Development and Testing of an Assessment to Measure Spatial Thinking about Enhanced Greenhouse Effect

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DEVELOPMENT AND TESTING OF AN ASSESSMENT TO MEASURE SPATIAL THINKING ABOUT ENHANCED GREENHOUSE EFFECT

By

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A dissertation submitted in partial fulfillment of the requirements for the

Doctor of Philosophy – Curriculum & Instruction

Department of Teaching and Learning
College of Education
The Graduate College

University of Nevada, Las Vegas
August 2016
This dissertation prepared by

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entitled

Development and Testing of an Assessment to Measure Spatial Thinking about Enhanced Greenhouse Effect

is approved in partial fulfillment of the requirements for the degree of

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Abstract

Americans, in general, do not behave in environmentally sustainable ways. We drive cars and fly in planes that emit planet-warming carbon. We purchase food in nearly indestructible packaging that is not recycled or repurposed. We do not consider the environmental impact of the “stuff” stuffed into our grocery and department stores, most of which is made of materials that had to be dug out of the ground, leaving rivers and skies full of pollution in its place. Citizens have a responsibility to understand complex global and local environmental problems. A person’s ability to think about the way that an environmental problem they are tasked with understanding changes over time and space can better prepare them to make sustainable decisions in the face of this complexity. Spatial thinking serves the learner’s ability to understand the impact of environmental actions and should be given a consistent place in environmental education.

Teaching practices and pedagogies that focus on spatial thinking are necessary to learners’ success. In order to know if these strategies are successful, educators need an assessment tool that targets the spatial thinking skills necessary to understanding environmental problems. This dissertation project used a models and modeling theoretical framework to develop and test an assessment of students’ spatial thinking abilities related to the environmental problem of enhanced greenhouse effect.

This assessment was developed from a review of existing spatial thinking literature, research on existing assessments of spatial thinking abilities, and existing assessment of enhanced greenhouse effect. In addition, I interviewed and surveyed experts in science, math, and environmental education to elicit their perspectives on the spatial thinking skills necessary for learners to understand enhanced greenhouse effect. All of this information was synthesized into 14 Central Concepts of spatial thinking for enhanced greenhouse effect. The assessment was developed for students to express their mental models related to these 14 Central Concepts.
The assessment was reviewed and tested by experts related to the project’s content, as well as students from the target population for assessment delivery. It was revised based on feedback and data collect from these groups.

Here I describe my findings, that students are more proficient at modeling simple spatial relationships, one at a time, than modeling more complex relationships; that students understand human-scale spatial relationships related to enhanced greenhouse effect better than very small or very large ones; and that students can associate and correlate spatially distributed features and phenomena to describe enhanced greenhouse effect.

Finally, I describe the ways in which student and expert feedback has informed not only revisions of this assessment specifically, but also to the assessment development process, for better assessment design, when spatial thinking assessments related to other environmental problems are developed in the future.
Acknowledgements

It certainly takes a village doesn’t it? I know it is supposed to be about raising a child, but I think a similar phrase applies to “raising” a dissertation. And I speak with some authority, because I began both of those journeys at the same time. I have been very lucky to have quite a village and family-like support from those around me. Some folks are actual family members, who are contractually obligated to love and support me, but many are chosen family, whether they are colleagues, mentors, friends, or neighbors. We picked each other, and that is important stuff.

I would first like to thank each member of my committee. Dr. MaryKay Orgill has been an amazing mentor and friend throughout this process. I am not sure that she could have escaped me as her mentee (even if she wanted to), after I realized her work ethic with, as well as commitment and generosity to those she mentors, but she did not have to agree to be my co-chair for this project and she did. It is infinitely appreciated. The impact of her guidance on the quality of this project cannot be measured, nor can the impact of her support on my well-being, while completing it. I can only hope to guide my own students with such high expectations, paired with such a high level of support.

Dr. Kent Crippen has offered his guidance, support, and friendship since 2007, when I persuaded him to advise my Master’s degree thesis. He did more than I could have expected then, and has continued such a high level of support, living near and far. When Dr. Crippen relocated to the University of Florida, he did not have to continue as my mentor. He not only stuck with me, but committed to guiding my work and my understanding as much as I needed…which was a lot, sometimes. I have to say that in addition to guiding me academically, he has been a compass for me to know how to value my work, how others should value it, and when to speak up for that when I need to. I have so much gratitude for that lesson.
I am grateful to Dr. PG Schrader for offering his guidance at every step of the project. His patience, as I navigated multiple interests to find the intersection that I truly wanted to explore is appreciated. He moved from advisor to co-chair, as Dr. Crippen departed and was always available, and I know that adopting graduate students is no easy task. His availability and help achieving my academic goals was so important to my completion.

Thanks to Dr. Sajjad Ahmad for his unique perspective as a system dynamicist who works in issues of sustainability. I was so thankful that my Graduate College representative had such important insight to offer and was able to connect my current project to my research interests at the beginning of my graduate career. His engagement and input, really makes me a bit regretful that I did not bother him a bit more during the process. I welcomed and was very grateful for each conversation that we had about my research.

I really think that each dissertation committee should have a colleague representative and mine would be Dr. Cindy Kern. My colleague representative guided my work and my thinking almost as much as my actual committee members, with so many conversations about research and the whole dissertation process. Our online work dates helped keep me on track. Having a friend who preceded me in dissertation completion, who was on call (sometimes against her will) to talk through the good, the bad, and the ugly, kept me sane. I also should thank her family for allowing those conversations during family outings and at dinner time.

I have been very lucky to have been put it the way of colleagues and friends with amazing ideas, work ethics, and maybe most of all, senses of humor. We are passionate about the work that we do, but to really enjoy it, we have to enjoy the people we do it with as well. Dr. Tricia Dutcher, Mr. Kristoffer Carroll, Mr. Ben Jurand, Ms. Carrie Sonders, and Ms. Jennifer Krause make work and research fun. I met Tricia my first day on campus at UNLV in 2007. She shared the experience of raising a baby and a dissertation at the same time and provided so much support as we were both
working through those processes. Kris Carroll is an amazing leader and watching him, I learned how to have confidence in my own leadership abilities. I shared an office and a research project with Ben Jurand and, in that time, I learned what a committed and generous hard worker is. It made my work better Carrie is my partner in crime and my was my support system when I just had to ride my bike to school from Boulder City or needed a cat-sitter during a family emergency. Everyone should have such a friend as they finish a dissertation or just when they are making weird transportation decisions that seem to require a back up plan. Jenn Krause was the first person that I met at UNLV on a very hot, August afternoon, when my feet were bloody from running to class in terrible shoes. We became friends and then roommates, and she remains a phone call away on days where I just need a joke and a kind word. These folks elevate the thoughtfulness and quality of work for everyone that has the pleasure of working with them, including myself. We met as fellow students and I am so happy to have them in my friend family long after.

I am so thankful for the friendship of Elizabeth Grant. Liz was my support as I made the move from Columbus to Las Vegas nine years ago, changing my life, even if she did not know it at the time. She is a hard-working, generous, honest, friend. I have never known someone who feels such an obligation to go the extra mile for everyone around her, when it is the right thing to do. She has provided a listening ear and a helping hand with a crazy work load. I have been lucky to have her in my corner for sixteen years. Wow.

I have to say a huge thank you to our neighborhood family. Whether it was the childcare we traded, a late-night swim or bike ride, or just a patient ear in the middle of the street, Erica and Ben Garcia, Hannah Todd and Los Vivaldo, Kathleen Kahr D’Esposito and Greg Esposito, and Bret and Esther Stanley (and all the associated kiddos) are the best neighborhood crew anyone could ask for. Thank goodness I do not have to do this again after we move, because whoever our new neighbors are will not hold a candle to them. How ever will we go?
Finally, I am immeasurably grateful for my family; the ones who are stuck with me. My parents deserve some thanks for raising me with probably too much praise and encouragement, which resulted in an over-inflated sense of what's possible, a crucial ingredient for Ph.D. completion. My dad puts up with infrequent phone calls and visits and is still an encouraging voice and a listening ear every time I talk to him. He is one of the smartest and most selfless guys I know and I am lucky that I get to know that and be loved by him. Without my mom, the house would have fallen down around us. While I completed this project, she did what she has always done, which is do all of the stuff that I do not want to do, so that I can do the thing that I love. That is true, even if she does not really want to do it either. My cousin Jamie and her family deserve a ton of thanks for making me know that I am loved by family, unconditionally, and for being the voice for me that sometimes I do not have. They also deserve thanks for years of visiting us more than we visit them. I love and appreciate them so.

And most of all, I owe everything that I have been able to do academically and professionally to my guys: Marco and August. I started my dissertation work just a few months after I met my husband…and he still decided I was worth it! Since then, we bought and renovated a house, got married, and started raising a crazy human together. He has been patient and loving through long nights working on papers and research. He has been accepting of family activities that I have missed out on. He has kept a forty hour work week, while I have moved from project to project, following my interests. He has supported us in so many ways and manages to make me laugh every single day through all of the chaos. And my Gus…this kid did not exist when I started this project and now he is a three-year-old explosion of words and creative ideas and love and energy, energy, energy. You might think that raising a baby, into a toddler, into a pre-schooler, while taking on a dissertation would make things so much more challenging, and maybe that is true, but
there is nothing that this kid does not make better, funnier, or truer just by being around. I cannot thank him enough for being my motivation and my inspiration every single day.
# Table of Contents

Abstract .......................................................................................................................... iii  

Acknowledgements ........................................................................................................ v  

Table of Contents .......................................................................................................... x  

List of Tables .................................................................................................................. xiii  

List of Figures ................................................................................................................ xiv  

Chapter 1: Introduction to the Study ............................................................................. 1  
  Purpose of Study ........................................................................................................... 6  
  Theoretical Framework ................................................................................................ 7  
  Importance of the Study ............................................................................................... 8  
  Scope of the Study ....................................................................................................... 8  

Chapter 2: Review of the Literature ........................................................................... 10  
  Environmental Literacy ............................................................................................... 10  
  Understanding Enhanced Greenhouse Effect .............................................................. 13  
  Spatial Thinking across the Sciences ......................................................................... 17  
  Theoretical Framework ............................................................................................... 33  

Chapter 3 Methods ..................................................................................................... 38  
  Overview .................................................................................................................... 38  
  Research Questions .................................................................................................... 38  
  Development Framework ............................................................................................ 40  

Chapter 4: Science and Math Faculty Expert Interviews ........................................ 54  
  Introduction ................................................................................................................ 54  
  Method ......................................................................................................................... 56  
  Results ......................................................................................................................... 62
Stage 4: Did we do something silly? .................................................................................................................. 242

Chapter 10: Discussion and Insights .................................................................................................................. 243

What are experts’ perceptions of the spatial thinking skills necessary to support students’ understanding of enhanced greenhouse effect? .................................................................................................................. 243

How do expert perceptions of the spatial thinking skills that support students’ understanding of enhanced greenhouse effect inform the design of an assessment to measure this construct? ..... 249

What do student-generated models reveal about their spatial thinking skills that support understanding of enhanced greenhouse effect? .................................................................................................................. 255

Themes in students’ spatial understanding for enhanced greenhouse effect. ........................................... 255

Chapter 11 Future Work and Conclusion ......................................................................................................... 259

Validity and Reliability Testing ......................................................................................................................... 259

Student Representations and Their Mental Models ......................................................................................... 263

Conclusion ..................................................................................................................................................... 265

Appendix A: Interview Protocol for Science and Math Faculty Experts ......................................................... 267

Appendix B: Survey Administered to Environmental Education Experts ....................................................... 275

Appendix C: Frequency of Environmental Education Expert Support for General and Contextualized Spatial Thinking Skills .................................................................................................................................................. 290

Appendix D: The First Draft of the STA-En GreenE Assessment ........................................................................ 293

Appendix E: A Second Revision of the STA-En GreenE Assessment .............................................................. 298

Appendix F: Final Revisions of the STA-En GreenE Assessment Informed by Cognitive Interview and Pilot Study .................................................................................................................................................. 304

References ....................................................................................................................................................... 314

Curriculum Vitae ........................................................................................................................................ 327
List of Tables

Table 1 Spatial Thinking Skills Taken from Existing Research and Presented to Science, Math, and Environmental Education Experts .......................................................... 58

Table 2 Spatial Information Needed by Learners to Understand Enhanced Greenhouse Effect ......................... 79

Table 4 Content Themes Identified from Existing Enhanced Greenhouse Effect Assessments ......................... 117

Table 5 Modeling Practices taken from the Literature and Resulting Guidance for the STA-En GreenE ........ 162

Table 3 Frequency of Environmental Education Expert Support for General and Contextualized Spatial Thinking Skills .................................................................................. 290
List of Figures

Figure 1. A temporal and spatial representation of deforestation................................................................. 4

Figure 2. The domain of environmental literacy.................................................................................................. 12

Figure 3. Spatial thinking across scales and across the sciences. ................................................................. 32

Figure 4. Instrument design methodological framework adapted from Standards for Psychological and Educational Assessment and Dillman’s Tailored Design Method................................................................. 41

Figure 5. Instrument design framework for this project .................................................................................. 53

Figure 6. Distribution of faculty participants by science and math discipline......................................................... 60

Figure 7. Concepts related to Theme 1: Greenhouse Gases, with example items. ........................................ 98

Figure 8. Concepts related to Theme 2: Radiation, with example items.................................................... 100

Figure 9. Concepts related to Theme 3: Atmosphere with example items.................................................. 102

Figure 10. Concepts related to Theme 4: Temperature and Climate, with example items......................... 104

Figure 11. Concepts related to Theme 5: Greenhouse Effect, with example items..................................... 106

Figure 12. Concepts related to Theme 6: Impacts, with example items....................................................... 108

Figure 13. Concepts related to Theme 7: Misconceptions and Opinions, with example items.............. 109

Figure 14. Example memorization type selected response items from existing enhanced greenhouse gas assessments. .............................................................................................................................................. 111

Figure 15. Example of a selected response item from existing enhanced greenhouse gas assessments that requires spatial thinking to answer ........................................................................................................ 112

Figure 16. Example of an open response item from an existing enhanced greenhouse gas assessment for which it is undetermined if spatial thinking is necessary ................................................................. 113

Figure 17. Mental rotation items taken from existing assessments................................................................. 128

Figure 18. Spatial perception items taken from existing assessments.............................................................. 130

Figure 19. Spatial visualization items taken from existing assessments.......................................................... 133
Figure 20. Example item testing students’ ability to use a spatial model........................................ 135

Figure 21. Verma’s 2015 assessment item testing several spatial thinking abilities ...................... 138

Figure 22. The starting point of STA-En GreenE development ................................................. 147

Figure 23. Descriptions of general spatial thinking abilities gathered from the literature ........... 149

Figure 24. Existing assessments’ content combined with expert perceptions to create central concepts ........................................................................................................................................ 151

Figure 25. 14 central concepts for spatial thinking about enhanced greenhouse effect. .......... 154

Figure 26. Item development process for Central Concept #4 .................................................. 156

Figure 27. The development process of Central Concept 1 ....................................................... 165

Figure 29. Methodological framework adapted from Standards for Psychological and Educational Assessment and Dillman’s Tailored Design Method. ............................................................................................................................... 168

Figure 30. Changes made to Part 2: Radiation and Greenhouse effect model space ................... 174

Figure 32. Model Space #1: Carbon at home ............................................................................. 194

Figure 33. Student representations of carbon dioxide emitters .................................................. 199

Figure 34. Model Space #2: Carbon dioxide in the year 1500 .................................................. 202

Figure 35. Modeling Space #2, Carbon dioxide in the year 1500 ............................................. 204

Figure 36. Student representations of carbon dioxide emitters, absorbers, and movement of carbon dioxide in the atmosphere in Modeling Space #2 ................................................................................................................................. 207

Figure 37. Model Space #3: Carbon dioxide in the year 2000 .................................................. 210

Figure 38. Student-generated models of carbon dioxide emissions, absorption, and movement in the atmosphere in the year 2000 ................................................................................................................................. 212

Figure 39. Student representations of the accumulation of greenhouse gases in the atmosphere.... 214

Figure 40. Model Space #4: Radiation and the Greenhouse Effect in the Year 1500 ............... 218
Figure 41. Student representation of radiant energy moving from the Earth to the sun, being reflected from the surface of the Earth and being trapped in Earth’s atmosphere. ........................................ 221

Figure 42. Student-generated models of the interactions of greenhouse gases and radiant energy in Earth’s atmosphere in 1500 and the year 2000 .......................................................................................... 226

Figure 43. Revision of assessment development process for gathering information sources .......... 253
Chapter 1: Introduction to the Study

Americans, in general, do not behave in environmentally sustainable ways. We drive cars and fly in planes that emit planet-warming carbon. We purchase food in nearly indestructible packaging that is not recycled or repurposed. We do not consider the environmental impact of the “stuff” stuffed into our grocery and department stores, most of which is made of materials that had to be dug out of the ground, leaving rivers and skies full of pollution in its place. Our environmentally impactful decisions are more complex than they may seem. There are “social, economic, and environmental issues resulting from interactions of human activities with the global ecosystem” (Hollweg et al., 2011, p. 1). Accordingly, people are increasingly asked to evaluate environmental policies and make decisions to minimize their own environmental impacts (Bozdin & Anastasio, 2006). Citizens have a growing responsibility to understand complex global and local environmental problems.

Previous studies have found a group of interrelated factors correlated with pro-environmental behaviors. These factors fall into two categories: cognitive and affective. Two cognitive factors are knowledge of environmental problems and knowledge of pro-environmental behaviors (Hines, Hungerford, & Tomera, 1987). Knowledge of the environmental problems and the behaviors that can change them requires an understanding of the scientific phenomena that underlie the problem. Moreover, environmental problems are not explained by just one science content area at one scale (i.e., biological understanding at the cellular level). Rather, many draw upon several science disciplines, across all scales, adding to the challenge of effectively educating citizens about their place in these complex systems.

A person’s ability to think about the way that an environmental characteristic changes over time and space—in other words, their spatial thinking ability—can better prepare them to make sustainable decisions in the face of this complexity. While it is widely agreed upon that spatial
thinking is not just one ability, but a collection of abilities and ways of thinking, a guiding idea is that spatial thinking involves thinking about the way that objects move and the spatial relations between and within objects of all scales (Shipley & Gentner, 2013). For example, understanding how a particular density of a microscopic water pollutant can lead to a decrease in aquatic life, which may lead to a decrease in other life forms that rely on the impacted organism for their food source, requires relating spatial characteristics of variables at multiple scales. Similarly, understanding how visible features, like the density of organisms living in a region, and the less visible characteristics, like a pattern of ground temperatures across a landscape, are related to each other requires thinking about patterns and relating them to each other.

Some of the most important advances of human knowledge in science are the result of extending human abilities of spatial perception to the very small, through the development of the microscope, and the very large, through the development of the telescope. Many of the most exciting scientific discoveries, like the study of emergent diseases or black holes, continue to occur at either end of the spatial spectrum (Tretter, Jones, & Minogue, 2006). The National Research Council’s Framework for K-12 Science Education: Practices, Crosscutting Concepts and Core Ideas (2012a) has recognized “scale, proportion and quantity” as a concept that benefits learner content understanding across science disciplines (National Research Council, 2012a). While scale can be a lens for understanding content related to size and distance, time, weight and temperature (Jones, Tretter, Taylor, & Oppewal, 2008) in a number of science disciplines, this study is focused on understanding spatial relationships across scales and specifically, those supporting the study of the environment.

Educators are developing tools and pedagogies to improve learners’ understandings of environmental issues. While, in many cases, the focus of these tools and pedagogies is not explicitly on spatial thinking, the design of the lesson and activities within them serve spatial thinking goals. For example, lessons attempting to teach principles related to greenhouse gas accumulation and
climate change have utilized computer simulations, as well as experiences in outdoor environments. A simulation called “The Climate Challenge: Our Choices,” developed in a collaborative effort between the Schlumberger Excellence in Education group, The Sustainability Initiative, and the Society of Organizational Learning, represents greenhouse gas emissions, absorption, and accumulation as a bathtub faucet, drain, and bathtub, respectively. This simulation allows users to make decisions to increase, decrease, or level off greenhouse gas emissions to view the accumulation of greenhouse gases, represented as water in a bathtub. This simulation uses the learner’s spatial understanding of accumulation related to a filling bathtub to make an analogy to something that is impossible to see: greenhouse gas emission (Sterman & Booth Sweeney, 2002). Outdoor and experiential education programs have endeavored to teach the same subject matter through experiences in the outdoors. One example is a climate change education program in a botanical garden in the Midwestern United States, where the spatial experience of moving around and interacting with distances and spatial relationships in a natural environment of greenhouse gas absorbers (plants) was found to be beneficial to learners’ understanding of how plants remove greenhouse gases from the atmosphere (Sellmann & Bogner, 2013). These lessons include instruction on spatial relationships in environmental education without making them the focus on the lesson.

To further illustrate the importance of recognizing spatial relationships to understanding environmental problems, refer to Figures 1 below. Figure 1a depicts the change in area of Brazilian rainforest over a period of fifteen years. The change is displayed as a line across an XY plane, with time on the X-axis and area on the Y-axis. The line gets closer to the X-axis as it moves to the right, representing a decrease in the number of acres of rainforest. Figure 1b shows the same change, over a slightly longer time period and represented by satellite images. The viewer can see the amount of green-covered land decrease as years pass. Land use patterns change dramatically, as viewed from
above. The image on the right in Figure 1 adds a spatial dimension to the change in rainforest area over time. For novices to environmental information, representation such as that shown in Figure 1b answer more questions than a line graph alone. Learners who are taught to think spatially about deforestation will not only be able to understand the rate at which the forest is being destroyed, but can also understand in what pattern that destruction takes place, what the transition looks like from forested area to deforested area, and on what scale the action is occurring. This provides understanding for richer discussions about the impact of deforestation on a natural environment and how to manage it. Because of the spatial nature of environmental problems and the benefit that a spatial understanding may provide to managing them, environmental educators should make spatial thinking a more explicit focus, to create a framework for understanding phenomena at multiple scales and to connect learners to the environmental problems they observe.

![Figure 1. A temporal (left) and spatial (right) representation of deforestation (NASA/Goddard Space Flight Center Scientific Visualization Studio, 2001, 1992, 1986, 1975).](image)

Given the importance of spatial thinking abilities to learners’ understanding of the impacts of environmental problems, my initial goal for this research included the development of lessons that make spatial thinking an explicit focus in environmental education. As the program has developed, however, the absence of an instrument to measure the change in spatial thinking that
might result from the implementation of such lessons has made measuring the effectiveness of those lessons a challenge. How would we know if the lesson or curriculum design has been effective?

While a spatial thinking assessment useful to measuring skills supporting an understanding of environmental issues specifically does not exist, general spatial thinking abilities and abilities supporting other content areas have been assessed and reported on in the literature. For example, Jee, Genter, Forbus, Sageman, and Uttal (2009) used learner sketches to assess learners’ understanding of spatial relationships between geologic structures like plates or rock strata. Lee and Bednarz (2012) developed a multiple choice and task-based instrument to measure learners’ general spatial thinking skills, like the ability to overlay maps in order to solve a problem or the ability to comprehend orientation and direction. Stieff, Ryu, Dixon, and Hegarty (2012) asked learners to solve spatially-focused organic chemistry problems and then used a strategy choice questionnaire for learners to report what spatial strategy they used to solve the problem.

While progress like this, made in other content areas, may inform our efforts, none of these studies address spatial thinking skills in the context of environmental problems; and most of them work within a narrow range of spatial scale. Research is needed to identify and articulate how spatial thinking skills across scales are applicable to environmental problem-solving. An original assessment is needed to measure changes in these important skills as new lessons are developed to improve learners’ environmental literacy. Environmental literacy is described as

knowledge and understanding of a wide range of environmental concepts, problems, and issues, a set of cognitive and affective dispositions, a set of cognitive skills and abilities, and the appropriate behavioral strategies to apply such knowledge and understanding in order to make sound and effective decisions in a range of environmental contexts. (Hollweg et al., 2011, p. 3-1)
An assessment to measure spatial thinking abilities relevant to this broad range of knowledge and affective dispositions would be an endless undertaking and probably an infinitely long assessment. Therefore, the focus of this study will be to develop an instrument for one content area, with the intention that a similar development process may be used in the future to develop assessments for other environmental science concepts and their related spatial thinking abilities. The focus for this study is spatial thinking about enhanced greenhouse effect, chosen for its prominent place in recent environmental discussion and for the spatial relationships across scales that are important to its comprehension.

**Purpose of Study**

The purpose of this study was develop and evaluate a tool to assess learners’ spatial thinking about enhanced greenhouse effect. The development was informed by both a review of existing literature describing existing tools that measure spatial thinking and enhanced greenhouse effect, as well as interviews and surveys with experts in various science disciplines and in environmental education. The resulting assessment will task learners with creating models to make their spatial understanding explicit. Therefore, the research questions are:

1. What are experts’ perceptions of which spatial thinking skills are necessary to support learners’ understanding of enhanced greenhouse effect?

2. How do expert perceptions of the spatial thinking skills that support learners’ understanding of enhanced greenhouse effect inform the design of an assessment to measure this construct?

3. What do learner-generated models reveal about the spatial thinking skills that support their understanding of enhanced greenhouse effect?
Theoretical Framework

The literature on spatial thinking and reasoning describes a range of abilities across scales. From the mental rotation of molecules (Linn & Peterson, 1985), to the use and creation of maps (Gersmehl & Gersmehl, 2006), the named skills suggest the making and using of a variety of models. For example, the mental rotation of molecules requires the thinker to visualize the elements of the molecules, then animate the molecule into action to see its characteristics. Creating a map requires the learner to create a model from information they are given or gather.

Since improving these modeling abilities, situated in the context of improving environmental literacy, is the overarching goal of this research program, then an assessment of learners’ spatial thinking abilities in this content area should measure their ability to understand, use, and create these types of models. Therefore, a models and modeling theoretical framework guided the development and implementation of the assessment.

A models and modeling theoretical framework is appropriate for the development of an assessment of spatial thinking for enhanced greenhouse effect for several reasons. First, spatial thinking abilities, as described in the literature, require learners to model spatial information in order to represent, evaluate, and synthesize that spatial information. Mental modeling of spatial information occurs when learners form and manipulate objects in their mind’s eye, when they imagine maps from verbal descriptions (Gersmehl & Gersmehl, 2006), and when they mentally rotate 2- and 3-dimensional objects (Linn & Peterson, 1985). Conceptual modeling occurs whenever learners make their understanding explicit, whether they are comprehending or using spatial hierarchies, comparing maps (Gersmehl & Gersmehl, 2006), orienting themselves to real world frames of reference, or manipulating spatial information to problem-solve (Linn & Peterson, 1985).

In addition, one of the objectives of using a models and modeling theoretical framework is that it enables learners’ representations of a complex system for an understanding of the problem
and the solution variables. This objective aligns closely with North American Association for Environmental Education’s (NAAEE) goals for an environmentally-literate populace: “knowledge and understanding of a wide range of environmental concepts, problems, and issues” (Hollweg et al., 2011, p. 2-3). By employing a models and modeling lens, we adopt a problem and solution-oriented view of spatial thinking for environmental literacy that uses learner representations of spatial information over time and instruction to measure changes in their understanding.

**Importance of the Study**

The development of an instrument to measure learners’ spatial understanding of environmental problems is an important first step toward the development of tools to improve such understanding. An instrument specific to this field and this purpose does not exist; therefore, there is no way to truly know if an intervention to improve spatial understanding useful to enhanced greenhouse effect is effective. If it is true, and I think it is, that understanding the way that an environmental characteristic changes over time and space can impact our willingness to act in environmentally-beneficial ways, then developing ways to improve one’s spatial understanding should be a focus in environmental education. The lessons, experiences and teaching strategies to be developed will need to be tested for their effectiveness. The attempt here is to provide a measure to do that for one important and complex environmental issue: enhanced greenhouse effect.

**Scope of the Study**

The instrument developed was administered to adult learners enrolled in an introductory environmental science course at a community college in the urban Southwestern United States. The population assessed was selected for two reasons. First, they were a population of convenience, as they were enrolled in four live sections of Introduction to Environmental Science for which I was the instructor. Second, it was important that the participants in this study were novices, as it is the population that will be targeted with interventions in future studies. It is important to know the
language they understand and what they will be able to demonstrate. The instrument’s language and content was designed for that population. While future revisions may address the needs of younger populations, or audiences in informal learning environments, that was beyond the scope of the current study.

The group of experts consulted in the development of the current instrument are university professors at a large university in the Southwestern United States, interviewed face-to-face, and members of a national professional organization for environmental educators, contacted by email. I make the assumption that their expertise has been developed and informed by studying in their field, in their part of the world. Since environmental problems are regionally different, there is potential for regionally different expertise.

**Summary**

Human beings are increasingly asked to understand and make personal and policy decisions about complex environmental issues. In many cases, the decisions we make are not environmentally sustainable ones. Of the cognitive factors known to be correlated with pro-environmental behaviors, knowledge of environmental problems and knowledge of environmental action can both benefit from a spatial understanding of the environment. With this in mind, lessons and teaching strategies should be designed focusing on spatial thinking skills for environmental literacy. Knowing if these lessons are effective in changing learners’ spatial thinking abilities requires an instrument that measures spatial skills specific to the environmental issues being studied. Such instruments do not exist. The aim of this project is to develop an assessment that measures spatial thinking skills that serve a learner’s ability to understand one environmental issue, enhanced greenhouse effect, so that moving forward, effective lessons can be developed to benefit sustainable decision-making.
Chapter 2: Review of the Literature

The main purpose of this project is to develop an assessment that measures spatial thinking abilities that support understanding enhance greenhouse effect. The assessment was developed to elicit learners’ mental models of the spatial relationships between variables within this environmental problem. In the future, it may be used to measure the effect of an intervention(s) on learners’ spatial thinking related to the topic of enhanced greenhouse effect. To situate the context of the assessment and the perspective taken in its development, it is necessary to review and elaborate upon the content and constructs that frame it. This literature review aims at answering a few questions. First, what is the current understanding of the content area that spatial thinking is intended to serve? In other words, what is it to be environmentally literate with regard to enhanced greenhouse effect? Next, as previously mentioned, spatial thinking is not one ability. It has been described in the literature as being made up of several interrelated abilities. So, what are those abilities and how might they improve an individual’s understanding of enhanced greenhouse effect? Finally, if models and modeling is the theoretical framework that shapes the design of the instrument, the expected participant response, and the way that the responses are evaluated, what are its fundamental guiding principles? These questions will be addressed below, to better situate the study’s design.

Environmental Literacy

The first discussion of environmental literacy was made by Roth in 1968 (Roth, 1968). Since that time, there have been many revisions to Roth’s original ideas in an attempt to characterize what an environmentally literate person does and understands.

In 1978, at the Intergovernmental Conference at Tbilisi, UNESCO further defined environmental literacy goals for the general public (Hollweg et al., 2011). Their definition included five types of competence: awareness (knowing of environmental issues), knowledge (understanding the principles that underlie environmental issues), attitudes (a positive affect toward the
environment), skills (pro-environmental abilities), and participation (willingness to engage in pro-environmental behaviors). This definition of environmental literacy shaped the design of environmental education initiatives for years to come. As environmental education developed during the 1990s, so did the community’s understanding of what it means to be environmentally literate.

The original five types of competencies defined by UNESCO were expanded to include environmental problem-solving (an understanding of behaviors that will benefit the environment), environmental sensitivity (a concern for environmental issues), and self-efficacy (an understanding of one’s ability to affect environmental issues) (Hollweg et al., 2011).

Most recently, the NAAEE, supported by previous work in environmental education and environmental literacy, described environmental literacy as being comprised of four components:

- knowledge and understanding of a wide range of environmental concepts, problems, and issues,
- a set of cognitive and affective dispositions,
- a set of cognitive skills and abilities, and
- the appropriate behavioral strategies to apply such knowledge and understanding in order to make sound and effective decisions in a range of environmental contexts. (Hollweg et al., 2011, p. 3-1)

Each component encompasses a range of characteristics that an environmentally literate person will have. An environmentally literate person will know about physical and ecological systems; social, cultural, and political systems; environmental issues; multiple solutions to environmental issues; and citizen participation and action strategies. They will be disposed to participate in understanding environmental problems and environmental decision-making. An environmentally literate person is competent in the identification and analysis of environmental problems when confronted with information about the affected environment. Finally, environmentally literate people act in ways that affect the environment in a positive way. These themes broadly correlate with those identified in the UNESCO document, as well as the framework developed by Roth (1992).
Figure 2 below shows the four components described above as they define the domain of environmental literacy. It also demonstrates the subcomponents of each theme.

![Figure 2. The domain of environmental literacy. Reprinted from Developing a Framework for Assessing Environmental Literacy (p. 3-2), by Hollweg, K.S. et al., 2012, Washington, DC: North American Association for Environmental Education. Copyright 2011 by the North American Association for Environmental Education (NAAEE). Reprinted with permission.](image)
For the purposes of this research, I adopted the NAAEE’s description of environmental literacy for several reasons. First, the NAAEE’s work is not independent of research that came before. It synthesizes and builds upon decades of research in environmental education and environmental literacy. Second, the NAAEE is the primary professional group for environmental education practitioners and has spear-headed efforts to advance environmental literacy. Finally, the NAAEE’s description of environmental literacy goes further than previous frameworks in breaking down the broader components. This will become important as we begin to think about how spatial thinking serves environmental literacy and learners’ understanding of enhanced greenhouse effect.

Understanding Enhanced Greenhouse Effect

**Climate literacy.** For the purposes of this project, and based on early challenges attempting to define spatial thinking for environmental issues as a whole, this study focused on developing an assessment to measure learners’ spatial thinking abilities related to an example environmental problem: specifically, enhanced greenhouse effect. Many discussions of enhanced greenhouse effect are embedded in the larger discussions of global climate change as the outcome of the accumulation of greenhouse gases trapping more infrared radiation in Earth’s atmosphere (National Research Council, 2011a). As the global scientific and policy communities support global climate change as real and accept the role that human-generated emissions have on the global increase in temperature (Intergovernmental Panel on Climate Change, 2007; National Research Council, 2011a; National Research Council, 2012b), there is an ever-growing need for education and communication tools to engage the public in informed decision-making and improve their understanding of this complex issue (Leiserowitz, 2007; National Research Council, 2011a; Sterman & Booth Sweeney, 2002).

Understanding of enhanced greenhouse effect as a part of global climate change is critical to creating a “climate for change” (Leiserowitz, 2007). There are a multitude of channels by which the public can participate in climate change education and communication, including formal schooling,
from early childhood to post-graduate education (Leiserowitz & Barstow, 2010). In the formal science education community, the importance of climate change education is evidenced in the inclusion of climate change in the benchmarked standards for K-12 education in the Next Generation Science Standards. Specifically, climate change is included in the earth science and human impact standards (Shea, Mouza, & Drewes, 2016). Finding educational solutions to understanding the complexity of climate change and enhanced greenhouse effect is a priority. A first step is a discussion of the goals of climate change education, as well as the challenges to its implementation.

There have been two major attempts to articulate goals for climate literacy and climate change education most comprehensively. First, a workshop sponsored by the National Oceanic and Atmospheric Association (NOAA) and the American Association for the Advancement of Science (AAAS) began the work of creating a guide to describe the essential understandings of climate science and global climate change. The result was a booklet entitled, *Climate Literacy: The Essential Principles of Climate Science* (2009). The publication articulates 7 principles supported by concepts that contributors deemed essential to a person’s understanding of their influence on climate and climate’s influence on them. The seven essential principles are:

1. The Sun is the primary source of energy for Earth’s climate system.
2. Climate is regulated by complex interactions among components of the Earth system.
3. Life on Earth depends on, is shaped by, and affects climate.
4. Climate varies over space and time through both natural and man-made processes.
5. Our understanding of the climate system is improved through observations, theoretical studies, and modeling.
6. Human activities are impacting the climate system.
7. Climate change will have consequences for the Earth system and human lives. (Climate
We can see many of the seven principles and their supporting concepts in the enhanced greenhouse effect “story.” Understanding enhanced greenhouse effect employs an understanding of the sun’s energy and its interaction with Earth’s system; the difference between greenhouse effect and enhanced greenhouse effect and the necessity of the greenhouse effect on Earth; the variables in Earth’s system, natural and man-made, that affect Earth’s system; and the resulting temperature increase that is the result. While understanding enhanced greenhouse effect is understanding just a piece of the climate change system and its impacts, it is foundational to learners’ understanding of how they impact the climate system. When we consider what it means to be literate in a subject and how general environmental literacy is described, much of what is described with reference to climate literacy fits with the environmental knowledge component of literacy, or the foundational principles that a person should understand to be literate in this subject.

A second important discussion of climate change education exists in the National Research Council’s, *Climate Change Education: Goals, Audiences, and Strategies: A Workshop Summary* (2011b). This document summarizes work that was done at a workshop convened by the Board on Science Education (BOSE), in collaboration with the Committee on Human Dimensions of Global Change and the Division on Earth and Life Studies, of the National Research Council (NRC) on October 21 and 22, 2010. It articulates participants’ ideas about climate change educational goals and outcomes for various audiences. While a definitive list of priorities for climate change education was not the result of the workshop, the workshop summary discusses some of climate change education’s challenges and goals for various audiences from the social, environmental, and policy perspectives:

improving understanding of climate-related issues (e.g., climate systems, climate change, and the impacts of climate change), raising awareness of the potential strategies for limiting the impacts of climate change, encouraging specific action to minimize human impacts and
adapt to the changing climate, and helping individuals and groups to make climate-friendly choices. (National Research Council, 2011, p. 52)

The summary also acknowledges that climate change education is somewhat unique even among environmental issues, in that it is an especially politically charged issue that includes stewardship as a part of its literacy plan. Therefore, the NRC divided its educational goals into two groups: those that target cognitive objectives (what people should understand about climate change) and those that target affective objectives (goals that inspire learners to act in sustainable ways). These two groups of goals can be supportive of each other. By contextualizing enhanced greenhouse effect in issues of import and familiarity to the learner, educators can address both the learners’ affect toward issues of climate change, such as interest and attitude, and their cognitive factors, such as knowledge of the issue and knowledge of solutions (Hines, Hungerford, & Tomera, 1987). Therefore, the National Research Council recommends

messages and information tailored to the specific needs, values, attitudes, and interests of the audience; engagement in active learning experiences as an individual and as part of a group; and interactive and ongoing interactions to sustain relationships. (NRC, 2011, p. 57)

Taken together with Climate Literacy: The Essential Principles of Climate Science (2009), the recommendations listed in Climate Change Education: Goals, Audiences, and Strategies: A Workshop Summary (2011) can help environmental educators envision an action plan to help learners develop correct understandings of climate change and, specifically, of enhanced greenhouse effect.

**Challenges to understanding climate and enhanced greenhouse effect.** Social and political challenges to understanding enhanced greenhouse effect and climate change add to the
complexity of the cognitive challenges learners already experience with this subject. The phenomenon is invisible, and while its impacts might be visible, they change very slowly over time and space, making them difficult to perceive. Learners have difficulty understanding how carbon emissions and absorption increase and decrease carbon in the atmosphere (Sterman & Booth Sweeney, 2002). Greenhouse gases, perhaps because of their invisibility, are also often conflated with other common air pollutants, like smog, which are visible (Gautier, Duetch, & Rebich, 2006). In addition, enhanced greenhouse effect and its impacts are often confounded with environmental problems related to the hole in the stratospheric ozone layer. Learners most often will describe that a hole in the ozone layer as the mechanism by which excess radiation enters Earth’s atmosphere, increasing Earth’s temperature above normal levels (McCuin, Hayhoe, & Hayhoe, 2014; Shea et al., 2006). Because of the importance, immediacy, and persistent misconceptions related to the problem of enhanced greenhouse effect and climate change, it is an important environmental issue to address with this piece of research. Because education about climate change and enhanced greenhouse effect requires strategies that impact learners’ affective factors and cognitive understanding, it is appropriate to support this education with spatial thinking skills. Spatial thinking and its relevance to both climate change education’s affective and cognitive factors will be discussed in the next section.

Spatial Thinking across the Sciences

An environmental problem can be characterized as a variable changing within an ecosystem. In other words, environmental problems change in space and over time. The example of enhanced greenhouse effect includes an accumulation of greenhouse gases in the atmosphere, which begins as the dispersion of greenhouse gas molecules from an emission source and their accumulation to absorb infrared energy, reflected from the Earth. The more densely accumulated the carbon molecules are, the more energy is absorbed. As energy is absorbed, temperature increases, precipitation patterns change, water molecules become less dense in the ocean, and vegetation zones
move northward on the globe. These are just a few changing spatial relationships over time that might be discussed in the context of just one environmental impact.

If we consider how to help learners understand a problem like enhanced greenhouse effect through this the lens of environmental literacy described previously, we must take into account the fact that learners’ knowledge, dispositions, competencies, and behaviors affect their understanding of that problem. Spatial thinking serves environmental literacy by adding to a learner’s knowledge of the origins and impacts of a problem. It can affect disposition because it allows the learner to understand how an environmental problem is changing over time and space and how they might impact the environmental problem through their actions. Spatial thinking can affect a learner’s competency by allowing them to envision and predict the behavior of an environmental variable over time. It can affect a learner’s environmental actions by changing their understanding of cause and effect within an environmental system.

In order to better understand how spatial thinking across scales is important to environmental literacy, it is necessary to examine the individual competencies, skills, and abilities that are a part of spatial thinking and, specifically, to examine those spatial skills that would benefit a learner’s environmental literacy. Therefore, a systematic review of the existing scholarly literature on spatial thinking in the sciences was conducted. Initially, resources were gathered from two databases: ERIC and Education Full Text. Both of the phrases “spatial thinking” and “spatial understanding” were searched in combination with “science education,” “environmental education,” and “models.” The search resulted in 117 publications. The focus of this literature review is to gather perspectives on how spatial thinking is defined and what abilities contribute to that definition. Therefore, the literature base for this section does not include empirical studies, testing the effect of interventions on spatial thinking. Rather, here the focus is on the attempts that have been made over the years to define spatial thinking to move the field further toward experimental studies. The literature base was
narrowed by including only papers that included “spatial thinking” or “spatial understanding” in the title or abstract, to ensure they were a central part of the paper. Excluding papers that did not explicitly define spatial thinking or understanding further narrowed the literature review to 20 publications.

The ideas presented here are a synthesis of the findings, which consist of three broad categories of research. The most recent body of research focuses on the spatial relationships that learners understand best and how they move to either end of the scale spectrum. The focus is on spatial thinking between scales. It is useful to start here, since it is this movement to scales that we cannot directly perceive that future interventions may influence, and particularly important for understanding enhanced greenhouse effect because so many of the related interactions are microscopic (the interaction of a carbon dioxide molecule with infrared radiation) or global (sea level rise). The second body of research, occurring since around the beginning of the 21st century, focuses on spatial understanding related to a global or at least regional scale, or phenomena too large to perceive directly with human senses. An example might be the mapping of characteristics across a landscape. The third category, and the earliest research on spatial thinking reported here, was published mostly in the 1990s and focused on spatial understanding as it pertained to objects and distributions from the microscopic scale to the human-scale; that is, phenomena too small to perceive directly and phenomena that are perceivable with human senses. All three bodies of research are described in the sections that follow.

Research about spatial thinking across scales. Scale is the unifying theme between the spatial thinking skills identified in the literature. Understanding scale is a critical component of spatial understanding, and scale can be seen as an organizational framework for other spatial thinking abilities.
Tretter, Jones, Andre, Negishi, and Minogue (2006) argue that there is a growing need for understanding phenomena on scales much larger and much smaller than what we are able to directly perceive. In fact, they describe the American Association for the Advancement of Science Project 2061 Benchmarks for Science Literacy (1994) four common themes in science curricula that create coherence and connections across subjects and grade levels: systems, models, constancy and change, and scale. Of those themes, the topic of scale is the only one that does not have a significant body of supporting research. To develop and implement interventions to increase learners’ ability to understand concepts at multiple scales and their ability to move between scales, an understanding of their cognitive processes related to this theme is required.

To this end, Tretter et al. (2006) assessed learners’ abilities to identify the absolute and relative sizes of 26 objects differing in size, from atomic particle-scale to galactic-scale. Their subjects were elementary learners, middle school learners, high school learners and doctoral learners. The purpose of their study was to understand how learners conceptualize size and scale and whether age or formal training had any bearing on a person’s conceptualization. Doctoral learners had formal training in biology, nanoscience and astrophysics, all fields that require practice in spatial thinking at scales far removed from the human scale.

Learners were most capable of identifying relative and absolute size at spatial scales closest to that of a human being; that is, at scales that the learners would be able to directly perceive. The results also showed that learners were better able to identify objects’ relative sizes, rather than their absolute sizes. Experts (doctoral learners) were more accurate in their relative categorization than lower level learners. Elementary learners found the most difficulty in relatively ranking the size of microscopic objects, like atoms and cells. The findings of this study point out the role that practice plays in a person’s ability to understand the scale and size of an object of group of objects. Doctoral learners of biology were more proficient ranking relative sizes of microscopic objects and
astrophysics learners were more proficient at ranking the relative sizes of very large objects because they used these abilities in their work. It is not that upper level learners had a more advanced innate understanding of spatial objects, but that they would have had more practice with objects that exist at unperceivable scales. These findings tell us that interventions designed to impact spatial thinking abilities that support understanding environmental issues at very large and very small scales can be effective in making a change.

Another study conducted by Tretter, Jones, and Minogue (2006) asked learners to identify objects that fell into given scale categories that ranged from nanometers to one billion meters. Again, learners’ accuracy was highest in categorizing objects of sizes close to a human scale and decreased as they moved toward the very large or very small scales. Another finding of the study related to the objects which learners categorized incorrectly. If the scale category was “microscopic,” the incorrectly categorized object would be much larger than the microscopic scale; if the scale category was “galactic,” the incorrectly categorized object would be much smaller than the galactic scale. In either case, the incorrectly categorized objects were closer to the human scale than the category in which they were placed. This provides more support for the idea that learners are more familiar with spaces and sizes closer to those they are able to perceive.

Finally, a study conducted by Jones, Tretter, Taylor, and Oppewal (2008) used the same classification of scale and size activity that was used in the previous study to test teachers’ concepts about scale and space. Teachers’ understandings followed the same patterns as seen in the previous studies. While the teachers were successful in categorizing objects at the human-scale, they were less successful in categorizing objects at scales that could not be perceived directly. The body of research presented here provides robust support for the idea that spatial understanding is best at a human scale, without practice at other scales. The following sections will discuss first, research on microscopic and human-size space, and then, more recent work on geospatial understanding.
Early studies in spatial understanding: microscopic and human-scale space.

Generally, early research in spatial thinking focused on skills and abilities useful to understanding phenomena at the very small (microscopic) to human-sized end of the spatial scale. These skills are most useful to content areas like chemistry or microbiology or to “everyday life” activities, like navigating a neighborhood or determining one’s location from a particular viewpoint. The abilities that fall broadly into these categories, as they have been described in the literature, are described below.

Saurino, Saurino and See (2002) state that spatial intelligence is “the ability to manipulate and create mental images in order to solve problems” (p. 3). This broad definition serves the sciences, because while scientific disciplines have very different applications for spatial understanding, they all utilize the ability to analyze and synthesize visual data to create a mental model for problem solving.

Human beings develop a folk understanding of psychology through social and personal interactions that guides our decision-making. We also develop a folk understanding of physics that guides our interactions in the physical world. Likewise, we develop an understanding of spatial relationships, through our interactions with the physical world, that guides other types of decision-making. For example, being able to detect movement relative to a stationary background and using depth perception to determine our location has served hunting purposes and avoiding danger (Mathewson, 1999). These are human-scale spatial thinking abilities. They are used in situations on the scale of things that humans can directly perceive. Many of these spatial thinking abilities are general and can be transferred to unfamiliar situations.

Mathewson (1999) describes visual-spatial understanding as having two components:

- vision — the process of using the eyes to identify, locate, and think about objects and orient ourselves in the world, and “imagery”—the formation,
- inspection, transformation, and maintenance of images in the “mind’s eye” in the
absence of a visual stimulus. (p. 34)

Vision is used to learn about, navigate, and make decisions in spaces that are human-scale. It requires analysis of direct perception. Imagery uses mental pictures to manipulate visual perceptions or things that cannot be perceived to make inferences and create an instructive image in our mind. One may be able to imagine something they have never seen, like the structure of a molecule, if they understand principles of symmetry and chemical rules. They might also be able to imagine the seasonal changes of a landscape they are looking at directly. This type of understanding can be useful to environmental decision-makers. For example, one might be able to deduce the direction of water flow, given a map of the local watershed, which would help them understand the impact of a pollutant.

Mathewson (1999) elaborates on spatial understanding by describing several “master images of science” (p. 40). These are patterns, shapes, and spatial relationships that can be observed frequently in science content. They include characteristics that we might use to describe objects or relationships between systems of objects: boundaries, branching, chirality, or points. These are the archetypes that can help define observable phenomena or create a model of things we cannot observe. Examples include the chirality of DNA, the cell membrane as a boundary, or the branching of capillaries in our bodies. Environmental examples include the origin of point source pollution or the boundaries of a watershed. Knowing these reoccurring patterns enables a learner to apply them to novel environmental situations for better understanding.

