Appendix F. Recoloring the Universe/Image Processing

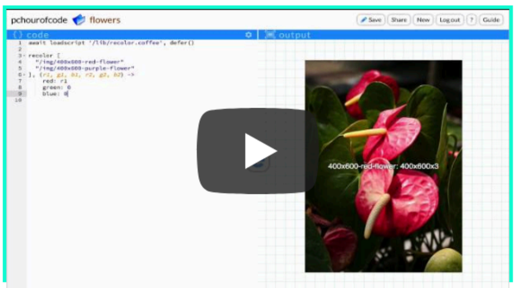




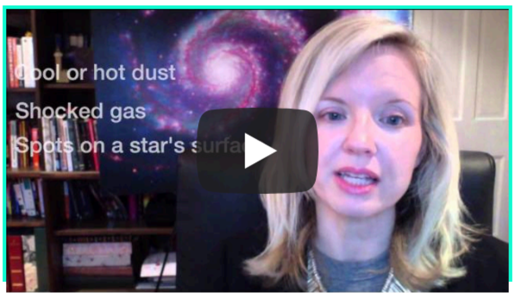
Lesson 3: Recolor
Create a color



Lesson 4: Scene
Explore filters and color-shifting



Lesson 5: Flowers
Mash up two images



Lesson 6: Supernova
Create a colored image of an exploding star

Appendix G. TinkerCad/3D Modeling

National Aeronautics and Space Administration

UNIVERSE IN 3D:

modeling and printing cosmic objects

Over the past decade, 3D modeling and 3D printing in science has blossomed while commercial 3D printers have become more common.

3D printing is essentially an additive process where an object is built up layer by layer. Applications range from creating personalized assistive devices and prosthetics, to 3D printing with bioinks (such as blood or other cells) to 3D printing of earthquake visualizations (using USGS data to compare Californian earthquakes).

3D modeling offers a new tool to represent and understand scientific data, particularly when we can create and manipulate models to gain new perspectives on the data being explored.

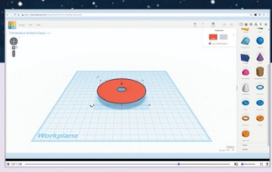
But 3D modeling in astronomy can be challenging. Scientists are not able to fly a spacecraft out to the cosmic objects that we want to study in 3D. So astronomers have to think outside the box, and use a wide range of tools.

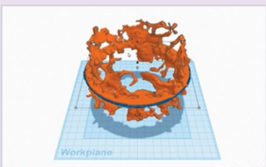
One of those tools is NASA's Chandra X-ray Observatory. Chandra was launched by the Space Shuttle back in 1999 and orbits about 1/3 of the way to the moon at its farthest. Chandra has to be up above our atmosphere in order to detect X-rays from space. Designed to observe the high energy Universe, Chandra looks at such things as colliding galaxies, merging black holes, and stellar nurseries.

When scientists combine data from Chandra with other telescopes, such as the Hubble or Spitzer Space Telescopes, or with scientist's mathematical models, we can create data-driven 3-dimensional maps of objects in our Universe, such as stars that have exploded.