Linn and Petersen (1985) describe microscopic and human-scale spatial thinking from a slightly different perspective, identifying several types of spatial understanding and how they might be used, stating also that there is no real consensus on the categorization of spatial ability, only that it requires multiple processes. They attempt to describe three broad categories of spatial understanding, nonetheless.
*Spatial perception* is the ability to determine spatial relationships in reference to oneself, in spite of distracting information. An example is a task in which subjects are asked to identify a horizontal line in a tilted bottle, like the line that would be created if the bottle were partially filled with liquid. Test results suggest that people may “use gravitational vertical to locate the correct orientation” (Linn & Peterson, 1985, p. 1482); but Linn and Petersen also suggest that people may use kinesthetic cues, like their body position or the tilt of their head, to determine the level, based on some subjects’ response that the correct representation of the water line just “feels” level. There may be a folk understanding that helps them make the determination. This is important to an understanding of environmental impact, because decision-makers will not always be able to rely on a calculated understanding of environmental variables, but will call upon environmental cues or spatial archetypes applied to new situations to make decisions with a short timeline. An example is the general principle of accumulation, which is a mechanism within many environmental problems. Carbon accumulates in the atmosphere as a net sum of the emissions that contribute to it and the absorption that takes it out of the atmosphere. While it may be impossible, without extensive research, to quantify this accumulation, the general principle that a greater outflow than inflow will decrease the accumulation is useful to decision-making.

The second type of spatial understanding that Linn and Peterson describe is the *mental rotation* of two and three-dimensional objects. This has been widely studied and seems to be most useful in chemical disciplines, where individuals are asked to mentally rotate atoms and molecules to understand how they will behave chemically (Urhahne, Nick, & Schanze, 2009; Wu & Shah, 2004). This ability might be applied to environmental problems when considering the microscopic origins of a problem. For example, understanding and being able to visualize the molecular structure of a water pollutant can lead to a better understanding of how that pollutant will behave chemically in the environment.
Finally, Linn and Peterson describe *spatial visualization* as, “the label commonly associated with those spatial ability tasks that involve complicated, multistep manipulations of spatially presented information” (p. 1484). These tasks tend to be more analytical and require moving between multiple data sets. When evaluating environmental problems, scientists often examine the variability of some characteristic over a landscape. This may be the level of pollutant in water or air over an area or variability in temperature. To be an effective decision-maker, one would have a better idea of the impact of environmental decisions if they understood how the products of that decision affected the natural world, both globally and locally, necessitating these multistep, complex spatial thinking processes.

The spatial abilities described in this section were restricted to microscopic and human scales, but could be applied environmental problems that occur in bigger spaces, like the dispersal of a pollutant. The more recent literature on spatial understanding focused on the global or regional application of the spatial understanding.

**Recent studies of spatial understanding: global and regional space.** Many spatial thinking abilities that may be particularly useful to environmental decision-making will exist in the global or regional end of the spatial scale; that is, spatial relationships that are too big to directly perceive. One must be able to manipulate spatial information that may be beyond his or her immediate perception to estimate the impact of a decision across a landscape or even globally.

There has been a recent surge of interest in global or regional spatial understanding as result of the wide availability of geo-spatial modeling software, like Geographic Information System (GIS) software and Google Earth. The potential for interactive models created with software systems such as these to be used to teach the nature of space and spatial relationships in science has inspired science education researchers to ask questions about the spatial thinking skills that might be supported by systems like GIS and Google Earth.
Bednarz and Lee (2011) describe a type of spatial reasoning of particular interest to geographers: understanding spatial relations, which they describe as the ability to recognize spatial distributions and spatial patterns, to connect locations, to associate and correlate spatially distributed phenomena, to comprehend and use spatial hierarchies, to regionalize, to orientate to real-world frames of reference, to imagine maps from verbal descriptions, to sketch maps, to compare maps, and to overlay and dissolve maps. (p. 104)

This type of spatial understanding is underrepresented in the spatial thinking literature, which is a frustration to geographers and environmental scientists because the more tested types of understanding, like mental rotation and relative orientation, do not test abilities on a scale relevant to their area of study, “a dimension important to real-world spatial patterns and processes” (Bednarz & Lee, 2011, p.104). Environmental scientists and learners of environmental science use abilities like recognizing spatial patterns and correlating spatially distributed phenomena more often than microscopic abilities to understand the impact of spatially distributed environmental problems like the disappearance of old growth forest or the accumulation of solid waste in the ocean, and yet there is less research at the global or regional end of the spatial scale. Existing literature that describes spatial skills at this end of the spectrum is reported on below, along with examples of how these skills apply to environmental literacy.

Gersmehl and Gersmehl (2006) conducted an extensive review of the literature on spatial thinking, leading to the development of a hierarchical taxonomy of spatial thinking skills useful to geographic and environmental problem-solvers. This development arose from what they describe as a “lack of clearly articulated consensus about the nature of spatial thinking” (p. 6). They describe spatial thinking skills organized in a hierarchy, from most basic to most advanced. Because the list is so comprehensive and their literature review so thorough, each spatial thinking ability in Gersmehl
and Gersmehl’s taxonomy is briefly described below, along with its importance to understanding complex environmental issues.

**Describing conditions** - The observation of features or attributes of a location. This can include natural features or social characteristics. This is important to environmental decision-makers’ understanding of the characteristics of a place that can cause change and may be changed.

**Tracing spatial connections** - Understanding how a place is linked to other places, either physically, by natural features such as rivers, or socially, through commerce or some other means. These connections are important to understanding how environmental impact spreads from one place to the next.

**Making a spatial comparison** - Understanding how places are similar and different, using the features of one place to describe another. Environmental scientists may use this ability to predict impact on similar and different locations.

**Inferring spatial aura** - Understanding the effect a feature or characteristic may have on the area that surrounds it. This is required to be able to predict variance in impact of an environmental action on an area based on the area’s proximity to the action.

**Delimiting a region** - Understanding how to group locations based on their similarities. This might enable a decision-maker to compare areas with similar characteristics and predict how similar environmental actions would impact those areas similarly. For example, based on similar topographic and vegetation characteristics, rivers in two similar watersheds might absorb a pollutant similarly.

**Fitting a place into a spatial hierarchy** - Understanding how an area fits in to a nested hierarchy of areas. This idea is very useful when thinking about climate in regions from small to large. Based on vegetation, altitude, or proximity to water, a region might have climate characteristics
very different from its surroundings, and it is important to understand how this microclimate interacts with the larger region it is nested within.

**Graphing a spatial transition** - Understanding how the landscape transitions from one condition to another. This determines how an environmental impact makes the transition from one location to the next. For example, urban regions situated in valleys experience air pollution differently than topographically flat areas. Because of the landscape transition and the air patterns associated with it, pollution is less likely to escape a valley, over a mountain and can therefore accumulate over the urban area.

**Identifying a spatial analog** - Understanding how places that are not connected are similar to each other. In an environmental context, this is useful to understanding the similarities in climate and organism characteristics for spatially distant biomes across the globe. This translates to thinking about how they might respond to environmental impact similarly.

**Discerning spatial patterns** - How characteristics are arranged in an area. This is important to understanding features like the spatial patterns of organisms in a region and the less visible characteristics, like a pattern of ground temperatures across a landscape. This kind of information can be synthesized to better understand why organisms may succeed or fail in a particular temperature.

**Assessing a spatial association** - Understanding the relationship that variables may have. Environmental impacts often are associated. For example, water pollution leads to a decrease in aquatic life, which may lead to a decrease in other life forms that rely on the impacted organism for their food source.

**Designing and using a spatial model** - Understanding how two, potentially distant places may be linked characteristically. This requires the ability to make several causal connections to be able to link characteristics. This is a sophisticated type of environmental understanding, but one that
a learner must be fluid with if they are to understand the impact of large scale human activity, like
the burning of fossil fuels or excessive water pollution and depletion.

**Mapping spatial exceptions** - Identifying anomalies in the regular pattern of characteristics
in the landscape. This may be the way to best identify environmental management policies for areas
that may be out of the norm for their area.

This taxonomy proposed by Gersmehl and Gersmehl (2006) is the most useful for
environmental decision-making for impacts across landscapes and similar large regions, because
these are the spaces these abilities are applied to. Considering learners in environmental science, a
learning objective might be moving from the more basic spatial skills to the more advanced skills of
the taxonomy in terms of their ability to understand environmental characteristics and how they are
changed by human impact. For example, a learner may only be able to describe the characteristics of
the place where they live at the beginning of their studies; but a strong foundation in the spatial
relationships in environmental science would lead them to be able to compare where they live to
other places, describe how the characteristics of their location change with human impact, how
human activity would affect a location differently than another with different characteristics, and so
on. Likewise, at the beginning of their studies, learners of climate change might only understand the
features in a landscape that emit carbon dioxide, but a strong foundation in spatial thinking related
to enhanced greenhouse effect might enable their understanding of how those emissions are spatially
related to the features that absorb carbon in the landscape and how the resulting accumulation
interacts with radiant energy entering Earth’s atmosphere.

**The spatial thinker.** This study is important because it attempts to design an instrument
researchers can use to assess the spatial skills learners apply in their descriptions of enhanced
greenhouse effect and its potential impacts. These spatial skills are useful understanding phenomena
that span the spatial scales, large to small, and include the ability to move between these scales to
relate spaces to each other. According to the National Research Council’s report, (2006), spatial thinkers

have the habit of mind of thinking spatially—they know where, when, how, and why to think spatially; practice spatial thinking in an informed way—they have a broad and deep knowledge of spatial concepts and spatial representations, a command over spatial reasoning using a variety of spatial ways of thinking and acting, have well-developed spatial capabilities for using supporting tools and technologies; and adopt a critical stance to spatial thinking—they can evaluate the quality of spatial data based on their source, likely accuracy, and reliability; they can use spatial data to construct, articulate, and defend a line of reasoning or point of view in solving problems and answering questions; and they can evaluate the validity of arguments based on spatial information. (p. 12)

In other words, for the purposes of this project, spatial thinkers are able to use the skills described in the previous sections fluidly to understand real-world phenomena and solve real-world problems. That is also how spatial thinking abilities will be considered for the purposes of assessment design. I will use the skills described here to create parameters for how I am defining spatial thinking and, therefore, what will be assessed in students. Some of the skills most commonly named in the literature, along with the disciplines across scales that they can be applied to are displayed in Figure 3 below. In the context of environmental literacy, learners apply this spatial fluency to environmental problem-solving. In the context of enhanced greenhouse effect, learners understand spatial phenomena across scales—from molecular to atmospheric—and can use that understanding to process information and make decisions. The task of this assessment design is to develop a way for learners to make spatial thinking—which, in many cases, is represented only to the thinker as a mental model—explicit so that it may be evaluated. The next section will describe the
theory supporting the design of such an assessment, along with a method for creating items that accomplish the task of making learners’ spatial thinking explicit.
Figure 3. Spatial thinking across scales and across the sciences.
Theoretical Framework

The literature on spatial thinking and reasoning describes a range of abilities across scales. From the mental rotation of molecules, to the use and creation of maps, the named skills suggest the making and using of a variety of models. For example, the mental rotation of molecules requires the thinker to visualize the elements of the molecules, then mentally animate the molecule into action to see its characteristics. Creating a map requires the learner to create a model from information they are given or gather.

Since improving these modeling abilities, situated in the context of improving environmental literacy, is the overarching goal of this research program, then an assessment of learners’ spatial thinking abilities in this content area should measure their ability to understand, use, and create these types of models. Therefore, a models and modeling theoretical framework will guide the development and implementation of the assessment. Models, the practice of modeling, and how they might be used to understand learner thinking are described below.

Models and modeling. There are several perspectives on the form and function of models in science education. Bodner, Gardner, and Briggs (2005) summarized many of these attempts:

- A model is a representation of an idea, object, event, process, or system, which concentrates attention on certain aspects of the system — thus facilitating scientific inquiry.
- Mental models represent significant aspects of our physical and social world, and we manipulate elements of these models when we think, plan, and try to explain events in that world.
- A model relates to a target system or phenomenon with which we have a common experience or set of experiences.
- Models are mental entities that people construct with which they reason; all
Scientific models are conceptual systems mapped onto a specific pattern in the structure/behavior of a physical system within certain limits of reliability. (p. 1)

Grosslight, Unger, and Jay (1991), in a survey of science educators, found that experts believe that models are “constructed in the service of developing and testing ideas and explanations about phenomena” (p. 819). Essentially, a model is a system that contains variables, the relationships between variables, and the operations that describe the variable interactions. A model system tells us something about another system and helps us think about or make sense of the other system (Lesh, Hoover, Hole, Kelly, & Post, 2000). Lesh and Fennewald (2000) importantly add that a model tells us something about another system for a clearly specified purpose. For example, the schematic of an airplane’s electrical system is a model that helps us make sense of that system, the purpose of which is articulated for the user. Defining that purpose places boundaries around the system the model represents. An airplane’s electrical schematic would not include a physical representation of the airplane’s interior.

Most basically put, a model is an analogy (Lehrer & Schauble, 2013). It expresses the relationship between a familiar concept or experience with a new concept or experience in order to make sense of the new information. The model must start with the learners’ understanding if it is to help them explain and make predictions about the physical system it represents (Greca & Moreira, 2000).

There are several types of models, including mental models, which exist in the mind of the learner only and can take many forms. Mental models are “internal, personal, idiosyncratic, incomplete, unstable and essentially functional” (Greca & Moreira, 2000, p. 5) only to the builder using them to make sense of the world. Mental models may be global or local. Global mental models
are more permanent in the mind of the learner. They contain characteristics that may be transferrable to solve a range of problems. Local models are more temporary and problem-specific. They may be used to understand an immediate problem or situation and then discarded. Many problem solving situations require interaction between both types of models (Briggs, 2007), as the learner calls upon global mental models to process familiar information and local mental models to process new information.

Conceptual models are external and shared by a community. They reflect an agreed-upon understanding and have coherence with the knowledge of the community in which they are used to communicate and facilitate comprehension (Greca & Moreira, 2000). A diagram of Earth’s atmosphere included in a text book is an example of a conceptual model designed by and agreed upon by experts for the purpose of teaching novices about the environment. Models, whether shared or personal, are a representation created by a person or group of people and, therefore, embody a perspective (Grosslight, Unger, & Jay, 1991). In fact, models from created from different perspectives to represent the same physical system can appear different from each other because they represent very different characteristics.

Modeling is the process of creating a model, whether mental or conceptual. In education, the process of modeling can serve several goals. Analogical and visual modeling, as well as thought experiments or mental model building, are integrated processes, are performed to create and transform the informal representations of a problem. Modeling is the learning of a new language that enables a learner to perceive the modeled system differently (Greca & Moreira, 2000). It is the adaptive creation and manipulation of conceptual models to solve a problem (Hamilton, Lesh, Lester, & Brillesyper, 2008).

Learners create their own models to make sense of phenomena they observe or experience. In order for learners to learn, their models must be challenged and tested (Lesh, Hoover, Hole,
Novices’ models are often unstable, as they are manipulated, tested and revised based on the learners’ new understanding (Lesh & Fennwald, 2010). Capturing these frequent changes in learners’ models can help researchers better understand common misconceptions and strengths in novices’ understanding.

**Student model-building as assessment of learner understanding.** A models and modeling theoretical framework informs research design to support learner model-building and revision and analyzes the artifacts of the revision process in order to understand “the mechanism by which knowledge construction occurs” (Briggs, 2007, p. 70). It aims to trace, through the modeling process, the learner’s solution path through a problem (Briggs, 2007).

In practice, scaffolding learners to express their mental models so that their change in understanding can be traced occurs when we support their expression in model-building activities, which are structured so that learners generate solutions by repeatedly revealing, testing, and refining or extending their thinking about a problem or phenomenon (Lesh, Hoover, Hole, Kelly, & Post, 2000). Assessment items for this instrument were created according to the best practices for guiding students in their model-building activities, so these practices and guidelines will be described further in the methods section below.

A models and modeling theoretical framework is appropriate for the development of an assessment of spatial thinking for enhanced greenhouse effect for several reasons. First, spatial thinking abilities, as described in the field’s literature, require learners to model spatial information in order to represent, evaluate, and synthesize that spatial information. Mental modeling of spatial information occurs when learners form and manipulate objects in their mind’s eye, when they imagine maps from verbal descriptions (Gersmehl & Gersmehl, 2006), and when they mentally rotate 2- and 3-dimensional objects (Linn & Peterson, 1985). Conceptual modeling occurs whenever learners make their understanding explicit, whether they are comprehending or using spatial
hierarchies, comparing maps (Gersmehl & Gersmehl, 2006), orienting themselves to real world frames of reference, or manipulating spatial information to problem-solve (Linn & Peterson, 1985).

In addition, one of the objectives of using a models and modeling theoretical framework is to enable understanding of phenomena to be able to solve a problem. This objective aligns closely with NAAEE’s goals for an environmentally-literate populace: “knowledge and understanding of a wide range of environmental concepts, problems, and issues” (Hollweg et al., 2011, p. 2-3). By employing a models and modeling lens, we adopt a problem and solution-oriented view of spatial thinking for environmental literacy that uses learner representations of spatial information over time and instruction to measure changes in their understanding.

In sections that follow, I will describe the methods by which the Spatial Thinking Assessment for Enhanced Greenhouse Effect (STA-En GreenE, pronounced [Stayin’ Green]) was developed and implemented and how these methods are informed and supported by the models and modeling theoretical framework.
Chapter 3 Methods

Overview

This study is situated within a larger effort to inform the design of lessons intended to improve learners’ spatial thinking about environmental problems, with the intention of improving their environmental literacy and facilitating more sustainable decision-making. Specifically, this study focuses on the development of an instrument to assess learners’ spatial thinking skills supporting their understanding of enhanced greenhouse effect, so that we might know if the lessons designed and implemented in the future are effective in improving learners’ abilities. The primary focus of the current study is not on an intervention intended to change spatial thinking, rather on developing an instrument, with the intention that it will be used in future studies in which the effectiveness of the intervention is the focus.

Assessment items were developed based on information gathered from (1) existing literature on spatial thinking in science education, (2) interviews with science and mathematics faculty experts, (3) surveys administered to experts in environmental education, (4) a literature review of existing assessments on enhanced greenhouse effect, and (5) a literature review of existing spatial thinking assessments. The assessment was written to elicit learners’ models of their understanding of enhanced greenhouse effect, and learners taking the assessment produced conceptual models to make their spatial thinking about the topic external. Learners’ responses were evaluated for the spatial thinking skills targeted in the model-eliciting prompt, informed by the literature review and expert interviews and surveys.

Research Questions

As both the process of assessment development, and the assessment product are of interest to this study, the research questions below guide this work.
(1) What are experts’ perceptions of which spatial thinking skills are necessary to support learners’ understanding of enhanced greenhouse effect?

(2) How do expert perceptions of the spatial thinking skills that support learners’ understanding of enhanced greenhouse effect inform the design of an assessment to measure this construct?

(3) What do learner-generated models reveal about the spatial thinking skills that support their understanding of enhanced greenhouse effect?

This research was qualitative, and as such, formal hypotheses for each research questions were not appropriate. However, based on extensive reviews of the literature in research areas that contributed to the study and a limited amount of preliminary original research of my own, I had expected findings that guided analyses of the results. They were:

1. As a group, expert perceptions of the spatial thinking skills necessary to support learners’ understanding of enhanced greenhouse effect would represent the spatial thinking abilities across scales that are represented in the spatial thinking literature. Individually, the spatial thinking skills experts perceive to be the most useful to understanding the enhanced greenhouse effect will be rooted in their own understanding of the phenomena.

2. Expert interviews and surveys would be useful to the development of the spatial thinking assessment by informing the design of test items around the themes identified by the experts as important to learners’ understanding of enhanced greenhouse effect.

3. It was expected that learners would express the spatial relationships that support an understanding of enhanced greenhouse effect using representations that have been modeled through instruction, as well as representations that are original and express their mental models. Therefore, their representation would reveal (a) the models they learned with and
incorporated into their understanding and (b) the models they built to better understand the phenomenon, independent of pre-existing instructional models.

Development Framework

The development of this assessment was guided by the *Standards for Educational and Psychological Testing*, published by the American Educational Research Association, the American Psychological Association, and the National Council on Measurement in Education (AERA, APA, & NCME) (1999). The purpose of the *Standards* is to provide guidance to test users and developers in the design, selection, evaluation, and implementation of assessments and assessment items (Camara & Lane, 2006). In addition to using the process of test development outlined in the Standards, I used Dillman’s (2000) Tailored Design Method to select, revise, and refine assessment items, after their initial development. Figure 4 outlines the 5-step framework, adapted by Chaney et al. (2007), I used to design and evaluate the Assessment of Spatial Thinking for Enhanced Greenhouse Effect. A description of each step, specific to this study, follows. The description in the next section is simply an overview, to outline the process for assessment development. A more detailed description of each piece will be described in Chapters 4 through 7.
Step 1—Purpose of Instrument

Step 2—Test Specifications
- Question Format
- Issues of Fairness
- Issues of Bias

Step 3—Pool of Items

Step 4—Dillman’s Stages of Pretesting
- 1. Panel of Experts
- 2. Cognitive Interviews
- 3. Pilot Test
- 4. Final Check

Step 5—Final Form of Instrument

Figure 4. Instrument design methodological framework adapted from Standards for Psychological and Educational Assessment and Dillman’s Tailored Design Method. Reprinted from Development of an Instrument to Assess Student Opinions of the Quality of Distance Education Courses (p. 148), by Chaney, B.H. et al., 2007, Lawrence Erlbaum Associates, Inc. Reprinted with permission.

**Step 1-Purpose of instrument.** The first step in the process of test development, as described by the Standards is to describe “the aspects (e.g. content, skills, processes, diagnostic features) of the construct or domain to be measured” (AERA, APA, & NCME, 1999, p.37). The
construct measured by the developed instrument was spatial thinking about enhanced greenhouse effect. Both domains (spatial thinking and enhanced greenhouse effect) have been described in the literature. I reported on a literature review of spatial thinking and environmental literacy related to enhanced greenhouse effect in Chapter 2, and the current understanding of assessment items that elicit a student’s understanding of enhanced greenhouse effect will be discussed in Chapter 6, as part of the data collection process for the instrument. The purpose of this instrument is to assess the spatial thinking skills that support learners’ understanding of enhanced greenhouse effect. While the overarching goal of my long-term research program is to be able to measure spatial thinking abilities relevant to many environmental problems, the parameters of each environmental problem are unique, making an assessment to capture all of these skills unrealistic. With this in mind, I chose to develop a spatial thinking assessment that addresses the problem of enhanced greenhouse effect, leading to global warming, so the domain of the assessment is the spatial thinking skills necessary to understand this phenomenon. Those skills and the items that assess them are defined by the literature review and expert interviews and surveys, which I will describe in a later in this report.

**Step 2-Test specifications.** Defining the test specifications requires the delineation of the format of test items, how participants are required to respond, and how their responses will be evaluated. In addition, the test specifications may describe the intended testing population and whether test responses will be evaluated on a criterion-referenced or norm-referenced basis (AERA, APA, & NCME, 1999).

**Format of test items.** This study adopts a models and modeling theoretical framework, for reasons described in Chapter 2. Briefly, spatial thinking requires learners to create mental, as well as conceptual, models to communicate their understanding. Therefore, assessment items were written according to current best practices for prompting students’ model-building, which I will describe in Chapter 8, Development and Design of the Spatial Thinking Assessment for Enhanced Greenhouse
Effect (STA-En GreenE), to enable learners’ external representation of their mental model of a phenomenon. The principles that guide learners to make their mental models explicit were employed here for the purposes of evaluating their external conceptual models.

**Participant response evaluation.** Participant responses were evaluated by comparing learners’ models and rationales with the spatial thinking skills applied to enhanced greenhouse effect synthesized from literature on enhanced greenhouse effect, literature on spatial thinking and assessment of spatial thinking, and interviews and surveys with experts in science, math, and environmental education. The focus of expert interviews and surveys, as well as the literature reviews, was on the spatial information that supports understanding of greenhouse gas accumulation in the atmosphere. The responses were then criterion-referenced, with the data collected from expert understanding and literature base providing the criteria by which models are evaluated (AERA, APA, & NCME, 1999). Based on the learning goals for learners’ spatial thinking in support of enhanced greenhouse effect established in this way, there will be a qualitative review of the ways in which (1) which spatial thinking abilities learners model, related to enhanced greenhouse effect, and (2) The methods by which they model their spatial understanding of enhanced greenhouse effect.

**Intended participants.** The assessment participants were learners in an introductory environmental science course at a community college in the Southwestern region of the United States. Ninety-six learners in four, live sections voluntarily completed the Spatial Thinking Assessment for Enhanced Greenhouse Effect (STA-En GreenE) on paper.

**Step 3-Development of a pool of items.** The content and construct foundation for the assessment was informed by five types of information: (1) a literature review of spatial thinking abilities, (2) data collected from interviews with science and mathematics faculty at a large university
in the Southwestern United States, (3) analyses of on-line surveys administered to experts in environmental education, (4) a review of existing assessments testing learners understanding of enhanced greenhouse effect, and (5) an analysis of existing spatial thinking assessments. Each of these sources of information is described briefly below, in the order in which they took place, to situate the reader in the assessment development process. The method by which the data was collected, analyzed, and contributed to the assessment is fully described in Chapters 4 through 7, for each of the information sources.

**Literature review of existing spatial thinking research.** A literature review of spatial thinking and the ways that it has been described has been conducted and summarized in this document in Chapter 2; but it is important to describe how this information informed assessment design specifically, so I mention it again here. Questions that guided the literature review were, (1) how is spatial thinking defined historically and in the current spatial thinking literature? and (2) what skills and abilities are described as components of spatial thinking? The information collected was used to inform the design of the math and science expert interviews, in which experts were asked for their perceptions of the spatial thinking skills important to a novice’s understanding of enhanced greenhouse effect.

**Science and mathematics faculty interviews.** Spatial thinking across scales is critical to the kind of environmental literacy that can change unsustainable behavior. Thinking spatially across scales and disciplines can improve understanding of the origins and consequences of complex environmental problems and how individual behavior can impact a system (Tretter, Jones, & Minogue, 2006).

Just as environmental education is supported by all science disciplines, spatial thinking for environmental education includes skills common to each of these supportive fields. To begin the work of understanding which spatial thinking skills are most necessary to understanding enhanced
greenhouse effect, semi-structured interviews were conducted with experts in the fields that support the study of environmental problems. In this case, those experts were university faculty in a college of sciences. The rationale for choosing these experts was rooted in their experience in the disciplines they practice and the supportive role each one of the disciplines has in understanding environmental phenomena. I selected faculty experts from biology, chemistry, physics, geology, and math. Each of these disciplines is applied to the study of environmental science and to environmental problem-solving, so the experts’ areas of expertise are relevant to the project. Without content understanding in each of these areas, a learner could not understand what they observe in human-environmental interactions. Since it was the experts’ experience and, therefore, their perspectives that were valued, a phenomenographical approach was taken to shape the interview guide. Phenomenography is an empirical research tradition designed to answer questions about thinking and learning, with an objective of defining the limited number of ways in which a group of people experience, interpret, understand, perceive, or conceptualize a phenomenon or certain aspect of reality (Marton, 1986; Orgill, 2007). This theoretical framework relies upon participants’ relating perceptions of their experience and from this, data was collected on the spatial thinking skills they perceived as most useful to understanding environmental phenomena.

For the purposes of this study, participants were asked to identify (1) general spatial thinking skills useful in the sciences, (2) the spatial information that would be useful to novice learners to better understanding enhanced greenhouse effect, and finally, (3) which spatial thinking skills described in the existing literature would be useful to understanding enhanced greenhouse effect.

I used the data collected from these interviews to establish initial ideas regarding the spatial thinking skills important to environmental literacy and, specifically, to understanding the accumulation of carbon and other greenhouse gases in the atmosphere and their impact on global
average temperature. The results of these analyses informed the design of a survey intended for experts in environmental education. The analysis will be described in Chapter 4.

**Survey administered to experts in environmental education.** I used themes identified from the data of interviews with science and math faculty and spatial thinking skills identified in the spatial thinking literature to design surveys to be administered to experts in environmental education. I asked the experts surveyed to rate the spatial skills and information identified from the interview and existing literature according to a Likert scale, naming levels of importance of each spatial skill to understanding enhanced greenhouse effect. I also asked participants to provide information and insight on any additional skills or information that would be useful to novices’ understanding of enhanced greenhouse effect.

Survey participants were environmental educators listed as members of the North American Association for Environmental Education (NAAEE). NAAEE is the “only national membership organization dedicated to strengthening the field of environmental education and increasing the visibility and effectiveness of the profession” (NAAEE website). Members of NAAEE are professionals in primary, secondary, and post-secondary education. They work in both formal and informal education settings. The value of their input lies in group members’ experience in environmental education of all varieties.

The survey was developed according to Dillman’s methodology for web-based survey development (2007), and its development will be described in greater detail in Chapter 5. I sent an invitation to participate and a link to the survey on line via NAAEE listserv. The survey was administered and data collected via Google Forms, a web-based survey authoring, delivery, and data collection software.

The survey included the same themes that are included in the interview protocol for the science and mathematics faculty. That protocol included two content-based themes: (1) perceptions
of spatial thinking abilities useful to understanding general scientific concepts, and (2) perceptions of spatial thinking abilities useful to understanding enhanced greenhouse effect. I analyzed survey data and coded for themes within each of the categories. The results informed assessment development by suggesting which spatial thinking skills are most important to understanding enhanced greenhouse effect.

**Review of existing assessments testing learners’ understanding of enhanced greenhouse effect.** It was important for test design to begin with the environmental science content (in this case enhanced greenhouse effect) and then consider the spatial thinking skills that are an integral part to understanding that content. For example, it may be necessary for a learner to understand how a carbon dioxide molecule interacts with radiant energy in order to be literate in the concept of the greenhouse effect. The spatial thinking skills that may be important to that understanding include the mental rotation of molecules, the formation and manipulation of images in the mind’s eye, and/or the understanding of spatial relationships. Beginning to understand which types of spatial thinking skills are necessary to understand particular content requires starting with the content; therefore, a literature review on existing assessments on enhanced greenhouse effect provided the content foundation of the assessment developed here. By analyzing the content of existing assessments, I gained an understanding of researchers’ priorities for student understanding. While many of these studies report on results regarding student understanding, I did not report on it here because those results do not provide content concepts for the design of a spatial thinking assessment for understanding enhanced greenhouse effect. I asked the following questions of the collected research: first, what concepts are included in, and therefore may be considered central to, understanding enhanced greenhouse effect? and then, what, if any, spatial representations or spatial thinking abilities are present—and therefore considered important to understanding enhanced greenhouse effect—in existing assessments?
Existing spatial thinking assessment items. Numerous studies that include an assessment of learners’ spatial thinking skills have been conducted and published. Instruments for measuring spatial thinking exist and have been validated. These include established metrics like the Spatial Thinking Ability Test (STAT) (Lee & Bednarz, 2012), as well as experimental techniques like concept mapping (Brandstädter et al., 2012) and software-enabled sketching (Jee et al., 2009). The deficiency in many of these instruments is their generality and, therefore, their limited applicability within the environmental science content domain. However, their utility is in their validity and reliability and the principles upon which they were built that were employed in writing new questions.

Step 4-Dillman’s stages of pretesting. The following sections describe the stages of pretesting outlined in Dillman’s (2000) protocol. The results of each are described in detail in Chapter 9.

Stage 1-Panel of experts. Once questions were written and ordered, the first stage of pretesting was for the assessment to be reviewed by experts with knowledge in areas relevant to the assessment. Reviewers were knowledgeable in the assessment’s content area, the goals of the assessment, the target population for assessment administration, and in assessment creation itself. The experts’ task was to review the assessment to ensure that it contains all of the necessary questions, if the questions are intelligible by the reader, or if questions might be eliminated or condensed (Dillman, 2000).

Three experts reviewed the assessment. Reviewer #1 is an expert in science education, with a Ph.D. Curriculum and Instruction with Science Education focus and experience in developing, implementing, and assessing lessons related to global climate change in the secondary classroom. This reviewer is uniquely qualified to review the presentation and wording of the current assessment for clarity from the learner participants’ perspectives. Reviewer #2 is the lead advisor for this
project. She is an expert in chemistry education and has extensive experience developing, implementing, and assessing curriculum for learners, as well as professional development for educators. She helped develop the scope and goals for this study. As such, she is uniquely qualified to review the assessment for clarity as well as for alignment to the goals of assessment, as they have been outlined in the study. Reviewer #3 is an expert in environmental science, and more specifically in enhanced greenhouse effect and climate change. She was tasked with ensuring that the questions’ content includes the important concepts to understanding enhanced greenhouse effect and that the concepts tested for are accurately conveyed in the text and presentation of the item.

The panel of experts evaluated the assessment for issues of bias and issues of fairness. Each expert has experience in education and as such, was able to contribute to a discussion of fair and unbiased language such that a learner participating in the assessment would be able to answer the questions based on content and construct and would not be confounded by language they do not understand.

The goal of this phase of pretesting was to finalize assessment items and their order, so that it could be tested on and evaluated by the population for whom it is intended. These are Stages 2 and 3, which are described below.

**Stage 2-Cognitive interviews.** The second step of the pretesting process is the cognitive interview, in which participants with the same characteristics as those for whom the assessment is intended are administered the assessment under special circumstances, so that data might be collected on their test-taking experience. The purposes for this stage are first, to ensure that each question is comprehensible by the intended audience and second, to ensure that questions can be answered accurately as they are expressed (Dillman, 2000). It is the aim of the cognitive interview to address any issues of bias and fairness that may exist in the language that is developed in the first form of the assessment. It is important that the language of the assessment be accessible to all
learners and that no group is disadvantage because of background or experience, outside of their experience in spatial thinking or environmental science (AERA, APA, & NCME, 1999).

For assessments that are completed autonomously, such as the one developed here, Dillman recommends pairing a think-loud protocol while taking the assessment with a retrospective interview to follow it. The think aloud process asks participants to verbalize everything that would usually take place in their head as they are taking the test. This includes reading the question, expressing problem-solving steps, and expressing confusion or difficulty in understanding the material. A limitation in this method is that participants may experience split attention between processing the test items and expressing their thought processes to a data collector. The retrospective interview minimizes this issue by enabling participants to reflect on their experience, facilitated by a researcher, who might ask questions related to their observations of the test-takers interaction with assessment items.

In this case, the intended audience for the assessment is made up of introductory environmental science learners. As such, introductory science learners were the target cognitive interview participants. Two learners participated in a think-aloud exercise as they completed a first revision of the assessment. The learners participated in a retrospective interview jointly. The learner characteristics and results of each interview are presented in Chapter 9.

**Stage 3-Pilot testing.** Expert review and cognitive interviews with the target audience refined the order, format, content, and language used in the assessment. The next stage of testing enables evaluating the assessment in the context that it will be applied. This step serves a few important purposes. First, it tests out the delivery of the assessment, including instructions, delivery, data collection, etc. Since the group taking the assessment is bigger in this step, it further directs item revision because response patterns are recognized. If, for example, one question has a high rate of non-response, the item should be reviewed for inclusion. Data analysis might reveal a high level of
correlation between two test questions that ask for similar information. In this case, one question might be eliminated. This phase also serves the important function of providing a testing ground for evaluation of item responses. Here, the rubric or another evaluation tool is tested. Learner data is collected and evaluated and it may be noted if the method of evaluation is accurate to the knowledge demonstrated.

Since the outcome of this research project is assessment development, pilot testing represents a sort of culmination of design and implementation. For this project it was the last major step in the development process. As described previously, the participants are introductory environmental science learners. The sample of that population targeted for this study are learners in an Introduction to Environmental Science class at a local community college. Ninety-six learners participated in taking the assessment as it would be delivered in a typical classroom setting. Learner responses were evaluated after the instrument was revised according to feedback from experts and learners participating in cognitive interviews.

**Stage 4-Final check.** Dillman calls this step “Did we do something silly?” This step is one last pass at catching a detail that escaped previous evaluators’ attention. For this step, the completed assessment is evaluated by a handful of people who, up to this point, have had no involvement with the assessment. These people are more likely to see mistakes that became invisible over time to those working closely with the assessment. This step is discussed at the end of Chapter 9.

**Step 5-Final form of instrument.** According to Dillman’s protocol, the final form of the instrument is the revised version that is valid, reliable, and ready for use. In this case, validity and reliability tests will be the work of future research. While revisions took place as a result of pilot test findings, the STA-En GreenE assessment is original in both content and development method. As such, I decided, with the help of my advisory committee, that the development process and the initial pilot testing for the sake of revising the instrument for clarity and content was a significant
undertaking. Including validity and reliability testing would increase the complexity and research time for this particular project to more than is manageable for one dissertation project. Therefore, validity and reliability testing will be the first step in the assessment development process, post-dissertation. A brief description of the relevant steps for this process is discussed in Chapter 10.

**Summary.** To effectively summarize the assessment development work that has been done, consider Figure 5 below. Figure 5 adapts Chaney’s (2007) synthesis of the *Standards for Educational and Psychological Testing* and Dillman’s Tailored Design Method to reflect the process specific to the assessment developed here. The purpose of the instrument is to assess spatial thinking abilities that improve learners’ understanding of enhanced greenhouse effect. Learners engaged in model building activities to make their mental models external. The concepts assessed and the prompts that elicit student models are informed by five sources of information: a literature review of the current spatial thinking literature, interviews with experts in the math and science fields that support environmental science, a literature review of existing assessments on enhanced greenhouse effect, surveys deployed to experts in environmental education, and a review of current spatial thinking assessments. The processes by which this information was gathered and the contributions they made to the assessment are described in the following chapters: Chapter 4 describes the expert interviews and surveys, Chapter 5 describes the surveys of environmental education experts, Chapter 6 describes a literature review of studies that employ, existing assessments of students’ understanding of enhanced greenhouse effect, and Chapter 7 describes a literature review of existing spatial thinking assessments. At the beginning of each chapter, a small image of the graphic below will let the reader know which section of Chaney’s (2007) methodological framework the chapter is describing. Chapter 8 will describe the construction of the assessment from these sources of information. The STA-En GreenE assessment was revised in Dillman’s (2007) four stages of pretesting: review by a panel of experts, cognitive interviews with the target population, pilot testing with the target
population, and a final check by a reviewer with no prior experience with the instrument. The testing processes are described in Chapter 9.

![Diagram of instrument design framework](image)

**Figure 5.** Instrument design framework for this project, adapted from Chaney’s revision of Standards for Psychological and Educational Assessment and Dillman’s Tailored Design Method.
Chapter 4: Science and Math Faculty Expert Interviews

The purpose of the following four chapters is to describe in detail each step of the development process and results of each of the smaller studies that contributed information to the STA-En GreenE. The development, delivery, and results of each of the information sources will be described separately. The rest of Chapter 4 is dedicated to the development, delivery, and results of the interviews and surveys conducted with science and math faculty experts, including a brief review of the spatial thinking literature that contributing to the interview protocol’s design. Chapter 5 will describe a survey administered to environmental education experts. Chapter 6 is dedicated to reporting on a literature review of existing assessments about enhanced greenhouse effect and, Chapter 7, on existing assessments of spatial thinking. I will begin with a description of the expert interviews and surveys in Chapter 4 below.

Introduction

Spatial thinking is described a variety of contexts, across scales, as crucial to the functional understanding of the disciplines in which it is applied. For example, Jee, Genter, Forbus, Sageman, and Uttal (2009) describe spatial thinking tasks crucial in the geosciences, such as learning about the structure of the Earth’s interior and the deformation processes that occur within its crust, over large ranges of space and time. Stieff, Ryu, Dixon, and Hegarty (2012) describe a student’s spatial thinking abilities as integral to their understanding of complex organic chemistry concepts such as structure,
reactivity, and kinetics. Spatial skills used in this context include spatial visualization and drawing a spatial diagram.

Environmental science and studies of sustainability are inherently interdisciplinary in nature. The expertise of various disciplines is turned toward a problem to be solved or an issue to be understood. Enhanced greenhouse effect, as our example here, is no exception. Scientists from multiple disciplines work toward understanding the phenomenon and its impacts. Research suggests that by bringing together appropriate disciplines (Jones et al., 2010), we can work towards environmentally sustainable solutions to today’s most pressing issues. Spatial thinking and the tools that support it are not tethered to one discipline and are therefore well suited to support the interdisciplinary inquiries of environmental issues, including enhanced greenhouse effect (Hwang, 2013). As such, in the planning and design of an assessment meant to test spatial thinking abilities employed in understanding enhanced greenhouse effect, considerable attention should be given to the spatial thinking abilities useful to the disciplines that support the study of environmental problems.

The first part of the data collection that informed this spatial thinking assessment for understanding enhanced greenhouse effect looked at existing literature describing spatial thinking in general, as well as specific spatial thinking abilities. That literature, and how it has been used in this study will be described in future sections. To collect more information on the spatial thinking skills useful to the disciplines that support environmental science, a sample of experts in those disciplines were interviewed: university faculty members in the science and math departments of a large university in the Southwestern United States. The research questions addressed with this part of the study are:

(1) What are experts’ perceptions of which spatial thinking skills are necessary to support learners’ understanding of enhanced greenhouse effect?
(2) What spatial information do faculty members perceive as useful to learners understanding enhanced greenhouse effect?

(3) How can expert perceptions of spatial thinking related to enhanced greenhouse effect inform the design of an assessment to test such abilities?

The input of the faculty members was used to inform the assessment design in two ways. First, it contributed to the design of the internet-based survey for environmental education experts, which will be described in the next section. Second, the data was used directly to design the spatial thinking assessment items included in the instrument.

**Method**

The first step in the design of the interview protocol was to refer to the literature on spatial thinking that already exists. This research program began with an interest in why learners did or did not understand complex environmental issues and their place in them. The human connection to the natural world is a complex system in and of itself. The focus of this research is on a piece of that complexity: how humans understand spatial relationships related to environmental problems. Therefore, one of the first tasks of this research was to understand what has already been done to describe spatial thinking and the spatial thinking skills humans employ to understand their world. This literature has been described as part of the literature review in Chapter 2. The purpose of this section will be to describe how that literature and the spatial skills named in it were used to inform the design of the science and math faculty interviews that would contribute to the design of the STA-En GreenE.

I analyzed 20 assessments found in 20 separate articles on the assessment of spatial thinking abilities. Of the 20 assessments analyzed as descriptors of spatial thinking, 4 attempted descriptions of specific skills that a proficient spatial thinker might have (Bednarz & Lee, 2011; Gersmehl & Gersmehl, 2006; Linn & Peterson, 1985; Mathewson, 1999). Each study described different spatial
thinking skills that spanned the scale spectrum, from microscopic to macroscopic. In order to capture the range of spatial thinking skills that might be necessary to understanding a complex problem like enhanced greenhouse effect, and to support Tretter, Jones, and Minogue’s (2006) conclusion that spatial thinking across scales is important to spatial understanding, all of the spatial thinking skills from the literature were included in the science and math faculty interview protocol.

Each spatial thinking skill named in the literature was identified, and a list was developed to share with faculty experts during their interviews. The list consisted of a brief, one-line description of each skill named in the literature. Where the same spatial thinking ability was named in two or more reports, the ability was described according to the study that most clearly articulated it for the novice learner. Some spatial thinking abilities named in the literature were given titles in their original manuscripts that might not be understandable to a lay-person reader, which is what the science and math, as well as the environmental education experts are presumed to be. Examples include, “inferring a spatial aura” and “graphing a spatial transition” (Gersmehl & Gersmehl, 2006). These spatial thinking skills were edited to be more descriptive for inclusion in the interview protocol and survey. Their descriptive wording came directly from the original text. The spatial thinking skills, their sources, and the text that is used to describe them in the interviews and surveys are included in Table 1 below. A full presentation of the list can be found in the interview protocol in Appendix A. Internal review board approval was received for this and all of parts of the study that involved human subjects.
Table 1

*Spatial Thinking Skills Taken from Existing Research and Presented to Science, Math, and Environmental Education Experts*

<table>
<thead>
<tr>
<th>Resource</th>
<th>Spatial thinking skill, as named in literature</th>
<th>Spatial thinking skill, as described for interviewees</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bednarz and Lee (2011)</td>
<td>Recognize spatial distributions and spatial patterns</td>
<td>Language in article used verbatim in interview guide</td>
</tr>
<tr>
<td></td>
<td>Associate and correlate spatially distributed phenomena</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Orientate to spatial phenomena to real-world frames of reference</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Imagine maps from verbal descriptions</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Sketch map</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Compare maps</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Overlay and dissolve maps</td>
<td></td>
</tr>
<tr>
<td>Gersmehl and Gersmehl (2006)</td>
<td>Tracing spatial connections</td>
<td>Tracing how a place is linked to other places</td>
</tr>
<tr>
<td></td>
<td>Making a spatial comparison</td>
<td>Understanding how places are similar and different</td>
</tr>
<tr>
<td></td>
<td>Inferring a spatial aura</td>
<td>Understanding the effect a feature or characteristic may have on the area that surrounds it</td>
</tr>
<tr>
<td></td>
<td>Delimiting a region</td>
<td>Understanding how to group locations based on their similarities</td>
</tr>
<tr>
<td></td>
<td>Fitting a place into a spatial hierarchy</td>
<td>Understanding how an area fits in to a nested hierarchy of areas</td>
</tr>
<tr>
<td></td>
<td>Graphing a spatial transition</td>
<td>Understanding how the landscape transitions from one condition to another</td>
</tr>
<tr>
<td></td>
<td>Identifying a spatial analog</td>
<td>Understanding how places that are not connected are similar to each other.</td>
</tr>
<tr>
<td></td>
<td>Designing and using a spatial model</td>
<td>Designing and using a spatial model</td>
</tr>
<tr>
<td></td>
<td>Mapping spatial exceptions</td>
<td>Identifying anomalies to the regular pattern of characteristics in the landscape.</td>
</tr>
<tr>
<td></td>
<td>Describing conditions</td>
<td>Describing features of attributes of a location</td>
</tr>
<tr>
<td>Linn and Peterson (1985)</td>
<td>Mental rotation</td>
<td>Mental rotation of two and three dimensional objects</td>
</tr>
<tr>
<td></td>
<td>Spatial perception</td>
<td>Determining spatial relationships relative to oneself</td>
</tr>
<tr>
<td></td>
<td>Spatial visualization</td>
<td>Complex multi-step manipulations of spatial information</td>
</tr>
<tr>
<td>Mathewson (1999)</td>
<td>Vision</td>
<td>Using the eyes to identify, locate, and think about objects and orient ourselves in the world</td>
</tr>
<tr>
<td></td>
<td>Imagery</td>
<td>Formation, inspection, transformation, and maintenance of images in the “mind’s eye”</td>
</tr>
</tbody>
</table>
None of the faculty interviewed are researchers or experts in spatial thinking, but each faculty member thinks spatially within their discipline. This is important to note, because it means that their contributions are their perceptions of important spatial thinking skills. As such, this portion of the research uses a phenomenographical approach. Phenomenography is an empirical research tradition designed to answer questions about thinking and learning, with an objective of defining the limited number of ways in which a group of people experience, interpret, understand, perceive, or conceptualize a phenomenon or certain aspect of reality (Marton, 1986; Orgill, 2007).

An email was sent to each of the 137 full-time faculty members in the College of Sciences of a large, Southwestern university. The College of Science at this university included the Department of Mathematical Sciences, so math faculty experts were included in the invitation to participate. Of the 137 full-time faculty members, 17 responded (12.4% response rate) with interest in participating. None of the faculty experts were environmental science specialists. Individual interviews were scheduled with each respondent. Participants represent several disciplines within the college: biology, chemistry, geology, math, and physics. The distribution of participants by discipline is represented in Figure 6 below.
As participation in the current study was voluntary, the distribution of faculty members interviewed is not representative of the university. All interviews were semi-structured and conversational in style, lasting approximately 30-60 minutes. Each interview began by asking faculty to describe their educational background, the type of research they do, classes they typically teach, and the number of years they had been at the university. Then, faculty were asked to describe how their area of expertise was related to environmental science. The interview questions were then directed more specifically toward spatial thinking skills and spatial thinkers. Faculty members were asked to generally describe spatial thinking and what skills a spatial thinker might have. Then, they described spatial thinking skills relevant to their discipline. The next section of the interview asked faculty to describe the spatial information they would need to understand two example environmental problems that were selected randomly from a pool of five problems generated by the interviewer. The example problems were: deforestation, enhanced greenhouse effect, radioactive contamination release, non-point source water pollution, and the spread of an invasive species. Each
of the problem descriptions, as the faculty experts read them can be read in their entirety in the interview guides in Appendix A.

Each faculty member was asked to describe the spatial information they would need to understand the impact of two of these problems. The example problems for each interview were selected prior to the interview by using a random number generator available online. Faculty were also asked to describe what spatial information a novice might need to understand such a problem, if it was different from what they, as experts, might need. Faculty were presented with maps and asked to describe what impacts they might be able to predict over time. Finally, faculty were presented with a list of spatial thinking skills generated from the literature on spatial thinking (the skills displayed in Table 1). This list is displayed in the full interview protocol in Appendix A. They were asked to identify the spatial thinking skills on the list that were important to understanding the two example environmental problems they were presented with during the interview. They did this by marking each relevant skill with a pen.

Each interview was transcribed verbatim. Based on an initial reading of the transcripts and knowledge of the spatial thinking literature, I identified response themes that would address the research questions named in the introduction and that would contribute meaningfully to the STA-En GreenE. The identification of response themes and, more specifically, spatial thinking skills, that would contribute directly to the development of a survey instrument for environmental educators and to a spatial thinking assessment was the focus of this examination of the transcripts.

Transcripts were examined for evidence of faculty members’ perceptions of the following: (a) general spatial thinking skills of a proficient spatial thinker and (b) spatial information necessary to understand enhanced greenhouse effects and its impacts. The first theme, general spatial thinking skills for the proficient spatial thinker, was researched to compare faculty perceptions of useful spatial thinking skills to the spatial thinking skills that are described in the literature on spatial
thinking and, if original ideas were presented by faculty members, to add to the inventory of spatial thinking skills that I have researched there. The second theme, the spatial thinking skills faculty members perceive as useful to understanding enhanced greenhouse effect was an important interview theme because it contextualized spatial thinking in the content that I am focusing on for this particular study.