www.nasa.gov

chandra.si.edu/tinkercad



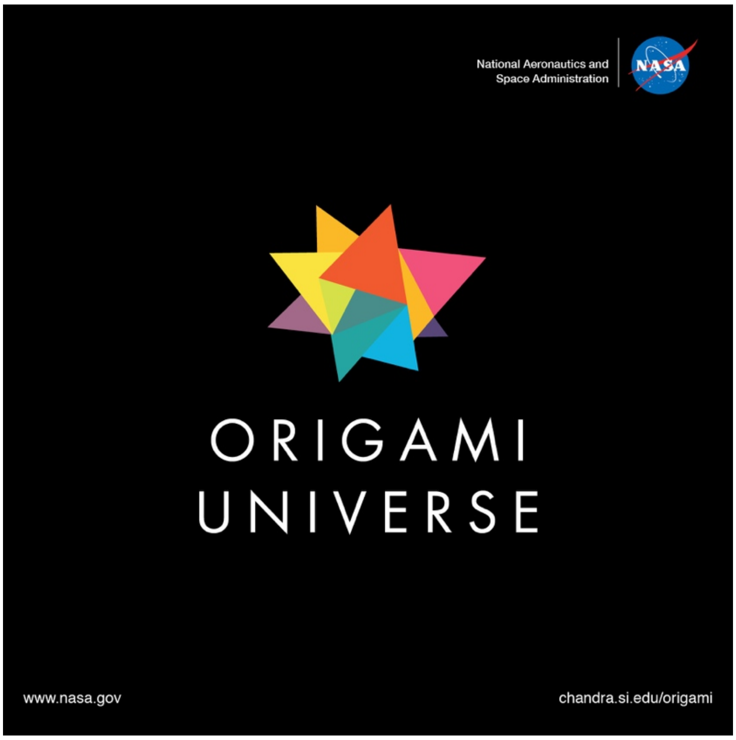


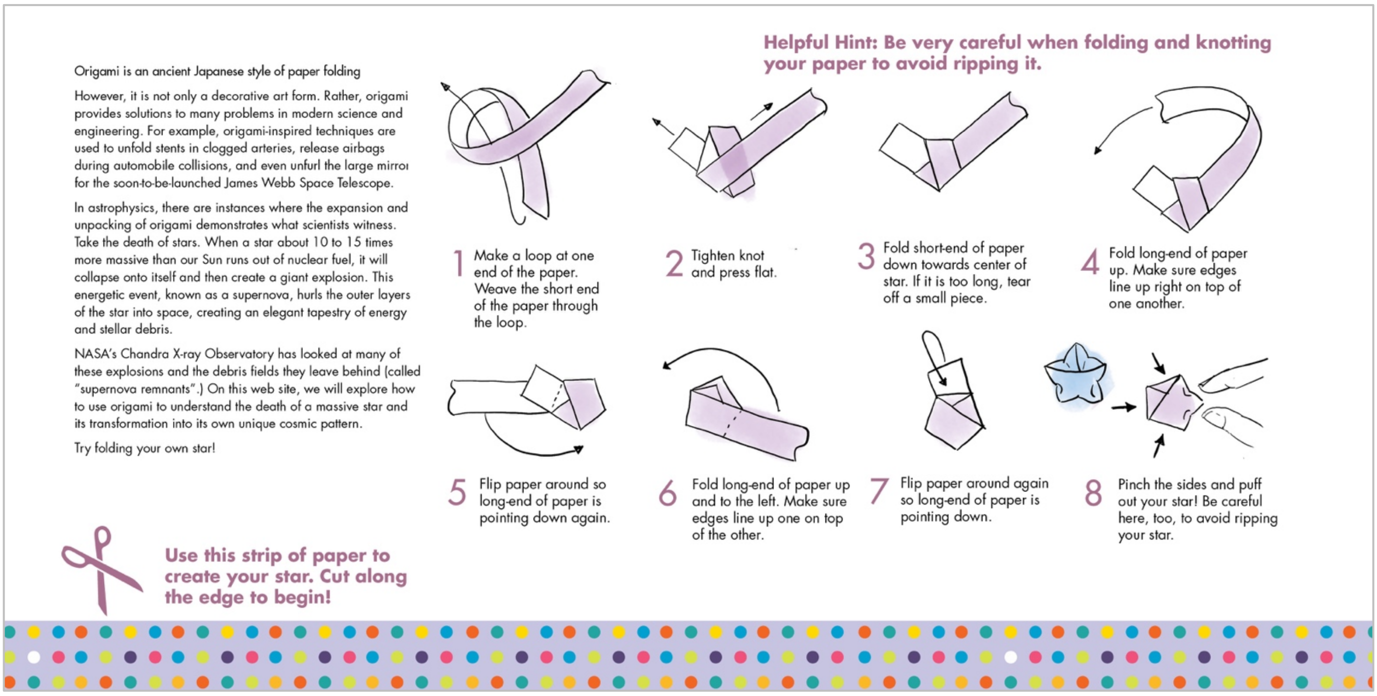
Explore the basics of 3D modeling in a free, browser-based software application, experiment creating simple astronomical shapes, create more complex models and forms in 3D, and work with real NASA data on exploding stars.

- **Create an accretion disk**
- **Create an Earth-Moon system**
- **Create an Proto Chicken in Space**
- **Freeform: Create a Celestial Object of your Choice**
- **Working with Real Data**

Learn more at chandra.si.edu/tinkercad

Appendix H. Origami





Appendix I. Paper Circuits (Light Up Exploded Stars)

A UNIVERSE OF MAKING AND DOING

LIGHT UP EXPLODED STARS
(PAPER CIRCUITS #1)

NASA'S UNIVERSE OF LEARNING

A hands-on activity using printable templates and creating simple paper circuits. Good for MakerFaires, libraries, classrooms and other STEM related events where participants can create their own take-away.

What is a Paper Circuit?
Paper circuits help learners of all ages explore the basics of electricity (energy that results from the existence of charged particles like electrons or protons) and conductivity (the degree to which a material can conduct electricity). Paper circuits function as simple low-voltage electronic circuits (a path through which electrons from a voltage or current source flow) made using paper, LED lights, a type of conductive tape such as copper, as well as a small battery for the power source.

Directions: Download the attached .pdf and print double-sided (so the shapes are lined up) and cut in half (you will get two handouts per page)

1. Have participants cut out the rectangle - see handout for instructions
2. Ask participants to fold paper in half on the dashed line so that the directions are on the INSIDE/images are on the OUTSIDE.
3. Punch a hole for the LED light - see template
4. Following the remaining steps outlined on the handout - placing copper tape, finding the positive lead on the LED and affixing the leads to the circuit, and folding over with the coin battery.
5. Use a binder clip to hold battery in place on the circuit (so the light stays on)

Troubleshooting
- Flip the battery over. If the LED was put in backwards, it just means the positive and negative parts of the circuit are reversed
- Check all connections - around the LED leads, alignment with the battery, any broken places in the copper tape. Use more tape to reinforce connection.