Once I identified the response themes, I reviewed the transcripts again to identify spatial thinking skills described within each of the themes described above. Then, using the inventory of spatial thinking skills from the literature, I coded each of the spatial thinking skills described by faculty, while at the same time looking for any original spatial thinking skills that faculty may have described that were not named in the literature. Any spatial skill described by faculty that did not match a spatial thinking skill described in the literature was given an original code. Finally, I noted the number of responses that corresponded to each coded spatial thinking ability, to better understand which abilities were more often identified. The results relating to each theme are described below.

Since the major focus of this dissertation project is the development of an assessment to test students’ spatial thinking related to enhanced greenhouse effect, faculty perceptions specific to this topic will be the primary focus here. I will report on all interviewed faculty members’ perceptions of spatial thinking in general, then report on faculty perceptions of spatial thinking related specifically to enhanced greenhouse effect for the 8 faculty members who were randomly selected to discuss that topic.

Results

Theme 1: General spatial thinking skills present in proficient spatial thinkers. Faculty member responses within this theme fell into five broad categories of spatial thinking abilities: visualization and dimensional thinking, understanding patterns, understanding place and relative
space, understanding data and data representation, and understanding matter. The skills described by faculty aligned with the spatial thinking abilities described in the spatial thinking literature. No additional themes emerged during the interview transcript analysis. The results will be reported in the faculty members’ language, with supporting quotations from faculty interviews. The faculty participants have been given pseudonyms to preserve their anonymity.

**Visualization and dimensional thinking.** The spatial thinking abilities faculty named most commonly as important to a proficient spatial thinker were abilities related to visualization and dimensional thinking. Faculty describe this skill as it is described in the spatial thinking literature: the ability to picture a phenomenon or object in the mind’s eye. In the case of dimensional thinking, this is a specific type of dimensional thinking in which the visualizer imagines an object in two or three dimensions. The most frequently named spatial thinking ability described as present in a proficient spatial thinker was three-dimensional thinking, with 7 out of 17 participants describing this ability.

For example, Dr. Barry, a faculty member in the geology department contextualized spatial thinking in the content that he is was most familiar with professionally:

My experience as a geology instructor, a lot of the things we talk about are things that are happening sub-surface, so you have to have real good three-dimensional thinking to be able to work out how faults are moving, how plates are moving against one another. Most people can’t do it.

A biologist, Dr. Gibbons, also described visualization in three dimensions by saying, “I guess being able to visualize things in three dimensions well. And I mean that is what I would think of.”

Five out of 17 faculty interviewed said that a proficient spatial thinker could visualize a problem or phenomenon. While this skill was described in a very general way, the faculty members who cited it did so with reference to the discipline in which they were trained. For example, Dr. Kernley (geology) said,
The notion that you can walk on the surface, map some rocks, and then creatively envision what they must be doing, and imagine what they did, both into the ground and out of the ground, which we call cross sections, that people have to be able to do that in their head.

Physicist Dr. Preston described the utility of a commonly used visual model, the right-hand-rule:

Actually looking at the right hand rule. That is a perfect example of spatial thinking. So, I actually focus on that because I want them to develop that sense in their head that okay, if you have $F=qVb$, so $V$ is going this way, let’s say $b$ is going this way…I want them to visualize a vector.

Another 5 faculty members described not just the ability to think in 2 or 3 dimensions, but particularly the ability to translate between 2- and 3-dimensional representations, such as connecting a diagram on a page to a real world environment. The ability to translate between two-dimensional representations of phenomena and three-dimensional representations, mental models, or reality was described as an important spatial thinking skill for a proficient spatial thinker. Geologist Dr. Barry described this spatial thinking skill as, “being able to take a two dimensional figure, diagram, being able to blow that up into three dimensions in your head.”

Chemist Dr. Barnes had conducted research of his own on students’ use and interpretation of visualizations and representations to understand chemistry concepts they could not directly perceive. He had more experience considering these topics than other faculty participants. He said,

This is one of the reasons I am interested in visualizations…they (students) don’t see molecules, they don’t interact with molecules, so how do they understand them? They understand them through representation. And the representation often misleads them as to what they are seeing because we are showing them three dimensional things in 2D space or
even, like if you are trying to project something, you are trying to show three dimensions, and we show depth, it is still a two-dimensional representation.

Dr. Dougherty is a biologist with the perspective that people have to be able to think about how often 2D images are flat images of something that actually has 3-dimensionality and so they need to be able to easily extrapolate directly, volumetric thinking, or they need some of the background you get in art for how perspective looks in 2D representation of a 3D image.

Another 3 out of 17 faculty members stated that greater than three-dimensional thinking is an important spatial thinking skill in a proficient spatial thinker, indicating that integrating dynamic spatial relationships over time is important. For example, Dr. Reiner from the biology department said,

I mean you probably have more dimensions than three. It’s probably four or five. But it’s the immediate environment you are in and how it changes over time but then what that environment is going to become as those changes are implemented.

Other spatial thinking abilities categorized within this theme, though less frequently, are the abilities to mentally rotate an object (2 faculty named this ability), to create a two dimensional image from an understanding of a real world object or phenomenon (2 faculty named this ability), and the ability to translate math equations into something the student can visualize (1 faculty member described this ability.

In summary, this category of spatial thinking abilities, Visualization and Dimensional Thinking, was by far the most cited by the faculty member participants. The spatial thinking abilities described ranged from the very general, like simply visualizing a problem or phenomenon, to the more specific, like translating between two-dimensional and three-dimensional representations.
**Understanding patterns.** Of the 17 faculty members interviewed for this study, 2 said that being able to recognize patterns was a skill of a proficient spatial thinker. Dr. Reiner described this general skill by saying that a proficient spatial thinker will succeed by, “just being a good animal that looks for patterns; trying to be predictive.”

Dr. Reiner also described the importance of understanding heterogeneic environments; that is, understanding the diversity of environments in a particular area. He describes an estuary changing over space and time: “Estuaries are both spatially and temporally dynamic; and that changes daily with tides, with seasons, I mean, so that is how I kind of come to that definition.”

**Understanding place and relative space.** Three out of 17 faculty members said that a general awareness of one’s surroundings is an ability of a proficient spatial thinker. While one geologist described this as an ability to understand how things fit together in your environment, 2 out the 3 chemistry faculty interviewed for this project described a specific spatial ability related moving around and understanding a laboratory environment. Dr. Zhang said,

I think they (the proficient spatial thinker) will work very efficiently. Because if you know what’s there then, before you go there, you will know the layout so that you will realize the time to find the implements or the chemicals that are there.

Another chemist, Dr. Priest relayed a similar idea, using the idea of working in rubber gloves as an example:

I work in a glove box…so it is kind of hard to do; you know, pick up a pen and all of that. So, being able to reach around, instinctively know how to do this, that, or the other, or how to hold things. I know this doesn’t really show up on the audio, but a lot of people are using a pipet with a bulb at the end here, they hold it like this. But if you have big bulky gloves, it kind of shakes around, so the way I always to teach them to grip firmly in your hand and if you need to manipulate it, manipulate it with
your wrists, rather than your fingers. So, that is kind of a spatial coordination type of element to it. I mean, it seems not really super scientific, but being able to do that kind of is the difference between spilling your stuff all over, which can be very unpleasant, and being able to do it quickly and accurately.

Two participants describe the ability to understand a phenomenon or environment from multiple perspectives. Comments that were categorized this way noted a spatial thinker’s ability to analyze their surroundings and deduce what it must look like from a place other than where they are located themselves. Dr. Kernley, a geologist said,

I can do things like walk into a house and as I am moving around in the house, if suddenly, I was outside the house, I could tell you what window I was looking out of. So I have this ability, because I have good spatial thinking to know where I am at a particular place and time, because I am kind of keeping track of where I am.

**Understanding data and data representations.** Three out of 17 interviewed faculty stated that the ability to integrate multiple types of data is important to proficient spatial thinking. Dr. Gibbons of the biology department referred to his own work, stating that, “When I collect data, it is often time multi-dimensional. I think about how everything fits together like that.” This touches on a previously-described skill, which is the idea of thinking multi-dimensionally, but in his case, Dr. Gibbons is referring to the ability in his own work to combine multiple sources of data to know something about the real world.

In addition, two faculty members said that being able to think across scales of data is important in a spatial thinker. To demonstrate what is meant by this, physicist Dr. Hestness stated,

I think is really important in my field is to integrate different sorts of data and to be able to think about them on relevant scales, so there is a time scale, but this is about space, so spatial scales. You know especially on spatial scales that aren’t simple for humans to think about.
He went on to describe that connecting data on microscopic scales to observable phenomena is important to understanding the underlying mechanism to something that we can use our senses to experience.

**Understanding matter.** The last category of general spatial thinking skills mentioned by the faculty was directed toward understanding matter and how it moves around in the world. The two skills described that fit into this category were (a) Understanding the movement of matter in the environment and (b) Estimating amounts and sizes of things. Each of these spatial thinking skills was named by 2 of the 17 faculty members that were interviewed for this study, though they were not named by the same two faculty members.

**Theme 2: Faculty perceptions of spatial thinking skills most useful to understanding enhanced greenhouse effect.** Since the original intent of the faculty interview process was to elicit science and math faculty perceptions of general spatial thinking abilities useful in the sciences and to elicit their perspectives on the spatial thinking abilities useful to understanding specific environmental problems, five environmental problems were selected for their differences in scale, impact, location, and medium (air, water, soil, etc.). The complete text for each of these problem descriptions can be found in Appendix A. I used a random number generator to select two environmental problems for each participant to discuss, to avoid an interview that was prohibitively long to productive discussion.

After the faculty interviews were complete, the focus of the project narrowed considerably to the spatial thinking abilities useful to understanding only enhanced greenhouse effect. As such, the number of participants who discussed spatial thinking specific to enhanced greenhouse effect is smaller than the total number of faculty participants. Eight faculty members discussed their perceptions of the spatial information that would be useful to understanding the phenomenon. By
discipline, they were 3 biologists, 2 geologists, 2 chemists, and 1 physicist. The responses of those 8 participants are described below.

Analysis of the transcripts followed a similar format as the analysis for Theme 1. Responses were read and types of spatial information named by faculty were identified. Categories were established based on common response patterns. Then, the transcripts were read again and each type of spatial information described was categorized, while still paying attention to new categories that might emerge. Participant responses fell into 5 broad categories of information. Unlike Theme 1, in which the categories were exclusively spatial, these categories were first content-based, but included a spatial component. They represented the areas of understanding one might have to understand enhanced greenhouse effect as a whole. They were: the greenhouse gases, atmosphere, radiation, the scale of the problem, and the impact of enhanced greenhouse effect. So, faculty experts described what a learner would need to understand spatially about the atmosphere or spatially about radiation, in order to fully understand enhanced greenhouse effect. This was unexpected, but useful, in that it connected general spatial thinking abilities to the content of enhanced greenhouse effect in explicit ways, which is not done otherwise in the spatial thinking or the enhanced greenhouse effect literature. Each theme and its components are described below, along with supporting quotations from the interviews.

It is important to note that no one category or type of information was largely agreed upon. Rather, each faculty member had a different perception of the spatial information that might be useful to students’ understanding of enhanced greenhouse effect. At the most 2 out of 8 participants named the same type of spatial information as important. Therefore, I will not report the numbers associated with each type of contextualized spatial thinking ability.

Greenhouse gases. Naturally, a main theme that faculty members perceived as central to learners’ understanding of enhanced greenhouse effect was related to the greenhouse gases that
absorb radiation that is reradiated from the Earth to the atmosphere. The greenhouse gases that are
named in novice literature, like textbooks, are carbon dioxide, water vapor, methane, nitrous oxide,
and tropospheric ozone (Christianson, 2013). However, the faculty interviewed for this study
referred to them in aggregate, as greenhouse gases, or referred specifically to carbon dioxide only,
which seemed to be a proxy for all greenhouse gases. This is typical of discussions related to
greenhouse effect since carbon dioxide, since it is the most abundant greenhouse gas and the one
that individuals can contribute to most regularly.

Faculty described a student’s ability to visualize greenhouse gases moving around, from their
sources to their accumulation in the atmosphere, as important to their understanding of enhanced
greenhouse effect. They perceived an importance also, in learners’ understanding of the relative
amounts of greenhouse gases in the atmosphere.

When speaking of carbon dioxide specifically, faculty perceived a need for students to know
that the carbon cycle occurs spatially. That is, it is moving around in the ground, the biota, the
atmosphere, etc.

Dr. Kernley, a geologist, described her own understanding, which she perceived as useful to
others saying,

I suppose it would be really tough to have a clue what this carbon cycle thing is without kind
of understanding that it occurs in space. It is going through various states, like it’s in the
ocean and it’s in plants and animals. Those are in different places, so at least when I read this
I am seeing pictures in my head.

In this quotation, Dr. Kernley is referring to the text description of carbon accumulation in
the atmosphere that was provided to her to describe the problem in a local and familiar area. Again,
the full text of the problem description can be found in the interview protocol in Appendix A

70
Similarly, interviewed faculty members described a similar type of understanding related to fossil fuels, in that students should know that fossil fuels are accumulations of carbon in the Earth’s crust that are burned to deposit carbon molecules in the atmosphere.

Participants also suggested that learners should know how sources of emission are distributed, including an ability to connect greenhouse gases commonly emitted, like automobile emissions, to an accumulation of greenhouse gases in the atmosphere. In addition, faculty members said that it would be important for learners to know the relative amount of greenhouse gases in the atmosphere, including both relative volumes and relative concentrations of different greenhouse gases. Learners should also know where greenhouse gases accumulate in the atmosphere; where they stratify in the atmospheric layers.

Dr. Barnes, a chemist, described spatial characteristics of enhanced greenhouse effect students should know by saying,

My first thought is about quantity and amounts, which again, I don’t know if it is directly spatial in context, but I think having and understanding of where the outputs are coming from, the quantities and volumes that we are talking about, and how these things that add into a total amount.

Notably, little discussion was given to the mechanisms by which greenhouse gases are removed from the atmosphere. Many of the important pieces of information faculty perceived as necessary to student understanding were related to emissions and to the accumulation of greenhouse gases in the atmosphere. One faculty member did, however, perceive that students should know how carbon dioxide interacts with plants to be taken out of the atmosphere.

Faculty participants described the following spatial concepts related to greenhouse gases as being important to a correct understanding of enhanced greenhouse effect:

1. Greenhouse gases move around in the atmosphere.
2. Greenhouse gases exist in larger and larger amounts as emissions increase.

3. The carbon cycle occurs in spaces on Earth as carbon changes form and moves around.

4. Greenhouse gas emissions come from various sources distributed across a landscape.

5. Greenhouse gas emissions come from individual action.

6. Greenhouse gas emissions can be measured by volume and by concentration as a proportion to other atmospheric components.

7. Greenhouse gases are absorbed by plant-life for photosynthesis.

8. An accumulation of greenhouse gases increases the amount of absorbed radiation in the atmosphere, which increases temperature.

_Atmosphere._ Two faculty members perceived that, in order to understand enhanced greenhouse effect, learners should have an understanding of various characteristics of Earth’s atmosphere. The location and the size of the atmosphere were both named as important spatial characteristics to understand. Dr. Kernley, a geologist, said that it was important to students to understand the size of the atmosphere relative to the Earth and as a human living in the atmosphere. She said students should understand that the atmosphere is just a really thin little skin around our planet helps inform my view of kind of the fragility of the system. Other people might not experience it that way. And at the same time as a person existing in the atmosphere and being really small compared to it.

Her recommendation was that students should be provided models of the atmosphere with the Earth, so that they might understand the relative sizes of each.

Dr. Priest is a chemist who described the necessity for learners to understand how air moves around in the atmosphere in order to understand how greenhouse gases might do the same. He said,
You kind of have to understand the overall wind patterns, for example. Now, how do they flow? How does stuff get distributed? I mean is it, is the CO₂ just staying in the place where there are not a lot of plants?

Dr. Preston, a physicist, described how this relationship is further complicated by considering the movement of the Earth and how that affects the movement of air in the atmosphere. He claimed learners needed information to understand these interactions in order to understand how greenhouse gases move in the atmosphere.

According to the faculty interviewed in this project, the essential spatially-related concepts students need to know about the atmosphere to understand enhanced greenhouse effect are:

1. The location of the atmosphere as a layer around the Earth.
2. The relative size of the atmosphere to the Earth.
3. The movement of air in the atmosphere.
4. The movement of the Earth and its impact on the movement of air in the atmosphere.

Radiation. Just one faculty member perceived information about radiation as integral to understanding enhanced greenhouse effect; however, this was the primary focus of our discussion, and he provided a large amount of information. Dr. Preston, a physicist, described several concepts as contributors to the larger concept of radiation in the enhanced greenhouse gas system. He stated that students needed information about the types of radiation involved in the enhanced greenhouse effect and how it moves from place to place, is absorbed, and radiated. Each concept is described in further detail below, with illustrative quotations.

Dr. Preston discussed the behavior of radiation from the sun once it reaches Earth as information he would want learners to know, saying, “So, the idea is that energy gets absorbed and what happens is that it forms a blanket and it is kind of reradiated.” The idea that the radiation that
is absorbed by greenhouse gases to enhance the greenhouse effect is actually radiation that is
reradiated from Earth after it is absorbed from the sun was an important one to Dr. Preston.

Again referring to novice students, he said,

I do want them to have that understanding of equilibrium. That the Earth picks up energy
from the sun. It’s always reradiating: energy in, energy out. And what we’re doing with the
greenhouse warming, is we are changing that equilibrium.

Dr. Preston felt it necessary for students to understand that the main impact of
anthropogenic emissions leading to enhanced greenhouse effect is the disruption of a natural
equilibrium of greenhouse gases, and therefore radiation, in the atmosphere.

Speaking to the transfer of radiation from the Earth to the sun, Dr. Preston said,

I want them to understand there is a vacuum, which they need to visualize, between the
Earth and the sun. And so we discuss the three forms of energy transfer. Conduction, then
there is radiation, and there’s conductivity. Conduction, convection and radiation. And the
point is to recognize that the sun, we are getting all of our energy via radiation from the sun.

Finally, he used a metaphor to describe how learners should understand the relationship
between the Earth and sun’s radiative forces as the, “basic visualization of two spheres. One is a
lamp, one is a less hot lamp, but they are both lamps. They are both radiating energy. I want them to
understand that.”

From our discussion of radiation, 9 spatial concepts emerged that Dr. Preston perceived as
important to students’ understanding of radiation related to enhanced greenhouse effect:

1. Radiation moves from the sun to Earth.

2. Earth absorbs the sun’s radiation and reradiates it to the atmosphere.


4. Radiant energy accumulates in the Earth’s atmosphere over time.
5. Absorbed radiation in the atmosphere increases its temperature.

6. Radiation in the Earth’s atmosphere is absorbed and reradiated in an equilibrium.

7. The sun and the Earth are connected by their radiative forces.

**Scale of the problem.** Several faculty members commented on the importance of students’ ability to understand enhanced greenhouse effect on multiple scales, from molecular to atmospheric. This was expressed in several ways.

Dr. Barry, a geologist, understood that, to have the greatest effect on student understanding, educators should provide them with information first on a local level. He used the impact of enhanced greenhouse effect and climate change on a local lake as an example and discussed that the local perspective can be used to hook students, pointing out that educators could move to a larger or smaller perspective from there. He said, “Lake Mead has a fifty-fifty chance of drying up in the next 7 years. You know, that’s a direct impact and it’s because of us. We’re taking steps, but let’s have a broader conversation about it.”

Faculty members said that an important spatial skill that learners should have is to be able to connect the very small phenomena that affect enhanced greenhouse effect to the very large phenomenon. Connecting and moving between scales was considered quite important. Dr. Hestness said, “Number one make a connection between a small molecule and a large, you know, a large atmosphere.” Dr. Priest continued with this idea saying,

Similar to the forensics you know, you have micro then you go up to I guess more regional, elements, both within an ecosystem, and also how the ecosystems react with each other. So, you have to understand where and how they interact, how all of those interactions kind of play upon each other.

Other participants were more attached to one end of the spectrum or the other. Dr. Hestness described microbial activities in the soil as contributors to methane in the atmosphere
from human activities, such as industrial rice production. At the same time, Dr. Priest was sure to describe students’ need to understand that greenhouse gases are not emitted only locally, but that the emissions and the problems associated with them are global.

Dr. Barry perceived the most important information that students should have should lead them to understand enhanced greenhouse effect holistically; to understand the interconnections between variables that contribute to an outcome of global average temperature change. He said that the most important thing is “approaching the work in a holistic view; [to] know all of these systems are interconnected.”

Combining their perceptions, faculty describe the following 4 spatial concepts as important to a student’s understanding of enhanced greenhouse effect:

1. Enhanced greenhouse effect occurs on scales from molecular to atmospheric.
2. The impacts of enhanced greenhouse effect are global.
3. Local phenomena related to enhanced greenhouse effect are connected to causes on much smaller and much larger scales.
4. Variables that are connected on scales that we cannot directly perceive cause enhanced greenhouse effect and a rise in temperature.

**Impacts of enhanced greenhouse effect.** The last category of information that faculty perceived as important to students’ understanding of enhanced greenhouse effect is the impacts associated with enhanced greenhouse effect. While the impacts of enhanced greenhouse effect are important to understand, as they are the results of climate change that humans will experience, they are also diverse. They differ greatly by region, by climate, by topography, by ecosystem, etc.

While I will report briefly on the spatial thinking abilities related to the impacts of enhanced greenhouse effect that were described by the faculty experts, spatial thinking objectives related to the impacts of climate change will not be included in the STA-En GreenE design. Impacts of climate
change include glacier retreat, sea level rise, changing vegetation zones, a decrease in annual mountain snowpack, decreases in fresh water availability, and more. Each of these impacts are unique and would be understood through its own set of spatial thinking abilities. There is enough complexity within each impact that a spatial thinking assessment could be developed, through the same development process that has been implemented here, for each of these topics. Therefore, to limit the length and complexity of this one assessment, I am defining boundaries for this assessment to exclude the impacts of enhanced greenhouse effect, and only include the enhanced greenhouse effect mechanism itself.

The faculty responses briefly summarized here demonstrate just how complex it would be to include spatial thinking skills related to the impact of enhanced greenhouse effect. Dr. Barry described the local impacts of enhanced greenhouse effect, like a decreasing amount of water in a local lake, because of a decrease in the snowpack that feeds it. Dr. Barnes described the spatial nature of sea level rise saying,

You need to have some sort of understanding of topography of places, and the idea of water inundation; that you are going to have and increase in level…here’s something that has some sort of natural topography, so there are going to be areas that are lower than others.

Dr. Barnes also described glacier retreat, using a map to say that students should understand that they will be considerably smaller; that the area that they cover will no longer be covered.

The few impacts described here are just a sample, but already it is clear to see that each have their own related set of spatial thinking abilities that would be employed to understand them fully. This would make just one assessment to capture an understanding of all of the potential impacts of enhanced greenhouse effect prohibitively long and complex. For this reason, a discussion of impacts were not included in the assessment design. A comprehensive list of the spatial information faculty
perceived as important to learners’ understanding of enhanced greenhouse effect is displayed in Table 2 below.
Table 2

Spatial Information Needed by Learners to Understand Enhanced Greenhouse Effect (organized by theme). Asterisks indicate concepts that bridge content themes.

<table>
<thead>
<tr>
<th>Content theme</th>
<th>Spatial information</th>
</tr>
</thead>
</table>
| Atmosphere             | 1. The location of the atmosphere as a layer around the Earth.  
2. The relative size of the atmosphere to the Earth.  
3. The movement of air in the atmosphere.  
4. The movement of the Earth and its impact on the movement of air in the atmosphere. |
2. Greenhouse gases exist in larger and larger amounts as emissions increase.  
3. The carbon cycle occurs in spaces on Earth as carbon changes form and moves around.  
4. Greenhouse gas emissions come from various sources distributed across a landscape.  
5. Greenhouse gas emissions come from individual action.  
6. Greenhouse gas emissions can be measured by volume and by concentration as a proportion to other atmospheric components.*  
7. Greenhouse gases are absorbed by plant-life for photosynthesis.  
8. An accumulation of greenhouse gases increases the amount of absorbed radiation in the atmosphere, which increases temperature.* |
| Radiation              | 1. Radiation moves from the sun to Earth.  
2. Earth absorbs the sun’s radiation and reradiates it to the atmosphere.  
4. Radiant energy accumulates in the Earth’s atmosphere over time.*  
5. Absorbed radiation in the atmosphere increases its temperature.  
6. Radiation in the Earth’s atmosphere is absorbed and reradiated in an equilibrium.  
7. The sun and the Earth are connected by their radiative forces. |
| Scale                  | 1. Enhanced greenhouse effect occurs on scales from molecular to atmospheric.  
2. The impacts of enhanced are global.  
3. Local phenomena related to enhanced greenhouse effect are connected to causes on much smaller and much larger scales.  
4. Variables that are connected on scales that we cannot directly perceive cause enhanced greenhouse effect and a rise in temperature. |
Discussion

The results of these interviews with science and math faculty experts in the College of Sciences at a large Southwestern university contributed to the STA-En GreenE by answering the following questions:

(1) What are experts’ perceptions of which spatial thinking skills are necessary to support learners’ understanding of enhanced greenhouse effect?

(2) What spatial information do faculty members perceive as useful to learners understanding enhanced greenhouse effect?

(3) How can expert perceptions of spatial thinking related to enhanced greenhouse effect inform the design of an assessment to test such abilities?

I will use the results reported above to describe themes related to questions 1 and 2. Then I will how I used the information to design the STA-En GreenE (question 3).

Most faculty perceived visualization and dimensional thinking as the most important spatial thinking skills in a proficient spatial thinker. Most commonly, faculty experts described a proficient spatial thinker as a person who can think about objects or phenomena in three dimensions. Several described general visualization as an important ability, and this included the ability to translate between two-dimensional and three-dimensional representations and reality. Therefore, the ability to visualize is important to consider when designing an assessment to test spatial thinking abilities related to a phenomenon that is largely invisible.

Enhanced greenhouse effect is the absorption of radiation by greenhouse gases in Earth’s atmosphere, leading to an accumulation of radiation and an increase in temperature. Learners are not able to directly perceive any part of this system. Greenhouse gases are invisible, their interaction with radiation does not create a perceptible effect, and the global average temperature change is small and occurs over a relatively long period of time, making it challenging for human perception.
For a learner to understand the mechanism by which enhanced greenhouse effect occurs, they have to build a dynamic model of the components and how they interact in their head. This is the three-dimensional visualization that faculty members describe.

In order to express what they understand and the images they are building in their mind’s eye, learners must use the dynamic three-dimensional model they hold in their head to answer questions about enhanced greenhouse effect. For the purposes of the model-based assessment designed for this project, learners must translate their dynamic three-dimensional, mental models to a static, two-dimensional representation for evaluation. This ability to translate between three- and two-dimensional representations is another ability of a proficient spatial thinker named by faculty experts.

Remembering that this study relies upon a models and modeling framework for its theoretical foundation, the spatial thinking abilities described here and an analysis for how they may support assessment design are supported by that framework. The spatial thinking skills named by faculty experts, like visualization and three-dimensional thinking, are methods for creating mental models (Bodner, Gardner, & Briggs, 2005). The method by which students will express the mental models that they are operating from is the creation of a conceptual model. As such, this study used the general abilities named here, the concepts to be described in the next section, and the modeling best practices described in the literature to design assessment items.

To get a clearer picture for how faculty experts’ perceptions shaped the assessment tasks in terms of the content, the next section addresses faculty responses related to enhanced greenhouse effect specifically.

Faculty experts’ perceptions of important spatial information to understanding enhanced greenhouse effect span many interrelated concept themes. The spatial information that faculty describe as important to students’ understanding of enhanced greenhouse effect fell into
5 broad categories: the atmosphere, greenhouse gases, radiation, scale, and impacts. For the purposes of this study, the spatial information or spatial thinking skills related to the impacts of enhanced greenhouse effect will not be assessed, to place reasonable boundaries around what a student need to know and articulate in one assessment. The concept themes named above are a useful way to categorize spatial information for assessment design because they are one way that groups of questions or model-building activities might be categorized. For example, one question might encompass all of the spatial concepts related to the atmosphere and ask students to model its location relative to the Earth, its relative size, that it exists in layers around the Earth, etc. This becomes a natural method for organizing students’ representations of their understanding.

Of note are the spatial thinking abilities that have been categorized within one concept theme or another, but include ideas that might be related to another. For example, within the content theme “Greenhouse Gases,” one concept is, “An accumulation of greenhouse gases increases the amount of absorbed radiation in the atmosphere, which increases temperature.” This idea includes a discussion of radiation, which is another content theme. These ideas that span multiple content themes will be called “bridging concepts” and will be discussed again in a section which describes findings of a literature review of existing assessments that test students’ understanding of enhanced greenhouse effect.

These bridging concepts should be recognized as the ideas that describe how components of the enhanced greenhouse effect system are interrelated and affect each other. The climate system is complex, with many interrelated variables. For students to understand some enhanced greenhouse effect concepts, it is sufficient that learners understand just one content theme (like concepts that only address the size or location of the atmosphere). However, if we are to explain the whole complex system that leads to an enhanced greenhouse effect, some concepts will connect content themes, for example, from atmosphere to radiation, or from radiation to greenhouse gases. The
concepts that have been identified as concepts that connect content themes are marked with an asterisk in Table 2 above. They are:

- Greenhouse gases move around in the atmosphere. (Content themes: Atmosphere and Greenhouse gases)
- Greenhouse gas emissions can be measured by volume and by concentration as a proportion to other atmospheric components. (Content themes: Atmosphere and Greenhouse gases)
- An accumulation of greenhouse gases increases the amount of absorbed radiation in the atmosphere, which increases temperature. (Content themes: Greenhouse gases and Radiation)
- Greenhouse gases absorb radiation. (Content themes: Greenhouse gases and Radiation)
- Absorbed radiation in the atmosphere increases its temperature. (Content themes: Radiation and Atmosphere)

Because the bridging concepts represent important interactions between themes, they should be the main focus of an assessment focused eliciting students’ understanding of enhanced greenhouse effect. These are the key concepts that students need to comprehend to understand enhanced greenhouse effect systemically. Taking a step back from these central bridging ideas brings the student to each of the underlying individual concept themes. Students must also understand the individual components to understand how they are interconnected to produce the effect that we can measure: increased temperature. For students to understand the bridging concepts, they have to understand where they come from, so the concepts that are well within the boundaries of addressing just one concept are important to students’ understanding as well.

Faculty experts’ perceptions about the spatial thinking abilities that support learners’ understanding of enhanced greenhouse effect can inform the development of performance objectives for the assessment. The contextualized enhanced greenhouse effect concepts named
here, described together with the general spatial thinking skills described by faculty, illustrate what it means to think spatially about enhanced greenhouse effect and its related components. For example, if faculty perceive that students need to understand the size and location of the atmosphere relative to Earth, and they also perceive that a proficient spatial thinker is able to visualize phenomena and objects in three dimensions, then it follows that to think spatially about the atmosphere, learners should be able to visualize its position and perhaps its volume and thickness compared to the Earth. If proficient spatial thinkers can also translate between two-dimensional representations and three-dimensional representations or reality, then staying with this concept, they would also be able to create a conceptual model of their understanding of a three-dimensional atmosphere relative to Earth. This may seem intuitive, but we will see in the next section that assessments that enable students’ expression of this type of understanding are almost non-existent.

Another dimension that faculty input adds to the creation of performance objectives is the inclusion of time as important to understanding environmental problems. While some previous research has described temporal and spatial understanding as linked both in human cognition and in language (Boroditsky, 2000; Gentner, 2001; Gentner, Imai, Boroditsky, 2002; Matlock, Ramscar, and Boroditsky, 2005), much of the literature deals with the two ideas separately, as is the case for the foundational spatial thinking literature for this study. However, given the experts’ focus on change here, and given that environmental problems are characteristics of a system changing over time, I included time as a factor in the learning objectives that were the foundation of the assessment item design. It is not explicitly dealt with, in that I did not research the temporal aspects of enhanced greenhouse effect as I did the spatial aspects, but faculty input here made it clear that students needed to be able to demonstrate an understanding of how environmental problems change over time. Therefore, time was implicitly included in the assessment item. The process by which this was done is described in Chapter 8.
Overall, faculty perceptions of the spatial thinking abilities useful to understanding enhanced greenhouse effect, along with additional concepts gathered from literature reviews conducted on existing spatial thinking and enhanced greenhouse effect assessments (described in Chapters 6 and 7), informed the development of performance objectives for the STA-En GreenE. The specific method by which this was done will be described in Chapter 8, Assessment Development and Design.

The original intention of gathering content experts’ perspectives from across the sciences was to inform the design of an online survey directed toward environmental education experts. I hypothesized that, during their interviews, the science and math faculty experts would provide in-depth and detailed information stemming from their areas of expertise and their spatial understanding within those areas. Then, the abilities and content that they describe would be presented to experts in environmental education for their input on which spatial thinking skills they deemed most useful to understanding enhanced greenhouse effect. The perceptions of experts in environmental education will be the focus of Chapter 5.
Chapter 5: Survey of Environmental Education Experts

Introduction

One purpose for gathering content experts’ perspectives from across the sciences was to inform the design of an online survey directed toward environmental education experts. I expected that, during their interviews, the science and math faculty experts would provide in-depth and detailed information stemming from their areas of expertise and their spatial understanding within those areas. Then, the abilities and content that they described would be presented to experts in environmental education for their input on which spatial thinking skills they deemed most useful to understanding enhanced greenhouse effect.

The environmental education experts that were accessed for the study were members of an international organization for environmental education: the North American Association for Environmental Education (NAAEE). These experts were accessed for their knowledge of environmental issues and particularly for their knowledge of learners in environmental studies. The research questions addressed for this part of the study were similar to those asked of faculty experts in math and science. They were:

(1) What are environmental education experts’ perceptions of which spatial thinking skills are present in a proficient spatial thinker and how does spatial thinking support an understanding of enhanced greenhouse effect?
What spatial information do environmental education experts perceive as useful to learners understanding enhanced greenhouse effect?

How can expert perceptions of spatial thinking related to enhanced greenhouse effect inform the design of an assessment to test such abilities?

The purpose of surveying these experts was to gain a different perspective than that of the faculty experts. A survey method was used for the convenience of access it allowed to experts who were far away. The intention of the survey was to reveal any spatial thinking abilities that were described by the science and math faculty experts but that were not supported by environmental education experts and to add any spatial thinking abilities environmental education experts deemed important that were not named by science and math faculty experts. The input of the environmental education experts was used to inform the assessment design in that it was to provide an additional perspective about the spatial thinking abilities useful to understanding enhanced greenhouse effect.

Method

An email invitation to participate in an online survey was sent to 99 members of the NAAEE who are listed as members in the organization’s online directory. The email invitation included a link to an online survey. None of the experts surveyed are researchers or experts in spatial thinking. This is important to note, because, as with the faculty experts that were interviewed, it means that their contributions are their perceptions of important spatial thinking skills. As such, this portion of the research uses a phenomenographical approach. Phenomenography is an empirical research tradition designed to answer questions about thinking and learning, with an objective of defining the limited number of ways in which a group of people experience, interpret, understand, perceive, or conceptualize a phenomenon or certain aspect of reality (Marton, 1986; Orgill, 2007).

Participants. An email was sent to 99 self-reported environmental education experts. Members who were contacted were from the United States, Canada, and Mexico. Of the 99
NAAEE members who were contacted, 27 responded and participated in the survey, for a 27 percent response rate. The 27 NAAEE members who responded were a mixture of teachers, informal educators, curriculum developers, administrators, and those who identified as belonging to more than one of these categories. They worked with learners of all ages, and most had greater than 5 years of experience. The trends in their responses are reported on below.

The survey. The survey that the environmental education experts participated in was made up of three sections. The first section included a very brief demographic survey. The second section included a list of general spatial thinking skills described in the literature and asked participants to rate each of them as “Very important,” “Important,” “Not very important,” or “Not important at all.” These four points, instead of a traditional 5-point scale were chosen for each of the Likert-type items, so that participants would commit to a non-neutral response (Clason & Dormody, 1994), if they chose to answer. The spatial thinking skills listed were the ones that were described in the Chapter 2 literature review.

The purpose of the third section of the assessment was to elicit environmental education experts’ perspectives of the spatial thinking skills that were specifically useful for learners’ understanding of enhanced greenhouse effect. These items utilized the same Likert-type items for participants’ evaluation. The items themselves were synthesized from the results of the faculty interviews. At the end of each section, there was an open item that prompted participants to describe any other abilities or make any recommendations they perceived as relevant to learners’ understanding of enhanced greenhouse effect. A complete version of the survey, as well as the invitation and reminder emails, are found in Appendix B.

Analysis

Participants’ perceptions of the spatial thinking abilities found in a proficient spatial thinker, as well as the their perceptions of the spatial thinking abilities useful to understanding enhanced
greenhouse effect specifically, were determined by analyzing the Likert-type items that were in Parts 2 and 3 of the online survey, respectively. Likert-type responses are considered ordinal data, in that they may be considered rankings that are higher or lower in relation to each other, but the intervals between rankings are not defined. That is, even though we assign numbers to response options to rank them, we cannot say how much high or lower a “Very important” ranking is than an “Important” ranking (Clason & Dormody, 1994). Therefore, parametric statistics are not recommended for this type of data (Clason & Dormody, 1994; Sullivan & Artino, 2013). Analyses that are recommended include determining the mode, the frequency, Kendall tau B or C, or Chi squared. Kendall tau B or C and Chi squared are not necessary in this case because I am not comparing subpopulations of participants. Determining the mode of participant responses is recommended for Likert-type items such as this (Boone & Boone, 2012).

Since the goal of this analysis was to determine which of the spatial thinking skills described in the literature and by science and math faculty experts were supported by the environmental education experts, I decided to first look at the mode for each of the items to determine very generally which spatial thinking skills were supported by the environmental education experts and which were not. Then, in order to assess which items were particularly important to environmental experts, I looked at the frequency distributions of responses for each item. Finally, I evaluated any comments made by participants when they were asked for additional spatial thinking abilities they perceived as important to learners’ understanding that were not named in the literature.

Results

The mode results of each Likert-type item, for both Parts 2 and 3, demonstrated that environmental education experts supported each of the spatial thinking skills present in a proficient spatial thinker. The mode for each item was either a “2,” representing an “Important” ranking or a “3,” representing a “Very important” ranking. To clarify, that means for Part 1, environmental
education experts perceived each of the spatial thinking skills named as either “Important” or “Very important” in a proficient spatial thinker. For Part 3, each skill, contextualized in enhanced greenhouse effect concepts, was perceived as either “Important” or “Very important” to learners’ understanding of enhanced greenhouse effect. Table 3, found in Appendix C, shows each of the abilities included in the survey and their mode ranking.
Environmental experts supported each of the spatial thinking skills named in the literature and by science and math faculty experts. Table 3 lists these abilities and their mode rankings. In addition, the table displays the frequency of each of the Likert-type item responses in order, from least important to most important: Not important at all, Not very important, Somewhat important, and Very important. The frequencies of response display which of the items the participants felt were “Very important.” The items that were selected as “Very important” by 80 percent of more of the participants are marked with an asterisk in Table 3.

In order to determine if environmental education experts had any additional spatial thinking skills to describe that might be present in a proficient spatial thinker or that are useful to understanding enhanced greenhouse effect, I prompted survey participants to add any such ideas at the end of each section. None of the participants added skills, and very few added anything at all when prompted at. While they did not add any spatial thinking skills, a few participants made a general recommendation for intervention and assessment design. Environmental educators recommended utilizing local examples to improve students’ spatial thinking abilities related to enhanced greenhouse effect. For example, one participant said,

I believe that the attainment of spatial thinking skills must begin from the individual’s perspective. Understanding first how and where other things relate to themselves is an important step to gaining an accurate understanding of how things relate to each other, both spatially and otherwise.

Another participant added to this idea by saying,

Many of these local information questions are much more important in certain regions. For example, while some regions face increased flooding, tornados, or hurricanes, in some regions, students might understand the impacts on coastal or river routes in other areas more easily than impacts in their local region.
This recommendation was taken into account during assessment design, when the assessment was designed to include a local and familiar image as the foundation for the first modeling space in which students created their models.

**Discussion**

Overall, the perceptions of the environmental experts supported the perceptions of the science and math faculty experts that were interviewed. Since this is the case, and since the environmental experts did not offer any additional spatial thinking recommendations, environmental education experts’ perceptions did not substantively influence the design of the STA-En GreenE assessment. The objectives that were established for students to be able to demonstrate their understanding were ultimately determined by a synthesis of literature review and expert input.

Of note, however, are the items that experts named as “Very important” most frequently. Of the skills present in a proficient spatial thinker, the only one identified so frequently was “recognizing patterns.” Among the contextualized skills, experts named an understanding of the accumulation of trapped radiant energy, the amount of greenhouse gas emissions, the interaction of carbon dioxide and plants, the relationship between greenhouse gases and temperature, the impact of enhanced greenhouse effect on everyday life, and local examples of the impact of enhanced greenhouse effect. While the spatial aspects of the *impacts* of enhanced greenhouse effect were not included in the assessment (for reasons mentioned in Chapter 4), the environmental educators’ perspective that spatial understanding should begin with a local focus, was factored into the assessment design.
Chapter 6: Literature Review of Existing Assessments about Enhanced Greenhouse Effect

Introduction

Enhanced greenhouse effect and its impacts are not new topics in environmental education; but, increasingly, they are considered some of the most pressing issues facing global society (National Research Council, 2012b). This is reflected in the national standards for science education in the United States, where for the first time, topics related to global climate change are articulated priorities in American science education (Shea, Mouza, & Drewes, 2016). This prioritization demonstrates a need for curriculum development in both formal and informal settings. In order to better understand the effectiveness of new curricula on student understanding of enhanced greenhouse effect, the development of assessments to test these interventions is also necessary. Speaking more specifically to the current study, the on-going discussion over enhanced greenhouse effect in science education tells us that work of this kind is timely, but also that it is already underway.

Spatial thinking abilities are essential to understanding enhanced greenhouse effect and its potential impacts. While existing curricula and assessments may not directly target students’ spatial thinking abilities related to enhanced greenhouse effect, they can inform this study by establishing boundaries around the content to be assessed. Learning from existing content in this discipline will inform my understanding of the most important topics for understanding enhanced greenhouse
effect as a whole. In reviewing the literature on existing assessments testing students’ understanding of enhanced greenhouse effect, I asked two questions:

1. What enhanced greenhouse effect content understanding is tested in existing assessment items?
2. What spatial thinking abilities are included in existing assessments that test students’ understanding of enhanced greenhouse effect?

Method

In order to answer the two questions listed above, I conducted a literature review of relevant reports and studies in peer-reviewed journals. To be included in the literature review, the publication had to include an assessment of student understanding of enhanced greenhouse effect. This included intervention studies, in which the assessment may not have been the primary focus of the study, but in which the assessment items were articulated and could be analyzed. This also included assessment development research, in which assessment development was the primary objective of the study. The latter studies were of particular interest because they articulated assessment development priorities and could, therefore, inform the priorities of the current assessment as well.

I conducted a systematic review of the existing scholarly literature on assessing student understanding of enhanced greenhouse effect. The following databases were searched for relevant literature: EBSCO Complete, ERIC, JSTOR, ProQuest, Science Direct, and SpringerLink. Within each database, the terms “assess” and “greenhouse effect” were searched together and were required to be included in the title or abstract of the paper, to ensure that enhanced greenhouse effect was a central topic in the study. Additionally, as mentioned, articles were only included in my review if an assessment was part of the research. While the focus of the current study is enhanced greenhouse effect, I decided that the search term “greenhouse effect” would be more inclusive and would result in a larger pool of research, from which I could discern the relevant literature by evaluating the
content of the paper. It is important to note that the search was limited to only research that assessed understanding of the mechanism of enhanced greenhouse effect and not related topics, such as impacts of enhanced greenhouse effect on glaciers, ecosystems, or sea level. This decision was made for two reasons. First, existing research across disciplines shows how the global average temperature increase that is the result of enhanced greenhouse effect has a global effect on human and natural systems (Sterman, 2010), and it is not the intent of this research to prioritize which impacts are the most important and should be included and which ones should not. Second, if the assessment design for this project were to include the impacts of enhanced greenhouse effect, the assessment would likely be too long for a student to complete to the best of their ability, within a reasonable timeframe. For this reason, only assessment items that focused on the mechanism of increased global temperature due to an increase of infrared radiation in Earth’s atmosphere, as it interacts with an increased amount of greenhouse gases in the atmosphere, because of anthropogenic emissions, were included for this research.

This search resulted in 17 papers. One of the 17 papers referenced an additional study on enhanced greenhouse effect assessment design, so that report was included as well, for a total of 18 studies that included enhanced greenhouse gas assessment and were analyzed for their assessment content and spatial representation.

I read each of the 18 publications and analyzed them to identify: (a) the enhanced greenhouse effect content understanding elicited in each assessment item; and (b) any spatial thinking representations and/or abilities elicited within each assessment item. This included spatial representations that students were asked to create and spatial thinking abilities that were required to accurately describe the concept the item was testing. I coded each assessment item for the content understanding that students were asked to represent and what type of assessment item it was (e.g., selected response, open response, model-based assessment, etc.). Many concepts were common to
more than one assessment. For each new item, the concept was identified, compared to concept categories established from the classification of items previously analyzed. If the concept matched an existing category, it was coded for that category. If it was identified as an original concept, a new category was created and the concept was coded accordingly. Through this method, the list of categories grew, as each assessment was analyzed. Then, I analyzed the codes for emergent themes present in the assessments.

Similarly, assessment items were analyzed for any ways in which students were asked to demonstrate spatial thinking abilities or create spatial representations. Where assessments of spatial thinking related to greenhouse effect were identified, they were compared to spatial thinking abilities already identified in the spatial thinking literature and were categorized as such. The next section describes the findings of this literature review.

**Results**

The combined 18 papers that included assessments of students’ understanding of enhanced greenhouse effect yielded a total of 190 assessment items, each of which was analyzed for enhanced greenhouse gas content and spatial thinking ability included in the assessment.

Of the 18 assessments analyzed, 5 were designed to be administered to undergraduate university students, 1 to elementary students, 7 to middle school students, and 1 to high school students. One study was designed to assess enhanced greenhouse effect understanding for elementary, middle and high school students.

Of the 190 items analyzed, 20 questions were asked in an interview format. Several of these were asked in a semi-structured interview with follow up questions when the learner’s expressed understanding warranted further discussion. The remaining 170 items that were analyzed were written assessment items. The item formats represented were as follows: 68 multiple choice selected
response, 71 true-or-false selected response, 28 open response, and 5 items that asked students to interpret or build a conceptual model to express their understanding.

I identified 40 separate concepts related to enhanced greenhouse effect across the 18 assessments analyzed. From those concepts, 7 themes supporting enhanced greenhouse effect were identified: greenhouse gases, greenhouse effect, radiant energy, the atmosphere, temperature and climate, the impacts of climate change, and misconceptions. The concepts assessed by each of the 190 items were associated with one of these broader ideas. Each of the concepts associated with these themes were rooted in content, but required spatial thinking abilities to fully understanding. Each of the themes and their associated concepts are described in further detail below and are summarized in Table 4 (p. 121).

**Theme 1: Greenhouse gases.** Assessment items that tested students’ understanding of greenhouse gases (41) required understanding of the nature of greenhouse gases and what they do. Items that assessed understanding within this theme assessed the 5 more specific concepts listed below. The number of assessment items that focused on each concept are reported next to each concept in parentheses:

1. Some human activities produce greenhouse gases (18)

2. Greenhouse gases influence the flow of energy through the atmosphere by increasing the amount of energy absorbed in the atmosphere. (11)

3. Carbon dioxide, methane, nitrous oxide, water vapor, and methane are the major greenhouse gases. (9)

4. Some variables decrease the amount of greenhouse gases in the atmosphere. (2)

5. Some societies add more greenhouse gas to the atmosphere than others. (1)

Examples of items of multiple formats that addressed each concept within the greenhouse gases theme are provided as a flowchart in Figure 7 below.
Figure 7. Concepts related to Theme 1: Greenhouse Gases, with example items.

**Theme 2: Radiant energy.** Assessment items that tested students’ understanding of radiant energy related to enhanced greenhouse effect (36) tested students’ understanding of the nature and kinds of radiant energy in the Earth/sun system. They assessed students’ understanding of the movement of radiation from the sun to the Earth, the way it is reflected from Earth’s surfaces, and what happens to it in the atmosphere. Items that assessed understanding within this theme assessed
the 6 more specific concepts listed below. The number of assessment items that focused on each concept are reported next to each concept in parentheses:

1. When radiant energy interacts with greenhouse house gases in Earth's atmosphere, it is absorbed and stays in the atmosphere longer. (15)

2. Albedo effect is when radiation is reflected from Earth's surface, back to outer space. (10)

3. Radiant energy entering and leaving Earth's system reaches an equilibrium that affects Earth's temperature. (4)

4. Most of the radiant energy from the sun to the Earth comes in the form of visible light, ultraviolet rays, and infrared rays, also known as heat. (3)

5. Radiant energy reflected from the Earth is absorbed by greenhouse gases in Earth’s atmosphere. (2)

6. Radiant energy from the sun travels to Earth's system, then gets absorbed or reflected, which affects Earth's temperature. (2)

Of note is the grouping of items that assess students’ understanding of radiant energy on just 4 out of 18 assessments analyzed. Some assessments focused strongly on radiant energy, while others did not. For example, on one assessment, 12 out of 64 assessment items were related to the nature and interactions of radiant energy in the Earth/sun system (McCuin, Hayhoe, & Hayhoe, 2014). Other assessments did not include radiant energy-related items at all. Examples of items of multiple formats that addressed each concept within the greenhouse gases theme are provided as a flowchart in Figure 8 below.
Figure 8. Concepts related to Theme 2: Radiation, with example items.

**Theme 3: Atmosphere.** Assessment items that tested students’ understanding of Earth’s atmosphere (4) required an understanding of the composition of the atmosphere and its structure to be answered correctly. Items that assessed understanding within this theme assessed just 3 more
specific concepts listed below. The number of assessment items that focused on each concept are reported next to each concept in parentheses:

1. Earth's atmosphere has layers that have separate functions and characteristics. (1)

2. Earth's atmosphere is made up of gases, like nitrogen, oxygen, carbon dioxide, argon and other trace gases. (2)

3. Earth's atmospheric system and its components are analogous to a greenhouse. (1)

There were far fewer assessment items related to this theme than other themes. That is not to say that other assessment items did not include the atmosphere in their description, but for most assessment items where the atmosphere was mentioned, it simply acted as the location for another interaction or phenomenon taking place. For example, if an item asked students to express their understanding of greenhouse gas behavior in the atmosphere, the item was classified as an assessment of students’ understanding of greenhouse gases, and not the atmosphere. There were very few items (4) that restricted their assessment to students’ understanding of just the atmosphere and its characteristics. Only three assessment items in two assessments included this concept at all (Bodzin & Fu, 2013; Varma and Linn, 2011). Examples of items of multiple formats that addressed each concept within the greenhouse gases theme are provided as a flowchart in Figure 9 below.
Figure 9. Concepts related to Theme 3: Atmosphere with example items.

Theme 4: Temperature and Climate. Assessment items that tested students’ understanding of temperature and climate (27) required an understanding of each of those concepts, the differences between them, and how they are changing on Earth. Items that assessed understanding within this theme assessed the 6 more specific concepts listed below. The number of assessment items that focused on each concept are reported next to each concept in parentheses:

1. Global warming/climate change is an increase in global average temperature due to an increase of radiation in the atmosphere, because of an increase of greenhouse gases in the atmosphere. (8)

2. An enhanced greenhouse effect causes global warming. (7)

3. There is an increase in global average temperature. (4)
4. Scientists use measures like ice core measurements and tree ring data as proxies to understand how climate has changed over long periods of time. (4)

5. Weather describes short term characteristics in temperature and precipitation. Climate describes long term characteristics. (3)

6. Geologic and geographic features affect local weather patterns. (1)

As with previous themes, the theme of temperature and climate was not equally represented among the enhanced greenhouse effect assessments that were analyzed. Some did not include specific temperature and precipitation concepts at all, while 10 out of a total of 27 items across assessments, related to this theme came from one assessment (Bodzin & Fu, 2013). Examples of items of multiple formats that addressed each concept within the greenhouse gases theme are provided as a flowchart in Figure 10 below.
Figure 10. Concepts related to Theme 4: Temperature and Climate, with example items.

**Theme 5: Greenhouse Effect.** Assessment items that were classified as testing students’ understanding of the greenhouse effect (24) required an understanding of an increased amount of energy reflected from the Earth remaining in the atmosphere, because it is absorbed by greenhouse gases in the Earth’s atmosphere. This causes an increase in temperature. This concept is an intersection of the other themes identified through the other assessment items. In many ways, it is
the synthesis of what learners know about greenhouse gases, radiation, and the atmosphere, and
temperature and climate. Items that assessed understanding within this theme assessed the 4 more
specific concepts listed below. The number of assessment items that focused on each concept are
reported next to each concept in parentheses:

1. Enhanced greenhouse effect is the absorption of radiation in the atmosphere by
   anthropogenic greenhouse gases, leading to an increase in temperature. (14)
2. Natural greenhouse effect is important to Earth's atmospheric temperature. (7)
3. Human actions can decrease the enhanced greenhouse effect. (2)
4. Natural greenhouse effect is necessary. Enhanced greenhouse effect has harmful impacts. (1)

   Examples of items of multiple formats that addressed each concept within the greenhouse
effect theme are provided as a flowchart in Figure 11 below.
Figure 11. Concepts related to Theme 5: Greenhouse Effect, with example items.

**Theme 6: Impacts of Climate Change.** Assessment items that were classified as testing students’ understanding of the impacts of enhanced greenhouse effect (22) asked students to describe or identify how global average temperature increase is going to change characteristics of Earth’s system. There were 5 major categories of impact represented: water availability, sea level, weather patterns, ecosystems, and people and society. Only 5 out of the 18 papers analyzed represented the impacts of enhanced greenhouse effect in their assessments. One assessment
focused on the mechanism of enhanced greenhouse effect leading to climate change, but was primarily focused on the impacts of enhanced greenhouse effect on local water supply. Therefore, 13 items were focused on water (Nussbaum et al., 2015). The other concepts were assessed evenly and sparingly. Items that assessed understanding within this theme assessed the 7 more specific concepts listed below. The number of assessment items that focused on each concept are reported next to each concept in parentheses:

1. Changing climate will change water availability. (13)
2. A changing climate will impact Earth in different ways across the globe. (4)
3. Climate change will affect ocean temperature and sea level. (1)
4. Changing climate will change local weather patterns. (1)
5. Changing climate will change ecosystems. (1)
6. Changing climate will affect culture and how people live their daily lives. (1)
7. Energy use causes the global changes we see by changing the climate. (1)

Examples of items of multiple formats that addressed each concept within the impacts of enhanced greenhouse effect theme are provided as a flowchart in Figure 12 below.
Theme 6: Impacts

6.A Changing climate will change water availability.
6.B A changing climate will impact Earth in different ways across the globe.
6.C Climate change will affect ocean temperature and sea level.
6.D Changing climate will change local weather patterns.
6.E Changing climate will change ecosystems.
6.F Changing climate will affect culture and how people live their daily lives...
6.G Energy use causes the global changes we see by changing the climate.

Multiple choice selected response: If climate change causes an increase in average temperature of the area, what happens to the water in Lake Mead?
   a. Nothing because higher temperatures will not affect water levels.
   b. Nothing because the climate is not changing.
   c. The water in Lake Mead will lower due to less snowpack and therefore, less water flowing into the Lake.
   d. The water in Lake Mead will rise due to the melting of the snowpack and therefore, more water flowing into the Lake. (Nussbaum et al., 2015, p. 811)

Multiple choice selected response: Scientists have reported that many glaciers in the world are much smaller than they were 100 years ago. Also, in the northern hemisphere, the habitat ranges of some typically southern animal specials are migrating northwards. These examples are evidence of...
   a. climate change.
   b. ozone depletion.
   c. land use change.
   d. snowball Earth. (Bodzin & Fu, 2013, p. 5)

Open response, interview: “If these scientists are correct what will happen to the oceans? Explain why you think this would happen.” (Shepardson et al., 2009, p. 501)

Open response, interview: “If these scientists are correct what things about the Earth’s weather will change? Explain why you think this would happen.” (Shepardson et al., 2009, p. 501)

Open response, interview: “If these scientists are correct what will happen to plants and animals? Explain why you think this would happen.” (Shepardson et al., 2009, p. 501)

Open response, interview: “If these scientists are correct what will happen to people and society? Explain why you think this would happen.” (Shepardson et al., 2009, p. 501)

Open response, interview: “Show photos from Ecological Scenarios and ask:
   a. Do you think that this energy use is related to what’s happening here?
   b. Why or why not?
   c. Why would using energy make it warmer?” (Varma & Linn, 2011, p. 460)

Figure 12. Concepts related to Theme 6: Impacts, with example items.

Theme 7: Misconceptions and Opinions. Controversy and opinion related to enhanced greenhouse affect were addressed primarily through open response questions, asking participants to
describe the controversy. Assessment items that were classified as testing students’ understanding of the misconceptions related to enhanced greenhouse effect (36) focused on the most pervasive misconception about the topic: the confluence of ideas related to the hole in the stratospheric ozone layer and enhanced greenhouse effect (Gautier, Deutch, & Rebich, 2006). Only 2 out of 18 assessments addressed this concept, one of which had a socioscientific focus, in which understanding contrasting public opinion was described as a key component to studying the topic (Sadler, Klosterman, & Topku, 2011). One study included 29 questions related to ozone and enhanced greenhouse effect in one assessment (McCuin, Hayhoe, & Hayhoe, 2014). It was a pervasive theme in within the 64 true/false selected response items that made up the instrument, creating an imbalance in the representation of that particular topic in that particular assessment. Items that assessed understanding within this theme assessed just 2 more specific concepts listed below. The number of assessment items that focused on each concept are reported next to each concept in parentheses:

1. Enhanced greenhouse effect and the hole in the stratospheric ozone layer are not related atmospheric phenomena. (31)

2. Individuals have different perceptions of enhanced greenhouse effect and global warming. (5)

Examples of items of multiple formats that addressed each concept within the misconceptions and opinions theme are provided as a flowchart in Figure 13 below.

Figure 13. Concepts related to Theme 7: Misconceptions and Opinions, with example items.
Spatial thinking represented in enhanced greenhouse effect content assessments. In order to understand what spatial thinking skills might already be represented in content assessments for enhanced greenhouse effect, each of the 190 items from 18 assessments were analyzed by comparing them to the list of spatial thinking skills compiled from existing research on spatial thinking, which was described in Chapter 2. Each item was coded according to the spatial thinking ability a participant would have to employ to answer the question correctly. Assessment items that did not require a spatial thinking skill to answer the question correctly were coded as such. In addition, open-response items that were very broad in the information that they requested were interpreted as requiring some spatial thinking ability or abilities, but were not specific enough in their wording to identify or code them as testing one spatial thinking ability or another. These items were categorized separately; they did not require a specific spatial thinking ability, but it was possible that students could represent spatial relationships when answering. The frequency of each of the item types is reported on below, with example items to illustrate the question wording and concept, and a discussion of their import to the spatial thinking assessment that is the focus of this research.

Items that did not require spatial thinking abilities. Of the 190 assessment items that were analyzed, 103 did not require spatial thinking abilities to answer the question correctly. Many of these items were true/false and multiple choice selected response, and many required memorization of some component or principle of the enhanced greenhouse effect and climate system. The items shown in Figure 14 below are examples of this type of assessment item.
**Items that might require spatial thinking ability.** Eighty-seven items warranted further consideration of the spatial thinking abilities they might require for completion. I recognized that for 35 out of those 87 items, a participant’s fully correct answer would employ spatial thinking skills, even though the item design does not make spatial thinking explicit in the language of the question or what it asks for in response. Of those 35, only 3 questions asked participants to represent their understanding with a sketch or a diagram. For example, for the items taken from Andersson and Waller (2016), displayed in Figure 15 below, a student would have to understand the spatial relationships between emission and accumulation in the atmosphere and have an understanding of the relative amounts of emission and absorption in order to correctly answer the question, though spatial language is not used, nor does it seem to be the focus of the item.

**Figure 14.** Example memorization type selected response items from existing enhanced greenhouse gas assessments.
Multiple choice selected response: What suggestions for the industrialized (I) countries will you vote for? What for the developing (D) countries?
I-COUNTRIES SHALL: A. Cut down their emissions drastically to about 1 ton per person and year, B. Cut down their emissions quite drastically to a few tons per person and year, C. Cut down their emissions a little, D. Keep to the present emission level, E. Be allowed to emit as much as they want.
D-COUNTRIES SHALL: A. Not be allowed to emit more than about 1 ton per person and year, B. Be allowed to emit a few tons per person and year, but not more, C. Be allowed to emit many tons per person and year, but not as much as the industrialized countries do, D. Be allowed to emit as much per person and year as the industrialized countries do, E. Be allowed to emit as much as they want. (Andersson & Walin, 2016, p. 1103)

Figure 15. Example of a selected response item from existing enhanced greenhouse gas assessments that requires spatial thinking to answer.

Three assessment items gave participants the opportunity to create or interpret spatial models in the form of sketches or diagrams to express their understanding of enhanced greenhouse effect. The three assessment items each asked participants to draw their understanding of or identify the correct representation of the enhanced greenhouse effect (Gautier, Deutch, & Rebich, 2006; Keller, 2006; Shepardson et al., 2009).

Many of the 35 out of the 87 items that required further consideration in this category were open response and quite broad in what they asked. Most questions asked for a written or spoken answer, but no spatial representation. It is certainly true that for many of these questions, participants would express their answer in spatial terms. An example item that was coded as “Too general to assume spatial thinking” is shown in Figure 16 below.
For these items, I referred to any published rubrics or evaluative criteria to determine the author’s ideal, normative answer. From this, I was able to analyze the expert response for spatial thinking skills employed in creating the answer. A rubric or some form of printed criteria for evaluation was available for 3 out of 35 assessments (McNeil & Vaughn, 2010; Varma & Linn, 2011; Visintainer & Linn, 2015), so I coded the 10 items that were a part of these three assessments according to the rubrics that were used to evaluate them. Examples of how these items were analyzed for spatial thinking abilities are described in the paragraphs that follow.

McNeil and Vaughn (2010) asked participants to describe three human behaviors that impact climate change and why they have an impact. The associated rubric described the following relationships as appropriate in a participant response: “Describes how the behaviors either increase or decrease greenhouse gases. Greenhouse gases trap heat which increases the amount of energy in the atmosphere” (p. 397). I coded this rubric answer under as requiring the spatial thinking ability, “Associating and correlating spatially distributed phenomena.”

Varma and Linn (2011) asked participants, in a series of 5 open response questions, to describe greenhouse effect, global warming, the difference between greenhouse effect and global warming, factors that affect greenhouse effect, the role of albedo effect to greenhouse effect, and the likeness of the Earth’s atmosphere to an actual greenhouse. The rubric that was used to evaluate those five items highlighted the need to explain how solar energy travels to Earth’s atmosphere, the transformation of solar to infrared energy, that Earth radiates the infrared energy, and where
greenhouse gases trap it in the atmosphere. Briefly, Earth’s surfaces that are more reflective, like ice or snow, increase the reflection of solar energy, so less of the infrared energy is trapped in the atmosphere, leading to lower temperatures. This rubric described a connection between locations, how changing greenhouse gas levels have an impact on their surroundings, as well as how greenhouse gas levels are affected by changing characteristics in the landscape, and finally, the spatial distribution of these phenomena. I coded the questions that could be answered to meet these rubric criteria as requiring spatial thinking skills, “Associate and correlate spatially distributed phenomena,” “Tracing how a place is linked to other places,” and “Understanding the effect a feature or characteristic may have on the area that surrounds it.”

Finally, Visintainer, and Linn (2015) also asked 5 questions in an interview format and probed for deeper understanding through their interview protocol. The rubric that was used to evaluate transcribed responses includes the very same themes and interconnections as those described in the Varma and Linn (2011) rubric, so assessment items from this assessment were coded the same way. They employed spatial thinking skills, “Associate and correlate spatially distributed phenomena,” “Tracing how a place is linked to other places,” and “Understanding the effect a feature or characteristic may have on the area that surrounds it.”

*Items that aligned with a specific spatial thinking ability.* The remaining 53 items (from the original 190 analyzed), were selected response items that were coded to align with a specific spatial thinking ability. Of the 53, 48 items included content that students would have to be able to “Associate and correlate spatially distributed phenomena” to correctly answer the question. This spatial thinking ability requires the thinker to understand two or more spatial phenomena and understand how the two are related (Bednarz & Lee, 2011). It should be noted that one assessment, McCuin, Hayhoe, and Hayhoe (2014), contained 64 true/false, selected response items. Of those, 37 items required the ability to associate and correlate spatially distributed phenomena and were focused on just a few
content themes. Those content themes that require spatial thinking are things like the accumulation of radiation in the atmosphere, how greenhouse gases accumulate and interact with radiation, and how radiation travels to Earth and is re-radiated into the atmosphere from Earth. Participants are expected to connect the major underlying concepts that support their understanding of enhanced greenhouse effect and the resulting temperature change. Since these phenomena are spatial, a participant would likely need to associate and correlate these phenomena in order to provide the correct answer for the item. Since there was no rubric provided for these questions, they were coded based on my understanding of the spatial thinking ability a student would need to employ in order to answer the question correctly as I interpreted it. What is not clear, since students are not expected to spatially represent their understanding, is whether they are actually employing their spatial thinking abilities or if this material can be memorized to provide the correct answer.

Finally, two assessment items, from two separate assessments (Bodzin & Fu, 2013; Keller, 2006) required an understanding the effect a feature or characteristic may have on the area that surrounds it. For example, Bodzin and Fu (2013) ask:

Which three factors have the most influence on seasonal weather patterns?

(a) Latitude, elevation, and proximity to an ocean
(b) Longitude, greenhouse effect, and proximity to lakes
(c) Ozone, greenhouse effect, and proximity to large cities
(d) Latitude, paleoclimate records, and proximity to mountains.

The question asks students to consider how characteristics of the physical environment have an impact on weather.

Discussion

Each enhanced greenhouse effect assessment item was analyzed for the content and spatial thinking ability that might be employed to express understanding of the concept. This was done to
answer two important questions to contribute to the design of an assessment that tests students’ spatial thinking abilities related to enhanced greenhouse effect:

1. What enhanced greenhouse effect content understanding is tested in existing assessment items?

2. What spatial thinking abilities are included in existing assessments that test students’ understanding of enhanced greenhouse effect?

Content understanding. Thirty-four concepts were identified in 7 themes from the 18 analyzed assessments. After excluding Themes 6 and 7, for reasons which will be described below, the remaining 24 concepts were organized into 5 themes, as expressed in Table 4. The concepts highlighted in bold text are categorized as bridge concepts. That is, concepts that bridge themes. They may connect students’ understanding of greenhouse effect to temperature increase or greenhouse gases to radiation, for example. Although bridge concepts describe more than one of the major themes, assessment items that included a bridge concept were classified according to the predominant theme represented in the assessment item. For example, a selected response, true/false item in McCuin, Hayhoe, and Hayhoe’s (2014) assessment reads, “Increased amounts of greenhouse gases in the atmosphere cause less absorption of radiation on Earth.” This item includes the content themes of Greenhouse Gases, Atmosphere, and Radiation, but the primary focus was on greenhouse gases as the subject, so the item was categorized accordingly.
Table 4

Content Themes Identified from Existing Enhanced Greenhouse Effect Assessments

Note. Items in boldface represent bridge concepts that contain more than one content theme. The concepts they bridge are stated in parentheses after the concept statement.

<table>
<thead>
<tr>
<th>Theme</th>
<th>Concept</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.B Carbon dioxide, methane, nitrous oxide, water vapor, and methane are the major greenhouse gases.</td>
</tr>
<tr>
<td></td>
<td>1.C Greenhouse gases influence the flow of energy through the atmosphere by increasing the amount of energy absorbed in the atmosphere.</td>
</tr>
<tr>
<td></td>
<td>(Greenhouse gases, atmosphere, radiation)</td>
</tr>
<tr>
<td></td>
<td>1.D Some variables remove greenhouse gases from the atmosphere.</td>
</tr>
<tr>
<td></td>
<td>1.E Some societies add more greenhouse gases to the atmosphere than others.</td>
</tr>
<tr>
<td>2. Radiation</td>
<td>2.A When radiant energy interacts with greenhouse gases in Earth's atmosphere, it is absorbed and stays in the atmosphere longer.</td>
</tr>
<tr>
<td></td>
<td>(Radiation, greenhouse gases, atmosphere)</td>
</tr>
<tr>
<td></td>
<td>2.B Albedo effect occurs when radiation is reflected from Earth's surface, back to outer space.</td>
</tr>
<tr>
<td></td>
<td>2.C Radiant energy entering and leaving Earth's system reaches an equilibrium that affects Earth's temperature.</td>
</tr>
<tr>
<td></td>
<td>(Radiation, Temperature and climate)</td>
</tr>
<tr>
<td></td>
<td>2.D Most of the radiant energy from the sun to the Earth comes in the form of visible light, ultraviolet rays, and infrared rays, also known as heat.</td>
</tr>
<tr>
<td></td>
<td>2.E Radiant energy from the sun travels to Earth's system, then gets absorbed or reflected, which affects Earth's temperature.</td>
</tr>
<tr>
<td></td>
<td>(Radiation, Temperature and climate)</td>
</tr>
<tr>
<td></td>
<td>2.F Radiant energy reflected from the Earth is absorbed by greenhouse gases in Earth's atmosphere.</td>
</tr>
<tr>
<td></td>
<td>(Radiation, Greenhouse gases, Atmosphere)</td>
</tr>
<tr>
<td>3. Atmosphere</td>
<td>3.A Earth's atmosphere has layers that have separate functions and characteristics.</td>
</tr>
<tr>
<td></td>
<td>3.B Earth's atmosphere is made up of gases, like nitrogen, oxygen, carbon dioxide, argon and other trace gases.</td>
</tr>
<tr>
<td></td>
<td>3.C Earth's atmospheric system and its components are analogous to a greenhouse.</td>
</tr>
<tr>
<td>4. Temperature and climate</td>
<td>4.A Global warming/climate change is an increase in global average temperature due to an increase of radiation in the atmosphere, because of an increase of greenhouse gases in the atmosphere.</td>
</tr>
<tr>
<td></td>
<td>(Radiation, Temperature and climate, Greenhouse gases, )</td>
</tr>
<tr>
<td></td>
<td>(Greenhouse effect and Temperature and climate)</td>
</tr>
<tr>
<td></td>
<td>4.C There is an increase in global average temperature</td>
</tr>
<tr>
<td></td>
<td>4.D Scientists use measures like ice core measurements and tree ring data as proxies to understand how climate has changed over long periods of time.</td>
</tr>
<tr>
<td></td>
<td>4.E Weather describes short term characteristics in temperature and precipitation, whereas climate describes long term characteristics.</td>
</tr>
<tr>
<td></td>
<td>4.F Geologic and geographic features affect local weather patterns.</td>
</tr>
<tr>
<td>5. Greenhouse effect</td>
<td>5.A Enhanced greenhouse effect is the absorption of radiation in the atmosphere by anthropogenic greenhouse gases, leading to an increase in temperature.</td>
</tr>
<tr>
<td></td>
<td>(Greenhouse effect, radiation, atmosphere, greenhouse gases, temperature)</td>
</tr>
<tr>
<td></td>
<td>5.B Natural greenhouse effect is important to Earth's atmospheric temperature.</td>
</tr>
<tr>
<td></td>
<td>5.C Human actions can decrease the enhanced greenhouse effect.</td>
</tr>
<tr>
<td></td>
<td>5.D Natural greenhouse effect is necessary. Enhanced greenhouse has harmful impacts.</td>
</tr>
</tbody>
</table>
Some concepts were included in multiple items across multiple assessments, while others were represented by only one assessment item across all 18 assessments that were analyzed. An initial analysis counted the number of times that a concept was included across assessments, but this may not accurately represent the importance of the topic across studies. As an example, consider that Concept 7.A, “Enhanced greenhouse effect and the hole in the stratospheric ozone layer are not related atmospheric phenomena,” is represented in 31 out of 190 items, making it the most represented concept out of all of the 40 original concepts that were described, prior to being synthesized and combined into the final 24 represented in Table 4. However, 29 of the items that included Concept 7.A are from just one assessment (McCuin, Hayhoe, & Hayhoe, 2014), making it a very strong theme within that assessment, while most other assessments did not include Concept 7.A at all. Another way to consider the importance of a concept to assessing students’ understanding of enhanced greenhouse effect is to consider how many assessments of the 18 included the concept. If the frequency of the items are analyzed from this perspective, a different picture forms of which concepts are central to understanding enhanced greenhouse effect. These concepts are listed below, with the number of assessments in which they were represented, in parentheses. The 5 concepts that appear with the greatest frequency are:

5.A Enhanced greenhouse effect is the absorption of radiation in the atmosphere by anthropogenic greenhouse gases, leading to an increase in temperature. (11)

1.C Greenhouse gases influence the flow of energy through the atmosphere by increasing energy absorption in the atmosphere. (7)

1.A Some natural and human activities add greenhouse gases to the atmosphere. (7)

4.B An enhanced greenhouse effect causes global warming. (6)
4.A Global warming/climate change is an increase in global average temperature due to an increase of radiation in the atmosphere, because of an increase of greenhouse gases in the atmosphere. (5)

Four of these 5 concepts (in bold text) are bridge concepts (all except Concept 1.A). It follows that they would be the most frequently assessed concepts because, (a) they include more than one type of understanding; and (b) they are especially important to students’ ability to connect the variables to tell the story of climate change because of an enhanced greenhouse effect. This informs the spatial thinking assessment for understanding enhanced greenhouse effect by highlighting the special attention that should be given to students’ understanding of the interconnections between one variable related to enhanced greenhouse effect and another.

Although the concepts named above were frequently mentioned and I could choose to identify those as most important for inclusion in the analysis, I did not want to give special weight to frequently named concepts over infrequently named ones at this point in the assessment development. The purpose of this study was to develop a first draft of the STA-En GreenE and pilot test it, so eliminating ideas to test would eliminate potentially important information about learners’ understanding. I chose to include all 24 concepts relating to the themes of greenhouse gases, radiation, atmosphere, temperature and climate, and greenhouse effect in the assessment. Each concept was considered important and needed to be compared against expert understanding of spatial thinking for understanding enhanced greenhouse effect, which was the next phase of the assessment development process.

As stated previously, for the purposes of this assessment, an understanding of the impacts of climate change was not assessed, to ensure that the assessment was of a manageable length, and to avoid placing value on one impact of climate change over another. The diversity and equal representation of impacts in the analyzed assessments demonstrate the undertaking that this would
be. Concepts related to impact were not included in the final concept list from this literature review to be used in the spatial thinking assessment design.

Another theme identified in the analysis of these 18 enhanced greenhouse effect assessments was not included as foundational content knowledge to be included in the spatial thinking assessment designed for this project. Concepts related Theme 7: Misconceptions and Opinions was not included for similar reasons to those that place Theme 6: Impacts outside of the boundaries of this assessment. Although explicitly dealing with the misconceptions associated with an issue is a well-supported method of instruction (Andersson & Waller, 2006), trying to include all of the possible misconceptions related to enhanced greenhouse effect would make this assessment too long and complex for the novice learner to complete in a reasonable time period. Likewise, although framing issues such as climate change and enhanced greenhouse effect as socio-scientific issues and studying them through the lens of understanding their associated controversies and public opinions is a useful frame to understanding the phenomenon (Sadler, Klosterman, & Topeu, 2011), the focus of this assessment will only include the spatial and scientific concepts related to enhanced greenhouse effect. In summary, then, concepts associated with Themes 6 and 7 were not included in this study’s spatial thinking assessment for understanding enhanced greenhouse effect.

**Spatial thinking abilities present in existing enhanced greenhouse gas assessments.**

A minority of assessment items reviewed for this study required spatial thinking abilities to complete the assessment task correctly. Some assessment items that were interpreted to employ spatial thinking may or may not require that skill to simply choose a selected response answer. In these cases, item design (selected response) prevents students from representing their understanding of the phenomenon spatially, so it is unclear if students are using spatial thinking to respond to the item. Of the assessment items that were interpreted to involve some degree of spatial thinking, it is
impossible to know for sure if spatial thinking was required without access to a rubric for the assessment, which was not provided in most cases.

Because spatial thinking was not an explicit focus of these enhanced greenhouse gas assessments, the analysis and articulation of whether they were important to understanding the concepts that were tested was a challenge. For this reason, I chose to recognize and keep in mind the spatial thinking skills I interpreted as useful to understanding these enhanced greenhouse gas concepts, but not use the identification of spatial thinking skills in this phase of data collection as the primary foundation of spatial thinking abilities for enhanced greenhouse effect. Instead, I combined the spatial thinking skills articulated in the spatial thinking literature (and described in Chapter 2) and applied them to the content of enhanced greenhouse effect to create the central concepts upon which the STA-En GreenE was based. This process is described in Chapter 8, Development and Design of the Spatial Thinking Assessment for Enhanced Greenhouse Effect (STA-En GreenE).

Conclusion

The strength of this literature review is in the content base that is provides to the final assessment design. It was used systematically in the following ways:

1. Content concepts represented across studies were used as a content foundation for the final assessment’s design.

2. Each of these concepts was integrated with spatial thinking abilities described in the spatial thinking literature, as well as the input from interviewed and surveyed experts in science and environmental education to determine:
   a. the spatial thinking skills that are necessary to build a mental model of the concept; and
   b. a useful way to design an assessment item that will enable students’ expression of that mental model.
3. Content concepts that were not strongly represented across studies were compared to input given by science and environmental education experts to determine their importance to this assessment. If these concepts were supported by expert input, they were included in the final assessment.
Chapter 7: Literature Review of Existing Assessments for Spatial Thinking

Introduction

The final source of information to be discussed here, contributing to the design of the STA-En GreenE, was a systematic literature review of existing assessments of spatial thinking ability. Up to this point, I have described an inventory of spatial thinking abilities developed from the research on spatial thinking; I have described how that inventory informed the development of expert interviews and surveys, to learn more about the spatial thinking skills that experts perceive as important to understanding enhanced greenhouse effect; and I have described the enhanced greenhouse effect concepts assessed in existing assessments. The purpose of this chapter’s literature review was to learn what types of measures have been used previously to assess learners’ spatial thinking abilities; and by analyzing them, to better understand if those measures may be used to assess learners’ spatial thinking abilities useful to understanding enhanced greenhouse effect or, if they cannot be used directly, how they can inform the design of items for this assessment.

A literature review of existing spatial thinking assessments presents a challenge, as there are “literally hundreds of hundreds of spatial tests and many factor analytic studies have suggested that there are several kinds of spatial abilities” (Newcombe & Shipley, 2015, p. 2). In addition, research has shown that spatial thinking ability is a predictor of success in science, and scientists from various disciplines report themselves to be proficient in different types of spatial thinking abilities (large...
scale and small scale), depending on the discipline they study (Hegarty et al., 2010). This suggests that spatial thinking abilities are not packaged or necessarily related. Therefore, individual spatial thinking assessments can be very specific to one ability or may cover a range of spatial thinking abilities. In order to place boundaries around the literature review conducted for this project, I attempted to answer two questions:

1. What spatial thinking abilities are tested in existing spatial thinking assessments, and how do they relate to spatial thinking abilities important to understanding enhanced greenhouse effect?
2. How can existing spatial thinking assessment items inform the design of assessment items for the STA-En GreenE?

**Method**

In order to understand the breadth of work that has already been done in the area of assessing the spatial thinking abilities of various types of learners, I conducted a literature review of relevant reports and studies in peer-reviewed journals. I also collected information on assessments made available online via a website dedicated to spatial education. To be included in the literature review, the publication had to include an assessment of spatial thinking abilities. This included intervention studies, in which the assessment may not have been the primary focus of the study, but in which the assessment items and the spatial thinking abilities they assessed were articulated. This also included assessment development research, in which assessment development was the primary objective of the study. These studies were of particular interest for their description of the development of assessment items.

I conducted a systematic review of the existing scholarly literature on assessing student’s spatial thinking abilities. The following databases were searched for relevant literature: EBSCO Complete, ERIC, JSTOR, ProQuest, Science Direct, and SpringerLink. Within each database, I
searched for two terms together. To capture the content of the assessment, I first searched “spatial thinking,” then “spatial ability,” and then “spatial reasoning.” To capture research that included the use or development of an assessment, I first searched each of the spatial terms with the term, “assessment,” and then with the term “test.” Each combination of these two categories of terms was entered into the database search terms. The two terms were required to be included in the title or abstract of the paper, to ensure that a spatial thinking assessment was central to the study and that an assessment was included as part of the research. I evaluated the content of each paper to ensure that its focus would contribute meaningfully to the literature reviewed here.

In addition to a literature review conducted by database search, I also referred to a repository of spatial thinking assessments published online with the Spatial Thinking and Learning Center (SILC). The SILC is a “Science of Learning Center funded by NSF to bring together scientists and educators to understand spatial learning and to use this knowledge to develop programs and technologies that will transform educational practice, especially in science, technology, engineering and mathematics” (Tests and Instruments, n.d.). The assessments published here include access to the complete instrument in many cases and a synopsis of the purpose of and instructions for administering the assessment. The website also includes metadata on the instrument’s author, intended audience, and associated publications. This search resulted in 48 publications.

Each of the 48 publications was analyzed to determine: (a) the spatial thinking skill(s) assessed; (b) the method of assessment; and (c) the format of the item. The spatial thinking skills assessed were determined by comparing the assessment item’s spatial content to the spatial thinking abilities outlined from the literature in the introduction of this dissertation, entitled “Spatial Thinking across the Sciences” and summarized in Table 1. A cursory review of the assessments demonstrated that the spatial skills tested roughly matched the spatial thinking abilities described previously and that each assessment only tested a few skills, if in fact more than one was assessed at
all. Most assessments tested the same skill with multiple questions. For this reason, it was not useful to the purposes of the STA-En GreenE design that each item was assessed individually, but that each assessment as a whole was coded for the spatial thinking skill(s) it assessed and how it assessed it/them (e.g., selected response, open response, model-based assessment, etc.). Many skills were common to more than one assessment.

Results are reported below, such that each spatial thinking skill is named corresponding to the assessments that tested it, followed by a report of how the skill was tested.

**Results**

I analyzed 48 publications, to evaluate and categorize their assessments of spatial thinking abilities. Most assessments tested just one or two spatial thinking abilities, so the assessments are organized below, by the spatial thinking ability that was tested (mental rotation, spatial perception, etc.). Some assessments will appear in reference to more than one ability.

*Mental rotation.* By far, the most commonly assessed spatial thinking ability found in the literature is the ability to mentally rotate objects to complete a task or solve a problem. Eighteen assessments tested participants’ mental rotation ability. Nine assessed this ability in adults and nine assessed the ability in children.

The ability to mentally rotate an object can be employed with objects and phenomena at multiple scales and with a diversity of objects and phenomena, so assessments of this ability took many forms. One study employed the Wheatley Spatial Ability Test, which assessed third grade students’ ability to rotate block-like figures and imagine them from another perspective. In this unit, students were directed to use a dynamic simulation to move geometric shapes together as in a puzzle, while the shapes were moving. Students could rotate the shapes to find the best fit. This assessment was completed during a mathematics unit on geometry and area (Clements, Battista, Sarama, & Swaminathan, 2015). Moses (2015) evaluated middle school students’ solutions as they
used their understanding of the volume of a space related to what might fit into it to design a space station. Ormand, Manduca, Shipley, Tikoff, Harwood, Atit, and Boone (2014) used the Purdue Visualization of Rotations Test (PVRT), which requires that participants mentally rotate block-like shapes, to assess undergraduate geology students’ ability to mentally rotate shapes. Similarly, Hornbuckle, Gobin, and Thurman (2014) applied the same test in pre- and post-assessments of organic chemistry students. Toptas, Celik, & Karaca, (2012) describe several other assessments are derived from Shepard and Metzler’s Mental Rotation Task (MRT), in which students are asked to mentally rotate a figure that is made up of several interlocking cubes in different configurations.

Several tests presented as part of the SILC repository were also used to test participants’ mental rotation abilities. They assessed adults’ ability to predict the position of two objects on a transparent piece of plastic if the plastic were bent (Atit, Shipley, & Tikoff, 2013); the ability of 4 to 6-year-olds to mentally rotate images of familiar animals (Wiedenbauer & Jansen-Osmann, 2008); and the ability of children as young as 3-years-old to place a physical object in a hole of the same shape, but different orientation (so that the student has to rotate the object for it to fit) (Frick, Ferrara, & Newcombe, 2013).

The studies described here are a sample of the ones reviewed that represent a number of different ways that mental rotation is conceptualized and assessed. Others that were reviewed (Clements, Battista, Sarama, & Swaminathan, 2015; Ehrlich, Levine, & Goldin-Meadow, 2006; Gersmehl & Gersmehl, 2007; Kozhevnikov & Thornton, 2008; Peters & Battista, 2008; Yurt & Sunbul, 2012) assess the same abilities in similar, decontextualized ways. A representation of example assessment items that test mental rotation abilities is presented in Figure 17 below.
Spatial perception. Mental rotation is one of the first spatial thinking assessments recorded in the literature, so standardized assessments, such as the PVRT and the MRT have been widely used and adapted. A related ability that is often tested simultaneously is a learner’s spatial perception. Linn and Peterson (1985) state that spatial perception is the ability to understand spaces relative to oneself. An example is the ability to identify a horizontal line, because “horizontal” is relative to the position of the subject. Only a few existing instruments assessed this ability, but they tested it in a number of ways. Uttal, Fisher, and Taylor (2006) utilized a physical space to test students’ ability to navigate a maze-like area to locate objects within it. In order to locate the objects, students were
given a map to examine, and then had to use it from memory to navigate a physical space they were placed within. Frick, Mohring, and Newcombe (2014) measured the perspective-taking abilities of 4-to 8-year-olds by showing them an image of a photographer snapping a photo of an object and then asking them to select what the photo would look like. Students had to envision what their perspective would be if they were behind the camera.

Another assessment tested students’ perspective as first-person, in a virtual driver’s seat. Gramann, Wing, Jung, Viirre, and Riecke (2012) tested adults’ abilities to navigate a virtual star-field in a simulation. The activity had the participant watch a brief video in which, from the first person perspective, the simulation takes a turn in the star-field. The task of the assessment is to name the direction of the point of origin of the simulation. In Moses’ 2015 experiment, in which students designed a space station, part of the task required students to understand the space relative to themselves, and so their spatial perception abilities were assessed in the design process. Examples of test items that test spatial perception are depicted in Figure 18 below.
Figure 18. Spatial perception items taken from existing assessments: (a) Gramann et al. (2012) used a first person perspective in a virtual star-field to take a turn (left) and then have participants decide the direction from which they came (right) in an online format. Image is a screenshot from the simulation; (b) Hegarty et al. (2012) tested children’s spatial perspective taking with the images above. Students were given the direction to select what they would see if they were standing at one point or another in the landscape.

**Spatial visualization.** The last of the spatial abilities described by Linn and Peterson (1985) is spatial visualization. In many cases, instruments that assess mental rotation also assess spatial visualization. Spatial visualization is the ability to perform multistep manipulations of data or visualizations for better understanding (Linn & Peterson, 1985).
The first applications of this idea were for three-dimensional paper folding tasks, in which participants were shown a piece of paper and asked to identify the shape the paper would make if folded along indicated lines. This is still the most common way this skill is applied. For example, Moses’ (2015) paper space station design task with middle-schoolers asked them to design the shape of their space station from a flat piece of paper, which contextualized the paper folding task in content relevant and interesting to middle school students. In Toptas et al.’s (2012) study of eighth graders creating a three-dimensional virtual space in Google Sketch from a two-dimensional plan, spatial visualization abilities were tested with a Spatial Visualization test developed by Winter, Lappan, Phillips, and Fitzgerald in 1896. This test consisted of items that tested students’ ability to predict the shapes a two-dimensional piece of paper will form when folded along marked lines, to a three-dimensional figure. Harris, Hirsh-Pasek, and Newcombe (2013), Koshevnikov and Thornton (2001), and Lord (2004) also employed paper folding assessments to test participants’ spatial visualization abilities.

Although paper folding tasks are the most common spatial visualization assessments, others exist and are being developed. Atit et al. (2013) tested mental rotation and spatial visualization at the same time, with their task that asks participants to predict the position of two objects on a transparent piece of plastic, when the plastic is bent in a particular way. Resnick and Shipley (2013) tested participants’ ability to visualize “brittle transformations,” which are transformations of an image in which parts of the image are flipped backwards, transposed to another location, or are flipped upside down. The idea is for test-takers to be able to visualize how to put the image together correctly and then select the image that represents their visualization from a set of closed response answers.

Spatial visualization, decontextualized, can be very broadly defined. It can be used to describe the permutation of data for multiple variables. For example, Ormond et al. (2013) focused
on spatial visualization through penetrative thinking and mental “slicing,” which are both common skills employed by those in the geosciences, to imagine or visualize what is going on beneath the surface of a landscape or object, based on what is visible on the outside. In this case, they used a number of standardized spatial thinking assessments (Purdue Visualization of Rotations Test, Planes of Reference test [Titus & Horsman, 2009]), as well as an originally designed, closed-response assessment, the Geologic Block Cross-Sectioning Test to assess geosciences students’ spatial visualization abilities. The mental “slicing” of a three dimensional object is the prediction the two dimensional cross-section that would result, if the object were actually sliced. Ping, Young, Ratliff, Schiffman, and Levine (2012) tested this ability in 5 to 9-year-olds to trace the development of their spatial visualization abilities as they aged.

Spatial visualization also includes the ability to translate between two-dimensional and three-dimensional representations, which is the ability Frick and Newcombe (2014) tested by presenting their 4- to 6-year-old participants with images depicting three-dimensional polygons in color and then asking them to select the black and white two-dimensional image that represented the first. In a different task testing the same ability, Verdine et al. (2014) asked 3- to 6-year-olds to follow instructions on a map to identify a location in a physical model.

The group of studies and assessments described here do not include all of the assessments that test spatial visualization skills; however, they are representative of the different ways in which spatial visualization skills can be tested. A representation of example assessment items that test spatial visualization abilities is displayed in Figure 19 below.
Figure 19. Spatial visualization items taken from existing assessments: (a) Folding task for 4 to 7 year olds to test their spatial visualization abilities (Harris, Hirsh-Pasek, & Newcombe, 2013, p. 1-2); (b) Task that tests geology students’ penetrative thinking ability. Participant selects image on right that represents the cross-section of the block figure on the left (Ormond et al., 2014, p. 152); (c) Task that tests students’ spatial visualization ability. The participant is to select the image on the right that represents the cross-section of the block figure on the left (Ormond et al., 2013, p. 14).

**Using a spatial model.** It would be tempting to suppose that any type of spatial thinking would employ the use of a model, since many tasks ask the thinker to create at least a mental model to solve a problem or understand a phenomenon. This spatial ability—using a spatial model—is defined specifically by Gersmehl and Gersmehl (2006) as a thinker’s ability to use a spatial model in such a way that they identify connections between the model and the spatial system that is represents. This ability, as defined by Gersmehl and Gersmehl (2006), is not employed in all types of
spatial thinking. I will discuss will the assessments that do employ this ability in the paragraphs that follow.

In some cases, participants were asked to use multiple models to represent their understanding. Verma (2015) used spatial models of environmental characteristics across a landscape and asked participants to interpret those models to select another model that represented how the variable was changing. The characteristics were geospatial, like the slope of land or the amount of precipitation. In Toptas et al.’s 2012 study, students created a three-dimensional environment from a two-dimensional sketch, using one model to create another. Frick and Newcombe’s (2013) also used models when 3- to 6-year-old participants used a map to navigate a virtual space and find objects within it.

Some studies assessed students’ abilities to use a model to understand or represent the real world system, though in all cases they were given representations of the real world, like maps or photographs, rather than asked to navigate the actual system. Golledge, Gale, Pellegrino, and Dougherty (2008) asked students to use several spatial thinking abilities to navigate, on a neighborhood level of scale, places that were familiar to them. They used maps and images to identify places. Similarly, Norman (2007) tested 10-year-olds’ abilities to navigate a miniature landscape comprised of various features (e.g., hill, lake, houses). The children were given a piece of paper and a pencil, with the verbal instructions to make a map of the model. The maps were scored for developmental level on each element by trained judges. Weisberg, Schinazi, Newcombe, Shipley, and Epstein, (2014) also measured navigation abilities with participants using a model of a city-scape to understand and identify where buildings are and what direction they might have to travel to get to a feature in the landscape. In this case, the participants were adults.

Newcombe et al. (2015) administered a more specific spatial thinking assessment, employing a familiar model, the Topographic Map Assessment (TMA), which utilized a familiar type of model,
the topographic map, to assess adults’ understanding of a landscape. An example item from this assessment is presented in Figure 20 below.

**Figure 20.** Example item testing students’ ability to use a spatial model (Newcombe et al., 2015, p.24)

**Associate and correlate spatially distributed phenomena.** This spatial ability is the first named here that is included in the inventory of spatial thinking skills that Golledge and Stimson (1997) described as “spatial relations.” These are skills that are sometimes contested in the literature as spatial thinking skills, but that are commonly used in and associated with geoscience or geographical spatial understanding. Learners who are able to associate and correlate spatially distributed phenomena can compare variables across an environment, large or small, and make sense
of how the variables are interrelated. Testing this ability, van der Henst (1999) guided students 15-17 years of age with directions for the positions of items in a group of items. For example, descriptions might include written cues like, “The butter is to the right of the egg, the yogurt is to the left of the egg.” Then, students are asked to relate the positions of two objects that were not directly named.

Verma (2015) contextualized spatially distributed phenomena across landscapes with maps and other representations of precipitation levels, topography, or the position of buildings in a neighborhood. Students were asked to select from other models, like graphs on an XY plane, the relationship between variables represented in the models that they were provided.

Dunn (2011) attempted a new type of assessment for first-year geography students to better understand location and place. Dunn used maps; and instead of asking students to identify places, asked them to describe relationships between places, a skill that relies on memorization less, and on understanding of the way places and characteristics are distributed more. On a neighborhood scale, Golledge et al.’s (2008) study that asked middle school students to navigate environments that were familiar to them, utilized their ability to associate and correlate spatially distributed phenomena in order to successfully move from one place to another, based on directions.

The assessments of spatial thinking abilities described so far were assessed in multiple contexts and related to many content areas over time. The following abilities were tested far less frequently in the literature than the ones described up to this point. While the report of each ability’s assessment is not exhaustive, for the sake of brevity and clarity, I describe an assessment of each spatial thinking ability.

**Orientate spatial phenomena to real world frames of reference.** This spatial thinking ability, first named by Golledge and Stimson (1997), is particularly important for this project’s assessment development, because recommendations from experts, as well as research on novice
spatial thinkers, suggests that orienting students to familiar spaces first is beneficial to their spatial understanding (Tretter, Jones, & Minogue, 2006; Tretter et al., 2006).

This ability contextualizes spatial thinking and spatial phenomena in the real world. For example, when Golledge et al. (2008) asked middle school students to navigate environments that were familiar to them based on images and maps of familiar structures, they were utilizing their ability to follow directions and navigate in a real-world environment.

Both Uttal, Fisher, and Taylor (2006) and Weisberg, Schinazi, Newcombe, Shipley, and Epstein (2014) tasked students with navigation as well: in a physical space, according to a map, and in a virtual space. In each case, students used cues that they understood from real-world experience, like looking around corners and using an aerial view in the ground level space to orient themselves on a human or real-world scale. It is worth noting that all of the studies identified as employing this type of understanding did so on a human to landscape scale. In other words, the spaces that the participants were navigating were spaces that they could directly perceive or perceive just by walking around a little, because they were on the scale of a room (at the smallest) to a neighborhood (at the largest).

**Recognizing spatial distributions and spatial patterns, comparing maps, making a spatial comparison, and describing conditions.** Spatial distributions and spatial patterns are the ways that a spatial feature or variable is spaced out across a landscape. An example is the density of trees in a forest or the way that an air pollutant moves and accumulates across a landscape, based on its topography. The best example of an assessment of students’ ability to recognize spatial distributions and spatial patterns, compare maps, make a spatial comparison, and describe conditions is found in Verma’s previously mentioned 2015 contextualized study that represented the change in amounts of things or characteristics of things across landscapes with maps and other representations of precipitation levels, topography, or the position of buildings in a neighborhood.
In one case, students are asked to choose a graph that represents the way that two variables change in relationship to each other. The variables are locations in a Midwestern region of the United States where pigs are raised and location in the same areas where corn is raised. If the student can accurately identify the relationship between the two variables on an XY plane, they have demonstrated spatial pattern recognition.

Using the same item, Verma (2015) also employed and assessed students’ abilities to compare maps representing more than one location or more than one variable to recognize the relationship between those variables. It is necessary for students to compare maps or features on a map in order to select the description of the relationship between the variables represented. By selecting the correct closed response item, they are indicating the description they have articulated to themselves to come up with the correct answer. This test item is displayed in Figure 21 below.

*Figure 21. Verma’s 2015 assessment item testing several spatial thinking abilities (p.50).*
**Tracing spatial connections.** To trace a spatial connection, learners should be able to relate two spatial features or phenomena that are not physically connected to each other; they should be able to trace how a place is connected to other places. On a neighborhood scale, Golledge et al.’s (2008) study that asked middle school students to navigate environments that were familiar to them utilized their ability to associate and correlate spatially distributed phenomena in order to successfully move from one place to another, based on directions. Similarly, Norman (2007) tested 10-year-olds’ abilities to navigate a miniature landscape comprised of various features (e.g., hill, lake, houses). The children were given a piece of paper and a pencil, with the verbal instructions to make a map of the model. The maps were scored for developmental level on each element by trained judges. If students were unable to trace the spatial connections or the ways in which places or phenomena are linked together spatially, navigation would be impossible.

**Imagine maps from verbal description.** This ability is named in plain, descriptive language. This is the ability to build an image in the mind’s eye of a location or a group of locations related to each other, based on a verbal description. Uttal, Fisher, and Taylor (2006) utilized a physical space to test students’ ability to navigate a maze-like area, according to a map to locate objects within it. In addition, they described to students where the objects were, to measure their ability to hold the image of the space in their head. This ability (imagining maps from verbal description) was also named in the suite of geospatial thinking abilities described by Golledge and Stimson (1997).

**Discussion**

The spatial thinking assessments described here were found as the result of a systematic literature review and a review of existing assessments available on the SILC Assessments and Instruments internet data base. The skills assessed represent a range of spatial thinking abilities across variables. Some items tested contextualized spatial thinking abilities, like the ability to navigate
a landscape, while most were decontextualized, assessing participants’ abilities to reason with generic shapes and spaces.

The purpose of a literature review of existing spatial thinking assessments was to better understand how the assessment designed here might be informed by what has already been done. I have asked two research questions of this review:

1. What spatial thinking abilities are tested in existing spatial thinking assessments, and how do they relate to spatial thinking abilities important to understanding enhanced greenhouse effect?