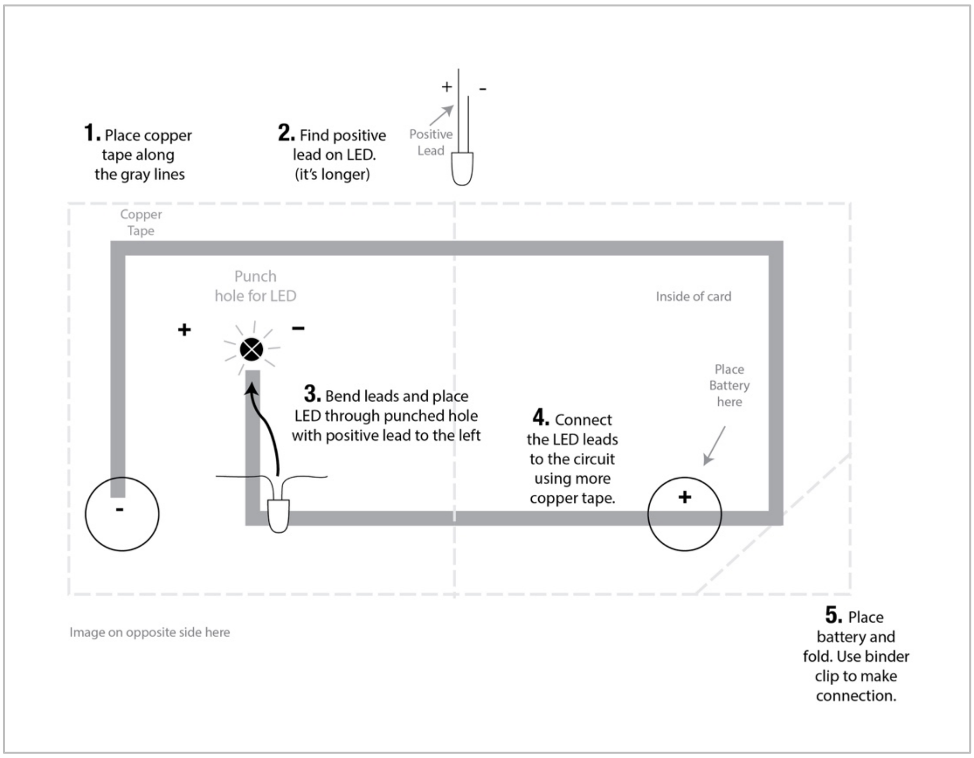
Cost: About $0.50 (50 cents) per item, estimates are provided in the materials list

Time: about 5 minutes to make a single item

Materials:
- Coin Batteries ($0.30 each)
- Copper tape with conductive adhesive ($0.10) - Less than 12 inches per badge
- LED's ($0.05)
- Small binder clips ($0.05)
- NASA Images of exploding stars/ pulsars/neutron stars (download template here: chandra.si.edu/make/ template.pdf)
- Hand held hole punchers
- Small trash can – little bits of trash are produced during the activity

nasa.gov

chandra.si.edu/make



Appendix J. Information Sheet & Consent Forms for Participants: Heads of Programs

[19/006]

[1 Feb 2019]

Putting the stars within reach: The potential effects of NASA 3D data-based models and 3D prints on spatial reasoning skills and STEM interest in young female learners

INFORMATION SHEET FOR

Heads of Programs, Principals, Librarians

Thank you for showing an interest in this project, which is part of Kimberly Arcand's research for her PhD. Please read this information sheet carefully before deciding whether to agree on behalf of your organization to allow participation. If you decide to allow participation, we thank you. If you decide not to take part there will be no disadvantage to you or your organization and we thank you for considering our request.

What is the Aim of the Project?

Spatial reasoning concerns mentally manipulating 2- or 3-dimensional objects to visualise what the objects represent. It is a critical skillset for most STEM (science, technology, engineering, and math) fields. Most researchers agree that the development of spatial skills in females is delayed as compared to males (Halpern, Benbow, Geary, Gur, Hyde, & Gernsbacher, 2007; Yilmaz, 2009). Recently, spatial reasoning has been shown to be improvable through targeted programmes (Gold et al., 2018; Hwang, Su, Huang, & Dong, 2009; Uttal et al., 2013; Yeh, 2007). This project investigates the effects of a targeted programme using astronomical 3D models and printing on increasing spatial reasoning skills and interest in STEM fields, for females aged 11-15.

What Type of Participants are Being Sought?

Female-identifying middle school students (ages 11-15) from a network of schools, afterschool clubs, and libraries known to the student researcher's existing network. No reimbursement will be provided, as activities will be done during class or club time to reduce any inconvenience to the participants and their families. We will, however, provide free NASA handouts and materials as a thank you for participants' time. A sign-up sheet will be provided at each location to receive notice of the resulting article or information after publication. All are welcome to this information, including those who don't participate.

What will Participants be Asked to Do?