2. How can existing spatial thinking assessment items inform the design of assessment items for the STA-En GreenE?

I will discuss the findings of the literature review from the perspective of each of these inquiries below.

**What spatial thinking abilities are tested in existing spatial thinking assessments and how do they relate to spatial thinking abilities important to understanding enhanced greenhouse effect?**

*Most of the spatial thinking skills found in the literature assess a learner’s understanding of spatial characteristics intrinsic to the object or phenomenon, like mental rotation, spatial visualization, and spatial perception.* Intrinsic spatial characteristics are related to the arrangement of an object or phenomenon’s intrinsic parts, relative only to itself, not to other objects. Examples of spatial thinking abilities related to intrinsic characteristics are mentally bending or rotating and object or creating two-dimensional images from three-dimensional objects (mentally creating a cross-section of an object, for example) (Newcombe et al., 2015). The fact that most of the assessed spatial thinking skills focus on intrinsic characteristics makes sense since these are the spatial thinking skills that were defined early on in the chronology of spatial thinking in the
literature. Several standardized tests have been developed and used to assess these spatial thinking abilities. In many cases, the spatial thinking ability is described as beneficial to another ability or aptitude that the researcher is interested in, so one of the relied upon assessments is administered with another, more content specific assessment. For example, the ability to mentally rotate is often investigated for its relationship to a student’s ability to understanding molecules from different perspectives.

It is important to consider the spatial thinking abilities that might support an understanding of enhanced greenhouse effect. Which intrinsic spatial thinking abilities, if assessed, might correlate with a spatial understanding of enhanced greenhouse effect? If we consider the tasks used to assess these skills, it is hard to imagine the applicability of mental paper folding to understanding radiation, the atmosphere, or greenhouse gas emissions. However, a task requiring students to mentally rotate an object might correlate with their ability to understand the behavior of a carbon dioxide molecule when it interacts with infrared energy.

It is also important to mention that when science, math, and environmental education experts were asked for their perceptions of the information important to understanding enhanced greenhouse effect, it was not the intrinsic skills that were named. Most of the spatial thinking skills described by experts would be considered extrinsic and mainly geospatial, as defined by the literature. Extrinsic spatial thinking abilities are described in the literature as “relations among objects and between objects and frames of reference” (Newcombe & Shipley, 2011, p.3)

The difference between expert recommendations for spatial thinking abilities useful to understanding enhanced greenhouse effect (extrinsic) and the spatial thinking abilities most often assessed in the spatial thinking literature (intrinsic) is important to note. Ultimately, I derived the most guidance in developing the central spatial concepts related to enhanced greenhouse effect from the expert recommendations, because they most clearly articulated the connection between spatial
thinking and content. This meant that there was less guidance to be derived from existing spatial thinking assessment items, because they were applicable to a different type of spatial thinking than what the experts perceived as important to understanding enhanced greenhouse effect.

*Most spatial thinking abilities were assessed using or requiring the creation of decontextualized representations.* When looking to the literature to study existing assessment design, it is notable that most of the assessment items test learners’ understanding using very general, decontextualized forms like cubes, lines, or other shapes. Even where the research question asked about a student’s spatial ability within a content area like geology or chemistry, students demonstrated their spatial abilities by manipulating these general forms. Whether an assessment about enhanced greenhouse effect should be decontextualized or not is an important question to consider. In the chapter that follows, I discuss this question and how its consideration affected the design of the instrument.

Another thing to note about the assessments described here is that they often only tested one spatial thinking ability at a time. This is an important idea to consider when we think about enhanced greenhouse effect, because of the complexity of the phenomenon. Considering the spatial thinking abilities described by our experts, it is clear that the assessment developed here should include a range of spatial thinking assessment items instead of one single spatial thinking ability.

*The method of assessment in most cases was closed response. Participants were rarely asked to create an original representation of spatial understanding.* Most items directed students to identify a trend or a figure or an image that represented their mental model of the spatial relationship described in the question or scenario. This is very important to consider, particularly since the theoretical framework chosen for the current project relies on the interpretation, use, and building of models to better understand learners’ conception of enhanced greenhouse effect as a complex environmental phenomenon. Accordingly, I am interested in students’ complete, individual
mental models of enhanced greenhouse effect and not in which of a number of provided models a student might pick as most closely representing that individual mental model.

In many cases, closed response items decrease the time it takes to complete an assessment and the extraneous cognitive load it takes to express understanding; however, a problem of this level of complexity may be better served by model-building than model-selecting.

**How can existing spatial thinking assessment items inform the design of assessment items for the STA-En GreenE?**

*Where the spatial thinking skills for enhanced greenhouse effect described by science, math, and environmental education experts align with spatial thinking skills assessed here, these spatial thinking abilities should be considered as important to enhanced greenhouse effect.* Some of the spatial thinking abilities that experts perceived to be important to understanding enhanced greenhouse effect were found in the literature review here and some were not. The existing spatial thinking items can be used as a reference for what is learned from the science and math experts. When there is alignment, it means that research has demonstrated the skill as useful and that it is also recognized by content experts. These spatial thinking abilities can be considered central to understanding enhanced greenhouse effect. These existing spatial thinking items will be used as a reference to determine if they might be used as a model for item design for the STA-En GreenE.

*Existing items will provide limited support for assessment design for this project.* In the next section I will go into detail about the role of each of the five information sources in designing the STA-En GreenE, but recognize here that the role of this review of existing spatial thinking assessments is as a guide for how each spatial thinking ability that is important to understanding enhanced greenhouse effect might be assessed. While each of the faculty and environmental education experts’ perceptions were compared to and held up to the assessment
items reviewed here to determine if the content might be assessed using one of these items as the foundation for item design, for my purposes, these items were abstract and decontextualized, which did not align with my goals for this assessment. However, I would continue to compare contextualized assessment items to the decontextualized assessment items in future studies to note any ways in which they might support assessment design. This process by which individual items were designed for the assessment is described in detail in the next chapter, Chapter 8.
Chapter 8 Development and Design of the Spatial Thinking Assessment for Enhanced Greenhouse Effect (STA-En GreenE)

The purpose of this chapter is to describe the role of each of the sources of information described in Chapter 4 through 7 in the development and design of the Spatial Thinking Assessment for Enhanced Greenhouse Effect (STA-En GreenE). Since an assessment of this type, contextualized in environmental science content and supported by models and modeling theoretical foundations and practices, does not have a match in existing literature, the assessment design process was quite original. The sections below will explain the significance of each information source and how information from that source was applied to the design of the assessment. The sections below will also describe the resulting objectives for student understanding and performance. They will describe the ways that the models and modeling framework was applied to the design of assessment items that would allow participants to express their mental models related to enhanced greenhouse effect and the variables connected to it. Finally, they will provide the assessment draft, in its entirety, as it was delivered to environmental science and education experts for revision and review.

Information Sources and How They Informed Assessment Design

**Source 1: Existing Spatial Thinking Literature.**

*Background knowledge for expert interview and survey design.* The first purpose of the initial literature review was to provide background knowledge, from which the faculty interview protocol and the environmental education expert interviews could be developed. The inventory of spatial thinking skills, gleaned from the literature and displayed in Table 1 in Chapter 4 (p. 57) was used in three ways. First, the list was provided to faculty members at the end of their interviews, after they had a chance to describe spatial thinking for enhanced greenhouse effect from their own perspectives. The list was provided with the instruction that the faculty members should select from the list all of the
spatial thinking abilities they felt were useful to understanding enhanced greenhouse effect. As was reported in the section discussing faculty interviews, in most cases, faculty indicated that all of the spatial thinking skills on the list could be important to understanding such a complex problem, with so many interconnected variables.

*Foundational language for expert interview and survey response analysis.* After transcripts were produced from the faculty interviews and the coding process began, I used the inventory of spatial thinking skills collected from the literature to interpret faculty members’ sometimes colloquial language about spatial thinking skills. For each skill that was described, I referred back to existing literature to find the appropriate words to describe the spatial thinking abilities faculty members discussed in their interviews, always staying true, first and foremost, to the intent of what the faculty members were saying.

The language from the literature review that described spatial thinking abilities was then used to develop the online survey for environmental educators. These same literature-derived descriptions of spatial thinking abilities were also used in the analysis of the other sources of information. Figure 22 shows the starting point of assessment development, spatial thinking skills, as identified in existing literature.
Figure 22. The starting point of STA-En GreenE development: Spatial thinking skills found in the literature.
Sources 2 and 3: Science and Math Faculty Interviews and Environmental Education

**Expert Surveys.** The importance of the expert interviews and surveys cannot be overstated. Experts in math, science, and environmental education contextualized the spatial thinking skills in the content of enhanced greenhouse effect, as they perceived it. In practice this means that, once interviews were transcribed, coded, and analyzed, the resulting abilities that faculty perceived to be important to understanding enhanced greenhouse effect were processed in two ways. First, identified spatial thinking abilities were referenced against the spatial thinking skills collected from the literature. This was done to ensure that each spatial thinking ability described was accurate to the faculty member’s intention, but also to ensure that the spatial thinking ability was described correctly, according to the expertise of researchers in spatial thinking. Second, once refined and made clear and accurate, the spatial thinking abilities identified through the faculty interviews were added to the web-deployed survey for environmental educators, for their evaluation using a four-point Likert scale for each concept. As described in Chapter 5, a web-based survey was deployed to members of the North America Association for Environmental Educators. Twenty-seven respondents evaluated each of the general spatial thinking abilities gathered from the literature (Source 1), as well as the refined spatial thinking skills supporting an understanding of enhanced greenhouse effect described by science and math faculty at a large university in the Southwestern United States. As was demonstrated in Chapter 4, the perceptions of environmental educators only served to confirm the perceptions of the interviewed science and math faculty members. Each and every concept included in the web-based survey was rated as “Very Important” to understanding enhanced greenhouse effect, or “Somewhat Important.” The interviews and supportive survey results resulted in the central concepts, grouped by content theme, displayed in Table 2 in Chapter 4. Figure 23 below demonstrates how expert perceptions of the spatial thinking abilities important to understanding enhanced greenhouse effect and the general spatial thinking
skills gathered from the literature informed each other to create the list of central concepts that are rooted in both enhanced greenhouse effect content and the spatial thinking abilities needed to understand how the related variables change and are connected.

**Figure 23.** Descriptions of general spatial thinking abilities gathered from the literature were applied to interviewed faculty members’ descriptions of spatial thinking skills that support understanding enhanced greenhouse effect. This process is demonstrated using an excerpt from the Dr. Kernley interview.

**Source 4: Existing Enhanced Greenhouse Gas Assessments.** Expert perceptions contextualized general spatial thinking abilities in the content of enhanced greenhouse effect. It is important to note, however, that the experts who volunteered for the study were not representative of all sciences, nor were they particularly selected for their expertise in enhanced greenhouse impact. Each one spoke to what they understood or knew best about the phenomenon. Because interviewed
and surveyed faculty members identified essential spatially-related information from their individual perspectives, literature on existing enhanced greenhouse effect assessments was used to supplement the guidance that faculty members provided.

The resulting list of content concepts, taken from existing enhanced greenhouse effect assessments, arranged by content theme, can be found in Chapter 6, Table 4. A vast majority of existing enhanced greenhouse gas assessments did not include a spatial component, nor did they enable students’ expressions of their mental models related to enhanced greenhouse effect, so the connections that faculty members made with their recommendations were critical to understanding how spatial thinking abilities are important to this particular topic.

The concept list from existing enhanced greenhouse effect assessment literature was used first as a comparison to the concepts that were the product of analysis of the expert interviews and surveys (Sources #2 and #3). I looked for alignment and for original concepts that were not described by faculty. Where content concepts were aligned with expert perceptions, I reviewed the way each concept was described and revised the concept to include the most complete and technically correct language that most clearly described the idea. Where the concept did not have a match in the expert perceptions, the concept was evaluated for its contribution to an explanation of enhanced greenhouse effect and its component variables. If I determined it filled in some part of the conceptual narrative of the phenomenon, the next step was to use the inventory of general spatial thinking skills derived from Source #1 to determine what spatial thinking abilities were important to understanding that concept, since the focus of this particular work is to assess spatial understanding of topics related to enhanced greenhouse effect. The process by which the enhanced greenhouse effect assessment concepts and the expert perception concepts informed each other and were combined is shown in Figure 24 below. The result was 14 concepts that participants should demonstrate their understanding of through the STA-En GreenE.
**Sources #2 & #3: Expert Interviews**
- Greenhouse gases circulate in the atmosphere.
- Amount greenhouse gases are emitted from various sources.
- The carbon cycle occurs in space.
- Fossil fuels move around on the Earth and in the atmosphere.
- The distribution of greenhouse gas emission sources.
- How greenhouse gases accumulate in the atmosphere.
- Emissions accumulate from driving a car.
- The volume of greenhouse gases in the atmosphere.
- The concentration of greenhouse gases in the atmosphere.
- Greenhouse gases are stratified in the atmosphere.
- The proportion of greenhouse gases to atmosphere.
- Interaction of carbon dioxide and plants.
- The relationship between greenhouse gases and temperature.

**Source #4: Enhanced Greenhouse Effect Assessments**
- Some human activities add greenhouse gases to the atmosphere.
- Carbon dioxide, methane, nitrous oxide, water vapor, and methane are the major greenhouse gases.
- Greenhouse gases influence the flow of energy through the atmosphere by increasing the amount of energy absorbed in the atmosphere.
- Some variables remove greenhouse gases from the atmosphere.
- Some societies add more greenhouse gas to the atmosphere than others.

**STA-E1 GreenE Greenhouse Gas Central Concepts**
1. The atmosphere contains both natural and anthropogenic sources of greenhouse gas emissions.
2. Features on Earth's surface absorb greenhouse gases from the atmosphere.
3. Greenhouse gases make up a relatively small amount of the atmosphere compared to the other gases in it.
4. Greenhouse gases in the atmosphere accumulate over time as emissions are greater than absorption.
5. Greenhouse gases are emitted from sources on Earth's surface, rise into the atmosphere and move around with circulation patterns.
Figure 24. Existing assessments’ content combined with expert perceptions to create central
concepts. Existing enhanced greenhouse effect assessment items provide a stronger content foundation than expert perceptions alone, while experts provide a connection between the spatial ability and the content. The diagrams above depict the combination of each set of affordances to create 14 central enhanced greenhouse effect spatial thinking concepts in 4 content areas: (a) greenhouse gases; (b) radiation; (c) atmosphere; (d) greenhouse effect.

All 14 Central Concepts, that have both a spatial thinking and an enhanced greenhouse gas foundation, are displayed in Figure 25 below.
STA-En GreenE **Greenhouse Gas** Central Concepts
1. The atmosphere contains both natural and anthropogenic sources of greenhouse gas emissions.
2. Features on Earth’s surface absorb greenhouse gases from the atmosphere.
3. Greenhouse gases make up a relatively small amount of the atmosphere, compared to the other gases in it.
4. Greenhouse gases in the atmosphere accumulate over time as emissions are greater than absorption.
5. Greenhouse gases are emitted from sources on Earth’s surface, rise into the atmosphere and move around with circulation patterns.

STA-En GreenE **Radiation** Central Concepts
6. Radiant energy moves from the sun and reaches the Earth’s surface.
7. Radiant energy is transformed to infrared energy and is reflected by surfaces on Earth.
8. Infrared energy moves from the surface of the Earth into the atmosphere.
9. Energy in the atmosphere reaches an equilibrium amount based on how much enters and leaves.
10. When the relationship between the amount coming in and the amount going out changes, the equilibrium changes.

STA-En GreenE **Atmosphere** Central Concepts
11. Earth’s atmosphere exist in a layer around Earth’s surface.
12. Earth’s atmosphere is a very thin layer relative to the thickness of the Earth.

STA-En GreenE **Greenhouse Effect** Central Concepts
13. As radiation and greenhouse gases interact in the atmosphere, the radiation accumulates because the greenhouse gases are holding it in.

*Figure 25. 14 central concepts for spatial thinking about enhanced greenhouse effect.*
**Source 5: Existing Assessments of Spatial Thinking.** The inventory of items collected from existing spatial thinking assessments was used after the STA-En GreenE concept list was complete. Once the 14 central concepts were established, the focus turned to deciding what format would best enable participants’ expression of their mental models of the spatial relationships of enhanced greenhouse effect phenomena. In other words, what does item design look like? Each STA-En GreenE central concept was connected to the spatial thinking skills that would be employed to express an understanding of the concept. For example, the fourth central concept in the Greenhouse Gases theme states, “Greenhouse gases in the atmosphere accumulate over time as emissions are greater than absorption.” This idea was referenced against each of the spatial thinking abilities taken from the spatial thinking literature (displayed in Table 1), and the following spatial thinking abilities were selected as important to the understanding of this concept: associate and correlate spatially distributed phenomena (the phenomena of emissions moving to the atmosphere from a distribution of sources and the distribution of absorbers pulling greenhouse gases from the atmosphere), making a spatial comparison (between the amount emitted and the amount absorbed), recognize spatial distributions and spatial patterns (of emitters and absorbers in the landscape, to deduce which one is bigger).

Then, for each, the existing spatial thinking assessment items that tested the skills with which the concept was aligned were used as a reference, to inform where possible, the assessment item design for the STA-En GreenE, for that concept. Following the same example, Figure 26, shows some of the spatial thinking assessments that were referenced, because they tested the spatial thinking abilities used to demonstrate an understanding that, “Greenhouse gases in the atmosphere accumulate over time as emissions are greater than absorption.” Then, a set of prompts and a model space were designed to enable students’ expression of those spatial concepts.
Figure 26. Item development process for Central Concept #4, from concept, including spatial thinking abilities, informed by existing spatial thinking assessments ([a] Verma, 2015, p.50; [b] Verma, 2015, p. 53; [c] Dunn, 2015, p. 85), to item design.
Assessment Item Design Informed by a Models and Modeling Framework

In Chapter 3, I described the models and modeling theoretical framework that supports this work. In the design of each item, it was important to be guided by that framework, not just in theory, but in practice. In other words, I used the models and modeling framework to develop guidelines that would turn each of the 14 central concepts that were described in the last section into model-building opportunities for participants. This section describes how the theory and practice of models and modeling guided the design of each item and of the format of the assessment overall. Below, I describe the goals for student modeling and how I used the models and modeling literature to enable student model-building, with those goals in mind.

I had the following goals in mind as I developed these guidelines:

1. Participants express their mental models of the spatial relationships of enhanced greenhouse effect.
2. Participants’ models express their understanding of each of the 14 central concepts of the STA-En GreenE for which they hold a mental model.

These are clearly very broad goals. Since the product of this assessment is a participant-generated model, the research task then, is to discover how previous work in models and modeling can inform the design of the assessment to reach these goals.

**Goal 1: Participants express their mental models of the spatial relationships of enhanced greenhouse effect.** Enabling learner expression of a mental model is a challenging. The hope is that learners’ mental models could be easily and directly translated into the conceptual models that they express on the page, in a simulation, in a physical three-dimensional model, or some other method of representation, but that is not supported in the literature (Greca & Moreira, 2000). In many cases this is because the expression of a mental model in language that aligns with the content and in a way that can be understood by others would itself require new knowledge
acquisition (Schwarz et al., 2009). For example, concept maps are often used in studies where learners are asked to represent the connections between objects, phenomena, or ideas; however, to be able to create a concept map that does that, the learner must also learn the model-building conventions associated with the practice (Novak & Cañas, 2008). It is unlikely that the learner’s mental model of the content they were asked to depict matched the concept map they expressed.

So then, how do we achieve the first goal described above, which is to ensure that learners are expressing, as closely as external expression will allow, their mental models of the spatial relationships at work in the phenomena of enhanced greenhouse effect? I returned to the literature that describes how to support learners in creating robust models of their understanding. The practices in two reports described below provided a foundation for model-creation that was then condensed and applied to each of the central concepts of the STA-En GreenE to construct assessment items such that participants could, with as much fidelity as possible for a summative assessment, translate their mental models to external conceptual ones. First, I will describe the practices as they are outlined in their original documents. Then I will describe how they were condensed and translated to be useful to the assessment design here. Finally, I will demonstrate how these practices were related to each of the 14 STA-En GreenE central concepts to provide guidance for item design.

Schwarz et al. (2009) developed a set of four foundations that they describe as supporting the practice of modeling. They are:

1. Students construct models consistent with prior evidence and theories to illustrate, explain, or predict phenomena.

2. Students use models to illustrate, explain, and predict phenomena.

3. Students compare and evaluate the ability of different models to accurately represent and account for patterns in phenomena, and to predict new phenomena.
4. Students revise models to increase their explanatory and predictive power, taking into account additional evidence or aspects of a phenomenon. (p. 4)

In the *Next Generation Science Standards* (NGSS) (NRC, 2012a), which describe models and modeling as 1 of 8 practices central to science and engineering disciplines, the most advanced student in the K-12 system “progresses to using, synthesizing, and developing models to predict and show relationships among variables between systems and their components in the natural and designed worlds” (NRC, 2012, p. 6). More specifically, these students will:

1. Evaluate merits and limitations of two different models of the same proposed tool, process, mechanism or system in order to select or revise a model that best fits the evidence or design criteria.

2. Design a test of a model to ascertain its reliability.

3. Develop, revise, and/or use a model based on evidence to illustrate and/or predict the relationships between systems or between components of a system.

4. Develop and/or use multiple types of models to provide mechanistic accounts and/or predict phenomena, and move flexibly between model types based on merits and limitations.

5. Develop a complex model that allows for manipulation and testing of a proposed process or system.

6. Develop and/or use a model (including mathematical and computational) to generate data to support explanations, predict phenomena, analyze systems, and/or solve problems. (NRC, 2012, p. 6)

There are two things to note about the resources used as a foundation here for guidance in eliciting learners’ mental models through assessment. First, there is considerable overlap in the abilities and understandings they espouse. Second, they speak to modeling as a *process* and not as a
summative assessment. To be sure, future work in this research program will tackle spatial modeling as a foundation of pedagogy and practice in the environmental science classroom, but for the purposes of this work, I will describe how these ideas can be applied to just the assessment developed here.

Table 5 below depicts the development of the STA-En GreenE guiding principles for item building that will elicit student expression of their mental models. The column on the left contains the modeling elements suggested by Schwarz et al. (2009). The middle column depicts the modeling elements suggested in the Framework for the Next Generation Science Standards. In each of these columns the concepts in each element that are appropriate for the assessment designed here are underlined. Concepts that are not underlined were not included in the resulting guidelines for assessment design. The concepts that were not included the ability of the student to design a test of a model to ascertain its reliability, to develop a complex model that allows for manipulation and testing of a proposed process or system, develop or use a model to generate data to support explanations, predict phenomena, analyze systems, and/or solve problems. These ideas were not used to guide item design for the assessment, as they speak to an ongoing model development and testing processes that will not be taking place as part of this assessment. The right hand column depicts the synthesis of the similar ideas expressed in the two resources, made practical for the participation in a model-based assessment. These are the things that we want to ensure each item facilitates for the test-taker to support them in expressing their understanding. The assessment design guiding principles for model development for the STA-En GreenE are:

1. Participant has the opportunity to compare and evaluate the models they create to best represent the concept the assessment prompts them to model.

2. Participant has the opportunity to incorporate evidence from previous work to develop and/or revise their model that illustrates and explains the spatial
relationships of enhanced greenhouse effect.

3. Participant is given the opportunity to create models in multiple contexts so that each one can most accurately describe the interrelated spatial relationships of enhanced greenhouse effect for that context.
Table 5

**Modeling Practices taken from the Literature and Resulting Guidance for the STA-En GreenE**

*Note.* Ideas applicable to the STA-En GreenE summative assessment are underlined. The right-most column depicts the resulting guiding principles for STA-En GreenE development.

<table>
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<tr>
<td>Students compare and evaluate the ability of different models to accurately represent and account for patterns in phenomena, and to predict new phenomena.</td>
<td>Evaluate merits and limitations of two different models of the same proposed tool, process, mechanism or system in order to select or revise a model that best fits the evidence or design criteria.</td>
<td>Participant has the opportunity to compare and evaluate the models they create to best represent the concept the assessment prompts them to model.</td>
</tr>
<tr>
<td>Students construct models consistent with prior evidence and theories to illustrate, explain, or predict phenomena. Students use models to illustrate, explain, and predict phenomena. Students revise models to increase their explanatory and predictive power, taking into account additional evidence or aspects of a phenomenon.</td>
<td>Develop, revise, and/or use a model based on evidence to illustrate and/or predict the relationships between systems or between components of a system.</td>
<td>Participant has the opportunity to incorporate evidence from previous work to develop and/or revise their model that illustrates and explains the spatial relationships of enhanced greenhouse effect.</td>
</tr>
<tr>
<td>Development and/or use multiple types of models to provide mechanistic accounts and/or predict phenomena, and move flexibly between model types based on merits and limitations.</td>
<td>NOT APPLICABLE</td>
<td></td>
</tr>
<tr>
<td>NO MATCH</td>
<td>Design a test of a model to ascertain its reliability.</td>
<td>NOT APPLICABLE</td>
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<tr>
<td>Develop a complex model that allows for manipulation and testing of a proposed process or system.</td>
<td>NOT APPLICABLE</td>
<td></td>
</tr>
<tr>
<td>NO MATCH</td>
<td>Develop and/or use a model (including mathematical and computational) to generate data to support explanations, predict phenomena, analyze systems, and/or solve problems.</td>
<td>NOT APPLICABLE</td>
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**Goal 2: Participants’ models express their understanding of each of the 14 central concepts of the STA-En GreenE for which they hold a mental model.** First, it is important that students are scaffolded enough in their model-building process that they express their mental models for specific learning objectives. Novice learners could miss target concepts that they may have an understanding of because of a lack of guidance in the task. This fails to produce the desired outcome because participants do not have the opportunity to express their full understanding and, therefore, assessment administrators do not have the opportunity to evaluate responses related to each of the concept objectives.

To address this need, two design principles were integrated into the assessment. First, each of the 14 central concepts was prompted individually in the assessment instructions. If students addressed each of the prompts to the best of their ability, they would address all of the central concepts. Second, the model development space, where students would create their models, was suggestive of particular environments and scales that correlated with the instruction given for students to express their understanding of each concept. That is, for concepts related to the size and location of the atmosphere, the model development space was structured or pre-loaded with a silhouette of the Earth to prompt students to model the atmosphere relative to it. I consider this the models and modeling equivalent to a sentence starter prompt, which are commonly used in educational assessment and activity design to “induce productive learning processes” (Harney, 2015, p. 3). In written assessments, they usually come in the form of guiding questions or question stems that provide clues or cues to scaffold students’ explanation. In this case, the goal is the same, and I use a model “prompt” by creating the environment in which the model will be created and providing some context for model development.

The next section describes each of the 14 central concepts by content theme and through the lens of these two guiding design principles. By applying the design principles to these ideas, the
item format really starts to take shape. Figure 27 below models the assessment design process for Central Concept 1, which was within the Greenhouse Gases content theme. Each of the Central Concepts was conceptualized by this process of being references against the sources of information that contributed to the assessment design. As is displayed in the figure, first I referred to the spatial thinking literature to determine which general spatial thinking skills were useful to understanding and modeling that concept. In this case, those skills were: associate and correlate spatially distributed phenomena (the phenomena of emissions moving to the atmosphere from a distribution of sources), designing and using a spatial model (the model that students will create as part of their assessment), fitting a place into a spatial hierarchy (the atmosphere contains the emissions, so we know that the amount of emissions are smaller than the atmosphere), tracing a spatial connections (between the emissions and the atmosphere), and describing conditions (as a requirement of the modeling process). Then, these spatial thinking skills were referenced to my literature review of existing spatial thinking assessment, to determine if any existing items could be modeled for the purpose of students demonstrating their understanding of enhanced greenhouse effect for the STA-En GreenE. In this case, existing assessment items were not useful, because most were decontextualized and far removed from the spatial thinking tasks students were required to have to successfully answer the STA-En GreenE assessment questions. It should be noted that, since spatial thinking literature, without an explicit temporal focus guided most of my work here, time is not the focus of each assessment item. Students are required to model their understanding of change by modeling enhanced greenhouse effect characteristics in two time periods; but they are not required to create a temporal representation, and their temporal understanding was not assessed directly. This addition might be created in future revisions or for other content areas; however, a similar research process, to learn about existing methods of assessing temporal understanding would be in order, to say with any degree of certainty what a starting point might be for creating an assessment that
explicitly addresses students’ understandings of the temporal and dynamic nature of environmental problems.

Finally, since an original assessment item needed to be designed (which turned out to be true for all Central Concepts), I referred to the guidance I developed to ensure that a prompt would enable students’ (a) expression of their mental models and (b) expression of their understanding of the specific concepts named. For this Central Concept, students were asked to represent their understanding with more than one item, they were prompted to use specific modeling representations and also given the opportunity to represent concepts in their own way, and they were presented with contextualized and familiar examples.

Figure 27. The development process of Central Concept 1, which is in the Greenhouse Gas content theme.
The resulting assessment is a contextualized spatial thinking assessment for enhanced greenhouse effect. I chose a contextualized assessment because of the sources of information that contributed to the study. Literature provided the content, and experts contextualized spatial thinking in the content. Since expert input was such a meaningful source of information, creating a contextualized assessment made sense for the project. Decontextualized spatial thinking assessments have certainly been administered and described here, with the results being separately correlated with students’ content understanding; however, in this case I am interested in the way students express their spatial thinking related to enhanced greenhouse effect specifically. Therefore, the developed assessment contextualized spatial thinking skills in that content. The initial version of the assessment, as it was developed from this design process for each central concept and as it was administered to the panel of experts, cognitive interview participants, and pilot test group, is found in Appendix E. Chapter 9 describes the testing and revision process for the assessment that follows here.
Chapter 9: Evaluation and Testing of the STA-En GreenE

This chapter describes the ways in which the STA-En GreenE was reviewed by experts with relevant experience and tested with a sample of the population of learners for whom it is intended. Referring to Figure 5, which is presented again below as Figure 29, this chapter describes the rationale, methods, and results that took place in Step 4 of Dillman's five steps of assessment design. Step 4 includes various stages of pretesting: (1) evaluation by a panel of experts, (2) cognitive interviews with representatives of the target population, (3) pilot testing with a sample of the target population, and (4) the “Did I do something silly?” test, a final check by an individual unassociated with the project. The following sections describe what was done for each of these steps in detail.
Stage 1: Review by a Panel of Experts

The first step in designing the STA-En GreenE assessment was to write individual assessment items, using the guidelines described in Chapter 8. According to Dillman, This initial draft of the assessment can be seen on pages 169 to 173. Once items are written and ordered, the first stage of pretesting is for the assessment to be reviewed by experts with knowledge in areas relevant to the assessment. Three experts were consulted to review the STA-En GreenE. Reviewer #1 is an expert in science education, with a Ph.D. Curriculum and Instruction with a Science Education focus and experience in developing, implementing, and assessing lessons related to global
climate change in the secondary classroom. This reviewer was uniquely qualified to review the presentation and wording of the current assessment for clarity from the student participants’ perspective. Her input led to revisions in the text and format of the assessment.

Reviewer #2 is the lead faculty advisor for this project, with a Ph.D. in Chemistry. She is an expert in chemistry education and has extensive experience developing, implementing, and assessing curricula for students, as well as professional development opportunities for educators. She helped develop the scope and goals for this study. As such, she was uniquely qualified to review the assessment for clarity as well as for alignment to the goals of assessment, as they have been outlined in this dissertation.

Reviewer #3 is an expert in environmental science, and more specifically in enhanced greenhouse effect and climate change. She is an informal environmental science educator, with a Ph.D. in Environmental Policy and Management and experience teaching a university-level course in climate change and its impacts. Reviewer #3 was tasked with ensuring that the questions’ content includes the important concepts to understanding enhanced greenhouse effect and that the concepts tested for are accurately conveyed in the text and presentation of the item.

The experts’ task was to review the assessment to determine if it contained all of the necessary questions, if the questions are intelligible by the reader, and if questions might be eliminated or condensed (Dillman, 2000). The panel of experts also evaluated the assessment for issues of bias and issues of fairness to students’ understanding. For example, as experts in content and education, they were able to read the assessment, evaluate the language, and determine how well novice students would understand the tasks asked of them. Each expert has experience in education and, as such, was able to contribute to a discussion of fair and unbiased language such that a learner participating in the assessment would be able to answer the questions based on content and construct and not be confounded by language they do not understand or are confused by. The goal
of this phase of pretesting was to finalize assessment items and their order, so that the assessment could be evaluated by and tested on the population for whom it is intended.

All reviewers provided their feedback, as typed commentary on a digital copy of the assessment, and then orally, in a follow-up, semi-structured interview. In each case, the comments and suggested revisions were minimal. The resulting comments and action taken from each expert interview are presented below. Suggested edits were incorporated all at once, after all expert reviewers had reviewed the assessment.

Reviewer #1: Expert in Science Education, with a Ph.D. Curriculum and Instruction.

This expert made several recommendations for editing in the interest of clarity and word choice. For example, for assessment items that asked students to model their understanding of the enhanced greenhouse effect system in the year 1500 and the 2000, her recommendation was to include the year the model represented in every prompt where students were to consider the year. This way, students would not have to reconsider the context or hold that information in their working memory while completing the model. These recommendations were accepted and the edits made accordingly.

For each model-building assessment item in which students were asked to represent emissions, absorption, and carbon accumulation and movement in the atmosphere, Reviewer #1 recommended adding follow-up open response questions to prompt students to describe the models they created. She recommended prompting students to describe their model of the relationship between greenhouse gas emissions and absorption in writing, in addition to creating the model itself. This was viewed as a valuable revision, since it would give a second representation of the students’ understanding of greenhouse gas absorption and emissions.

In a written document, the reviewer also pointed out where wording the wording of a particular prompt was confusing or unclear. In follow up interviews, the reviewer described why the
text was confusing. For example, in Part 2: Radiation and Greenhouse Effect, for both the model prompts addressing the year 1500 and the model prompts addressing the year 2000, the initial version of prompt #5 stated, “In the greenhouse gas viewing box (B), represent energy and greenhouse gases. What is energy doing and how does it move?” For Expert #1, the use of the word “represent” to direct the student to draw their model in the space provided was not specific enough. While this recommendation was considered, “represent” is still the preferred word for this iteration of the assessment. Other words considered include, “model,” “draw,” or “sketch.” Instructing students to model their understanding was considered jargon for an audience that has no specific training in what a model is or what it can represent. Many of these students, during a discussion at the beginning of the semester, expressed their understanding of a model as something physical and miniature, like a model airplane or train. Accordingly, the use of the word “model” as a verb may be confusing. To instruct students to “draw” or “sketch” their understanding was determined to be too directive. Part of this study’s purpose is to discover how students represent their understanding naturally, so that future assessments may be designed with those ideas in mind. If students are not naturally prone to drawing or sketching what they know, and express it more naturally with words, I want to know that and learn how to design prompts to enable their clearest expression. The recommendation to replace the word “represent” in item #5 was, therefore, not accepted; however, I did note that the word “represent” might be confusing for students, in case that fact might be relevant during data analysis.

Finally, Reviewer #1 recommended including more specific instructions about where students should model their understanding in the modeling space in item #____. This recommendation was accepted, and verbiage was added to the suggested prompt directing students to represent carbon dioxide movement in the atmosphere, within the diagram provided.
Reviewer #2: Expert in Chemistry Education, lead advisor for project. Reviewer #2 also made several recommendations for wording clarity. In addition, as someone who is closely associated with the project, she was able to make recommendations to ensure that the assessment items’ design was such that students’ responses to assessment items would inform my ability to answer the research questions for the project.

Two recommendations Reviewer #2 informed the revision of several assessment items: (1) to include sufficient space in the assessment for students to represent their understanding and (2) to prompt students to explain their modeling choices. For example, in Part 1, for a prompt that directs students to identify, by circling, all sources of carbon dioxide emissions in a map of a location that was familiar to them, Reviewer #2 recommended adding a follow-up prompt, in which students could explain why they circled what they did: “In the space below, describe why you circled the things that you did.” A space was provided for this explanation. Similar prompts and spaces were provided throughout the assessment, enabling students’ explanation of their models. Future revisions of the assessment may not include this explanation if it is determined that students’ understanding of enhanced greenhouse effect can be determined from their expressed models alone.

Reviewer #2 also recommended providing students more specific instruction on which topics they are to speak to or model in their responses. For example, In Part 1: Carbon Dioxide Emissions, prompt #3 originally asked students to “describe any conclusions you come to or observations that you can make by looking at the model that you have created here.” Upon the suggestion of Reviewer #2, this was changed to, “describe any conclusions you come to or observations that you can make about carbon in the atmosphere by looking at the model that you have created here.” This wording change enabled students’ explanation of the specific central concepts that were targeted with the modeling prompts in this part of the assessment.
Reviewer #2 also recommended using more specific language for a portion of Part 1: Carbon Dioxide Emissions that asked students to identify the sources of emissions and absorption that they understood to be the greatest contributors to greenhouse gas emissions. In the original version of the assessment, students were simply asked to *identify* the sources of carbon dioxide emission they thought to be the largest. The recommendation for more directive language was accepted and the wording was changed so that students were asked to “place a star next to” what they understood to be the largest source of emission. Parallel recommendations were made for assessment items that asked students to identify the largest carbon dioxide absorbers. This edit was made for both the model prompt for the year 1500 and the year 2000.

In one case, it was important that Reviewer #2 was not an expert in the content or modeling of enhanced greenhouse effect, because she was able to identify instructions that would not be clear to the novice learner. In Part 1: Carbon Dioxide Emissions, students were originally asked to “Represent the relationship between carbon emissions and absorption” in the model space. Reviewer #2 correctly identified the wording choice as vague and the modeling task as conceptually difficult. This prompt was changed such that students were directed to simply describe the idea with words, rather than model their understanding. Again, this was changed for both the modeling prompts directed at the year 1500 model and the year 2000 model. The new prompt read “In the space below, describe any conclusions you come to or observations that you can make about carbon in the atmosphere by looking at the model that you have created here.” A space was provided for them to write their description.

Finally, Reviewer #2 made an important comment about the original model space for Part 2: Radiation and Greenhouse Effect, which depicted the space between the sun and the earth and a “zoomed in” view of the atmosphere as a cutout box in which students were to represent their understanding of the interaction between greenhouse gases and radiation. The two model spaces
(the sun/Earth model and the cutout box) are connected with an arrow to represent the cutout as a close-up of the atmosphere. Expert #2 suggested that the arrow might indicate to the student the location of the atmosphere relative to the Earth and the sun. Because one of the student’s tasks in the assessment is to draw their understanding of the location of the atmosphere, Reviewer #2 suggested another method of representation so students are not inadvertently given a “hint” about the location of Earth’s atmosphere. This recommendation was accepted and the representation was changed so that the arrow between boxes only extended from the edge of the Earth/sun model to the edge of the cutout, eliminating the suggestion of atmospheric location. Figure 29 below shows the change that was made to the model space in Part 2.

Figure 29. Changes made to Part 2: Radiation and Greenhouse effect model space, based on the
recommendation of Reviewer #2. Image (a) suggests the position of Earth’s atmosphere. Image (b) only connects the two model spaces.

**Reviewer #3: Expert in Environmental Science and Climate Change Education.**

Reviewer #3 did not identify any content changes or recommend any changes in format. The feedback this reviewer gave was in the form of two questions: “Why do the conceptual models follow the Google Earth map of a local environment?” “What are students intended to identify on the Google Earth image when they are directed to identify carbon dioxide emitters and absorbers?”

In a follow up interview, Expert #3 described the intention of the questions further and gave me the opportunity to describe the rationale for my design decisions. Expert #3 agreed with beginning the assessment with a context that was familiar to the students, after the reasoning and support from the literature was explained. However, Expert #3 felt that students might struggle with identifying buildings and other objects that utilized electricity as carbon dioxide emitters; that they would only identify vehicles. While this may be true, that will be an important finding during cognitive interviews and pilot testing. We agreed that the design should not change, but that particular attention should be paid to student modeling in response to this prompt. If students struggle with the identification of carbon dioxide emissions from sources in the image other than vehicle emissions, changes should be considered that might direct them to recognize other sources.

**Summary.** The changes made to the initial version of the STA-En GreenE assessment were changes in wording for clarity and to direct novice students more specifically to the modeling targets desired in their responses. The changes to the modeling spaces were made to prevent cuing students to one modeling answer or another. The recommendations that were accepted directed changes that were made prior to cognitive interviews and pilot testing that occurred with the assessment’s target population. The resulting assessment is displayed in Appendix E. The results of the cognitive interviews are described in the following section.
Stage 2: Cognitive Interviews

The second step of the pretesting process is the cognitive interview, in which participants with the same characteristics as those for whom the assessment is intended are administered the assessment in an environment where they can express their thought process out loud as they take the assessment, so that more can be learned about the development of their ideas to inform future revisions. The purposes for this stage are, first, to ensure that each question is comprehensible by the intended audience and, second, to ensure that questions can be answered accurately as they are expressed (Dillman, 2000). It is the aim of the cognitive interview to address any issues of bias and fairness that may exist in the language that are still present after the first revision, which was informed by the expert interviews. It is important that the language of the assessment be accessible to all students and that no group is disadvantaged because of background or experience, outside of their experience in spatial thinking or environmental science (AERA, APA, & NCME, 1999).

For assessments that are completed autonomously, such as the one developed here, Dillman (2000) recommends pairing a think-aloud protocol while taking the assessment with a retrospective interview to follow it as part of the cognitive interview stage of pre-testing. The think-aloud process asks participants to verbalize everything that would usually take place in their head as they are taking the test. This includes reading the question, expressing problem-solving steps, and expressing confusion or difficulty in understanding the material. A possible limitation in this method is that participants may experience split attention between processing the test items and expressing their thought processes to a data collector. The retrospective interview minimizes this issue by enabling participants to reflect on their experience, facilitated by a researcher who might ask questions related to their observations of the test-takers interaction with assessment items.

In this case, the intended audience is introductory environmental science students at a large community college in the Southwestern United States. The community college accessed for this
study is one of the 5 largest in the United States, with 31,456 enrolled students, according to the latest available enrollment records (Website for college at which study took place, Internal Review Report, 2014). Female students make up 56 percent of the population; and the institution is federally designated as a Hispanic Serving Institution, with 27 percent of its enrolled student body self-reporting as Hispanic. The average age of the community college students here is 27, and most (75%) are attending classes only part-time. Anecdotally, it can be noted that many students speak English as a second language, which was important to consider as I tried to ensure the fairness and clarity of the assessment to all learners. In selecting students to participate in the cognitive interviews, I attempted to represent some of the important characteristics of the student population described here.

Broadly, introductory science students were the target cognitive interview participants. Students from an Introduction to Environmental Science class at the local community college where the pilot test was administered were solicited for their participation. These students were enrolled in one section of the introductory environmental science course that I taught during the Spring 2016 semester. Sampling from respondents was purposeful, to target specific student populations and represent a diversity of student experience. Variables that were considered are student age, experience in the sciences, and whether English is the primary language of the test taker. Two students participated in a think-aloud exercise as they completed the assessment revised from the expert reviewers suggestions. Both students also participated in a retrospective interview. The retrospective interviews were conducted in a focus group format, which was a product of poor scheduling, but which ended up being extremely productive method for eliciting student expression of their thought processes. The unexpected result of the format was that these two students, who had different educational experience and, as it turned out, different perceptions of the assessment, required very little prompting in their statements. They engaged in vigorous conversation with each
other about their thought processes and their perceptions of the assessment and model-building as they completed each task. Each of the students who participated and the results of their cognitive interviews are described below. The students are referred to by pseudonyms in order to protect their anonymity.

**Student Participant #1: Allegra.** Allegra is a 35-year-old returning student. She is attending school part-time. English is her second language (Spanish is her first), though she is a fluent and natural English-speaker. She had never taken a science course in college before the environmental science course in which she was currently enrolled, though her educational goals are science-related, as she would like to pursue a career as a park ranger or something similar. She was selected for her representation of several of these demographics and because of her general willingness in class to participate. Allegra was an engaged and vocal participant in my class all semester, so I was certain that she would provide ample feedback about the assessment. Descriptions of her think-aloud response and her retrospective interview that are relevant to the design of the assessment or to the analysis of student responses are below. The subtitles indicate each subsection of the assessment, which is how her responses are organized. The sections that follow describe only Allegra’s responses.

**Part 1: Greenhouse Gases, Model 1: Campus map emissions and absorption**

*Identification.* Allegra’s general willingness to diagram her spatial understanding of greenhouse gas emissions, absorption, and how it moves in the atmosphere was low. While completing the assessment, she remarked several times, including while she was completing the first model, that she was not comfortable creating drawings or modeling her understanding with images. Nevertheless, she provided useful commentary as she looked at the first model space and associated prompts, which instructed her to identify the sources of emission and absorption in a familiar landscape, a Google Maps image of the community college campus.
Think-aloud commentary. Allegra described her ideas while circling sources of carbon dioxide emission, saying things like, “So the things that are big, like an industrial park or a big building, it definitely emits and I circle it.” She also placed circles around vehicles in a large parking lot. Vehicles were circled as a group, not as individual vehicles. She identified absorbers while she placed squares around them by saying, “Green areas are easy to identify as absorbers” and noted the absence of water, which she knew to be a carbon dioxide absorber from class group work and lecture time. She said, “This map is missing water. If water was there that would be an absorber.”

Retrospective interview. Allegra noted that most of her knowledge in class was situated in very general models of the atmosphere, as well as carbon emission and absorption. She noted that the contextualized model-building opportunity presented in the assessment, with the map of a familiar location, was more difficult than working with decontextualized conceptual models. This idea is touched upon again in later commentary.

Part 1: Greenhouse Gases, Model 2: Emission and absorption in the year 1500. In the model of the coastal landscape of 1500, where students are directed to model their understanding of emission and absorption as they may have been at that time, Allegra was also more comfortable describing her understanding, than modeling it on the page.

Think-aloud commentary. Allegra described her representations of emissions sources by saying, “I am starting by drawing factories. I am drawing grazing animals, but not a lot. I am not sure what would have been here in 1500. I am drawing a human population and growth, because I know that people were here. There is a human component of CO₂. I am drawing a little oil drill. I really don’t know about the time frame.” This is of note, because the year 1500 was chosen for the first model, because of its proximity to 1492 and an assumption that students would have a rough idea about the general technology, or lack thereof, during that time. The fact that Allegra really had no idea of the
level of technology or human impact at the time implies that other students might struggle with situating the timeframe as well.

Retrospective interview. Most of Allegra’s retrospective discussion focused on the choice of the year 1500 for this modeling prompt. She felt that her understanding of what took place or what kind of technology existed during that time were so limited that she could not represent carbon dioxide emitters and absorbers at that time.

**Part I: Greenhouse Gases, Model 2: Emission and absorption in the year 2000.** The model space and prompts corresponding to the year 2000 were, as expected, easier for Allegra to address than the model corresponding to the year 1500.

Think-aloud commentary. Representing human population existence and growth was a priority. “I am representing a lot more people this time; more people than animals. I am drawing a fracking operation,” she said referring to the term we used in class for hydraulic fracturing, a method for removing natural gas from Earth’s crust. While she drew, she commented on her preferred method of modeling, stating, “I am more of a labeller.” This sentiment was echoed throughout the think-aloud protocol and retrospective interviews and it was apparent in her models, which often included text to describe what she drew and notes in the margins.

Retrospective interview. Allegra addressed Prompt #5 for this modeling task specifically with her retrospective interview. Prompt #5 asked the modeler to compare carbon dioxide emissions and absorption and declare which was bigger or smaller or that they were the same. Allegra said that this was a much easier task for the year 2000, than it was for the year 1500, because she was more familiar with conditions in the year 2000.

Prompt #6, also associated with Model 2, instructs the modeler to represent the movement of carbon dioxide in the atmosphere. Allegra noted that she did not follow the prompt because she looked ahead in the assessment and noticed that an instruction for the next modeling task prompted
the same thing. This is important to take note of, since part of the assessment design was intended to give students multiple opportunities to represent the same phenomenon, so when a student forgoes one of those opportunities, our ability to evaluate their understanding from multiple perspectives is limited.

Finally, one prompt on the page that contained the prompts for Model 2, was displayed outside of the text box where the other prompts for Model 2 were displayed. It prompted students to compare the two years, 1500 and 2000, and express their conclusions in text. Allegra did not answer this prompt and stated that she did not see it, because it was outside of the text space. The assessment was revised to include this prompt in the same space as the other Model 2 prompts, so that it was certain to be noticed.

**Part 2: Radiation and Greenhouse Effect, Model 1: The year 1500.** Allegra commented less about the last two models than she did about the first part of the assessment, both during the think-aloud procedure and during the retrospective interview.

*Think-aloud commentary.* While drawing the relative positions of the atmosphere and specifically, the stratosphere, she stated as much, “I am just drawing lines and labeling sun, stratosphere.” Her representation was accurate as to the position, but not the relative size of the atmosphere. It was much larger or represented as having a wider diameter from the surface of the Earth than it actually has. Allegra’s representation was most likely influenced by the way that the atmosphere was represented in class, as disproportionately large, so that greenhouse gas dynamics could be represented within it. This is notable because it indicates that students are likely to mimic modeling techniques that they have experienced through instruction. Therefore, it will be important to look at how closely student representations in the pilot study correlate with representations they might have seen in class or in the course text book.
Retrospective interview: Allegra struggled with her understanding of the greenhouse effect and what the system may have looked like in the year 1500. She said, “I didn’t know enough about enhanced greenhouse effect to tell you about 1500. I used what we did in class; and we represented present day more, so it was harder to know “normal” greenhouse effect.” By normal, Allegra indicated greenhouse effect, as opposed to enhanced greenhouse effect. She again stated that she “would be more comfortable listing bullet points, but it was harder to create visual.” This was supported by her general modeling approach, which included a large amount of labeling and other forms of text.