Should you agree to have your organization take part in this project, your students will be asked to spend a half day or full day in class/club/school, working with and exploring various 3D models of scientific data. That time commitment will include taking a spatial skills evaluation (either before or after the activities), a STEM interest survey (either before or after the activities), and a brief

demographic survey. Completing the evaluation and surveys will take no more than 10 minutes pre- and 10 minutes post-.
Students who are not participating will also complete the activities; however, their ID numbers will indicate that their data should not be included in the analyses. Their activity sheets will be shredded immediately upon the conclusion of the workshop.

Parents/legal caretakers of the students, and the students, will each receive a description of the programme and a form to complete for consent to participate (see samples attached). Those students who do not want to participate will take part in all activities but will not be asked to complete the spatial skills evaluation, STEM interest survey, or the demographic survey.

We do not expect any adverse physical or psychological risks associated with participating in the research.

No compensation will be provided to the participants; however, your organisation will be given NASA handouts/literature for the students, regardless of participation levels.

What Data or Information will be Collected and What Use will be Made of it?

No personal information will be collected (e.g., no names or other identifiers). The demographic data will ask each participant's age, grade, ethnicity, zip code, self-rating in STEM, and approximate number of hours spent per day on video games. The data will be used in aggregate only.

Only the student researcher and her advisors will have access to the data.

All data collected will be securely stored in such a way that only those mentioned above will be able to gain access to it. Data obtained as a result of the research will be retained for **at least 5 years** in secure storage.

Results of this project may be published and/or presented at conferences, and will be available in the University of Otago Library (Dunedin, New Zealand), but every attempt will be made to preserve participants' anonymity.

Can Participants Change their Mind and Withdraw from the Project?

You may withdraw your organization's participation, and any parent/legal caretaker or individual participant may withdraw from participation in the project at any time prior to the conclusion of the activities, without any disadvantage of any kind.

What if Participants have any Questions?

If you have any questions about our project, either now or in the future, please feel free to contact either:

Kimberly Arcand
College of Education
Sciences
University of Otago
617 218 7196 (USA)
Email: arcki929@student.otago.ac.nz

or

Professor Lisa F. Smith
University of Otago School of Social
University Telephone Number:
011 64 3 479 9014 (New Zealand)
email: lisa.smith@otago.ac.nz

This study has been approved by the University of Otago Human Ethics Committee. If you have any concerns about the ethical conduct of the research you may contact the Committee through the Human Ethics Committee Administrator (ph 011 64 3 479 8256 or email gary.witte@otago.ac.nz). Any issues you raise will be treated in confidence and investigated and you will be informed of the outcome.

Putting the stars within reach: The potential effects of NASA 3D data-based models and 3D prints on spatial reasoning skills and STEM interest in young female learners

CONSENT FORM FOR
Heads of Programs, Principals, Librarians

I have read the Information Sheet concerning this project and understand what it is about. All my questions have been answered to my satisfaction. I understand that I am free to request further information at any stage.

I know that:

1. My organization's participation in this project is entirely voluntary;
2. Participation involves either a half day or full day of time in class/club/school, working with and exploring various 3D models of scientific data;
3. Parents/legal caretakers of the students, and the students, will each receive a description of the programme and a form to complete for consent to participate
4. Participants will complete a spatial skills evaluation (either before or after the activities), a STEM interest survey (either before or after the activities), and a brief demographic survey;
5. Those students who do not participate will take part in all activities but will not be asked to complete spatial skills evaluation, STEM interest survey, or the demographic survey;
6. I am free to withdraw my organization from the project at any time prior to the conclusion of the activities without any disadvantage, as are any parents/legal caretakers and participants;
7. Personal identifying information will not be collected, and every attempt will be made to preserve the participants' anonymity;
8. The results of this project may be published or presented at a conference, and will be available to both participants and non-participants in the University of Otago Library (Dunedin, New Zealand) and by a sign-up sheet in your organization;
9. Any raw non-personal data on which the results of the project depend will be retained in secure storage for at least five years;
10. There are no known adverse physical or psychological risks associated with participating in the research;
11. No compensation will be provided to the participants; however, your organisation will be given NASA handouts/literature for the students, regardless of participation levels.

I agree for my organization to take part in this project.

....
(Signature of organization head) (Date)

…………………………………………………..
(Name of person - please print)

This study has been approved by the University of Otago Human Ethics Committee. If you have any concerns about the ethical conduct of the research you may contact the Committee through the Human Ethics Committee Administrator (ph 011 64 3 479 8256 or email gary.witte@otago.ac.nz). Any issues you raise will be treated in confidence and investigated and you will be informed of the outcome.

Appendix K. Information Sheet & Consent Forms for Participants: Parents/Legal Caretakers

[19/006]

[1 Feb 2019]

Putting the stars within reach: The potential effects of NASA 3D data-based models and 3D prints on spatial reasoning skills and STEM interest in young female learners

INFORMATION SHEET FOR

Parents/Legal Caretakers

Thank you for showing an interest in this project, which is part of Kimberly Arcand's research for her PhD. Please read this information sheet carefully before deciding whether to agree to have your child participate. If you decide to have your child participate, we thank you. If you decide not to agree to have your child participate there will be no disadvantage to you or your child, and we thank you for considering our request.