She noted that, “The “B” box was confusing. I didn’t understand its intention.” With this, she referred to the cutout, or zoomed in model of the atmosphere, where students were to represent greenhouse gases in the atmosphere and how they interact with radiation. This part of the assessment design is of particular interest, to discern how students interpret it. If other students are confused by the cut-out “B” as Allegra was, the Central Concepts that were intended to be represented there might be represented incorrectly, or not represented at all.

Part 2: Radiation and Greenhouse Effect, Model 2: The year 2000

Think-aloud commentary. Allegra’s modeling was minimal for this modeling task; and she did not think aloud when prompted, in this case.

Retrospective interview. Allegra’s frustration with this task and the cut out “B” box was apparent. She said, “This was not easy for me. I think I just added more dots,” indicating that she drew more dots representing carbon dioxide in the model for the year 2000 than for the year 1500. When asked which part of the task she found confusing, she stated, “The directions were clear; it was just an understanding thing.” This is important to note for future intervention design. If the directions were clear, then Allegra’s inability to represent ideas was because she did not have an understanding of some spatial concepts related to enhanced effect, not because she had a conceptual understanding.
and did not know what was being asked in the assessment. So, the assessment is serving its purpose, which is to give us an idea of the spatial relationships students understand, related to enhanced greenhouse effect. From there, I can plan interventions that target the concepts students like Allegra are struggling with.

**Student Participant #2: Zachary.** Zachary is a 21-year-old returning student, who aspires to be a pilot after completing his associates degree at the community college where he is currently enrolled full-time. He had never taken a science course in college before the environmental science course in which he was currently enrolled. His described his educational goals as not related to science, though his career goal, to be a pilot, would require extensive coursework in science and math. He was selected for his representation of several of these demographic descriptors and because of his general willingness in class to participate. Zachary was always a vocal participant in class and often took a leadership role in class. He was very analytical in class discussions. Descriptions of his think-aloud response and his retrospective interview that are relevant to the design of the assessment or to the analysis of student responses are below. The subtitles indicate each subsection of the assessment, which is how his responses are organized. The sections that follow describe only Zachary’s responses.

**Part 1: Greenhouse Gases, Model 1: Campus map emissions and absorption**

**Identification.** In general, Zachary was very vocal during his think-aloud protocol and was an active modeler during the exercise. His representations were more often pictorial then in text. In fact, he was more likely to draw an image representation than other types of indicators, like arrows or text.

**Think-aloud commentary.** Zachary’s modeling was detailed, and he explained his reasoning as he created diagrams. He stated that he understood the word “emit” in reference to carbon dioxide to mean “give off,” which is a good indicator that the word choice is not jargon and can be understood by novice students. Zachary used arrows to indicate the emissions given off by the buildings and the
cars, rather than circling the sources, which is a spatial representation of the relationship between the source of the emission and the atmosphere. This was not the prompted representation and was, in fact, more descriptive. Zachary also used two pens to create his models, and changed colors to represent emissions different from absorptions. Zachary pointed out and also indicated with his pen that the landscaping on the campus map was a small absorber of carbon dioxide from the atmosphere, a detail that I had not considered previously. He described the air conditioning units on each of the buildings in the landscape as “constant sources of CO₂ emissions,” adding that they probably increase the carbon dioxide they emit in the summer time, when they would be running at higher power. This illustrates an interesting misconception, that it is the units themselves that emit the carbon dioxide into the atmosphere and not the burning of a fossil fuel that produces the electricity that runs the air conditioning units. This is something to note in analyzing the pilot test results.

Retrospective interview. Zachary noted that the Google image that was used was not very clear and that it made it more difficult to identify features that might be carbon dioxide emitters or absorbers. This is important to note for future assessment design or revision.

Zachary’s perception of the difficulty understanding the familiar versus the decontextualized model was different from Allegra’s. He described the modeling tasks related to the Google Map image of a familiar location as easier than the general, conceptual models on the following pages, because he knew the local environment and the surroundings.


Think-aloud commentary. Again, Zachary’s models were pictorial. He described what he was drawing as he drew it: “I am drawing a small mining operation, but just a small one. And a small village, and a forest fire. I am drawing trees, snow, a river coming down as absorbers. I don’t think
there was a lot of absorption.” He did not offer much in the way of think aloud dialogue, other than a verbal description of exactly what he was drawing at the time.

*Retrospective interview.* As the retrospective interviews were conducted in a focus group format, there was an interesting dialogue between the student participants. When Allegra noted that she was not certain what the world looked like in the year 1500, Zachary said, “I would think that the year 1500 did look like this scene (referring to model). When did we come to America?” This was an important observation and demonstrated that he was focused on the intent of choosing that particular year: to be able to compare it with a more familiar year, 1492.

**Part 1: Greenhouse Gases, Model 3: Emission and absorption in the year 2000.**

*Think-aloud commentary.* Zachary’s think aloud commentary here was sparse. “I am drawing bigger mining operations,” was all that he said, as he did just that. In addition, he drew a greater number of residences, vehicles, and roads than he drew in the model for the year 1500. He showed carbon being emitted into the air from each of these sources. He drew airplanes in the sky, as well.

As Zachary reached Prompt #5, which asked him to compare the emission and absorption rates at this time, he said, “We are putting out more than the environment can get rid of, if it can. It’s doing it at a slower rate.” His understanding of the difference was correct and he stated it for the model prompts related to the year 2000, but not for the similar prompts for the year 1500 model.

Prompt #6 was not answered. Instead Zachary asked the question, “How does CO₂ move? I am not sure how to represent this?” This might be both an issue of content knowledge and item design, but is certainly something to pay attention to in the analysis of the pilot tests.

*Retrospective interview.* In the retrospective interview, Zachary elaborated on some of his think-aloud commentary. He said, “I wanted to represent bigger mining operation than before, so I represented them physically bigger in the model. More things are being emitted.” This was an original method of representation, but certainly one to pay attention for in future analysis, as it is
very spatial in nature. He demonstrated the difference using both models, showing me the 1500 version and the 2000 version.

Finally, Zachary used a spatial analogy to describe the difference in emission levels in the year 1500 and the year 2000: “We are emitting more carbon in 2000, because everything gets done faster. Use mail delivery as an example, Pony Express, compared to…it’s in Tennessee tonight and on your doorstep in the morning. So, everything takes a lot more energy.” Then he added, “You know what I forgot to put? Agriculture.” He followed this up by describing that industrial agriculture is a large emitter of carbon dioxide and other greenhouse gases, but did not revise his model.

**Part 2: Radiation and greenhouse Effect, Model 1: The year 1500**

*Think-aloud commentary.* While representing carbon dioxide in the atmosphere as particulate, as though it could be seen, Zachary said, “I think there was definitely more carbon there. It was there, just less.” By there, he was referring to the landscape in the time frame represented in the model, the year 2000. He indicated that he understood the idea of a natural greenhouse effect, in which carbon already exists in the atmosphere.

*Retrospective interview:* Providing a rationale for his representations in the model Zachary said, “I just kind of remembered general things about 1500: less people and they didn’t know how to access more energetic fuels, but there have always been things in the atmosphere.” Once again, he indicated the difference between greenhouse effect and enhanced greenhouse effect, as a result of burning fossil fuels.

**Part 2: Radiation and greenhouse Effect, Model 2: The year 2000.**

*Think-aloud commentary.* For his representation of the year 2000, Zachary did not change the things that he represented. The model still included carbon dioxide and radiation, as it did in the year
1500, just an increased amount. He explained only this out loud, “My depiction is not changing, just more.”

*Retrospective interview:* By way of explanation for his representation, Zachary said, “Countries developing have to burn more fossil fuels. Lots of coal. They can’t afford to be more efficient.” By this he meant that developing countries do not have environmental interests in mind, because their primary interest has to be increasing productivity for a higher quality of life. This is a concept we discussed in class many times.

**General Comments from Participant Discussion.** The participants agreed that the length of the assessment was fine. Allegra completed the assessment in 34 minutes and Zachary in 52 minutes.

An interesting discussion developed between the two participants about the use of models in assessment. Allegra persisted that modeling her understanding was more difficult than writing it out, but also stated that she felt that model-building was a better way to represent a person’s understanding.

Zachary replied that he thinks because he has always learned that way (with and by creating models), it was perhaps a more natural way for him to express his understanding. Allegra felt it was a gender difference, stating, “But, you are a boy. That’s your choice and how you have always been encouraged to learn and play and all of that.”

Zachary added that he had always enjoyed the time in class that was spent modeling; and Allegra expressed the opposite, stating that she preferred days when text was the focus of the learning experience. She noted how Zachary had completed the assessment, “You had fun putting the drawings on the page while we were taking the assessment, but I really just wanted to write it out.”
This discussion was interesting and has support in the spatial thinking literature. Gender differences have been noted in spatial thinking ability (Ganley & Vasilyeva, 2011; Nazareth, Herrera, & Pruden, 2013; Wan, Newcombe, & Fitzhugh, 2013), so it follows that for an assessment that is intended to enable student modeling of their spatial thinking, there may also be gender differences. At the very least, it will inform the scaffolding included for future revisions of the assessment, to ensure that all students have the support and direction they need to accurately represent their mental models.

**Summary.** The two student representatives of the target population who agreed to participate in the cognitive interviews provided insight that directly informed changes made to the STA-En GreenE. They also provided feedback that informed the way that pilot test data was analyzed, as will be discussed in the next section. Based on the cognitive interviews, the following ideas were considered and will be implemented in future revisions:

1. That an image of a familiar landscape that includes water could replace the map of the community college campus. Students are aware of water as a carbon absorber; and they should be given the opportunity, in whatever context the model represents, to express their understanding fully.

2. Students were variably comfortable with modeling as opposed to verbally describing or writing their answers. This may indicate that modeling instruction should take place or it might indicate that there should be more scaffolding included in the assessment itself, to ensure students’ security that their representations, whatever form they take, will be interpreted for their understanding.

3. Students did not have a clear understanding of absorption and emission conditions in the year 1500. That is not to say that this year should not be considered for representation in the assessment, but that students may need contextualization in the form of an explanation. I do
not think a description of human features and features of the natural world in the year 1500 would jeopardize students’ representation of their own mental models.

4. At one point, Allegra stated that she did not represent a relationship on one page, because she knew it was asked for again on another page. One intention of the assessment design, with support from the models and modeling literature, was to give students ample opportunities to express their understanding. This was something to pay attention to in the analysis of the pilot data and will be discussed further in the next section. If it is determined that students commonly represented their understanding only one time, a revision to the assessment might be made, to guide participants to address each prompt to the best of their ability.

These changes were not implemented for the pilot study, because I wanted to be able to use the cognitive interview participants’ comments and models to inform my interpretation of the pilot test participants’ comments and models where possible. If I revised the assessment between those tests, the cognitive interview results would be less meaningful to the interpretation of the pilot test results.

The next section describes the results of a pilot test of the STA-En GreenE with a sample population of 96 Introduction to Environmental Science students, upon which further revisions were made. The goal of the pilot test was to aggregate common response patterns, deficiencies in understanding or representation, or unforeseen response patterns to learn more about how the assessment is interpreted across a larger population. The results and analysis are described in the section that follows.

**Stage 3: Pilot Test with Target Population**

The next stage of testing enables evaluating the assessment in the context that it will be applied. This step serves a few important purposes. First, it tests out the delivery of the assessment,
including instructions, delivery, data collection, etc. Since the group taking the assessment is bigger in this step, it further directs item revision, because response patterns are recognized. If, for example, one question has a high rate of non-response, the item should be addressed. Analysis might reveal strong similarities between item response between two items that ask for similar information. In this case, one question might be eliminated.

This phase also serves the important function of providing a testing ground for evaluation of item responses. Here, I can also evaluate student responses and reference them to existing spatial thinking and enhanced greenhouse gas literature that has been described in previous sections, to better understanding students’ spatial thinking abilities related to enhanced greenhouse effect. Since the outcome of this research project is assessment development, pilot testing represents an important step in design and implementation. For this project it will inform the last major revision of the development process. The research questions associated with this part of the project are:

(1) What do student-generated models reveal about their spatial thinking skills that support understanding of enhanced greenhouse effect?

(2) How do student responses inform the next steps of assessment development?

**Participants.** As described previously, the intended audience for the STA-En GreenE are introductory environmental science students. The sample of that population accessed for this study are students in an Introduction to Environmental Science class at a community college in the southwestern part of the United States. Ninety-six students enrolled in four sections of Introduction to Environmental Science participated in the assessment. Each section was comprised of 25 to 35 students, although not all students were in attendance on the day of the assessment.

The community college accessed for this study is the same one that cognitive interview participants attended. It is one of the 5 largest in the United States, with 31,456 enrolled students, according to the latest available enrollment records (Internal Review Report, 2014). Female students
make up 56 percent of the population and the institution is federally designated as a Hispanic Serving Institution, with 27 percent of its enrolled student body self-reporting as Hispanic. As described previously, many students speak English as a second language. The average age of the community college students here is 27, and most (75%) are attending classes only part-time.

**Setting.** Each student participant was assessed during a regular class period at the end of their of the class unit on climate change and its impacts, which included enhanced greenhouse effect as a topic. During the semester, students were instructed with interactive lectures, textbook readings, and in-class group activities. Their instruction included models of climate change and enhanced greenhouse effect, though nothing from which the assessment format was derived, other than the general principles that they both included.

Participating students provided their informed consent on paper and were verbally informed of the voluntary nature of their participation. They were also informed that no course grade was dependent upon the correctness of their response, only on their participation. To ensure students’ anonymity, the assessment contained a cover page, on which they would write their name only. Students were informed of the time period available for the assessment, which was one hour and twenty minutes, a standard class period. Students took between 20 and 55 minutes to complete the assessment. Once assessments were complete, informed consent documents, as well as the assessment’s cover page containing the student’s name, were separated from tests and sealed in an envelope. Each assessment was assigned a serial number for analysis.

**Evaluation.** Since the sampling of students in this case was by convenience, I make the assumption for the purposes of the pilot test that the classes assessed are representative of the characteristics of the school. Students completed their assessments anonymously. The STA-En GreenE was evaluated question by question to identify the enhanced greenhouse effect central concepts that students represented in their individual answers. Representations of the prompts and
each model space, with their associated concepts is included in Figures 31, 33, 36, 39 below. In order to determine how each student represented or if they represented their understanding of these concepts, each item of each of their submissions was analyzed and coded for the concepts in Figure 30 that they represented for each item.

Tests were analyzed to identify (1) the Central Concepts represented in each in each student response and (2) the method of representation that students used to model their ideas related to that concept. Once I analyzed each item of each student’s assessment, I synthesized information across students, item by item, to note the Central Concepts most commonly described for each item and to note which Central Concepts were not addressed or identified in students' models. Finally, I compared the Central Concepts that I identified to those intended to identify the concepts that students were successful with representing and which ones they struggled with representing. The results are described below, organized item by item and the Central Concepts that were intended to be addressed through them. There are 5 model spaces with several prompts guiding students within each model space. Some prompts guided students to model their understanding. Some guided them to reflect on their models and express some understanding they gained from them in text. I will describe each model space and the prompts attached to it, the Central Concepts associated with each prompt and how students represented them. Finally, I will discuss what student representations tell us about their understanding of the spatial thinking abilities supporting an understanding of enhanced greenhouse effect.

Since the primary way in which the pilot tests inform this study is through the analysis of the ways in which students model their spatial understanding of enhanced greenhouse effect and what their modeling tells us about what they know, it was decided that a sampling of the 96 completed assessments was sufficiently representative of the breadth of student response. With this in mind, 50 percent of the assessments (48) were randomly chosen and analyzed.
Results.

Modeling Space #1: Carbon Dioxide at Home. This modeling task and its prompts were labeled “Carbon Dioxide at Home,” because the modeling space the students are given is a representation of the college campus where they attended class. This was done upon the suggestion of several experts, as well as spatial thinking literature on scale, that students should be guided in their spatial thinking, first in spaces they are familiar with. Students are prompted to either circle or place a square around the features in the landscape they perceive to be carbon dioxide emitters and absorbers, respectively. A last prompt asks them to describe any conclusions they can draw about carbon dioxide in the atmosphere, based on what they represented. The prompts read:

1. Using the map, circle everything that you think emits carbon dioxide into the atmosphere. In the space below, describe why you circled the things that you did.

2. Using the same map, put a square around anything that you think absorbs carbon dioxide from the atmosphere. In the space below, describe why you put a square around the things that you did.

3. In the space below, describe any conclusions you come to or observations that you can make about carbon in the atmosphere by looking at the model that you have created here.

These prompts target Central Concepts #1, #2, and #4. Figures 32, 34, 37, and 40 below depict the Central Concepts mapped onto the prompts, and also depicts the model space where students were to model their ideas.
PART 1: CARBON DIOXIDE IN THE ATMOSPHERE

Carbon Dioxide at Home

The map to the right depicts a familiar landscape. This is the West Charleston campus of the College of Southern Nevada, bordered by Charleston Blvd. to the north, Oakley Blvd. to the south, Torrey Pines Dr. to the west, and Jones Blvd.

1. Using the map, circle everything that you think emits carbon dioxide into the atmosphere. In the space below, describe why you circled the things that you did.

   Central Concept #1. The atmosphere contains both natural and anthropogenic sources of greenhouse gas emissions.

2. Using the same map, put a square around anything that you think absorbs carbon dioxide from the atmosphere. In the space below, describe why you put a square around the things that you did.

   Central Concept #2. Features on Earth's surface absorb greenhouse gases from the atmosphere.

3. In the space below, describe any conclusions you come to or observations that you can make about carbon in the atmosphere by looking at the model that you have created here.

   Central Concept #4. Greenhouse gases in the atmosphere accumulate over time as emissions are greater than absorption.

Figure 32. Model Space #1: Carbon at home, annotated with Central Concepts #1, #2, and #4.
**Learners’ Representations.** The following sections describe the Central Concepts employed in creating a model that responds to the prompts in this model space, as well as students’ common representations in the model space. Then, I discuss what students’ representations tell us about how they think spatially about enhanced greenhouse effect.

**Central Concept 1: The atmosphere contains both natural and anthropogenic sources of greenhouse gas emissions.** This central concept was included in both the existing literature of enhanced greenhouse gas assessments and was described by the experts that were interviewed and surveyed for this project as an important concept to understanding the phenomenon. The spatial thinking concepts employed in this concept’s understanding are the abilities to *associate and correlate the spatially distributed* presence of both anthropogenic and naturally-created greenhouse gases; *trace the spatial connections* between anthropogenic greenhouse gases with their sources and natural greenhouse gas emissions and their sources; *describe the conditions* of greenhouse gases in the atmosphere; and, in this case, where students are externally representing their understanding, *design and using spatial models.*

Students represented their understanding almost exclusively by following the instructions, which were to circle the things in the landscape that they understood to be sources of carbon dioxide emissions in the atmosphere. What they circled varied, but they almost always indicated their understanding with a circle. They were also asked to explain with words why they circled the objects in the landscape that they did.

Students most often circled both the campus buildings visible in the landscape and the vehicles that could be seen in the aerial view. Most often, an entire building was circled as one unit. The vehicles in the image are located in parking lots, so with few exceptions, the vehicles were circled as a large group and not individually.

Circling buildings and vehicles and buildings on campus as emitting features was the most common representation of student understanding (26 out of 40 assessment analyzed). However,
there were variations in the way students identified these features. Two students circled air conditioning units visible on top of the building. Two students circled the entire campus, with all buildings included. Seven students circled only vehicles in the photograph. Of those, 2 students circled vehicles that were on roadways, in addition to the vehicles that were in parking lots. Six students identified only the campus buildings as emitters of carbon dioxide. One student did not indicate their understanding by circling carbon dioxide emitters, but by listing them in the margin of the model prompt. That student did not label or indicate their understanding at all on the model prompt itself. In all cases, students’ verbal descriptions matched their spatial indication on the map, meaning that, if students included text, it would state something like “vehicle emissions” over the parking lot, where they had also circled vehicles to represent them as emitting features.

Four students added that the buildings themselves were not the sources of the carbon dioxide emission that resulted from their existence; that, in fact, it was the burning of fossil fuels that supported the electricity and air conditioning and made them run. This is an important distinction and a conceptual insight.

**Central Concept 2:** *Features on Earth’s surface absorb greenhouse gases from the atmosphere.* This central concept was mentioned more commonly in the existing literature of enhanced greenhouse gas assessments than it was described by the experts that were interviewed and surveyed for this project as an important concept to understanding the phenomenon. However, it was determined to be important because it provides the counter-mechanism to carbon emission. The spatial thinking abilities it employs are the same as those used to understand Central Concept 1: the ability to *associate and correlate the spatially distributed* greenhouse gas absorbers, *tracing the spatial connections* between greenhouse gas absorbers, *describing the conditions* of greenhouse gases in the atmosphere; and, in this case, *designing and using spatial models.*
Students were asked to identify, by placing squares around them, all of the carbon dioxide absorbers in aerial view of a familiar landscape, their college campus. Again, students represented their understanding by following the instructions, so in all cases, where understanding was demonstrated, students did so by placing a square around their perceptions of carbon absorbers. They were also asked to explain with words why they indicated the objects in the landscape that they did.

There was far less variety in the features that students indicated as absorbers. All indications of carbon dioxide absorption were directed toward areas where plant life covered the landscape or on areas that were covered in soil.

In all cases, students’ verbal descriptions matched their spatial indications on the map. Two students indicated in words that they understood water, and primarily oceans, to be a carbon dioxide absorbers and would have indicated it as such, would it have been represented in the model. Since the community college is situated in a desert in the Southwestern part of the United States, there were no bodies of water in sight. Examples of student representation carbon dioxide emissions and absorption for Modeling Space #1 are shown in Figure 32 below.

Central Concept 4: Greenhouse gases in the atmosphere accumulate over time as emissions are greater than absorption. The first model asks students to use the model of emissions and absorption that they have created on a map of their college campus to draw conclusions about what the relative amounts of emitters v. absorbers might mean to carbon dioxide in the atmosphere. The spatial thinking concepts employed in this concept’s understanding are the abilities to associate and correlate the spatially distributed presence of both anthropogenic and naturally-created greenhouse gas emissions and absorption; spatial visualization of the relative amount of carbon dioxide being emitted versus what is being absorbed; and designing and using a spatial model of the spatial relationships between emissions and absorption.
All students who answered the question used the model that they created, in which they identified carbon emitters and absorbers, to describe a gap between the amounts of carbon emissions and carbon absorption. Most students stated that their depiction caused them to reach the conclusion that there were more emitting features than absorbing features in the landscape. Students described this basic principle in several ways. Some said that there were not enough features that absorbed carbon dioxide to keep up with the amount of emissions that were given off. Some described a very high number of carbon dioxide emitting variables. Some described the features specifically, saying that there were too many cars and buildings for the trees and grass to even out the amount of carbon. This general principle was by far the most frequently described. Only 1 student out of the 40 analyzed described another relationship, stating that the absorbing features and emitting features created a stable amount of carbon in the atmosphere, creating an equilibrium.

Some students only described either the inflow or the outflow of carbon dioxide to the atmosphere. In other words, they would either mention that there are many things in the landscape that emitted carbon or describe the lack of absorbing features in the campus area. For example, one student stated, “In Las Vegas, we don't have a lot of trees to absorb CO₂.” For this question, students were asked to use their model to describe a phenomenon, so their descriptions were exclusively text. In the next sections, I will discuss the models students created to describe changes in carbon dioxide from the year 1500 to the year 2000.
Figure 33. Student representations of carbon dioxide emitters (circled) and absorbers (squares) in Modeling Space #1.

What do student-generated models reveal about their spatial thinking skills that support understanding of enhanced greenhouse effect related to carbon dioxide emissions, absorption, and the accumulation that results from their relationship?

Student models revealed that they do associate and correlate the spatially distributed phenomena of carbon dioxide emissions and absorption. In this case, they represented this ability most clearly, not by the representations (circles and squares) in the model space, but by the text they used to describe how emissions and absorption were related. Students can make a spatial comparison and recognize that the distribution of emitters and absorbers across the landscape is unequal and that emissions were greater than absorption. They used their spatial models, to trace the spatial connections between the number and size of circles they saw the number and size of squares, to describe the conditions that lead to
carbon dioxide accumulation in the atmosphere. Their *correlations*, by and large, led them to the conclusion that there were far more things in the landscape that emitted carbon dioxide than absorbed it, which they expressed in text, in answer to the last question that asked them to make observations or draw conclusions based on their models.

In general, students were able to describe these connections and the conditions of the landscape that emit and absorb carbon. For students who were challenged by these modeling prompts, they were unable to correctly identify the all of the carbon dioxide emitting and absorbing features in the landscape, but were sometimes still able to describe that emissions were greater than absorption, leading to an accumulation of carbon dioxide in the atmosphere. That they can deliver the correct response without modeling the spatial connections brings up a questions about the necessity of their spatial understanding to stating the correct conclusion. If they had no demonstrated spatial thinking abilities, as described above, but were still able to conclude the correct relationship, was the answer memorized? Were they unable to think spatially about carbon dioxide in the atmosphere or simply unable to represent it?

Students, by and large, were proficient spatial thinkers about this phenomenon. They drew the conclusions and represented the connections that one would expect a proficient spatial thinker to draw. For this representation of a landscape, the conclusions they drew based on their representations was correct; however, it may not always be true that the “bigger” and “more” features that are circled correlate with a larger amount of emissions. For example, a larger building may emit less carbon dioxide than a smaller building, if the larger building is designed with sustainability measures in mind. These exceptions are simply something to pay attention to in assessment design. We want to ensure that students have a correct understanding of emissions and absorption, spatial exceptions included.
Modeling Space #2: Carbon Dioxide in the Year 1500. This model space depicts a pastoral landscape that includes sky, sea, land with vegetation, rivers, and a cross section of the land area, so that the participant can see underground. The prompts related to this space are:

1. Pretend it is the year 1500. Using the landscape model to the right as your starting point, indicate on the model or draw in sources of carbon dioxide as they might have been during the year 1500.

2. Continuing to use the model you are building to the right, place a star next to the biggest source of carbon dioxide emission in the year 1500.

3. It is still the year 1500. Now, indicate on the model or draw in the things in the landscape that absorb carbon, as they might have been during the year 1500.

4. Using the model you have built here, place a star next to the things that you think are the biggest absorbers of carbon dioxide at this time.

5. In the space below, describe the relationship between emissions and absorption at this point in history. Which one is bigger, smaller, or are they the same? Why?

6. You have drawn, written about, or represented carbon dioxide emissions and absorption in a year 1500 landscape. Visualize carbon dioxide moving around in this system. Now, on the diagram, draw how you imagine the carbon dioxide to move around or collect in this atmosphere.

These prompts target Central Concepts #1, #2, and #4. Figure 32 below depicts the Central Concepts mapped onto the prompts and also depicts the model space where students were to model their ideas.
Figure 34. Model Space #2: Carbon dioxide in the year 1500, annotated with Central Concepts #1, #2, and #4.
**Learners’ Representations.** The following sections describe the Central Concepts employed in creating a model that responds to the prompts in this model space, as well as students’ common representations in the model space. Then, I discuss what students’ representations tell us about how they think spatially about enhanced greenhouse effect.

**Central Concept 1: The atmosphere contains both natural and anthropogenic sources of greenhouse gas emissions.** The most common type of representation that students provided to express their understanding of emissions as they may have been prior to industrialization were small images of the emitting features. For example, most often students drew small houses, stick figures of human beings, and animals into the landscape. Many students drew cooking fires and volcanoes. Other items that were placed in the landscape as carbon dioxide emitters, however less frequently, were guns, farming landscapes, boats and blacksmiths.

Spatially speaking, where images were used to represent students’ spatial understanding, the images were placed in context in the landscape. That is, a boat was placed in the water, or a house was placed on the land. In addition, quite often, the objects had an indication of emission, such as a smoking chimney or an arrow extending from the object to the atmosphere. Some features were labeled, particularly if the drawn image was not clear. Some were labeled with identifying words and some were labeled, identifying them only as carbon dioxide emissions. Students who represented this could associate and correlate spatially distributed carbon dioxide emissions, and to could describe the spatial impact of a feature on the area around it.

**Central Concept 2: Features on Earth’s surface absorb greenhouse gases from the atmosphere.** I represented most carbon dioxide absorbing features in the modeling prompt, since most carbon absorbing features are part of a natural landscape, which this modeling prompt was. This changed the way that students were able to represent features they understood to absorb carbon from the atmosphere. Rather than depict them as small images as they had for emissions sources, they most
often indicated that the features already in place in the landscape were carbon absorbers. For example, students drew arrows, pointing from the atmosphere to a forest of trees on land. In several cases, students labeled the absorbing features. For example, an arrow might be used to indicate toward the representation of the ocean, labeled with the words, “ocean absorption.”

As with carbon emissions, students also provided small images to express their understanding of absorption as they may have been prior to industrialization. In most cases, however, they were bigger or more plentiful features that were already shown in the model space. Students drew trees where trees were present in the image, presumably to draw attention to them as absorbing characteristics. Figure 34 below shows the model space with absorbing features highlighted by students. In this model, students demonstrate an understanding of the spatial distribution of features that affect enhanced greenhouse effect and the spatial impact of a feature on its surroundings.

*Figure 35. Modeling Space #2, Carbon dioxide in the year 1500, with carbon absorbers and emitters. Note the student’s annotation next to carbon absorbers already depicted in the scene: ocean, river, trees.*
Central Concept 4: Greenhouse gases in the atmosphere accumulate over time as emissions are greater than absorption. The most common relationship that students described was one in which carbon dioxide absorption are greater than carbon dioxide emissions. They expressed this in many ways. For example, one student stated, “I believe that absorption is extremely bigger because the only big thing emitting is fires and feces, and there is green everywhere absorbing!” Another said that, “At this point there was less emissions of carbon compared to today. Over time, population has cut down many things that absorbed carbon.” This student described a mechanism, specifically, that would reduce an ecosystem’s ability to remove carbon dioxide from the atmosphere. This common response is notable, since it is incorrect.

Absorption and emission rates were at levels that created an equilibrium of greenhouse gases in the atmosphere, but at this point in time the equilibrium amount of greenhouse gases was less. This was before human intervention and the industrial revolution. Several students identified this correct relationship. One said, “Absorbers are relatively close to emitters.” Most students stated simply that emission and absorption are the same. Students in this case were able to make a spatial comparison based on the models that they created.

Central Concept 5: Greenhouse gases are emitted from sources on Earth’s surface, rise into the atmosphere, and move around with circulation patterns. Two items included with both Models #2 and #3 give students the opportunity to model their understanding of the movement of greenhouse gases on Earth and in the atmosphere. This item, written for the year 1500 read: “You have drawn, written about, or represented carbon dioxide emissions and absorption in a year 1500 landscape. Visualize carbon dioxide moving around in this system. Now, on the diagram, draw how you imagine the carbon dioxide to move around or collect in this atmosphere.”

The spatial thinking abilities related to this Central Concept are: designing and using a spatial model, because of the nature of the assessment; spatial visualization of the movement of greenhouse gases that move from emission sources, with weather patterns, and get absorbed again on the surface;
associating and correlating the spatially distributed phenomena of greenhouse gas emitters, absorbers, and movement; and recognizing spatial distributions and spatial patterns of greenhouse gas movement. Students represented this movement in a number of ways. They are described below, with illustrative examples.

Fewer students represented the movement of carbon in the system, than represented sources of emission and features that absorb carbon dioxide from the atmosphere. Of those who did represent the dynamic nature of carbon dioxide in the atmosphere, most students who represented the movement of carbon dioxide in the atmosphere relied upon arrows to indicate the direction of the movement. Typically, this was the inclusion of one or several arrows pointing from carbon dioxide emitters to the atmosphere. In a reciprocal representation, arrows also pointed from the atmosphere to the features of the landscape that students understood to absorb carbon dioxide from the atmosphere. The exact placement of the arrows, as well as their size might have changed from student-generated model to model, but the movement they represented was the same.

In addition to the arrow movement representation, some students represented the carbon dioxide that accumulates in the atmosphere as shading or smalls circles or dots in the atmosphere portion of the model prompt. In two cases, students represented carbon in the atmosphere as a box to be filled in the atmosphere, with an arrow going in from the emitters, and an arrow going out, to the absorbers. This representation paralleled a representation they had been working with in class called a stock and flow diagram, to represent an inflow and outflow of carbon.

Three students represented the flow of carbon through the system represented in the model prompt with very similar flows and accumulations as what would be represented when describing the carbon cycle. Arrows led and were labeled, from the ocean to the atmosphere, as precipitation from the atmosphere down to the river, which led back to the ocean, or was infiltrated into the soil or rock bed. These three students also represented carbon dioxide in the ground; and 2 of the 3
labeled the carbon in the ground as fossil fuel. The representation was spatial in that it demonstrates how carbon moving from place to place changes form in the environment. Figure 35 below displays student models related to carbon dioxide emissions, absorption, and accumulation in the year 1500.

Figure 36. Student representations of carbon dioxide emitters, absorbers, and movement of carbon dioxide in the atmosphere in Modeling Space #2. Student representations of landscape features, as well as the movement of carbon, are visible.

What do student-generated models reveal about their spatial thinking skills that support understanding of enhanced greenhouse effect related to carbon dioxide emissions, absorption, the accumulation that results from their relationship, and the movement of carbon dioxide in the atmosphere?
Learners are very able to design and use a spatial model in this context. This model prompt removed a layer of scaffolding from Model Prompt #1, in that students generate their own representations and do not simply follow directions to identify features. They were able to add features and locate them properly in the landscape and they were able to accurately identify emitters and absorbing features that were already present. Students were able to trace the spatial connection between emitting features located on the ground and the direction of carbon dioxide flow into the atmosphere. They indicated the movement with an arrow. Similarly, they traced the spatial connections between carbon dioxide in the atmosphere and where it would go when it is absorbed by an emitting feature on the ground. Again, they demonstrated this understanding with an arrow. In order to draw a conclusion about the spatial relationships between emissions, absorption and accumulation in the atmosphere, students responded to a prompt that asked them to describe the relationship for the year 1500. From their models, learners were able to describe the conditions as being approximately equal. That is, they represented about the same amount of emitters as there were absorbers. Their models supported their text, in that the landscape was not crowded with emitters.

Fewer students possessed the ability to spatially visualize the movement of carbon dioxide throughout the carbon system, to model or describe it on the assessment. While most students could trace a simple spatial connection, from emitter to sky or atmosphere, fewer students were able to continue to make the spatial connections involved in describing the movement of carbon in the atmosphere, from the atmosphere to precipitation, from precipitation to waterways, etc. This is the complex ability to spatially visualize and then display that spatial story as a conceptual model. It makes sense that one causal link would more often be understood and represented than a multi-step spatial connection.

**Modeling Space #3: Carbon Dioxide in the Year 2000.** This model space depicts the same pastoral landscape as in Model Space #2, that includes sky, sea, land with vegetation, rivers,
and a cross section of the land area, so that the participant can see underground. The prompts related to this space are:

1. Now, pretend it is the year 2000. Using the landscape model to the right as your starting point, indicate on the model or draw in sources of carbon dioxide as they might have been during this time.

2. Continuing to use the model you are building to the right, place a star next to the carbon dioxide emission sources that you think are the biggest sources during this time.

3. It is still the year 2000. Now, indicate on the model or draw in the things in the landscape that absorb carbon, as they might have been during this time.

4. Using the model you have built here, place a star next to the ones that you think are the biggest absorbers of carbon dioxide at this time.

5. In the space below, describe the relationship between emissions and absorption at this point in history. Which one is bigger, smaller, or are they the same? Why?

6. You have drawn, written about, or represented carbon dioxide emissions and absorption in a year 2000 landscape. Visualize carbon dioxide moving around in this system. Now, on the diagram, draw how you imagine the carbon dioxide to move around or collect in this atmosphere.

7. Based on your representations above, what can you say about carbon dioxide in the atmosphere in 1500 and in the year 2000?

These prompts target Central Concepts #1, #2, #4, and #5. Figure 33 below depicts the Central Concepts mapped onto the prompts, and also depicts the model space where students are to model their ideas.
Figure 37. Model Space #3: Carbon dioxide in the year 2000, annotated with Central Concepts #1, #2, #4, and #5.
Learners’ responses. The following sections describe the Central Concepts employed in creating a model that responds to the prompts in this model space, as well as students’ common representations in the model space. Then, I discuss what students’ representations tell us about how they think spatially about enhanced greenhouse effect.

Central Concept 1: The atmosphere contains both natural and anthropogenic sources of greenhouse gas emissions. Prompt: “Carbon Dioxide in the Year 2000, “Now, pretend it is the year 2000. Using the landscape model to the right as your starting point, indicate on the model or draw in sources of carbon dioxide as they might have been during this time.” Students’ method of representation was consistent from the year 1500 to the year 2000. That is, if they used small images to represent their understanding for Model #2, they did the same for Model #3. The features they drew were different, but the method was the same.

The most common emitters represented for the year 2000, were vehicles and industry. In addition, students commonly represented houses and people as they had done in the model for the year 1500, but hey represented more of them in the landscape. This is a significant spatial representation, because as students represent a greater number of things in the landscape, the model space begins to look crowded with emitters. Other items that were placed in the landscape as carbon dioxide emitters, however less frequently, were agricultural industry, boats, airplanes, fire, deforestation, factories, and fossil fuel extraction. Once again, where images were used to represent students’ spatial understanding, the images were placed in context in the landscape and arrows or lines indicated the emission into the atmosphere. In this case, students were able to associate and correlate spatially distributed emissions and describe how those emissions were had a spatial impact on their surroundings.

Central Concept 2: Features on Earth’s surface absorb greenhouse gases from the atmosphere. Prompt: “Model 3: Carbon Dioxide in the Year 2000, “Now, pretend it is the year 2000. Using the landscape model to the right as your starting point, indicate on the model or draw in sources of carbon dioxide as they might have been during
Students’ method of representation was consistent from the year 1500 to the year 2000. In both sets of images students used primarily arrows, lines, and labels to indicate their perceptions of carbon dioxide absorbers. In this case, the absorbing mechanisms were identical to those that were identified in the year 1500. The difference between the two representations for absorption was only in the indication of deforestation in the year 2000 and sea level change. This was only indicated in a few cases and where it was represented with shading, words, or Xs marked through the existing trees in the model prompt. Figure 36 below gives an example of the difference in absorbers and emitters in the landscape.

Figure 38. Student-generated models of carbon dioxide emissions, absorption, and movement in the atmosphere in the year 2000.
Central Concept 4: Greenhouse gases in the atmosphere accumulate over time as emissions are greater than absorption. Model 3: Carbon Dioxide in the Year 2000, “In the space below, describe the relationship between emissions and absorption at this point in history. Which one is bigger, smaller, or are they the same? Why?” All students said that emission was greater than absorption in the year 2000. Some very simply stated that emissions were greater, while others described features in the landscape, represented in their models that contributed to a higher level of carbon dioxide emissions. One student said, “Emissions surpass absorption, because of cars, agriculture, farms, and processed and packaged items.” The same features were represented in their model.

There were unanticipated expressions of student understanding for Central Concept 4. While Question 6, associated with Model #3, was not intended to produce responses related to this central concept, student representations illustrated their mental models of changes in carbon dioxide levels from the year 1500 to the year 2000 by representing a sky that was shaded in or filled with small dots, where it was not shaded or filled with small dots in the model for the year 1500. This, taken together with their representations of the carbon dioxide emitters and absorbers in the landscape, gives a more complete conceptual model of students’ understanding than the verbal descriptions, which in most case stated very generally that emission is greater than absorption or vice versa.

For students that represented the presence of carbon dioxide in the atmosphere, they did so by drawing small dots or circles to represent molecules of carbon dioxide. Alternatively, students shaded in or drew circles in the upper region of the model prompt, which represented the sky. The combined image that demonstrated students’ understanding of the increase of carbon dioxide in the atmosphere over time includes both the models from 1500 and 2000. Students who demonstrated this type of understanding represented appropriate emissions and absorption for each year. For example, animals are emission sources in the 1500s and vehicles are emission sources in 2000. Trees
are carbon absorbers in both eras. In addition, students demonstrate a larger amount of carbon (a larger shaded area or more circles representing carbon) in the year 2000, than in the 1500. These combined representations reveal students’ correlation of emissions, absorption, and accumulation of carbon dioxide, which was the focus of this central concept. An example of this understanding is depicted in Figure 37 below.

Figure 39. Student representations of the accumulation of greenhouse gases in the atmosphere, represented by and increasing density of circles from the year 1500 (left) to the year 2000 (right).
Central Concept 5: Greenhouse gases are emitted from sources on Earth’s surface, rise into the atmosphere, and move around with circulation patterns. Students’ representations of carbon dioxide movement from emitters to the atmosphere, and then from place to place in the atmosphere was represented using the same notation that was used in Model Space #2. Students used arrows and images of a vapor or something that looked like smoke rising from a chimney to indicate emissions. In this case, there were more emissions and accumulation of emissions in one space.

What do student-generated models reveal about their spatial thinking skills that support understanding of enhanced greenhouse effect related to carbon dioxide emissions, absorption, the accumulation that results from their relationship, and the movement of carbon dioxide in the atmosphere? Students’ spatial thinking abilities here mirror what was described for Model Space #2. Learners designed and used their spatial models similarly, using the same representations and still able to accurately place the emitters and absorbers in the landscape. Students were able to trace the spatial connection between emitting features located on the ground and the direction of carbon dioxide flow into the atmosphere and from the atmosphere to absorbing features on the ground.

The new spatial thinking ability that students demonstrated in their models for Modeling Space #3 was their ability to think about spatial change over time. When comparing Modeling Space #3 to Modeling Space #2, it is clear that students understand the difference in the amount of emission sources between the two years. Learners displayed very different spatial distributions of emitters and absorbers and, therefore, more emission and absorption. Then, in their text response, they could make a spatial comparison to describe that there is an increased amount of carbon dioxide in the air during the year 2000. In order to draw a conclusion about the spatial relationships between
emissions, absorption and accumulation in the atmosphere, students responded to a prompt that asked them to compare what they represented for the year 1500 and the year 2000.

**Modeling Space #4 and Modeling Space #5: Radiation and the Greenhouse Effect in the Year 1500 and 2000.** So that they can represent their understanding of radiant energy, as it moves from the sun to the Earth, students were given model prompts for Model Spaces #4 and #5, which depict both the Earth and the sun in the same space. The image is not to scale and excludes any other features that would exist in that space in reality, but the space gives students an opportunity to consider and demonstrate their mental models related to the relationships between these two features. In addition, the model space included a “zoomed in” view, cut out box that represented a space where learners would represent what they imagine greenhouses gas molecules to look like in the atmosphere. The box was labeled “B,” while the main modeling space was labeled “A.” I will discuss both Modeling Spaces #4, which represents the year 1500, and #5, with prompts like Model Space #4, but representing the year 2000, because (a) their prompts are identical; and (b) many of the understandings here are demonstrated by representing differences in the two spaces (the year 1500 and the year 2000). The prompts related to these model spaces are:

1. Using the Earth horizon image above (A) as a starting point, represent the Earth’s atmosphere with as much detail as you can.
2. Now, in the model that you have created in image (A), represent greenhouse gases and where they exist in this Earth/Sun system in the year 1500 (2000 for Model Space #5).
3. Imagine the cutout square on the right (B) is a lens that we can use to see greenhouse gases in the atmosphere. In that square, represent greenhouse gases in the atmosphere, as you understand them to be.
4. How does energy move around in the Earth/Sun system? Represent energy in the Earth/Sun system (A), as you understand it. Demonstrate:
a. All of the places energy might come from and all of the places where it might go.

b. If it is a lot or a little bit of energy in the place you represent.

5. In the greenhouse gas viewing box (B), represent energy and greenhouse gases. What is energy doing and how does it move?

6. What can you say about greenhouse effect or enhanced greenhouse effect in the year 1500 (2000 in Model Space #5)? Write your answer below and include a discussion of the effects on temperature.

These prompts target Central Concepts #3, #6, #7, #8, #9, #10, #11, #12, #13, and #14. Figure 34 below depicts the Central Concepts mapped onto the prompts, and also depicts the model spaces where students are to model their ideas.
1. Using the Earth horizon image above (A) as a starting point, represent the Earth's atmosphere with as much detail as you can.
   Central Concept #11. Earth's atmosphere exist in a layer around Earth's surface. and Central Concept 12; Earth's atmosphere is a very thin layer relative to the thickness of the Earth.
   Central Concept #12. Earth's atmosphere is a very thin layer relative to the thickness of the Earth.

2. Now, in the model that you have created in image (A), represent greenhouse gases and where they exist in this Earth/Sun system in the year 1500.
   Central Concept #3. Greenhouse gases make up a relatively small amount of the atmosphere, compared to the other gases in it.
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3. Imagine the cutout square on the right (B) is a lens that we can use to see greenhouse gases in the atmosphere. In that square, represent greenhouse gases in the atmosphere, as you understand them to be.
   Central Concept #3. Greenhouse gases make up a relatively small amount of the atmosphere, compared to the other gases in it.

4. How does energy move around in the Earth/Sun system? Represent energy in the Earth/Sun system (A), as you understand it. Demonstrate:
   a. All of the places energy might come from and all of the places where it might go.
      Central Concept #6. Radiant energy moves from the sun and reaches the Earth's surface.
      Central Concept #7. Radiant energy is transformed to infrared energy and is reflected by surfaces on Earth.
      Central Concept #8. Infrared energy moves from the surface of the Earth into the atmosphere.
      b. If it is a lot or a little bit of energy in the place you represent.
      Central Concept #9. Energy in the atmosphere reaches an equilibrium amount based on how much enters and leaves.
      Central Concept #10. When the relationship between the amount of energy coming in and the amount of energy going out of the atmosphere changes, the equilibrium change.

5. In the greenhouse gas viewing box (B), represent energy and greenhouse gases. What is energy doing and how does it move?
   Central Concept #13. As radiation and greenhouse gases interact in the atmosphere, the radiation accumulates because the greenhouse gases are holding it in.

6. What can you say about greenhouse effect or enhanced greenhouse effect in the year 1500? Write your answer below and include a discussion of the effects on temperature.

Figure 40. Model Space #4: Radiation and the Greenhouse Effect in the Year 1500, with Central Concepts #3, #6, #7, #8, #9, #10, #11, #12, #13, and #14 mapped onto the prompts. Model Space #5 is identical, with the year updated to 2000.
**Student Responses.** The following sections describe the Central Concepts employed in creating a model that responds to the prompts in this model space, as well as students’ common representations in the model space. Then, I discuss what students’ representations tell us about how they think spatially about enhanced greenhouse effect.

**Central Concept 3: Greenhouse gases make up a relatively small amount of the atmosphere, compared to the other gases in it.** Students will employ several spatial thinking abilities in understanding the relative amounts of greenhouse gases, compared to other gases in the atmosphere. Because of the nature of the assessment students will be designing and using a spatial model. They will have to consider the amount of carbon dioxide they visualize in the atmosphere and the amount of other gases they visualize. Then, they will have to make a spatial comparison to recognize that the greenhouse gases make up far less than other atmospheric gases. Any representation of this in the model space will reflect the difference in amounts and will represent all of these atmospheric gases together, since they all exist in the same space.

There were no student representations of the relative amounts of carbon dioxide or other greenhouse gases to other atmospheric components. Students represented only greenhouse gases in general. They were represented in small amounts during 1500 and in larger amounts in the year 2000, but were not represented relative to other atmospheric components.

**Central Concept 6: Radiant energy moves from the sun and reaches the Earth’s surface.** So that they can represent their understanding of radiant energy, as it moves from the sun to the Earth, students were given model prompts for Models 4 and 5 that depicts both the Earth and the sun in the same space. The image is not to scale and excludes any other features that would exist in that space in reality, but the space gives students an opportunity to consider and demonstrate their mental models related to the relationships between these two features.
To understand and demonstrate their understanding of the dynamic nature of radiant energy as it moves from the sun to the surface of the Earth, students will design a spatial model of the direction of the movement. Since this Central Concept is all about motion and change of position, students will have to visualize the spatial relationship between the sun and the Earth, and then the movement of radiant energy from one place to another. Finally, they will trace a spatial connection between the two bodies to understand the relationship of the movement of energy between them.

Question #4a for both Model Spaces #4 and #5 addresses Central Concept #6 directly. It asks, “How does energy move around in the Earth/Sun system? Represent energy in the Earth/Sun system. Demonstrate all of the places energy might come from and all of the places where it might go.” Of course, this statement could prompt several other concepts related to radiation, but if students have a spatial understanding of radiation between the sun and the Earth, they should be able to demonstrate it here. Their common responses are described below.

Almost all students (35 out of 40) represented this relationship. That is, they did not skip this item as they did others. Students represented the energy relationship between the sun and the Earth exclusively with arrows and line. Arrows pointed from the half-circle representing the sun, toward the half-circle representing the Earth. In a few cases, there were only lines in the same position, but in most cases the representation of energy was an arrow. While the general position of the arrows around the sun was the same, they indicated a few different “landing points” for the radiant energy coming from the sun. In some cases the arrows terminate somewhere in the space between the sun and the Earth. In some cases they stop at the outer edge of Earth’s atmosphere, as students have chosen to represent it, and in some cases, the arrow extends all the way from the sun to touch the surface of the Earth.

In a few cases the arrows are labeled with words like, “energy” or “energy comes from sun,” indicating their specific intention with the arrow. Two people used a double-headed arrow between
the sun and the Earth, which can be interpreted to indicate a concept discussed in class, that energy from the sun is, in some cases, reflected back to space. This represents more than Central Concept 6 intends, but is not incorrect. Figure 39 below represents a common student representation of radiant energy from the Earth to the sun.

![Figure 39](image)

**Figure 39.** Student representation of radiant energy moving from the Earth to the sun, being reflected from the surface of the Earth and being trapped in Earth’s atmosphere.

*Central Concept 7:* Radiant energy is transformed to infrared energy and is reflected by surfaces on Earth.

*Central Concept 8:* Infrared energy moves from the surface of the Earth into the atmosphere.

These two concepts are discussed together, since they both address a spatial understanding of radiation once it enters Earth’s atmosphere and they were not address separately by students.

With the same prompt as was used for Central Concept #6, students were given the opportunity to represent their understanding of infrared energy in the Earth-sun system by *designing and using a spatial model.*
Similar spatial thinking skills are employed to demonstrate Central Concepts #7 and #8, since they are both related to the movement and transformation of energy. These skills are even more complex than Central Concept #6, however, so students really must visualize the spatial relationships and particularly the movement of energy, recognizing the transformations it undergoes when it is reflected from Earth’s surface. To represent this understanding, students will graph a spatial transition.

None of the student participants identified infrared energy and named it specifically, but several did represent energy that redirected once it entered Earth’s atmosphere. While I am unable to say if their mental model includes the transformation of energy, they do represent the movement of energy in the system.

In addition to the radiant energy arrows pointing from sun to Earth, described in the last section, students also drew arrows or lines coming from the surface of the Earth, extending to the inside edge of the atmosphere, indicating trapped energy inside the atmosphere. In addition, students drew arrows, with their origins at the surface of the Earth, extending out of the atmosphere, as students chose to represent it, and back into the space between the Earth and the sun. These arrows can be interpreted to represent the energy that is reflected from the surface of the Earth back to outer space.

It should be noted that only a portion of the students that represented energy traveling from the Earth to the sun also represented energy reflected back from the Earth. Only 12 out of 40 students did this, which is notable, since this is the energy that is actually absorbed by greenhouse gases in the atmosphere.

*Central Concept 9: Energy in the atmosphere reaches an equilibrium amount based on how much enters and leaves.*
Central Concept 10: When the relationship between the amount of energy coming in and the amount of energy going out of the atmosphere changes, the equilibrium changes. Again, these two central concepts are discussed together since they address a spatial understanding of the equilibrium of energy in Earth’s atmosphere. Students modeled their understanding of a change in the equilibrium of the energy in the atmosphere by diagraming the amount of energy during two different time periods. Related to the amounts of energy in the atmosphere are the amounts of greenhouse gases that keep the energy there, and the greenhouse gas emitters and absorbers that change the amount of greenhouse gas accumulation in the atmosphere. When students demonstrate a change in the amount of greenhouse gases in the atmosphere related to changes in emissions and they demonstrate that the energy in the atmosphere is related to these changes, they have demonstrated the change in energy’s equilibrium.

Central Concepts #9 and #10 are more complex than previous Central Concepts related to radiation and its spatial relationships in the Earth/sun system. To be proficient in their understanding of these central concepts, students build upon their understanding of radiation’s movement, transformation, and reflection to include the rates at which it enters and leaves Earth’s atmosphere. This employs complex abilities of multi-step spatial visualization. It adds to the list of spatial thinking abilities the ability to associate and correlate spatially distributed phenomena because students must understand the distribution of energy entering and leaving the atmosphere. By examining the relationship between the year 1500 model and the year 2000, I can analyze students’ understanding of the changes in the amount of radiation in the atmosphere.

Questions #4 and #5 ask students to represent their spatial understanding of the amount of energy in the atmosphere and how it moves around and interacts with greenhouse gases. First, students are asked to represent these ideas in a modeling space that includes the Earth and the sun. Then, they are asked to represent energy in a “zoomed in” model, so that they can represent how they understand it to interact with greenhouse gases.
Students represented their understanding of energy in Earth’s atmosphere in almost exclusively one way: with arrows indicating the movement and location of energy in the atmosphere. Where students represented energy traveling from the sun to the Earth with arrows pointing from the former to the latter, they also represented their understanding of the reflected energy that stays in Earth’s atmosphere with arrows pointing from the Earth’s surface, outward, but staying inside the boundary of the atmosphere they represented. It should be noted that very few students represented the reflection of energy from the surface of the Earth to Earth’s atmosphere. Those that did represented energy with arrows.

As stated previously, this central concept is demonstrated by illustrating energy in the atmosphere in the year 1500 and the year 2000 to note any differences. For this modeling task, students who represented radiant energy in Earth’s atmosphere in the year 1500 did not represent it differently in the year 2000. That is, where the goal for understanding for the central concept is to recognize how energy exists at an equilibrium and how that equilibrium can change, students did not represent the change for this particular set of items.

The second item that enables students’ expression of their mental models gave students space to represent energy on a much smaller scale as it interacts with greenhouse gases in the atmosphere. This was in the “zoomed in” modeling box, labeled “B.”

In this case, students were much more expressive of change over time and of energy remaining in the atmosphere as a result of its interactions with greenhouse gases. They did this with a number of representations that all demonstrated the same principle: that an increase in atmospheric greenhouse gases changes the equilibrium of energy in the atmosphere. Fifteen students represented the accumulation of energy in the atmosphere. Students represented greenhouse gases in the “B” box as small circles, dots, shading, or circular scribbles. Relating the energy to the greenhouse gases, in some cases, students used lines or arrows to connect the greenhouse gas
molecules, indicating energy moving between them. In one case, a student represented energy in the atmosphere as a diagonal line through each of the small circles they used to represent a greenhouse gas. They labeled the lines “energy,” to clarify their representation.

In four examples, students did not perceive the purpose of the “B” box as a zoomed in feature. They simply replicated the Earth-sun model found in the larger model space on the page. These students represented the greenhouse gases as visible particles as the model prompt suggested.

The characteristic of student representation that demonstrates their understanding of a change in the equilibrium of radiant energy is found in the difference in representation between the year 1500 and the year 2000. In the case of the zoomed in “B” box, students were more likely to show a change in amount of radiant energy that has accumulated in the atmosphere from one year to the next. Student used more lines, more arrows, or more shading to represent how energy has come to an equilibrium at a higher level. The spatial appearance of energy in the atmosphere is more dense or more crowded in the modeling space. Examples of student models representing Central Concepts 9 and 10 are shown in Figure 40 below.
Figure 42. Student-generated models of the interactions of greenhouse gases and radiant energy in Earth’s atmosphere in 1500 (left) and the year 2000 (right).
Central Concept 11: Earth’s atmosphere exists in a layer around Earth’s surface.

Central Concept 12: Earth’s atmosphere is a very thin layer relative to the thickness of the Earth. The central concepts that address relative size and position of Earth’s atmosphere are discussed here.

One item gave students the opportunity to model their understanding of Earth’s atmosphere relative to the Earth. Experts and the literature both related that the size and the relative position of the atmosphere were important spatial ideas for students to understand.

To understand Earth’s atmosphere spatially, according to these two central concepts, a learner will have the ability to make a spatial comparison between the size of the Earth and how big they perceive the atmosphere to be. In order to understand its location, as wrapped around the Earth, as a cell membrane to a cell, a student would be able to associate these spatially distributed features. Students would have the ability to describe the atmosphere’s location and trace the spatial connection between the atmosphere and the Earth that it is associated with, to know and relate its location.

The item that asked students to model their understanding of these relationships stated, “Using the Earth horizon image above (A) as a starting point, represent the Earth’s atmosphere with as much detail as you can.” Almost all students were able to represent their understanding. Students represented this idea almost exclusively by drawing a horizon line around the perimeter of the Earth. The characteristics of the line varied slightly from model to model, but the basic representation was the same: a curved line that paralleled the curvature of the Earth that was represented in the model prompt.

With few exceptions, students represented the atmospheric boundary with one line. While the relative thickness of the atmosphere was a central concept priority, only one student represented the atmosphere in what might be considered an appropriate scale. That is, they represented the atmosphere as a very thin layer or skin around the outside of the Earth. All of the other participants
represented the atmosphere as much thicker than it would actually exist around the Earth. This served an important purpose to the rest of the concepts they modeled, allowing them space to represent radiation and greenhouse gases close to the Earth.

Three students represented several layers in the atmosphere, and one labeled the stratosphere. Two students represented holes in the atmospheric layer, but without a label, it is impossible to know if what they represented was a hole in the stratospheric ozone layer or another phenomenon that is not described otherwise. Figure 40, above, provides several examples of student models related to Earth’s atmosphere.

Central Concept 13: As radiation and greenhouse gases interact in the atmosphere, the radiation accumulates because the greenhouse gases are holding it in. Central concepts 13 and 14 focus on the interactions that lead to the greenhouse effect. They combine two or more of the content themes previously described: atmosphere, radiation, and/or greenhouse gases. One item gave students the opportunity to model their understanding of the interaction between greenhouse gases and radiation in the atmosphere.

As the last two Central Concepts are related to greenhouse effect, and a spatial understanding of greenhouse effect requires the synthesis of other content areas, like greenhouse gases and the atmosphere, the spatial thinking abilities that students should have also require synthesis. To understanding the interaction between radiation and greenhouse gases in the atmosphere, students should be able to spatially visualize each component and how they exist in the same space. The dynamic nature of their interaction, requires the spatial thinking ability of associating and correlating the phenomena that the student has spatially visualized in their head.

The item that asked students to model their understanding of these relationships stated, “In the greenhouse gas viewing box (B), represent energy and greenhouse gases. What is energy doing and how does it move?” This was posed for the year 1500, as well as the year 2000. The key to students'
demonstrating their understanding can be found in the way they represented it differently between the two years.

Eighteen students represented energy interacting with greenhouse gases in the atmosphere. They did so consistently with a line or an arrow moving between a representation of carbon dioxide or greenhouse gases in general. The line or arrow was sometimes drawn in a zig-zag pattern. The representation of carbon dioxide or other greenhouse gases was usually as a small circle, a dot, or a cloud-like representation.

A few students provided a text description to accompany their drawings. In these cases, the text labeled the energy or named what the energy was doing in the system. One student stated, “Energy is slowly accumulating.” Another described the model by saying, “GHGs attract the sun’s energy.”

The important aspect of students’ representations was the difference between their models for the year 1500 and their models for the year 2000. In this regard, student representations were also consistent, both within their own representations (1500 to 2000) and among their peers. All students who represented the accumulation of energy over time did so by using the same representation from the year 1500 to the year 2000, just altering the latter representation to represent “more.” Since the general concept is the accumulation of energy in Earth’s atmosphere as a result of the interaction with greenhouse gases, students represented a greater number of greenhouse gases by drawing more small circles, dots, or clouds and then more representations of radiation, like lines and arrows in their models representing the year 2000. The visual result is the appearance that the atmosphere is “filling up” or that the box that represents the close-up view of the atmosphere is getting more crowded. The top-most figure in Figure 40 provides one example of student model representing the interaction between radiation and greenhouse gases. This student represented this
interaction using arrows representing radiation, intersecting with small circles, representing the greenhouse gases.

Central Concept 14: Greenhouse effect is caused by the natural sources of greenhouse gas emissions interacting with radiation in the atmosphere. Enhanced greenhouse effect is caused by added anthropogenic greenhouse gases absorbing more radiation in Earth’s atmosphere. The key idea embedded in this central concept is the difference between greenhouse effect as a natural phenomenon and an enhanced greenhouse effect, as a result of anthropogenic greenhouse gas emissions.

As with Central Concept #13, Central Concept #14 requires the synthesis of other content areas and, therefore, spatial thinking abilities. To understand the interaction between radiation and greenhouse gases in the atmosphere, students should be able to spatially visualize each component and how they exist in the same space. The dynamic nature of their interaction, requires the spatial thinking ability of associating and correlating the phenomena that the student has spatially visualized in their head.

One question prompted students to address, in text, the difference between the two by analyzing the models they created with prompts for Models 4 and 5. The last question for both the year 1500 and the year 2000 read, “What can you say about greenhouse effect or enhanced greenhouse effect in the year (1500 or 2000)? Write your answer below and include a discussion of the effects on temperature.”

Twenty-six student participants answered the question which asked them to interpret their model and describe what they understood about greenhouse effect and enhanced greenhouse effect for the year 1500. Their understanding was expressed in a number of ways, but most focused on the same idea, which was that greenhouse effect was not as intense during this time period because there was not as large of an accumulation of greenhouse gases in the atmosphere due to anthropogenic emissions. Generally, student descriptions tell us that, while they understand the interaction between variables that leads to a greenhouse effect; that is, they understand that the more greenhouse gases in
the atmosphere, the more radiation is held, they do not make the distinction between greenhouse effect and enhanced greenhouse effect. If this is a phenomenon they understand, it is not expressed in their descriptions. Some of the most common response types are described below.

One student described the relationship between technology and the enhanced greenhouse effect but did not make a connection to greenhouse gases or the natural greenhouse effect, so it is difficult to know from the description which concepts are included in the student’s understanding. This student said, “The EGE didn't exist because humans had not built the technology of today.”

One student described only enhanced greenhouse effect, stating that, “There is little enhanced greenhouse effect. Enhanced greenhouse effect traps heat in the atmosphere and thus heats up the Earth.” The concept that they described is correct, though it does not incorporate the interaction of greenhouse gases. They are missing a description of natural greenhouse effect, however.

Another student said that, “There were not a lot of greenhouse gases and a lot of absorption (in the year 1500). When we started to create more greenhouse gases, more energy was able to enter and not be absorbed by anything relevant.” Their perspective focused on the abundance of features that might absorb greenhouse gases from the atmosphere. Their text explanation indicates a misconception, that an increase in greenhouse gases in the atmosphere will allow more radiation to enter the atmosphere, where the capacity to be absorbed is less in the year 2000; but their model demonstrates a normative understanding, that the greenhouse gases absorb radiation that enters Earth’s atmosphere.

Several students simply stated that the greenhouse effect or the enhanced greenhouse effect is not as impactful on Earth’s climate as it is during the present day. They did not make the distinction between the two, so it is impossible to know if they do understand the distinction.
Eighteen students responded to the prompt associated with the year 2000. For students’
descriptions related to the models they developed for the year 2000, they continued to draw
comparisons between the amount of greenhouse gases and, therefore, radiation in Earth’s
atmosphere between the two time periods they modeled; but they did not describe the distinction
between enhanced greenhouse effect and natural greenhouse effect. Even though some students
described the interconnections between content themes (greenhouse gases, radiation, etc.) leading to
greenhouse effect and enhanced greenhouse effect quite well, they were no more descriptive of the
fact that there is a difference between the two. One student stated, “As more carbon is trapped in
the atmosphere, the radiant energy is getting trapped, bouncing between particles and from there it
causes the temperature to rise and causes more carbon to be released.” The intent of the last part of
their statement is difficult to interpret, but the student may be referring to some of the impacts of
global climate change, not explored here, in which carbon trapped in ice is released, as temperatures
rise and ice melts. Nevertheless, their understanding of the phenomenon of enhanced greenhouse
effect is correct, although they do not name it.

Most responses were simple, stating something like, “Greenhouse effect has risen
significantly from year 1500 to year 2000.” Again, the response does not make the distinction
between enhanced greenhouse effect and a natural greenhouse effect; but it acknowledges, at the
very least, that students understand that the greenhouse effect is enhanced, even if it is not named
that way. These basic statements of change, examined together with the students’ representations,
give a more complete picture of the students’ understanding of the dynamic nature of the

greenhouse effect, as a result of accumulating greenhouse gases interacting with radiation in the
atmosphere. The most complete story is told when we look at students’ complete set of
representations. The question analyzed here asks students to synthesize several of the concepts they
were asked to model with previous prompts. It is clear that their understanding is much more clearly
What do student-generated models reveal about their spatial thinking skills that support understanding of enhanced greenhouse effect related to radiation, the atmosphere, and the interaction of radiation and greenhouse gases? The spatial thinking abilities required to accurately display an understanding of the atmosphere, radiation, greenhouse gases, and the interactions between them to produce greenhouse effect and enhanced greenhouse effect become much more complicated for Model Space #4 and Model Space #5 and representing the difference between them. Nevertheless, students demonstrated sophisticated spatial thinking abilities and the ability to synthesize spatial relationships to draw conclusions.

Student-generated models tell us that students are able to trace a spatial connection between the Earth and the sun to demonstrate an understanding of the way that radiation moves from the sun to the Earth. They were less frequently able to associate and correlate spatially distributed radiation once it enters Earth’s atmosphere and is reflected to sometimes be trapped and sometime be reflected back to outer space. This is a more complex ability that required multi-step spatial visualization abilities, while tracing the spatial connection between the Earth and the sun only requires an understanding of three variables: Earth, sun, and radiation. Likewise, students do not have the spatial ability to graph the spatial transition of radiant energy’s transformation to infrared energy, once it is reflected from Earth’s surface.

Learners were able to locate the Earth’s atmosphere and represent it accurately in most cases in their models, telling us that they are able to trace a spatial connection between the two; however, they were not able to make the spatial comparison between the two features (Earth and atmosphere) to know their relative sizes to each other. This was expected by our faculty experts, as they
understood that students’ perspective was related to their own size inside a “giant” atmosphere, as opposed to the atmosphere’s thin diameter, compared to Earth’s.

In synthesizing content areas spatially, student-generated models tell us that they are able to make a spatial comparison between the amount of greenhouse gases in Earth’s atmosphere in the year 1500 and the year 2000. Their models represented an increase in greenhouse gases by increasing the density of whatever representation they chose. In addition, in some cases students are associating and representing the association of the spatial relationships between radiation and greenhouse gases inside the atmosphere, correlating an increase in greenhouse gases to an increased amount of radiation.

The prompts that directed students are key in the assessment. If students were not directly prompted to represent a feature spatially, they usually did not do it. For example, students represented densities and amounts of greenhouse gases in the atmosphere, but did not represent any of the other gases. This posed a problem in knowing their spatial thinking abilities related to greenhouse gases relative to other gases in the atmosphere. Students may have an understanding of the relative amounts of these two components, but were not specifically prompted for it, so did not express their ability to make a spatial comparison this way.

In the next section, I will describe my ideas related to the second research question that the pilot test informs: how will students’ representations inform revisions to the assessment. I will also discuss some general themes of students’ spatial thinking abilities.

**Discussion.** To better understand students’ spatial mental models related to enhanced greenhouse effect, I analyzed the prompted models that they created, with accompanying text where it was included. The purpose of this analysis was to answer the following questions:

(1) What do student-generated models reveal about their spatial thinking skills that support an understanding of enhanced greenhouse effect?

(2) How do student responses inform the next steps of assessment development?
I presented ideas related to the first research question at the end of each Modeling Space discussion in the last section, but will discuss themes that emerged from those ideas here. Then, I will discuss the ways in which student responses informed a revision of the piloted version of the assessment, in answer to the second research question.

**What do student-generated models reveal about their spatial thinking skills that support an understanding of enhanced greenhouse effect?**

*Student-generated models reveal complex and interconnected spatial thinking abilities supporting their understanding of enhanced greenhouse effect.* Several prompts and questions probed students’ understanding, and the richest information was obtained by combining their responses to get a broad picture of their spatial thinking that supports their understanding of all aspects of enhanced greenhouse effect. Model Space #1 required a text response in which students *used the spatial models* they created to *make a spatial comparison* between emissions and absorption to form a conclusion about carbon in the atmosphere. Model Spaces #2 and #3 gave students the opportunity to *model a spatial distribution* of the features that added to and took away from carbon dioxide in the atmosphere, as well as represent the movement of carbon dioxide in the atmosphere. Prior to their representation, students would have to *visualize the spatial relationships* between these variables. Model Spaces #4 and #5 revealed students’ *spatial correlation* between the amount of carbon dioxide or greenhouse gases in the atmosphere and the amount of radiation *spatially associated* with the amount of greenhouse gases in the atmosphere. If we let students’ representations of all of these concepts tell the story of their understanding, we can see a more complete picture of all of the spatial thinking abilities they employ in creating a mental and then external, conceptual model of the spatial relationships present in the enhanced greenhouse gas phenomenon.

*Student-generated models reveal an understanding of spatial relationships that are on the human scale that they would be able to directly perceive.* For Modeling Spaces #2 and
#3, there was a distinct difference between the representations students gave of carbon emitting features and carbon absorbing features on Earth’s surface and the movement of carbon in the atmosphere. Students were easily able to represent homes, cars, airplanes, trees, oceans, etc.; but they were challenged by the prompt that directed them to represent where they thought carbon moved around and accumulated in the atmosphere. This was the only feature or behavior they were unable to represent in Earth’s system of carbon dioxide in the atmosphere. Interestingly, this was the variable they were asked to model that was not visible in the real world. That could be one explanation for students’ challenges.

For Modeling Spaces #4 and #5, students again represented human-scale features on the surface, like buildings and cars. Their most common representation of energy was from the sun to the Earth, which was also the most common way that energy was represented in the lessons they experience in class. In some, but very rare cases, students represented the energy reflected back from the surface of the Earth and either leaving Earth’s atmosphere or remaining trapped in it. In no way did students represent the change in energy’s form from radiant to infrared. This was a challenging content area, perhaps because also because of its invisible nature. The transformation of energy was not a concept that was directly addressed through instruction, probably adding to the challenges students met trying to represent this idea. In this case, the phenomenon itself is imperceptibly small and the scale on which it occurs, imperceptible large.

Students’ spatial perceptions of scale may have also contributed to their understanding of the relative size of the atmosphere. In order to understand the relative size and position of Earth’s atmosphere, students would need to associate and correlate the Earth and its atmosphere. An important characteristic of the atmosphere was its size relative to Earth. To understand how thin the atmosphere is compared to the planet it protects, students have to make a spatial comparison of the
Students’ representations did a great job of noting the position of the atmosphere, relative to the Earth; that is, that the atmosphere is wrapped around it. What was less accurately represented, however, was the atmosphere’s relative thickness. While it was not expected that students get the proportions exactly right, the experts that participated in the study felt it was important that students understand that the atmosphere was really just a very thin layer around the Earth, to better understand the effect humans might have on something that might seem big, relative to the student standing in it, but is not actually big at all relative to Earth.

The good news is that we know from Tretter et al.’s work on scale that an understanding of phenomena at either end of the spatial scale can be learned (2006), so this challenge in students’ spatial thinking abilities can be addressed with instruction.

Students mimic the representations used in class and literature, so it is sometimes hard to know what student-generated models reveal. Students most commonly used arrows to indicate movement of matter and energy in the Earth/sun system. An arrow or line traces the spatial connection of energy from the sun to the Earth and from the Earth back outward to space or to Earth’s atmosphere. That representation accurately conveys the spatial relationship and is most commonly used in the representations of radiation and enhanced greenhouse effect presented in class and in text books. The almost unanimous use of this notation is important to bring up in reference to this research questions because in order to draw conclusions from students representations, I have made assumptions, based on previous research on spatial thinking, about what students’ models represent. An important question to ask might be whether students are using arrows to represent their own mental models, or if they are simply mimicking a representation method that they have seen previously.
How do student responses inform the next steps of assessment development?

*Student responses highlight the challenge to representing multiple scales in one modeling space.* Students did not accurately represent the size of the atmosphere relative to the size of the Earth. In all cases but one, the atmosphere was modeled much thicker than it is in reality. It is important to enhanced greenhouse effect education that this misconception is not perpetuated, because it gives the learner an incorrect idea that we might have a smaller impact on this vast atmosphere than they might perceive we would have if they understood it to be smaller.

The original intention of combining several modeling prompts for expression in one space was to prevent students from having to create too many models in one assessment. It was intended to be a time saving measure so that students did not tire of completing the assessment and give less thoughtful responses toward their completion of the assessment. However, in combining modeling spaces, I overlooked the fact that in order for students to represent all of the interactions taking place in the atmosphere, between radiation and greenhouse gases, it would be necessary for them to represent the atmosphere as much thicker than it is.

Accuracy overrides thrift in space and time in this case. A small additional model was added to the assessment so that students can separately model the atmosphere and the interactions that go on within it. The general concept moving forward, for future assessment design as well, is to avoid representing or asking students to represent phenomena on multiple scales in one space. Where the scales or representations are preventative to accurately modeling the concept, items should be separated. In this case specifically, a separate model space will be used to represent phenomena inside the atmosphere and a “zoomed out” perspective to represent the atmosphere itself.

*Students do not represent features or phenomena unless explicitly prompted.* Students did not represent greenhouse gases relative to other atmospheric components, given the opportunity to do so in Models #4 and #5. In order to do this accurately, they would have had to
employ their spatial thinking ability to spatially compare the density or amount of one atmospheric component to another. This was not accomplished, presumably because it was not explicitly named as a task in the modeling guidance. One concern when drafting the STA-En GreenE was, to what degree to guide students in their model-building. I erred on the side of a more open format, but in this case students may require more direction, so as not to miss this central concept, if they in fact understood it. In the assessment revision, more explicit instruction was added to represent all atmospheric components, so that I might learn more about students’ understanding of the relative amounts of the components of the atmosphere, including greenhouse gases. I will prompt them to represent greenhouse gases as they understand them to be, but will also prompt them to represent other atmospheric gases as they understand them to be.

*Students did not represent an understanding of the different spatial relationships between natural greenhouse effect and enhanced greenhouse effect.* Generally speaking, students were able to represent the interaction and spatial relationships between radiation and greenhouse gases in the atmosphere by drawing them together and representing the motion of their interactions. They were not, however, able to represent the spatial difference between natural greenhouse effect and enhanced greenhouse effect. Students represented the accumulation of greenhouse gases as a result of anthropogenic emissions by increasing the density of greenhouse gas models, like dots, small circles, or shading; and some were also able to represent the increase of radiation in the atmosphere as a result of the increase in greenhouse gases. It is clear that they understand the spatial relationships related to natural and enhanced greenhouse effect, but do not associate their models with those names (natural and enhanced greenhouse effect). It is important that students are cognizant of the distinction between the two phenomena and the spatial representations that represent them because it is the verbiage they will most often encounter in their science learning, formal and informal. It is important that they call upon the correct mental models
of emissions, absorption and accumulation of greenhouse gases and be able to compare their mental models to understand the difference between these two phenomena. With this in mind, Modeling Spaces #4 and #5 in the STA-En GreenE assessment were revised to represent natural greenhouse effect (Modeling Space #4) and enhanced greenhouse effect (Modeling Space #5), instead of calling them by the year 1500 and the year 2000, as they are labeled now.

**Summary.** Students’ representations were consistent and not diverse. They represented spatial concepts in only a few ways. Associations and correlations between spatial phenomena were represented with arrows and lines, if they were in motion, like radiation moving from the sun to the Earth. Spatial associations were represented by modeling two features on top of each other, if connectivity was the desired spatial association to model, as with the interaction between radiation and greenhouse gases. Spatial conditions were described in a number of ways, including small drawings of the features or conditions to be described, as with the description of emitting and absorbing features in both the 1500 and the year 2000 landscape. Sometimes, student descriptions included text to label or explain a spatial relationship. Excluding students’ misrepresentation of the relative size of Earth’s atmosphere, their models depicted a normative understanding in most cases.

The consistency of student representations leads to two questions. First, are student representations so consistent because they received the same instruction and are using the representations that were part of their instruction as models for expressing their own understanding? Second, if this is the case, does it matter? Do their representations still represent their normative ideas about enhanced greenhouse effect and the phenomena connected to it, or are they mimicking representations they have seen without really understanding their meaning? These questions will be explored further in Chapter 10.

The final version of the assessment is still a draft. In addition to adding to our understanding of the ways in which students model enhanced greenhouse effect, the pilot test contributed to a set
of revisions that will improve the assessment and how it enables students to express their understanding. The revisions outlined here contribute to changes in the assessment that will hopefully facilitate students’ clear expression of their ideas and will help those evaluating students’ models know the mental models that students hold. A final revision is, based on cognitive interview and pilot test results, is displayed in Appendix F.
Stage 4: Did we do something silly?

The final stage of the testing and review process, as described in Dillman’s adapted methodology (Chaney et al., 2008), is something Chaney et al. calls the “Did we do something silly?” test. The guidance for this stage stipulates that the assessment, in its latest form should be delivered to a reviewer that has had no previous experience as a reviewer or a test-taker, with the assessment. The job of this reviewer is to take one final look at the assessment to make sure that no big mistakes still exist, following the revisions that resulted from the expert interviews, the cognitive interviews, and the pilot test. The reviewer need not be a particular expert in the subject matter, but perhaps knowledgeable in the general ideas.

In this case, the STA-En GreenE was reviewed by an individual familiar with environmental science concepts, as he has a graduate degree in Environmental Policy and Management. He is employed as a manager of a county park natural area in the Southwestern United States. This reviewer was instructed to read through the assessment for any text or conceptual mistakes, and also to take the assessment, as though he were a student, to notice any challenges or mistakes made from that perspective.

The reviewer reported no conceptual or textual error and reported that he was easily able to understand the requirement of each model space and their associated prompts. No additional revisions were made to the assessment, as a result of his participation.
Chapter 10: Discussion and Insights

Up to this point, I have discussed my purpose and rationale for the current study, which was to develop an assessment to test students’ spatial thinking abilities that support an understanding of enhanced greenhouse effect; I have described the literature-supported method by which I designed, developed, and tested the assessment; and I have reported on the results of that development and testing process. The results of development and testing contribute directly to answering the three research questions which are the foundation of this study. It is the purpose of this chapter to use the results of the development and testing process to answer those three research questions, which are:

1. What are experts’ perceptions of which spatial thinking skills are necessary to support students’ understanding of enhanced greenhouse effect?

2. How do expert perceptions of the spatial thinking skills that support students’ understanding of enhanced greenhouse effect inform the design of an assessment to measure this construct?

3. What do student-generated models reveal about their spatial thinking skills that support understanding of enhanced greenhouse effect?

Each section of this discussion will address a separate research question by briefly summarizing the relevant findings, describing how the findings relate to the expected findings, discussing any important insights related to the findings, and describing any future work that could result from these findings.

What are experts’ perceptions of the spatial thinking skills necessary to support students’ understanding of enhanced greenhouse effect?

For the purposes of this study, I accessed experts with several areas of expertise. First, the experts in the sciences came from a variety of sub-disciplines in the fields of biology, chemistry, geology, physics, and math. These participants were chosen for their expertise in the disciplines that
support the study of the environment and of complex environmental problems, like enhanced greenhouse effect. These experts were interviewed in a semi-structured format and asked for their perceptions of the spatial thinking skills they perceived as important to students’ understanding of enhanced greenhouse effect. The interviews were recorded, transcribed, and analyzed for specific spatial thinking abilities and for any themes in the experts’ perceptions that might have emerged from the interviews.

The second group of experts was environmental education experts. They were asked to evaluate the spatial thinking skills relevant to understanding enhanced greenhouse effect presented by the first group of experts in science and math. These experts were chosen for their expertise in the teaching and learning about the environment and for their particular understanding of novice learners in environmental science.

The emergent spatial thinking priorities described by experts contributed to the study in two ways. First, an inventory of spatial thinking skills related to understanding enhanced greenhouse effect was developed to contribute to the design of the assessment, with support from the enhanced greenhouse effect assessment literature and literature about existing spatial thinking assessments. This contribution will be discussed in the next section, about research question #2. Second, expert perceptions were analyzed for any emergent themes related to the spatial thinking abilities or spatial information that a student would need to better understand enhanced greenhouse effect, to inform both the general design of the assessment, and also future assessment design. These themes tell us more about how expert perceptions are, in general, useful or not to the assessment design process.

Four themes emerged in expert perceptions of spatial thinking abilities critical to students’ understanding of enhanced greenhouse effect. Two of these are relevant to Research Question #1 and are reported on below, while the second two are reported on in reference to Research Question #2.
1. *Most faculty perceived visualization and dimensional thinking as the most important spatial thinking skills in a proficient spatial thinker.*

Most commonly, faculty experts described a proficient spatial thinker as a person who can think about objects or phenomena in three dimensions. Faculty indicated that students should have the ability to visualize the phenomena related to enhanced greenhouse effect in their mind’s eye. In order to express their understanding as a two-dimensional representation and in order to understand the three-dimensional reality of a two-dimensional representation, students should also have the ability to translate between these two types of models, according to experts.

These are particularly challenging and important skills for novice students when they are contextualized in the problem of enhanced greenhouse effect. Virtually all of the interactions at work in this complex phenomenon are too large or too small to directly perceive with the senses. Tretter, Jones, and Minogue (2006) demonstrated that students and teachers alike are challenged in predicting spatial relationships as phenomena or objects move farther away from human size. Since all of the processes associated with the enhanced greenhouse effect occur at a scale that is far away from human size, it would be challenging for students to predict spatial relationships between the variables, like molecules or planets, involved in these processes. This makes the ability to visualize things like the interaction of carbon dioxide and radiation particularly useful.

Although the research carried out by Tretter, Jones, and Minogue (2006) suggest that it is challenging for students to predict spatial relationships at non-human scales, we also know from the same group’s research that practice at each end of the spatial scale can improve an individual’s ability to reason with spaces very large or very small (Tretter et al., 2006). Accordingly, finding a way to give novice students an opportunity to practice visualizing the relationship between carbon dioxide in the atmosphere and radiation is very important if we want students to develop correct understandings of the enhanced greenhouse effect. Once way to provide these practice
opportunities is to require students to translate between two- and three-dimensional representations. Models and model-building are a useful means of assessment and instruction where direct perception is not available, as is the case in helping students develop an understanding of enhanced greenhouse effect (Sterman & Booth Sweeney, 2002). Because direct perception of the processes associated with enhanced greenhouse effect is not possible, models and model-building are useful means of assessing students’ spatial thinking abilities that support enhanced greenhouse effect.

In addition, the faculty identification of the importance of dimensional thinking suggests that instruction about the enhanced greenhouse effect should explicitly include opportunities for students to translate between two-dimensional and three-dimensional representations. While the effect of such instruction is not the focus of the current study, it may be the focus of future studies, as interventions related to improving students’ understanding of enhanced greenhouse effect are the next objective of this research program.

Remembering that this study relies upon a models and modeling framework for its theoretical foundation, the spatial thinking abilities described here and an analysis for how they may support assessment design, are supported by that framework. The spatial thinking skills named by faculty experts, like visualization and three-dimensional thinking, are methods for creating mental models (Bodner, Gardner, & Briggs, 2005). The method by which students will express their mental models is through the creation of a conceptual model. As such, this study used the general abilities named here, the concepts to be described in the next section, and the modeling best practices described in the literature to design assessment items.

2. Faculty experts’ perceptions of important spatial information to understanding enhanced greenhouse effect spans many interrelated concept themes.

The original expectation related to this research question stated, “As a group, expert perceptions of the spatial thinking skills necessary to support students’ understanding of enhanced greenhouse effect will represent
the spatial thinking abilities across scales that are represented in the spatial thinking literature. Individually, the spatial thinking skills experts perceive to be the most useful will be rooted in their own understandings of the phenomenon.” While faculty perceptions of the spatial thinking skills important for novice learners to understand enhanced greenhouse effect were widely varied and did span all scales, there were certainly gaps in their collective knowledge. For example, many faculty named skills related to understanding one content area or another, like understanding the spatial distribution of greenhouse gas emissions or understanding the relative size and position of Earth’s atmosphere, but none described skills that synthesized multiple content areas. For this reason, it was necessary to consult the literature on enhanced greenhouse gas assessments, as well as existing spatial thinking assessment literature to ensure that the STA-En GreenE assessment was comprehensive in both regards.

Faculty members also described skills important to introductory students. That is, rather than naming skills that were at scales and involving content relevant to their own disciplines, they seemed very aware of the needs of learners new to this content area. They described using local and familiar examples of enhanced greenhouse effect with new learners, to connect unfamiliar concepts with things that students are more likely to understand before they experience instruction. They also recommended teaching novices about very small and very large spaces by relating those spaces to things at a human scale. Their perceptions are aligned with the literature on scale and spatial thinking (Tretter et al., 2006; Tretter, Jones, & Minogue, 2006). They also recommended providing students with representations of relevant spatial information. These recommendations were insightful and somewhat unexpected. This expertise informed the assessment by directing me to include a modeling opportunity at a human scale and in a familiar setting for Modeling Space #1, the students’ college campus.
It is important to recognize the effect that sample size may have had on the results discussed here. While the entire faculty of the College of Sciences was invited to participate in the faculty interviews, only 17 faculty members responded and completed an interview: 5 biology faculty members, 4 chemistry, 3 geology, 3 math, and 2 physics faculty members. Were I to expect that the breadth of spatial thinking skills and content foci would be represented by interviewing expert participants from across the sciences, it would be difficult to imagine that it would be represented by this group alone, with such small numbers represented from each content area. It was for this reason that I chose to supplement my findings from the expert interviews with findings from the literature on existing assessments of enhanced greenhouse effect and spatial thinking.

I did not elicit the most useful information that I could have from the group of environmental educators that were accessed for their particular expertise with students new to environmental education and education regarding environmental problems in particular. In the current study, environmental educators were asked to rank the importance of certain spatial skills for developing a correct understanding of enhanced greenhouse effect.

While these responses informed the development of the assessment, future studies could take advantage of the unique knowledge base of these educators. They are experts, not in content (though this is probably also true), but in the goals of environmental literacy (knowledge, attitude, behaviors, etc.). Thus, their expertise may be useful in connecting spatial thinking to those goals. Surveys or interviews for these participants should be designed so that they can provide input about how to serve the goals of environmental literacy with our assessments and interventions. Future work can build upon this work by interviewing environmental education experts for their original perceptions on the spatial thinking skills related to enhanced greenhouse effect or another example environmental problem. In addition, one idea related to this work is that the ability to think spatially about the environment may increase a person’s knowledge of environmental problems and their
perception that they have some impact on it. Affective factors are included in a person’s environmental literacy, as described by the NAAEE. So, with their expertise in mind, I would like to interview environmental experts about their perceptions of the spatial thinking abilities that would enable a person’s pro-environmental behaviors.

**How do expert perceptions of the spatial thinking skills that support students’ understanding of enhanced greenhouse effect inform the design of an assessment to measure this construct?**

Faculty perceptions were a very important component to the design process for the STA-EnGreenE, but not the only component. In this section, I will discuss the important ways in which expert perceptions informed the design of the assessment here, the ways in which expert perceptions were not sufficient to inform the design of the assessment, and how a more complete picture of spatial thinking related to enhanced greenhouse effect was formed.

Theme #3 from the results of the expert interviews reads:

*Faculty experts’ perceptions of the spatial thinking abilities that support enhanced greenhouse effect contribute directly to the design of the assessment when the general spatial thinking skills and spatial information about enhanced greenhouse effect are synthesized to draft performance objectives for the assessment.*

While a review of the spatial thinking literature led to the coding of topics found in the literature *arranged by spatial thinking ability*, faculty perceptions were analyzed and coded by content theme, like “greenhouse gases,” “radiation,” or “atmosphere.” This is because, in most cases, faculty tied their recommendations for students’ spatial understanding to content. For example, they recommended understanding the spatial distribution of carbon emission sources across a landscape, instead of recommending a decontextualized skill, like understanding relative space and distribution of characteristics. Experts’ connection of specific content related to enhanced greenhouse effect
with specific spatial thinking abilities strongly informed the design of the STA-En GreenE assessment. This contextualized depiction of spatial thinking skills was not information that could be obtained from the literature because learning objectives related to enhanced greenhouse effect have not been framed with spatial thinking skills in mind previously. In the end, this was the most important function of the expert interviews and surveys.

As was described in the previous section, participants were targeted for their expertise in the various science disciplines that support the study of enhanced greenhouse effect and for their expertise in environmental education. However, they were not experts in either enhanced greenhouse effect itself or in spatial thinking. For this reason it was important to rely upon that literature to complete the picture of spatial thinking for enhanced greenhouse effect that the expert participants began to construct.

An important conclusion to draw from this part of the study is the importance of the human perspective in contextualizing spatial thinking abilities within the specific content needed to develop a correct understanding of enhanced greenhouse effect. This contextualized description of spatial thinking abilities was not present in the literature. Instead, existing literature either described (1) the decontextualized spatial skills that environmental science students should have or (2) the specific pieces of prior content knowledge that are necessary for understanding enhanced greenhouse effect. Expert perceptions were crucial to marrying spatial thinking to content.

Previous studies have used decontextualized assessments to assess students’ spatial thinking abilities and then correlated the scores from those tests with content scores in areas like geology and chemistry (see Chapter 7 literature review). At the same time, other spatial thinking literature has described that spatial thinking abilities are very specific and that demonstration of one spatial thinking ability does not translate to being able to think spatially in other ways (Newcombe & Shipley, 2011). It makes sense, then, that researchers should be very specific in assessing the spatial
thinking abilities they want to target for a particular purpose. This includes contextualizing them in the content they are teaching. Therefore, this method of assessment development that includes experts in the field of interest should be used in the development of future spatial thinking assessments for other topics in environmental science.

One of the limitations of the current method used to elicit expert perceptions was their limited expertise in the content area of enhanced greenhouse effect. In order to gain more information, future attempts at developing contextualized spatial thinking assessments for environmental issues should target participants’ areas of expertise more directly to match the topic of assessment. The rationale for accessing the experts that I did for this study was to understand the breadth of perception related to environmental issues, based on varying areas of expertise. In the future, however, targeting experts in the topic on which the assessment focuses will enable the collection of even more information related to the relevant spatial thinking abilities, because the experts will know even more about the topic. It would also be more likely that the experts would have experience with novice students within that specific field of study, since, as faculty members, they will have worked as instructors with novice students. For example, if I were interested in creating an assessment about the spatial thinking abilities related to the accumulation and movement of water pollutants, it might beneficial to access a group of knowledgeable hydrologists. While the number of participants is not likely to increase by making the subject matter more specific, the amount and quality of information that they are likely to provide would be greater.

Also, in selecting the environmental education experts that completed my survey, my hope was to access their expertise of environmental education students and the learning goals that would be most appropriate for them. The online survey that was administered to them did not enable them to provide the best information that they could and, in fact, only allowed them to support or reject the learning goals established by the literature review and the faculty interviews. Environmental
educators are experts in the knowledge, attitudes, abilities, and actions of environmental literacy (Hollweg, 2011). For this reason, they should be given the opportunity to speak to all of these areas and provide insight outside of just the content understanding, which could be identified by content experts. For the design of future spatial thinking assessments, I will interview these experts, just as the experts in the sciences were interviewed to gain their original perspective and avoid limiting what they are able or willing to say. In fact, an interesting future study might include a comparison of the perceptions of important spatial thinking skills supporting enhanced greenhouse effect, according to experts in the content, such as atmospheric scientists or climatologist, and environmental educators of climate change.

Finally, experts’ contributions might be more targeted and, therefore, productive if literature reviews of all subject matter were conducted and used to inform interview protocol design. In this case, spatial thinking literature was included in the interview protocol design, but I let expert perceptions lead the information gathering as to what content was most important for novice students to understand. In future work, a thorough literature review of the assessment’s subject matter will come first; then interview questions can be designed with that information. In this way, I hope to develop content themes prior to expert interviews, so that experts can be asked about their perceptions of spatial thinking skills related to more specific content ideas related to enhanced greenhouse effect. This would allow me to capture a more specific and complete picture of the experts’ understanding. Figure 41 below depicts one version of a revision to the assessment development process that could be the result of putting the literature review first to more directly prompt experts’ understanding.
Figure 43. Revision of assessment development process for gathering information sources, to include more focused experts and a literature review preceding expert interviews.
Discussion of this research question spoke to the contribution of experts to the design of the STA-En GreenE assessment, in its final product, but also in its design process, which has become at least as important, if not more important, as an outcome of this project. The original focus was to develop a design framework in the service of the assessment as a product. However, as the project has progressed, it has been a developing interest to consider how this design process might be applied to create spatial thinking assessments for other content areas, for example, the spatial thinking skills necessary to understand a problem like deforestation or water pollution. Figure 41 above demonstrates, side-by-side, the revision of the design process, from Figure 5, presented in Chapter 3, to the revised version, which includes the revisions described above.

*Faculty perceptions guided the design of not only the assessment items, but of the model spaces that the students were provided to scaffold their own model-building.* Several faculty members described the need to start the assessment with students’ local and familiar understandings. Based on faculty input, I chose to include a human scale and familiar landscape as the first model space. Faculty also described learning objectives like being able to understanding that the carbon cycle occurs in space. For Model Spaces #2 and #3 I designed the model space so that each stage of the carbon cycle could be modeled, if students were so inclined. Faculty described a student’s need to understand that the Earth and the sun are both radiating energy, so Model Spaces #4 and #5 were designed to include both the sun and the Earth. These are just a few examples of the decisions that were made in model space design, informed by faculty perceptions.

While the model spaces were informed by faculty perceptions, other criteria were important in designing the model spaces. Students should not have seen the model space in any previous material, to avoid their mimicking what they may have seen in that model space. The space was designed at such a scale that each of the Central Concepts associated with the Content Theme that
the model space depicted could be modeled within the space. This was done to avoid students’ needing to complete more than one model of the same topic.

Faculty perceptions informed the design of the model spaces here and will continue to define the criteria they should meet in the future. Faculty perceptions informed Central Concept design, and the Central Concepts were grouped into model spaces. Faculty recommendations for scaffolding students in the assessment should also be considered. For example, faculty recommendations might influence the order of the assessment items, the model space prompts, or the language that is used in the text prompts. Whether any one of these recommendations might affect students’ responses to the assessment would need to be examined through future research.

What do student-generated models reveal about their spatial thinking skills that support understanding of enhanced greenhouse effect?

In Chapter 9, in the results and discussion sections of the pilot test results, I described some of the spatial thinking abilities supportive of an understanding of enhanced greenhouse effect that were revealed through students’ models and modeling. In the sections below, I will discuss some of the emergent themes that I synthesized from that information and how it might apply to future research.

Themes in students’ spatial understanding for enhanced greenhouse effect.

Students’ spatial understanding of enhanced greenhouse gas phenomena is best represented at a human scale, in a familiar landscape. This is supported by the literature in two ways. First, spatial thinking literature related to scale tells us that human beings are most adept at negotiating spaces closest to human-size (Tretter, Jones, & Minogue, 2006). For this reason, it follows that students would be most proficient in their spatial thinking about local and small spaces. The content situated in this model (Modeling Space #1) was the emission, absorption, and accumulation of greenhouse gases. Students’ models demonstrated that they understood this content
most proficiently, of the content themes on which they were tested. The question to ask in future research is: What is the effect of the scale of representation on students’ content understanding and ability to represent it in a particular subject? In other words, if students engage with models at a spatial scale that is closer to a human spatial scale to learn about enhanced greenhouse effect, are they more likely to incorporate the content into their working understanding of enhanced greenhouse effect? For example, if they learn about carbon dioxide emitted from a car tailpipe as they drive to school, for example, are they more likely to understand its interactions with radiant energy, than if they learned about it on a global scale in the atmosphere? The literature on scale and the results of the pilot test here suggest that it might.

The research finding that individuals can be instructed in their spatial thinking abilities at scales that are much smaller or much larger than they can perceive (Tretter et al., 2006) also has implications for both assessment and instruction. Pilot test participants were more likely to recognize and represent an accumulation of greenhouse gases in a familiar landscape than they were in a general one at a much larger scale; however, understanding greenhouse gas accumulation and greenhouse effect on a global scale is important because enhanced greenhouse effect is a global problem. The path from local to global understanding, then, can be paved with spatial thinking skills married to content at each scale, beginning with the local and most familiar.

The previous paragraphs described how the strategy of starting the assessment with a familiar scenario was effective, but it should also be noted that ideas about item order in assessment and their impact on student performance are an area of study in assessment development all to itself. Significant to this study, Hambleton and Rodgers (1995) found that students’ mean scores were significantly higher on math tests with items ordered easy-to-difficult than on tests ordered difficult-to-easy. While the intention here was to scaffold students’ ability to move through the test, it is important to consider that ordering the items in this way may have been instructive to students’
understanding, inflating their scores. A future study might explore changing item order in future versions of the assessment to see if students represent their mental models any differently.

**Students are challenged understanding spatial relationships that cannot be directly perceived.** Consistent with the notion that learners are less proficient at negotiating spaces much larger and much smaller than human scale, the 96 students tested as part of the pilot study struggled more representing phenomena and features related to enhanced greenhouse effect that could not be perceived directly with the senses. These ideas included things like the movement of radiation and the interaction of radiation with greenhouse gases.

This finding has important implications for interventions directed at spatial thinking for enhanced greenhouse effect. Referring back to our understanding of the effect of practice on students’ spatial thinking abilities, it is possible that students’ understanding and, therefore, performance on the assessment will improve with instruction that is aimed at moving students from spatial scales of their understanding to the ones at either end of the spectrum.

**Students understand spatial relationships and how to represent them within one content theme, but their understanding is challenged when concept themes are bridged and become more complex.** Not only do students struggle understanding spatial relationships at either end of the spatial scale, they also had difficulty understanding, or at least communicating their understanding of the spatial relationships related to enhanced greenhouse effect when the model-building scenarios were more complex. By this I mean that when students were prompted to model their understanding of greenhouse gases or the characteristics of the atmosphere alone, they were more successful in demonstrating a correct understanding of the spatial relationships involved. When they were asked to combine more than one concept theme to talk about greenhouse effect, they might only represent one or another of the relationships they were asked to represent. Complexity or multiple spatial relationships in one presentation was not as often represented.
Again, instruction could address this deficiency. In addition to serving students’ understanding of phenomena that occur at either end of the spatial scale, an enhanced greenhouse effect curriculum that develops students’ spatial thinking skills—from a low level of complexity and a high level of scaffolding, moving toward a high level of complexity and a low level of scaffolding—will move students towards a complex understanding of the spatial relationships that support an understanding of enhanced greenhouse effect.
Chapter 11 Future Work and Conclusion

Validity and Reliability Testing

An original goal of the assessment development process for this project was to ensure a valid and reliable assessment and to conduct the necessary testing related to that goal. After careful consideration with my committee, this was determined to be too ambitious for one project given that so many other pieces were to be originally developed from several information sources. However, validity and reliability testing are still a priority; and the information that has already been collected in assessment development will be useful to the process.