What is the aim of the project?

3D modeling in science has become increasingly common in the past ten years. This project will look at the use of 3D models in science by working with digital models, a 3D printer and/or a Virtual Reality educational application, to see if those activities lead to any change in your interest in STEM (science, technology, engineering, and math) fields or how you look at 3D objects.

Who will participate?

Female-identifying middle school students (ages 11-15) from schools, libraries, or clubs where Kimberly Arcand has worked, to take part in this project.

No payment will be provided, because activities will be done during class or club time to make it easier to participate. Arcand will provide free NASA handouts and materials to your schools, libraries, and clubs as a thank you.

If you'd like to know the results of this project, even if you do not participate, please use the sign-up sheet where we do the activities.

What will Participants be Asked to Do?

Should you agree for your child to take part in this project, your child will be asked to spend a day in class/club/school, working with and exploring various 3D models of scientific data. That time commitment will include taking a spatial skills evaluation (either before or after the activities), a STEM interest survey (either before or after the activities), and a brief demographic survey.

If you consent to have your child participate, please give your child the description of the programme and the form to complete for consent to participate included in this packet. Both signed consent forms (yours and your child's) should be returned prior to the day of the workshop, to the organisation's head or principal, where your child will take part in the workshop.

If you do not want your child to participate, your child will take part in all activities, but their activity sheets will be coded in such a way that they will not be used as data, and will be shredded immediately after the workshop.

You or your child may decide not to continue to take part in the project at any time prior to the conclusion of the activities, without any disadvantage to yourself or your child.

We do not expect any adverse physical or psychological risks associated with participating in the research.

What Data or Information will be Collected and What Use will be Made of it?

No personal information will be collected (that is, no names or other identifiers). The demographic data will ask each participant's age, grade, ethnicity, zip code, self-rating in STEM, and approximate number of hours spent per day on video games. The data will be used in aggregate only.

Only the student researcher and her advisor will have access to the data. It will be securely stored in such a way that only the student researcher and her advisor will be able to gain access to it. Data obtained as a result of the research will be retained for **at least 5 years** in secure storage.

Results of this project may be published and/or presented at conferences, and will be available in the University of Otago Library (Dunedin, New Zealand). Every attempt will be made to preserve your child's anonymity. If you or your child would like a copy of any results, please use the sign-up sheet at the location where your child participates.

Can Participants Change their Mind and Withdraw from the Project?

You may withdraw your child and she may also choose to withdraw from participation at any time prior to the conclusion of the activities, without any disadvantage of any kind.

What if Participants have any Questions?
If you have any questions about our project, either now or in the future, please feel free to contact either:

Kimberly Arcand	or	Professor Lisa F. Smith
College of Education Sciences		University of Otago School of Social
University of Otago		University Telephone Number:
617 218 7196 (USA)		011 64 3 479 9014 (New Zealand)
Email: arcki929@student.otago.ac.nz		email: lisa.smith@otago.ac.nz

This study has been approved by the University of Otago Human Ethics Committee. If you have any concerns about the ethical conduct of the research you may contact the Committee through the Human Ethics Committee Administrator (ph 011 64 3 479 8256 or email gary.witte@otago.ac.nz). Any issues you raise will be treated in confidence and investigated and you will be informed of the outcome.

[19/006]
[1 Feb 2019]

Putting the stars within reach: The potential effects of NASA 3D data-based models and 3D prints on spatial reasoning skills and STEM interest in young female learners

CONSENT FORM FOR

Parents/Legal Caretakers

I have read the Information Sheet concerning this project and understand what it is about. All my questions have been answered to my satisfaction. I understand that I am free to request further information at any stage.

I know that:

1. My child's participation in the project is entirely voluntary;
2. Participation involves either a half day or full day of time in class/club/school, working with and exploring various 3D models of scientific data;
3. Upon my consent for participation, my child will receive a description of the programme and a form to complete for consent to participate
4. All participants will complete a spatial skills evaluation (either before or after the activities), a STEM interest survey (either before or after the activities), and a brief demographic survey;
5. Those students who do not participate will take part in all activities but will not be asked to complete spatial skills evaluation, STEM interest survey, or the demographic survey;
6. I am free to withdraw my child from the project at any time, and my child may decide not to participate at any time, without any disadvantage;
7. Personal identifying information will **not** be collected, and every attempt will be made to preserve my child's anonymity; the data will only be used in the aggregate.
8. The results of this project will be available to both participants and non-participants. Results may be published or presented at a conference, in the University of Otago Library (Dunedin, New Zealand) and by a sign-up sheet in your organization;
9. Any raw non-personal data on which the results of the project depend will be retained in secure storage for at least five years;
10. There are no known adverse physical or psychological risks associated with participation;
11. No compensation will be provided to the participants; however, NASA handouts and materials will be given to participating schools, afterschool clubs, and libraries as a thank you.

I agree for my child to take part in this project.

....
(Signature of parent/legal caretaker)   (Date)

. ………………………………………………………..
(Name of parent/legal caretaker - please print)

....
(Name of child – please print)

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Appendix L. Information Sheet & Consent Forms for Participants: Student Participants

[19/006]
[1 Feb 2019]

UNIVERSITY of OTAGO
Te Whare Wānanga o Otāgo
NEW ZEALAND

Putting the stars within reach: The potential effects of NASA 3D data-based models and 3D prints on spatial reasoning skills and STEM interest in young female learners

INFORMATION SHEET FOR
Participants

Thank you for showing an interest in this project, which is part of Mrs. Arcand's research for her PhD. Please read this information sheet carefully before deciding whether or not to participate. If you decide to participate, we thank you. If you decide not to take part there will be no disadvantage to you, and we thank you for considering our request.

What is the aim of the project?

3D modeling in science has become increasingly common in the past ten years. This project will look at the use of 3D models in science by working with digital models, a 3D printer and/or a Virtual Reality educational application, to see if those activities lead to any change in your interest in STEM (science, technology, engineering, and math) fields or how you look at 3D objects.

Who will participate?

Female-identifying middle school students (ages 11-15) from schools, libraries, or clubs where Mrs. Arcand has worked, to take part in this project.

No payment will be provided, because activities will be done during class or club time to make it easier to participate. Mrs. Arcand will provide free NASA handouts and materials to your schools, libraries, and clubs as a thank you.

If you'd like to know the results of this project, even if you do not participate, please use the sign-up sheet where we do the activities.

What will I be asked to do?

Should you agree to take part in this project, you will be asked to:

Take part in activities with digital models, a 3D printer, and/or a Virtual Reality educational application for a day in your class/club/school. You will also be also be asked to complete a brief pre-activity survey, a brief survey after the activity, and some demographics (like your age, ethnicity, and zip code).

If you do not want to participate, you can take part in all the activities, but your activity sheets will not be used in this project and will be shredded immediately after the workshop.

You may decide not to continue to take part in the project at any time before we end the activities, without any disadvantage to yourself or your group.

What data or information will be collected and what use will be made of it?
We will not ask you for any personal information on the activity surveys (for example, we won't ask you for your name on them), so we will not be able to identify you by your survey answers. Any information we collect will be used in aggregate, which means in combination with everyone else's information.

Only Mrs. Arcand and her PhD advisors will have access to the survey data, and they will store it securely for **at least 5 years** in such a way that only Mrs. Arcand and her advisors will be able to gain access to it.

We may publish the results of this project, or present it at conferences. The results also will be available in the University of Otago Library (Dunedin, New Zealand). Every attempt will be made to preserve your anonymity. Remember, if you'd like to know the results of this project, even if you do not participate, please use the sign-up sheet where we do the activities.

Can I change my mind and withdraw from the project?

You may leave the project at any time before we end the activities, without any disadvantage of any kind.

What if I have any questions?
If you have any questions about our project, either now or in the future, please feel free to contact either:

Kimberly Arcand	or	Professor Lisa F. Smith
College of Education Sciences		University of Otago School of Social
University of Otago		University Telephone Number:
617 218 7196 (USA)		011 64 3 479 9014 (New Zealand)
Email: arcki929@student.otago.ac.nz		email: lisa.smith@otago.ac.nz

This study has been approved by the University of Otago Human Ethics Committee. If you have any concerns about the ethical conduct of the research you may contact the Committee through the Human Ethics Committee Administrator (ph 011 64 3 479 8256 or email gary.witte@otago.ac.nz). Any issues you raise will be treated in confidence and investigated and you will be informed of the outcome.

[19/006]

[1 Feb 2019]

Putting the stars within reach: The potential effects of NASA 3D data-based models and 3D prints on spatial reasoning skills and STEM interest in young female learners

CONSENT FORM FOR

Participants

I have been told about this study and understand what it is about. All my questions have been answered in a way that makes sense.
I know that:

1. My participation in this study is voluntary, which means that I do not have to take part if I don't want to and nothing will happen to me. I can also stop taking part at any time and don't have to give a reason.

2. Anytime I want to stop, that's okay.

4. If I don't want to answer some of the questions, that's fine.

5. If I have any worries or if I have any other questions, then I can talk about these with Mrs. Arcand or send an email to her advisor, Professor Smith.

6. The activities that I complete will only be seen by Mrs. Arcand and the people she is working with at the University. They will keep whatever I do private.

7. My group will receive some NASA handouts and materials as thanks for helping with this study.

8. Mrs. Arcand will write up the results from this study for their University work. The results may also be written up in journals and talked about at conferences. My name will not be on anything Mrs. Arcand writes up about this study.

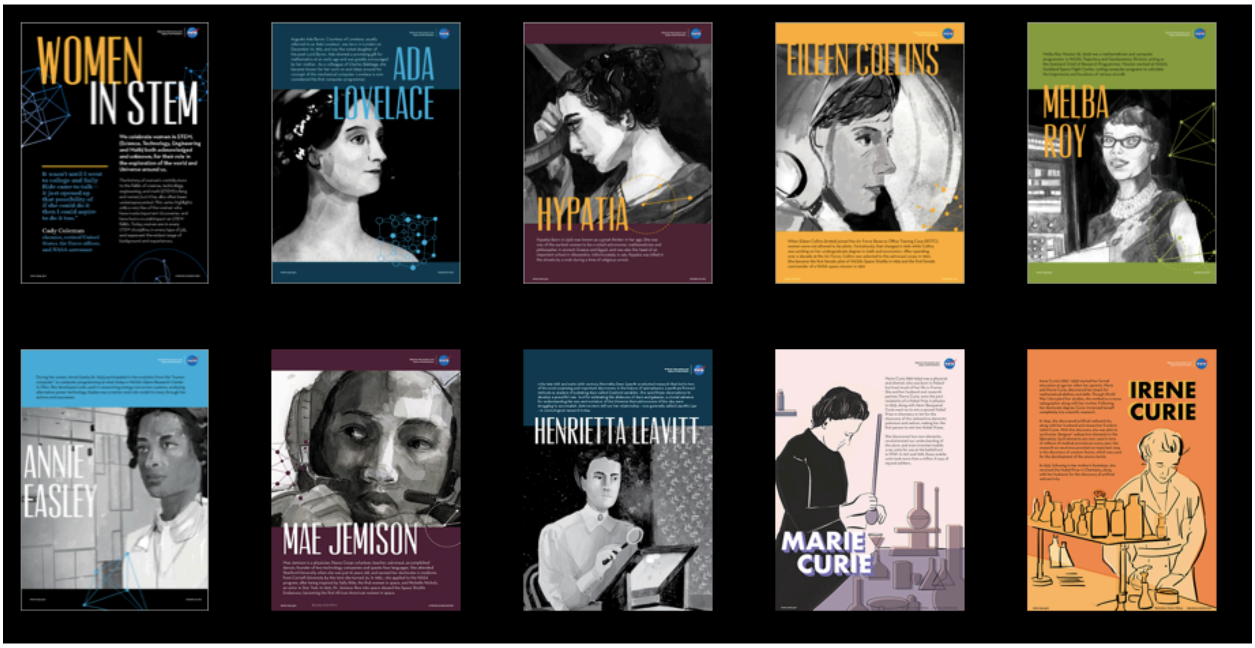
I agree to take part in this study.

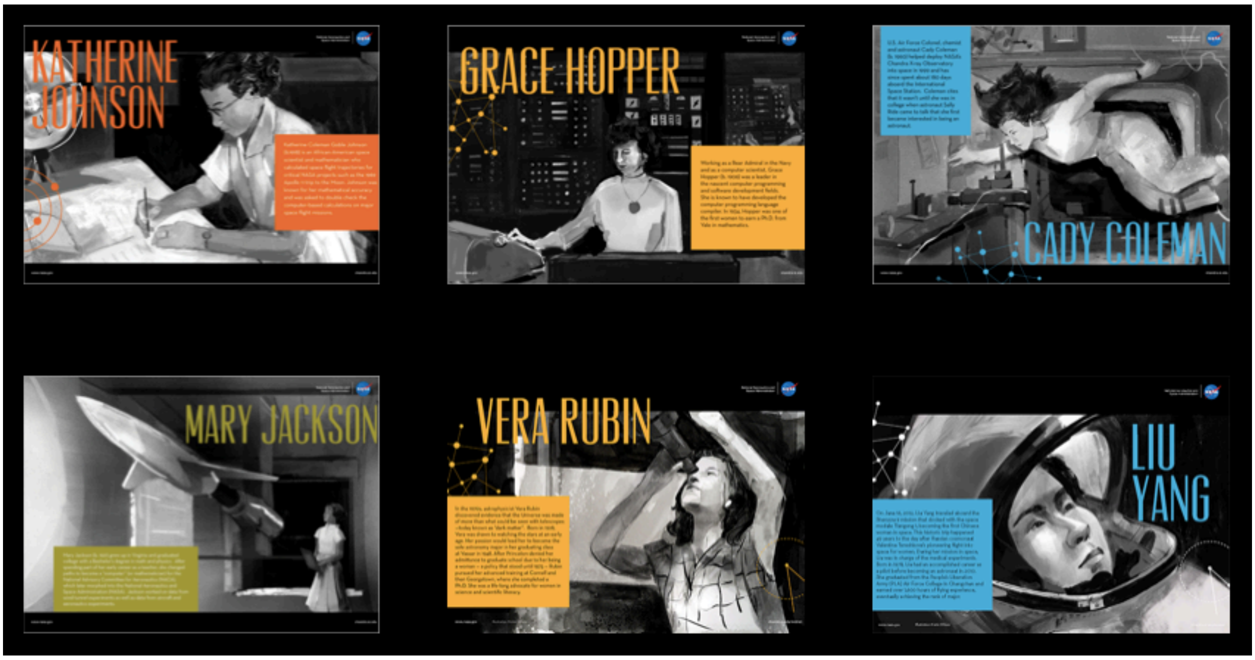
You Name – signature, please: ….. Date:…………..

You Name – please print: ....

Appendix M. Women in STEM handouts

Additional details and downloads are at https://chandra.si.edu/women/





Appendix N. Additional Works Consulted

Chakravorty, D. (2018, June 16). *4 most common 3D printer formats of 2018.* All3DP. https://all3dp.com/3d-printing-file-formats/

Collier, S., Burston, B., & Rhodes, A. (2016). Teaching STEM as a second language: Utilizing SLA to develop equitable learning for all students. *Journal for Multicultural Education*, *10*(3), 257-273. https://doi.org/10.1108/JME-01-2016-0013

Harris, L. J. (1978). Sex differences in spatial ability: Possible environmental, genetic, and neurological factors. In M. Kinsbourne (Ed.), *Asymmetrical function of the brain* (pp. 405-522). Cambridge, England: Cambridge University Press.

Jacklin, C. N., Maccoby, E. E., & Dick, A. E. (1973). Barrier behavior and toy preferences: Sex differences (and their absence) in the year old child. *Child Development*, *44*(1), 196-200. https://doi.org/10.2307/1127703

Kennedy, R. (2017, July 26). Quaker education: What's different about a Friends school? *Boarding School Review*. https://www.boardingschoolreview.com/blog/quaker-education-whats-Different-about-a-friends-school

Kuhlen, T., & Dohle, C. (1995). Virtual reality for physically disabled people. *Computers in Biology and Medicine*, *25*(2), 205-211. https://doi.org/10.1016/0010-4825(94)00039-S

Larivière, V., Ni, C., Gingras, Y., Cronin, B., & Sugimoto, C. R., (2013). Bibliometrics: Global gender disparities in science. *Nature*, *504*, 211-213. https://doi.org/10.1038/504211a

Lemberger, M., Carbonneau, K., Selig, J., & Bowers, H. (2018). The role of social-emotional mediators on middle school students' academic growth as fostered by an evidence-based intervention. *Journal of Counseling and Development*, *96*(1), 27-40. https://doi.org/10.1002/jcad.12175

Lent, R. W. (2005). A social cognitive view of career development and counseling. In S. D. Brown & R. W. Lent (Eds.), *Career development and counseling: Putting theory and research to work* (pp. 101–127). John Wiley & Sons Inc.

Lohman, D. F. (1996). Spatial ability and g. In I. Dennis & P. Tapsfield (Eds.) *Human abilities: Their nature and measurement* (pp. 97-116). Hillsdale, NJ: Erlbaum.

Newcombe, N. (1982). Sex-related differences in spatial ability: Problems and gaps in current approaches. In M. Potegal (Ed.), *Spatial abilities: Development and physiological foundations* (pp. 223-250). New York, NY: Academic Press.

Reback, R. (2010). Schools' mental health services and young children's emotions, behavior and learning. *Journal of Policy Analysis and Management, 29*(4), 698-727. https://doi.org/10.1002/pam.20528

Rose, J., & Steen, S. (2014). The Achieving Success Everyday group counseling model: Fostering resiliency in middle school students. *Professional School Counseling, 18*(1), 28-37. https://doi.org/10.1177/2156759X0001800116

Steen, S., Henfield, M. S., & Booker, B. (2014). The Achieving Success Everyday group counseling model: Implications for professional school counselors. *Journal for Specialists in Group Work, 39*(1), 29-46. https://doi.org/10.1080/01933922.2013.861886

Smith, L. F., Smith, J. K., & Tinio, P. P. L. (2017). Time spent viewing art and reading labels. *Psychology of Aesthetics, Creativity, and the Arts*, *11*(1), 77-85. https://doi.org/10.1037/aca0000049

Smith, J. K., & Smith, L. F. (2001). Spending time on art. *Empirical Studies of the Arts*, *19*, 229-236. https://doi.org/10.2190/5MQM-59JH-X21R-JN5J

Steen, S., Liu, X., Shi, Q., Rose, J., & Merino, G. (2018). Promoting school adjustment for English-language learners through group work. *Professional School Counseling, 21*(1), 1-10. https://doi.org/10.1177/2156759X18777096

Using VRML Files for color 3D printing. (2015). https://www.advancedtek.com/wp-content/uploads/2016/08/Best_Practice_-_Using_VRML_Files_For_Color_-_Web_English_11-15.pdf

Venkatesh, V., Brown, S. A., & Sullivan, Y. W. (2014). Guidelines for conducting mixed-methods research: An extension and illustration. *Journal of the Association for Information Systems*, *17*(7), 435-495.

Versypt, J., & Ford Versypt, A. (2013, June 23-26). Mapping rural students' STEM involvement: Case studies of chemical engineering undergraduate enrollment in the states of Illinois and Kansas. Paper presented at 120th ASEE Annual Conference & Exposition: "How do We Compare?" - Students, Case Studies, and Learning Approaches, Atlanta, Georgia. https://www.asee.org/public/conferences/20/papers/7257/view

Wiersma, W., & Jurs, S. G. (2005). *Research methods in education: An introduction* (8th ed.). Boston, MA: Pearson.