Validity Measures. Validity measures tell us if the assessment measures what it is supposed to measure (Kubiszyn & Borich, 2007). That is, if the assessment is intended to measure the English language skills of 5th grade students, it should measure exactly that and not the English language skills of 3rd grade students or the reading skills of 5th grade students. The assessment developed through this study is intended to measure the spatial thinking skills related to enhanced greenhouse effect of novice environmental science learners, in secondary and undergraduate education. This may seem like a broad range of student experience, in terms of grade level, but for the purposes of this assessment, all students are novices and, therefore, at about the same level of experience in environmental science specifically.

There are several validity measures, and the results of each one say something about a different aspect of and instrument’s validity. Many are briefly outlined below to justify the future validation procedure for this assessment in particular.

Face validity is a broad evaluation in which the assessment is evaluated against the construct it is intended to measure to establish if the assessment is measuring the construct as intended. This can be a very subjective assessment; however, it can be made more systematic by selecting experts from the field or fields represented in the assessment to do the work of establishing its face validity.
Subjectivity can be further decreased by providing the evaluating experts context and criteria for their evaluation (Kubiszyn & Borich, 2007).

Content validity may be established in a similar way; however, each item of the test is evaluated against the concepts that define the broader construct (Kubiszyn & Borich, 2007). For example, in the case of spatial thinking, spatial thinking might be the construct to be evaluated for face validity and skills such as visualization or recognizing spatial patterns might be evaluated for content validity, as part of that construct.

Criterion-referenced validity measures evaluate the instrument against an established measure or expectation. Predictive validity evaluates the assessment after data is collected. It measures a correlation between the assessment outcome and a predicted behavior it is hypothesized to have an impact on (Kubiszyn & Borich, 2007). For example, if assessment designers hypothesize a correlation between an aptitude in life science and a student’s grade in biology, they would be able to evaluate the predictive validity of a life science content test by measuring the correlation between scores on the test with students’ grades in biology. This measure would indicate that the assessment is valid (or not), because the predicted behavior came to bear (or did not). While this is a useful measure, the focus on this study is not on a future change in understanding or behavior, so predictive validity will not be evaluated.

Finally, another type of criterion-referenced validity is concurrent validity. This measure evaluates how the assessment correlates with another criterion or expected outcome. In this case, it is possible to establish this instrument’s concurrent validity because it is expected that students’ spatial thinking in support of an understanding of enhanced greenhouse effect will improve with instruction. By administering the assessment prior to and after instruction, a significant improvement in assessment performance would indicate the assessment’s concurrent validity. In the future, a t-test for dependent means will be calculated between pre-instruction scores and post-
instruction scores to determine this significance. Another measure of concurrent validity can be performed by correlating the developed assessment with another, similar, but reliable and valid instrument (Kubiszyn & Borich, 2007). It may be possible to use the assessment items that were collected and analyzed in the development of this instrument to create a parallel, though not spatially related, instrument to test the STA-En GreenE’s concurrent validity. Alternatively, we would expect that students’ performance on an enhanced greenhouse effect assessment that was strictly content-related would correlate with their score on the spatially-related test.

**Reliability.** The reliability of an assessment refers to the likelihood that it will yield the same ranks over repeated administrations. As was the case with validity, several measures can evaluate an assessment’s reliability. The most significant of these are discussed below with a rationale for their use or exclusion in this study.

Test-retest reliability is used to determine if the assessment will yield the same results over a period of time. Participants are given the assessment at two separate times, with no intervening instruction in the construct the assessment measures. If the test yields similar results in both instances, it is said to be reliable. The Pearson correlation coefficient is calculated to determine score similarities or differences (Salkind, 2008). To test this assessment for reliability in the future, participants will be administered the assessment on two occasions prior to instruction in spatial thinking for that supports climate literacy and once after. The first two assessments will take place one week apart and will be evaluated for test-retest reliability.

Internal consistency reliability is evaluated to determine if all of the items for an instrument intended to measure one construct, indeed measure just that construct. This is typically accomplished by calculating Cronbach’s alpha statistic between assessment item scores to measure their correlation (Salkind, 2008). If Cronbach’s alpha is greater than 0.7, the instrument is said to be internally consistent (deVaus, 2002). For this assessment, the first step following this study, will to
be the creation of a rubric that can be used to evaluate students’ models related to each prompt. This will create a scoring system, from which I can derive scores that can be compared and analyzed for internal consistency, using this method. It should be noted that previous studies on spatial thinking have done the same and noted lower than expected Cronbach’s alpha values. This difference was explained by the fact that spatial thinking, as a construct, is not just one ability, but is made up of many abilities. Some are quite dissimilar and may not contribute to each other understanding (Lee & Bednarz, 2012). It is understandable they may not be correlated, and so it may be for this assessment as well.

Validity and reliability testing will be the first order of business in testing the new assessment. I have, in this study, collected the data. Now, I will create a rubric for the STA-En GreenE, with a foundation of qualitative data I have collected here, to create scores for the assessment. Validity and reliability can be measured using these scores, as described above. Also, I will compare students’ scores on the STA-En GreenE with students’ scores on enhanced greenhouse gases assessments, to measure its validity. Data on these existing assessments have also been collected for this project.

Taking these steps to measure validity and reliability also serves the important purpose of readying the assessment for wider use among educators that were not a part of its design. To ensure that the assessment can be administered independent of my guidance, a scoring rubric would have to be developed; and to do that, a collection of all of the ways that student might represent their understanding should be synthesized and compiled. Each educator should receive the rubric, as well as guidance for what they might see in students’ representations and how each should be evaluated. I expect these materials to be complete and tests to take place sometime during the fall semester of 2016.
Student Representations and Their Mental Models

An expectation connected to this research question was that students would express the spatial relationships that support an understanding of enhanced greenhouse effect using representations that have been modeled through instruction, as well as representations that are original and express their mental models; therefore, their representation would reveal (1) the models that they have learned and incorporated into their understanding and (2) the models that they build to better understand the phenomena, independent of pre-existing instructional models. The statements made above were predicated on the assumption that we can accept students’ conceptual models to represent their mental models. The assumptions that are made in the previous section connect student representations to their ideas and also assume that the common symbols they use represent the same ideas represented in the models that the students learn from. While these assumptions seem to be supported by the consistency of student-generated models, an interesting and maybe important area for further investigation is how to ensure the fidelity of student models to the spatial thinking abilities we presume them to represent. The paragraphs below describe two ideas that might add to our ability to interpret student representations

Models versus modeling. The STA-En GreenE assessment was designed as a summative assessment to test students’ spatial thinking abilities related to enhanced greenhouse effect prior to and following instruction that engages students in subject matter of the same topic. It provides a static representation of students’ mental models on either side of an intervention. Since it taps into students’ understanding only once or twice, there is plenty of time for the development of students’ mental models without monitoring, which may make it more challenging for model evaluators to understanding what students are representing with their models. In the case of this pilot test, the assessment was administered only once, further limiting the information available about students’ mental models.
An alternative assessment method can be found in the models and modeling literature. Instead of a summative assessment format, a more formative framework is used. Instead of focusing on the model as a product, the process of modeling is used to better understand learners’ ideas about a system (Lehrer & Schauble, 2013). In its very simplest form, this would mean administering the assessment at various points in the students’ instruction to better understand how their ideas develop. Many of the ideas brought up in the discussion section here would more likely be traced to instruction at various points. For example, if a student begins to use a spatial representation at a particular point and it mirrors representations used in the curriculum program, evaluators would easily be able to consider how the student interprets the model and incorporates it into their own understanding.

Students’ pre-instruction representations would be free from the influence of notation that is included in their instruction. That students were only evaluated after an instructional unit on climate change was a limitation to the current study. In a future study, I will implement the assessment following each major phase of instruction. Alternatively, the assessment itself might be edited to administer piecewise throughout the course of instruction, rather than implementing the entire assessment multiple times. This will change the validity and reliability testing described above, but will give more comparision points, for both internal consistency and when comparing the STA-En GreenE to existing assessments.

**Experts’ perceptions of students’ spatial representations.** In order to better understand or gain more information about students’ representations it is necessary to do additional research. For this project, I attempted to find interpretations of spatial representations to apply to student-generated models to confirm their meaning. However, in the spatial thinking literature, previous assessment item design made finding interpretation of spatial representations a challenge. Most spatial thinking assessments tested students’ understanding of spatial thinking abilities in a selected
response format, so the representations were already presented and not made explicit to be translated for other applications. In fact, most of the time the spatial thinking assessment items were not similar enough to what I wanted to test here to be helpful.

One group of experts that were not accessed for their perceptions of students’ spatial thinking abilities supporting climate change were experts in spatial thinking. In fact, their expertise was only gained through the peer-reviewed literature they published. If what would aid in the interpretation of student models is more support for what those models and symbols mean, these experts are the ones to provide that confirmation. With this in mind, a future study will access spatial thinking experts to gain their perceptions on two things: first, the general design of the assessment and whether they interpret it to be most effective in eliciting students’ spatial thinking abilities related to enhanced greenhouse effect and second, and more relevant to the discussion here, their interpretation of students’ models and the spatial thinking skills they believe the students are representing. The spatial thinking experts to be interviewed will include spatial thinking scholars and authors of peer-reviewed articles referenced in this study.

Conclusion

This study is, in so many ways, a beginning. Since nothing of its nature exists in the literature, much of it was original. From this project, I developed an assessment that will continue to be tested and revised, but I also developed a method for developing assessments of this variety in the future. That development process contributed to the body of research on spatial thinking by helping us understanding how experts from various disciplines perceive the importance of spatial thinking to the study of enhanced greenhouse effect. The results of the cognitive interviews and the pilot test not only tell us how students think spatially about enhanced greenhouse effect, but also how they represent it. This project also provides a significant path for future research that examines
the unique insights that contextualized assessments can provide about students’ understandings over decontextualized assessments.

My goal moving forward is to continue to refine the STA-En GreenE, but to do it by using it the way that it was intended: to measure the effectiveness of interventions that I hope will change learners’ perceptions of the environment and their place in it. In addition, I have the goal of developing similar assessments for other environmental issues, such as sea level rise or deforestation.

In order to develop an effective assessment, it is useful to start with the overarching goal. My goal for environmental instruction, in this case, is more sustainable decision-making or pro-environmental behavior. Pro-environmental behavior is supported, in part, by environmental knowledge, which in turn is supported by, to some degree, spatial thinking ability. Spatial thinking is built of several interrelated abilities, as described here and in the literature, and is a skill that we use every day to navigate our lives, figuratively and literally. This study takes a step towards leveraging that this everyday ability in the service of understanding environmental problems, which free from context, are complex and often overwhelming to the novice learner. The goal for this project was to take a step toward understanding spatial thinking as it applies to understanding environmental issues; but the ultimate goal that it serves is to develop an environmentally literate citizenry, which is critical for the achievement of large-scale sustainable decision-making.
Appendix A: Interview Protocol for Science and Math Faculty Experts

I. INTERVIEW GUIDE FOR FACULTY (Goal: To elicit experts’ perspectives on the spatial thinking skills necessary to environmental literacy)

a. Informed Consent
   i. Hello. My name is Heather Skaza. I want to thank you for meeting with me today. I think your insights will really help us with our project. Before we start, I wanted to ask if you received the Informed Consent document that I emailed you earlier.
      1. Did you have a chance to read it?
      2. Do you have any questions for me about it?
      3. Do you agree to participate in this interview? Do you agree to be audio-taped during the interview? If so, could you please sign this copy of the Informed Consent document for me? Thank you.

b. Demographics Questions
   i. OK. Let’s get started. Tell me a little about yourself (i.e., How long have you been teaching here? Have you taught anywhere else? Where did you go to school? What kind of research do you do?)
   ii. How does your area of expertise relate to environmental education or environmental studies?

Transition: If you’ll recall, a few weeks ago, the email that was sent to prompt this interview explained that we were interested in developing an assessment and instructional framework to better address students’ abilities to think spatially in the field of environmental studies specifically. We asked you to participate because of your expertise in a field that supports environmental science. The input of experts across the sciences will be valuable to determining which spatial thinking skills might be most useful to a novice in trying to understand complex environmental problems.

c. Domain specific spatial thinking
   i. When I say “spatial thinking” what comes to mind?
   ii. What skills or abilities would you expect to see in a proficient spatial thinker?
   iii. Discuss some of the ways in which spatial thinking is a part of your research specifically.
   iv. Discuss some of the ways in which spatial thinking is a part of your field.
   v. What spatial thinking abilities are most useful in your content area?
   vi. How do you think the spatial thinking abilities that you have described related to your own work are useful to other areas of science research?
   vii. Thinking about students new to your field of science, what spatial thinking abilities would be most useful to their understanding?
   viii. What are some ways in which your field supports the understanding of environmental problems and the problems of sustainability?

Transition: For the next part of our discussion, we are going to shift gears a little and talk about some environmental problems. I will describe for you a scenario that has developed into an environmental problem. It may or may not be a problem you are familiar with or to which you feel your field of science contributes. That’s okay. I just want to hear your perspectives on the problems. After I describe a scenario, there will be a few follow up questions, so that we can discuss your
perspective on the problem, how your field contributes to its understanding, spatial thinking that might relate to understanding the problem and how students might best think spatially about the problem. Are you ready?

d. Open response- Spatial thinking for environmental problems (Each participant will be provided only 2 of the examples below for discussion. Selection of the examples will be randomized.)

i. Example #1- Tamarisk population growth: Tamarisk (also known as salt cedar) is a deciduous shrub or small tree from Eurasia. It is an invasive species in the desert Southwest. Tamarisk can grow as high as 25 feet tall. The seeds are dispersed by wind, water, and animals. Seeds are small with a tuft of hair attached to one end enabling them to float long distances by wind and water. Seeds are short-lived and can germinate within 24 hours after dispersal, sometimes while still floating on the water. Eight species were first brought to North America in 1800’s from Southern Europe or the eastern Mediterranean region (DiTomaso, 1998). They were first planted as ornamentals and later as windbreaks, and to stabilize river banks. Tamarisk species escaped cultivation and are now widespread throughout the United States, with heavy concentrations in the Southwest. Now imagine the initial introduction of Tamarisk to the desert Southwest.

1. How is this environmental problem spatial in nature?
2. What spatial information would you need to understand the impact of this invasive species?
3. Let’s talk a little bit about the rate of distribution. What is a relevant time period to discussing the impact of this invasive species?
   a. [Added question for clarity, if necessary] How long before we see a significant impact on the environment?
   b. How long does the impact last?
4. If we want to represent the significant impact of this environmental problem [refer to time period participant named above] after its introduction, which of these maps would be most useful. [Present maps on scales of immediate area, landscape, city, county, state, country, continent, world]
   a. [Added question for clarity, if necessary] Is it going to affect the city, county, state, etc.?
   b. How did you decide on that scale?
5. [Present 3 blank maps of the scale chosen in the last question] Imagine these maps are meant to display the impact of this environmental problem at different time periods [name half of time period mentioned in Question 3, time period mentioned in Question 3, twice time period mentioned in Question 3. Can you outline the area where there will be a significant impact after [half of time period]? Can you outline the area where there will be a significant impact after [time period]? Can you outline the area where there will be a significant impact after [twice time period]?]
6. Just a moment ago, we discussed the spatial information you would need to consider this problem. Is that different than what a student might need?
7. What spatial thinking skills would be necessary for a student to understand this environmental problem?

ii. Carbon dioxide (CO\textsubscript{2}) is the primary greenhouse gas emitted through human activities. In 2012, CO\textsubscript{2} accounted for about 82% of all U.S. greenhouse gas emissions from human activities. Carbon dioxide is also naturally present in the atmosphere as part of the Earth's carbon cycle (the natural circulation of carbon among the atmosphere, oceans, soil, plants, and animals). Human activities are altering the carbon cycle—both by adding more CO\textsubscript{2} to the atmosphere and by influencing the ability of natural sinks, like forests, to remove CO\textsubscript{2} from the atmosphere. While CO\textsubscript{2} emissions come from a variety of natural sources, human-related emissions are responsible for the increase that has occurred in the atmosphere since the industrial revolution. The main human activity that emits CO\textsubscript{2} is the combustion of fossil fuels (coal, natural gas, and oil) for energy and transportation, although certain industrial processes and land-use changes also emit CO\textsubscript{2}.

(http://www.epa.gov/climatechange/ghgemissions/gases/co2.html) Now imagine one of these types of combustion: the burning of gasoline for automobile transportation.

1. How is this environmental problem spatial in nature?
2. What spatial information would you need to understand the impact of carbon in the atmosphere?
3. Let's talk a little bit about the rate of accumulation. What is a relevant time period to discussing the impact of carbon in the atmosphere?
   a. [Added question for clarity, if necessary] How long from the time of introduction before we see a significant impact on the environment?
   b. How long does the impact last?
4. If we want to represent the significant impact of this environmental problem [refer to time period participant named above] after its introduction, which of these maps would be most useful. [Present maps on scales of immediate area, landscape, city, county, state, country, continent, world]
   a. [Added question for clarity, if necessary] Is it going to affect the city, county, state, etc.?
   b. How did you decide on that scale?
5. [Present 3 blank maps of the scale chosen in the last question]
Imagine these maps are meant to display the impact of this environmental problem at different time periods [name half of time period mentioned in Question 3, time period mentioned in Question 3, twice time period mentioned in Question 3]. Can you outline the area where there will be a significant impact after [half of time period]? Can you outline the area where there will be a significant impact after [time period]? Can you outline the area where there will be a significant impact after [twice time period]?
6. Just a moment ago, we discussed the spatial information you would need to consider this problem. Is that different than what a student might need?

7. What spatial thinking skills would be necessary for a student to understand this environmental problem?

iii. Example #3- Water pollution in a lake: Nonpoint source pollution, or polluted run-off, is created when rain, snowmelt, irrigation water, and other water sources run over the land, picking up pollutants and transporting them to local water bodies. Nonpoint source pollution is also called "people pollution" because much of it is the result of activities that people do everyday. With each rainfall, pollutants are washed from surface and land areas into storm drains that flow into our nearby waterways. Because each individual contributes to nonpoint source pollution simply by performing daily activities, it is not surprising that nonpoint source pollution is the biggest threat to our ponds, creeks, lakes, streams, rivers, bays, estuaries and oceans. Common household products (drain and oven cleaners, paint products/thinners, cleaning agents, pesticides, mothballs, etc.) contain toxic ingredients. When these products are overused or improperly discarded they pose a threat to public health and the environment. ([http://www.epa.gov/region02/water/npspage.htm](http://www.epa.gov/region02/water/npspage.htm))

Thinking about the relationship between these improperly discarded chemicals and their potential effect on bodies of water:

1. How is this environmental problem spatial in nature?
2. What spatial information would you need to understand the impact of nonpoint source pollution on a body of water?
3. Let’s talk a little bit about the rate of distribution. What is a relevant time period to discussing the impact of these pollutants on a body of water the size of Lake Mead?
   a. [Added question for clarity, if necessary] How long before we see a significant impact on the environment?
   b. How long does the impact last?
4. If we want to represent the significant impact of this environmental problem [refer to time period participant named above] after its introduction, which of these maps would be most useful. [Present maps on scales of immediate area, landscape, city, county, state, country, continent, world]
   a. [Added question for clarity, if necessary] Is it going to affect the city, county, state, etc.?
   b. How did you decide on that scale?
5. [Present 3 blank maps of the scale chosen in the last question]
Imagine these maps are meant to display the impact of this environmental problem at different time periods [name half of time period mentioned in Question 3, time period mentioned in Question 3, twice time period mentioned in Question 3. Can you outline the area where there will be a significant impact after [half of time period]? Can you outline the area where there will be a significant impact after [time period]? Can you outline the area where there will be a significant impact after [twice time period]?
6. Just a moment ago, we discussed the spatial information you would need to consider this problem. Is that different than what a student might need?

7. What spatial thinking skills would be necessary for a student to understand this environmental problem?

iv. Example #4: Deforestation: Nowhere on Earth is the threat of biological impoverishment because of deforestation greater than in the Amazon Basin of South America. The Amazon supports approximately 300 million hectares of tropical forest, the largest single area of tropical forest communities in the world. Estimates of global biodiversity point to the tropics as the source of 50 to 90% of all species on Earth (Wilson, 1992); the richest forests often support the 300 tree species per hectare, approximately the same number of tree species in all of North America. Recent estimates of deforestation suggest that between 1 and 3 million hectares are being cleared annually in the Amazon Basin (Laurence, 1997). Based on estimates of 1% annual tropical forest loss, the Amazon may be losing as many as 11 to 16 species per day (Wilson, 1989), and the resulting ecosystems are often highly degraded (Buschbacher, 1986).

8) Thinking about this deforestation example:

1. How is this environmental problem spatial in nature?

2. What spatial information would you need to understand the impact of deforestation in the Amazon rainforest?

3. Let’s talk a little bit about the rate of deforestation. What is a relevant time period to discussing the impact of deforestation?
   a. [Added question for clarity, if necessary] How long before we see a significant impact on the environment?
   b. How long does the impact last?

4. If we want to represent the significant impact of this environmental problem [refer to time period participant named above] after it began, which of these maps would be most useful. [Present maps on scales of immediate area, landscape, city, county, state, country, continent, world]
   a. [Added question for clarity, if necessary] Is it going to affect the city, county, state, etc.?
   b. How did you decide on that scale?

5. [Present 3 blank maps of the scale chosen in the last question]
Imagine these maps are meant to display the impact of this environmental problem at different time periods [name half of time period mentioned in Question 3, time period mentioned in Question 3, twice time period mentioned in Question 3. Can you outline the area where there will be a significant impact after [half of time period]? Can you outline the area where there will be a significant impact after [time period]? Can you outline the area where there will be a significant impact after [twice time period]?

6. Just a moment ago, we discussed the spatial information you would need to consider this problem. Is that different than what a student might need?
7. What spatial thinking skills would be necessary for a student to understand this environmental problem?

v. Example #5 - Spread of radioactive contamination: On Saturday, April 26, 1986, reactor number four at the Former Soviet Union's Chernobyl nuclear power station, exploded and burned. The accident, which occurred during unauthorized testing, emitted large quantities of radioactive material. The heat from the fire was so intense that the glowing reactor could be seen even from space. The U.S. detected slightly elevated radioactivity levels, but they were well-below levels requiring protective actions. (http://www.epa.gov/radiation/rert/chernobyl.html)

1. How is this environmental problem spatial in nature?
2. What spatial information would you need to understand the impact of radioactive contamination from the Chernobyl incident on the environment?
3. Let’s talk a little bit about the rate of distribution. What is a relevant time period to discussing the impact of this accident?
   a. [Added question for clarity, if necessary] How long before we see a significant impact on the environment?
   b. How long does the impact last?
4. If we want to represent the significant impact of this environmental problem [refer to time period participant named above] after its introduction, which of these maps would be most useful. [Present maps on scales of immediate area, landscape, city, county, state, country, continent, world]
   a. [Added question for clarity, if necessary] Is it going to affect the city, county, state, etc.?
   b. How did you decide on that scale?
5. [Present 3 blank maps of the scale chosen in the last question]
   Imagine these maps are meant to display the impact of this environmental problem at different time periods [name half of time period mentioned in Question 3, time period mentioned in Question 3, twice time period mentioned in Question 3]. Can you outline the area where there will be a significant impact after [half of time period]? Can you outline the area where there will be a significant impact after [time period]? Can you outline the area where there will be a significant impact after [twice time period]?
6. Just a moment ago, we discussed the spatial information you would need to consider this problem. Is that different than what a student might need?
7. What spatial thinking skills would be necessary for a student to understand this environmental problem?

Transition: Now that we have discussed some of your ideas about the spatial thinking skills necessary to understanding a couple of environmental problems, I want to share with you some spatial thinking abilities that have been identified in the literature. We will use them to take another look at these environmental problems.
e. Selected response-Spatial thinking for environmental problems
   i. Taking a look at the group of spatial thinking skills here [present list], are there any that surprise you, need clarification, or that stand out as particularly important?
   ii. Now, we are going to go back to the first example. I am going to provide you with a list of spatial thinking abilities (provide handout), as they have been described in the literature. Name the five spatial thinking abilities you think are the most critical to understanding this environmental problem.
   iii. For the second example, use the same list provided, name five spatial thinking abilities you think are the most critical to understanding this environmental problem.

f. Closing
   i. What other insights that might help us think about how to help students think spatially about environmental problems would you like to share?
   ii. Do you have any final questions for me?
   iii. Thank you for your time. We really appreciate your insights.
Spatial thinking abilities handout to be provided to participant to complete Section e.

Mental rotation of two and three dimensional objects

Recognize spatial distributions and spatial patterns

Identifying anomalies to the regular pattern of characteristics in the landscape.

Associate and correlate spatially distributed phenomena

Determining spatial relationships relative to oneself

Orientate to spatial phenomena to real-world frames of reference

Imagine maps from verbal descriptions

Sketch map

Compare maps

Overlay and dissolve maps

Designing and using a spatial model

Describing features of attributes of a location

Tracing how a place is linked to other places

Understanding how places are similar and different

Understanding the effect a feature or characteristic may have on the area that surrounds it

Understanding how to group locations based on their similarities

Understanding how an area fits in to a nested hierarchy of areas

Understanding how the landscape transitions from one condition to another

Understanding how places that are not connected are similar to each other.
Appendix B: Survey Administered to Environmental Education Experts

Email Invitation and Reminder Schedule

<table>
<thead>
<tr>
<th>Email</th>
<th>Time Frame</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prenotification</td>
<td>Day 1</td>
</tr>
<tr>
<td>Survey Link</td>
<td>3 days after Prenotification</td>
</tr>
<tr>
<td>Reminder #1</td>
<td>1 week after Survey Link</td>
</tr>
<tr>
<td>Reminder #2</td>
<td>2 weeks after Reminder #1</td>
</tr>
<tr>
<td>Reminder #3</td>
<td>1 week after Reminder #2</td>
</tr>
</tbody>
</table>

Prenotification

Dear __________,

I am a graduate student at the University of Nevada, Las Vegas, writing to you today to ask for your help with a dissertation project that focuses on the spatial thinking abilities that might be useful to students’ understanding of environmental issues. My goal is to develop an instrument to assess spatial thinking abilities in novice students, first using enhanced greenhouse effect as an example environmental issue.

As an educator and a member of the North American Association for Environmental Education, I value your perspective and expertise in environmental education and would like to ask you to participate in an online survey that will inform the design of this instrument. Your input will be extremely helpful to the project.

I am writing in advance so you will recognize the request when it comes in just a few days and will be less likely to delete it.

Your generous participation in this study will help ensure its success. Thank you in advance for your time and consideration.

Sincerely,

Heather Skaza
Department of Physical Sciences
College of Southern Nevada
6375 W. Charleston Blvd. H201
Las Vegas, NV 89146
heather.skaza@csn.edu
702-417-9030
Dear __________,

I am a graduate student at the University of Nevada, Las Vegas, writing to request your help with a survey I am conducting about the spatial thinking abilities students should use to understand environmental problems. The information collected will be used in the completion of my dissertation research. As indicated in the previous email, my goal is to design an instrument that will assess students’ spatial thinking abilities in environmental education.

In order to know which spatial thinking skills are most important to new environmental science students, I am reaching out to experts in the field of environmental education to participate in a survey titled, "Spatial Thinking for Environmental Problem Solving." I believe that your input will be invaluable to this study and invite you to participate in an online survey that will take approximately 30 minutes. The survey can be found at:

<link>

Your input would be greatly appreciated. Should you have any questions, please feel free to contact me at heather.skaza@csn.edu, or my graduate program advisor and principle investigator on the project, Dr. MaryKay Orgill at marykay.orgill@unlv.edu.

Thank you in advance for your participation,

Heather Skaza
Department of Physical Sciences
College of Southern Nevada
6375 W. Charleston Blvd. H201
Las Vegas, NV 89146
heather.skaza@csn.edu
702-417-9030

MaryKay Orgill, Ph.D.
Associate Professor
Department of Chemistry & Biochemistry
Mail Stop 4003
University of Nevada, Las Vegas
4505 S. Maryland Parkway
Las Vegas, NV 89154-4003
phone: (702) 895-3580
fax: (702) 895-4072
e-mail: marykay.orgill@unlv.edu
Reminder #1

Hello ____________,

Last week an online survey was sent to you regarding the spatial thinking skills of environmental science students.

If you have already taken the time to complete the questionnaire, thank you very much. If you have not completed the questionnaire, we hope that you will do so today by clicking on the following link:

<link>

We are very appreciative for your help, because it is only by receiving information from educators like you that we can gain a better understanding of the ways in which students understand environmental issues.

Again, thank you for your time and attention.

Heather Skaza  
Department of Physical Sciences  
College of Southern Nevada  
6375 W. Charleston Blvd. H201  
Las Vegas, NV 89146  
heather.skaza@csn.edu  
702-417-9030
Reminder #2

Dear __________,

A few weeks ago you were notified of a survey about the spatial thinking skills of environmental science students. If you have completed the survey, thank you for your participation. If you have yet to complete it, we hope that you will consider participating. We anticipate the results will be useful in helping us understand how novice students learn about environmental issues, which will ultimately inform the design of an instrument to measure students’ spatial thinking skills.

We are writing again because of the importance your response plays in obtaining accurate results. The more environmental educators we hear from, the more confident we can be that our results are truly representative of the expertise in the group.

Please consider competing the survey, which you can access via the secure link below.

<link>

Thank you again for your consideration,

Heather Skaza
Department of Physical Sciences
College of Southern Nevada
6375 W. Charleston Blvd. H201
Las Vegas, NV 89146
heather.skaza@csn.edu
702-417-9030
Reminder #3

Dear __________,

During the past month you have received several emails about a survey. The purpose of this study is to expand our understanding of how environmental science students think spatially about environmental problems like enhanced greenhouse effect. The study is drawing to a close and this is your final opportunity to participate. You were selected to participate in this study based on your expertise as an environmental educator. Your input is critical to obtaining accurate results. I hope that you will still consider participating. Click on the following link to access the survey:

<Link>

Thank you again for your time and consideration. Hope to hear from you soon!

Heather Skaza  
Department of Physical Sciences  
College of Southern Nevada  
6375 W. Charleston Blvd. H201  
Las Vegas, NV 89146  
heather.skaza@csn.edu  
702-417-9030
Spatial Thinking for Environmental Education

Thank you for participating. As environmental education experts, your input is critical to our understanding of how learners begin to think about the environment and their relationship to it. This survey is intended to elicit your perspective on the spatial thinking skills necessary for novice students to understand complex environmental issues. We use enhanced greenhouse effect as an example.

The survey has three parts. First, you will be asked about your role as an environmental educator and your general understanding of spatial thinking. Part 2 asks for your input about the general spatial thinking abilities that might be useful to a novice students trying to understand enhanced greenhouse effect. The questions in Part 3 asks you to identify spatial information novice students need to understand specific concepts that are connected to enhanced greenhouse effect.

There are no "right" answers. We are simply trying to gain expert perspectives to inform the future development of an instrument to assess learners’ spatial thinking abilities applied to understanding enhanced greenhouse effect. In order to develop such an instrument, it is important to know which spatial thinking skills are most important to understanding. The survey should take no more than 45 minutes.

Thank you again for your participation in this research.

PART 1: GENERAL INFORMATION
Your answers to the questions on this page will tell us a little more about who you are and your general ideas about spatial thinking.

1. What is your role in environmental education?
   Please select all that apply
   Check all that apply.
   [ ] Teacher
   [ ] Researcher
   [ ] Student
   [ ] Curriculum Developer
   [ ] Administrator
   [ ] Other: ____________________________
2. What is the primary grade/age group of the learners with whom you interact?

Please select all that apply:
Check all that apply.

☐ Pre-school students (~0-4 years)
☐ Elementary students (~5-10 years)
☐ Middle school students (~11-13 years)
☐ High school students (~14-18 years)
☐ Adults
☐ I work with all ages
☐ Other: ____________________________

3. How long have you worked in environmental education?

Mark only one oval.

☐ <1 year
☐ 1-5 years
☐ 5-10 years
☐ >10 years

4. Please describe your area of expertise in environmental education.

________________________________________
________________________________________
________________________________________
________________________________________

5. Are you familiar with the concepts of spatial thinking or spatial reasoning?

Mark only one oval.

☐ I am very familiar with those concepts.
☐ I am somewhat familiar with those concepts.
☐ I am not very familiar with those concepts.
☐ I have never heard of spatial thinking or spatial reasoning.

PART 2: GENERAL SPATIAL THINKING ABILITIES

This section includes a list of spatial thinking skills that other educators identified as important to understanding general scientific concepts.

As experts in environmental education, please rank how important each spatial thinking skill is to understanding enhanced greenhouse effect.
### 6. SKILLS RELATED TO VISUALIZATION AND DIMENSIONAL THINKING

*Mark only one oval per row.*

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<th>Not very important</th>
<th>Somewhat important</th>
<th>Extremely important</th>
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<tbody>
<tr>
<td>Creating or visualizing a two-dimensional image</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
</tr>
<tr>
<td>Translating from two dimensional to three dimensional understanding and vice versa</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
</tr>
<tr>
<td>Understanding multiple perspectives of one object/phenomena</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
</tr>
<tr>
<td>Mentally rotating objects</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
</tr>
<tr>
<td>Translating mathematical data into visualization</td>
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</tbody>
</table>

### 7. SKILLS RELATED TO SPATIAL UNDERSTANDING OF PATTERNS

*Mark only one oval per row.*

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<thead>
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<th>Not very important</th>
<th>Somewhat important</th>
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<tr>
<td>Recognizing patterns</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
</tr>
<tr>
<td>Identifying anomalies to the regular pattern of characteristics in the landscape</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
</tr>
<tr>
<td>Understanding heterogenetic environment</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
</tr>
<tr>
<td>Associating and correlating spatially distributed phenomena</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
</tr>
</tbody>
</table>
8. SPATIAL SKILLS USED TO UNDERSTAND PLACE AND RELATIVE SPACE
Mark only one oval per row.

<table>
<thead>
<tr>
<th>Activity</th>
<th>Not important at all</th>
<th>Not very important</th>
<th>Somewhat important</th>
<th>Very important</th>
</tr>
</thead>
<tbody>
<tr>
<td>Determining spatial relationships relative to oneself</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Orienting spatial phenomena to real-world frames of reference</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Describing features of attributes of a location</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tracing how a place is linked to other places</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Understanding how places are similar and different</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Understanding the effect a feature or characteristic may have on the area that surrounds it</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Understanding how to group locations based on their similarities</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Understanding how an area fits in to a nested hierarchy of areas</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Understanding how the landscape transitions from one condition to another</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Understanding how places that are not connected are similar to each other</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

9. SPATIAL THINKING SKILLS USED TO UNDERSTAND DATA AND REPRESENT DATA
Mark only one oval per row.

<table>
<thead>
<tr>
<th>Activity</th>
<th>Not important at all</th>
<th>Not very important</th>
<th>Somewhat important</th>
<th>Extremely important</th>
</tr>
</thead>
<tbody>
<tr>
<td>Integrating multiple types of data/information</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thinking across scales of data</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Imagining maps from verbal descriptions</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sketching maps</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Comparing maps</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Overlaying and dissolving maps</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Designing and using a spatial model</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
10. MATTER
Mark only one oval per row.

<table>
<thead>
<tr>
<th>Not important at all</th>
<th>Not very important</th>
<th>Somewhat important</th>
<th>Extremely important</th>
</tr>
</thead>
<tbody>
<tr>
<td>Understanding movement of matter in environment</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Estimating amounts and sizes</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

11. Please name and describe any additional spatial thinking skills, not included above, that you feel are critical to students’ understanding of enhanced greenhouse effect.

________________________________________________________________________
________________________________________________________________________
________________________________________________________________________
________________________________________________________________________

PART 3: SPATIAL INFORMATION IMPORTANT TO UNDERSTANDING ENHANCED GREENHOUSE EFFECT

Researchers from various science disciplines identified the following spatial information as important to understanding enhanced greenhouse effect; however these researchers were not experts in environmental education.

As an environmental educator, your input is very important to our understanding. Please rank the importance of each type of spatial information listed below to understanding enhanced greenhouse effect.

12. SPATIAL INFORMATION ABOUT THE ATMOSPHERE
Mark only one oval per row.

<table>
<thead>
<tr>
<th>Not important at all</th>
<th>Not very important</th>
<th>Somewhat important</th>
<th>Extremely important</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location of the atmosphere</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Size of the atmosphere</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Movement of air in the atmosphere</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Movement of the Earth</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
13. SPATIAL INFORMATION ABOUT RADIATION

Mark only one oval per row.

<table>
<thead>
<tr>
<th></th>
<th>Not important at all</th>
<th>Somewhat important</th>
<th>Extremely important</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mechanism of greenhouse gas absorption of radiation from the sun</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Movement of sun’s radiation</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>How much energy is absorbed as a function of time</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Temperature model resulting from absorbed radiation</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Interaction of greenhouse gases and radiant energy</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>How radiant energy is trapped and accumulates in the atmosphere</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Equilibrium of radiant energy as it enters and leaves the atmosphere</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>How the equilibrium of radiant energy changes</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>How radiation moves to the Earth from the sun</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>
### 14. Spatial Information about Greenhouse Gases

*Mark only one oval per row.*

<table>
<thead>
<tr>
<th>Topic</th>
<th>Not important at all</th>
<th>Not very important</th>
<th>Somewhat important</th>
<th>Extremely important</th>
</tr>
</thead>
<tbody>
<tr>
<td>How greenhouse gases circulate in the atmosphere</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>The amount of greenhouse gases that are emitted from various sources</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A spatial understanding of the carbon cycle</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>How fossil fuels move around on the Earth and in the atmosphere</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>The distribution of greenhouse gas emission sources</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>How greenhouse gases accumulate in the atmosphere</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>How emissions accumulate from driving a car</td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>The volume of greenhouse gases in the atmosphere</td>
<td></td>
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<tr>
<td>The concentration of greenhouse gases in the atmosphere</td>
<td></td>
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<tr>
<td>The stratification of greenhouse gases in the atmosphere</td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>The proportion of greenhouse gases to atmosphere</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Interaction of carbon dioxide and plants</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>The relationship between greenhouse gases and temperature</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>
15. **SPATIAL INFORMATION ABOUT THE IMPACTS OF ENHANCED GREENHOUSE EFFECT**

*Mark only one oval per row.*

<table>
<thead>
<tr>
<th></th>
<th>Not important at all</th>
<th>Not very important</th>
<th>Somewhat important</th>
<th>Very important</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spatial understanding of impacts, like sea level rise</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Topography of sea level rise (i.e. that it won't rise uniformly)</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Impact of enhanced greenhouse effect on daily life</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Local examples of impact of enhanced greenhouse effect</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>That glaciers are retreating due to increased global average temperature</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Understanding how a map can represent an impact of enhanced greenhouse effect</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
16. SPATIAL INFORMATION RELATED TO SCALE
Mark only one oval per row.

<table>
<thead>
<tr>
<th></th>
<th>Not important at all</th>
<th>Not very important</th>
<th>Somewhat important</th>
<th>Extremely important</th>
</tr>
</thead>
<tbody>
<tr>
<td>How to connect the scales of enhanced greenhouse effect phenomena and impacts: molecules to large atmosphere</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>What enhanced greenhouse effect phenomena and impacts occur at a molecular scale</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>The local and distant interconnections to enhanced greenhouse effect</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Impact of enhanced greenhouse effect on a global scale</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Local examples of impact of enhanced greenhouse effect</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Holistic perspective on impacts of enhanced greenhouse effect</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A map of enhanced greenhouse effect phenomena and impacts in their own location</td>
<td></td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

17. Please name and describe any additional spatial information or understanding, not named above, that you feel is critical to students’ understanding of enhanced greenhouse effect.

____________________________________________________________________________________
____________________________________________________________________________________
____________________________________________________________________________________
____________________________________________________________________________________
____________________________________________________________________________________
Appendix C: Frequency of Environmental Education Expert Support for General and Contextualized Spatial Thinking Skills

Table 3

Frequency of Environmental Education Expert Support for General and Contextualized Spatial Thinking Skills

<table>
<thead>
<tr>
<th>Spatial thinking ability</th>
<th>Mode</th>
<th>Frequency by percentage (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>(Not important at all, Not very important, Somewhat important, Very important)</td>
</tr>
<tr>
<td>Part 1: Visualization and dimensional thinking</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Two dimensional imaging</td>
<td>2</td>
<td>3.70, 14.81, 51.85, 29.63</td>
</tr>
<tr>
<td>Translating from two-dimensional to three-dimensional understanding and vice versa</td>
<td>3</td>
<td>3.70, 3.70, 37.04, 55.56</td>
</tr>
<tr>
<td>Understanding multiple perspectives of one object or phenomena.</td>
<td>3</td>
<td>0.00, 0.00, 38.46, 61.54</td>
</tr>
<tr>
<td>Mental rotation</td>
<td>2</td>
<td>3.70, 22.22, 51.85, 22.22</td>
</tr>
<tr>
<td>Translating mathematical data into visualization</td>
<td>2</td>
<td>0.00, 0.00 62.96, 37.04</td>
</tr>
<tr>
<td>Part 1: Patterns</td>
<td></td>
<td></td>
</tr>
<tr>
<td>*Recognizing patterns</td>
<td>3</td>
<td>0.00, 3.70 11.11, 85.19</td>
</tr>
<tr>
<td>Identifying anomalies to the regular pattern of characteristics in the landscape</td>
<td>3</td>
<td>0.00, 3.70, 22.22, 74.07</td>
</tr>
<tr>
<td>Understanding heterogenetic environment</td>
<td>2</td>
<td>3.85, 15.38, 50.00, 30.77</td>
</tr>
<tr>
<td>Associate and correlate spatially distributed phenomena</td>
<td>3</td>
<td>0.00, 7.69, 34.62, 57.69</td>
</tr>
<tr>
<td>Part 1: Understanding of place and relative space</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Determining spatial relationships relative to oneself</td>
<td>3</td>
<td>0.00, 7.69, 34.62, 57.69</td>
</tr>
<tr>
<td>Orientate spatial phenomena to real–world frames of reference</td>
<td>3</td>
<td>0.00, 11.11, 22.22, 66.67</td>
</tr>
<tr>
<td>Describing features of attributes of a location</td>
<td>3</td>
<td>0.00, 11.11, 33.33, 55.56</td>
</tr>
<tr>
<td>Tracing how a place is linked to other places</td>
<td>3</td>
<td>0.00, 3.70, 22.22, 74.07</td>
</tr>
<tr>
<td>Understanding how places are similar and different</td>
<td>3</td>
<td>0.00, 0.00, 29.63, 70.37</td>
</tr>
<tr>
<td>Understanding the effect a feature or characteristic may have on the area that surrounds it</td>
<td>3</td>
<td>0.00, 0.00, 25.93, 74.07</td>
</tr>
<tr>
<td>Understanding how to group locations based on their similarities</td>
<td>2</td>
<td>0.00, 3.70, 48.15, 48.15</td>
</tr>
<tr>
<td>Understanding how an area fits in to a nested hierarchy of areas</td>
<td>2</td>
<td>3.85, 3.85, 57.89, 34.62</td>
</tr>
<tr>
<td>Activity</td>
<td>Value</td>
<td></td>
</tr>
<tr>
<td>--------------------------------------------------------------------------</td>
<td>----------------</td>
<td></td>
</tr>
<tr>
<td>Understanding how the landscape transitions from one condition to another</td>
<td>3, 0.00, 3.85, 42.31, 53.85</td>
<td></td>
</tr>
<tr>
<td>Understanding how places that are not connected are similar to each other</td>
<td>3, 0.00, 7.41, 37.04, 55.56</td>
<td></td>
</tr>
</tbody>
</table>

### Part 1: Data and representing data

<table>
<thead>
<tr>
<th>Activity</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Integrating multiple types of data/information</td>
<td>3, 0.00, 0.00, 44.44, 55.56</td>
</tr>
<tr>
<td>Thinking across scales of data</td>
<td>3, 0.00, 11.11, 37.04, 51.85</td>
</tr>
<tr>
<td>Imagine maps from verbal descriptions</td>
<td>2, 3.70, 11.11, 51.85, 33.33</td>
</tr>
<tr>
<td>Sketch maps</td>
<td>2, 3.70, 7.41, 55.56, 33.33</td>
</tr>
<tr>
<td>Compare maps</td>
<td>3, 0.00, 3.70, 33.33, 62.96</td>
</tr>
<tr>
<td>Overlay and dissolve maps</td>
<td>2, 3.70, 14.81, 44.44, 37.04</td>
</tr>
<tr>
<td>Designing and using a spatial model</td>
<td>2, 0.00, 11.11, 51.85, 37.04</td>
</tr>
</tbody>
</table>

### Part 1: Matter

<table>
<thead>
<tr>
<th>Activity</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Understanding movement of matter in environment</td>
<td>3, 0.00, 0.00, 26.92, 73.08</td>
</tr>
<tr>
<td>Estimating amounts and sizes</td>
<td>3, 0.00, 3.70, 48.15, 48.15</td>
</tr>
</tbody>
</table>

### Part 2: Atmosphere

<table>
<thead>
<tr>
<th>Activity</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location of the atmosphere</td>
<td>3, 0.00, 3.70, 33.33, 62.96</td>
</tr>
<tr>
<td>Size of the atmosphere</td>
<td>2, 0.00, 14.81, 44.44, 40.74</td>
</tr>
<tr>
<td>Understand movement of air in the atmosphere</td>
<td>3, 0.00, 3.70, 29.63, 66.67</td>
</tr>
<tr>
<td>Movement of the Earth</td>
<td>3, 0.00, 3.70, 37.04, 59.26</td>
</tr>
</tbody>
</table>

### Part 2: Radiation

<table>
<thead>
<tr>
<th>Activity</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mechanism of greenhouse gas absorption of radiation from the sun</td>
<td>3, 0.00, 0.00, 37.04, 62.96</td>
</tr>
<tr>
<td>Movement of sun’s radiation</td>
<td>3, 7.41, 0.00, 44.44, 48.15</td>
</tr>
<tr>
<td>How much energy is absorbed as a function of time</td>
<td>3, 3.70, 0.00, 44.44, 51.85</td>
</tr>
<tr>
<td>Temperature model resulting from absorbed radiation</td>
<td>3, 7.41, 0.00, 37.04, 55.56</td>
</tr>
<tr>
<td>Interaction of greenhouse gas and radiant energy</td>
<td>3, 0.00, 0.00, 26.92, 73.08</td>
</tr>
<tr>
<td>*Accumulation of trapped radiant energy</td>
<td>3, 3.70, 0.00, 11.11, 85.19</td>
</tr>
<tr>
<td>Equilibrium of radiant energy</td>
<td>3, 3.70, 0.00, 29.63, 66.67</td>
</tr>
<tr>
<td>Change of equilibrium of radiant energy</td>
<td>3, 3.70, 0.00, 37.04, 59.26</td>
</tr>
<tr>
<td>Visualize the radiation relationship between Earth and sun</td>
<td>3, 3.70, 0.00, 33.33, 62.96</td>
</tr>
</tbody>
</table>

### Part 2: Greenhouse Gases
<table>
<thead>
<tr>
<th>Topic</th>
<th>Scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>Visualization of greenhouse gases circulating in the atmosphere</td>
<td>3</td>
</tr>
<tr>
<td>*Understand an amount of emissions</td>
<td>3</td>
</tr>
<tr>
<td>Understanding that the carbon cycle occurs in space</td>
<td>3</td>
</tr>
<tr>
<td>Visualization of fossil fuels movement</td>
<td>3</td>
</tr>
<tr>
<td>Distribution of where emissions are coming from</td>
<td>3</td>
</tr>
<tr>
<td>*Accumulation of greenhouse gases from emissions</td>
<td>3</td>
</tr>
<tr>
<td>Using everyday understanding of cars driving to understand where emissions come from</td>
<td>3</td>
</tr>
<tr>
<td>Volume of greenhouse gases</td>
<td>3</td>
</tr>
<tr>
<td>Concentration of greenhouse gases</td>
<td>3</td>
</tr>
<tr>
<td>Stratification of greenhouse gases</td>
<td>2</td>
</tr>
<tr>
<td>Proportion of greenhouse gases to atmosphere</td>
<td>3</td>
</tr>
<tr>
<td>*Interaction of carbon dioxide and plants</td>
<td>3</td>
</tr>
<tr>
<td>*Relationship between greenhouse gases and temperature</td>
<td>3</td>
</tr>
<tr>
<td>Part 2: Impacts</td>
<td></td>
</tr>
<tr>
<td>Spatial understanding of impacts like sea level rise</td>
<td>3</td>
</tr>
<tr>
<td>Topography of sea level rise (it won’t rise uniformly)</td>
<td>3</td>
</tr>
<tr>
<td>*Impact of enhanced greenhouse effect on daily life</td>
<td>3</td>
</tr>
<tr>
<td>*Local examples of impact of enhanced greenhouse effect</td>
<td>3</td>
</tr>
<tr>
<td>Retreat of glaciers</td>
<td>3</td>
</tr>
<tr>
<td>Maps of impact of enhanced greenhouse effect</td>
<td>3</td>
</tr>
<tr>
<td>Part 2: Scale</td>
<td></td>
</tr>
<tr>
<td>Connect scales (molecules to large atmosphere)</td>
<td>2</td>
</tr>
<tr>
<td>Molecule scale perspective</td>
<td>2</td>
</tr>
<tr>
<td>Start local and move to interconnected factors</td>
<td>3</td>
</tr>
<tr>
<td>Impact of enhanced greenhouse effect on a global scale</td>
<td>3</td>
</tr>
<tr>
<td>*Local examples of impact of enhanced greenhouse effect</td>
<td>3</td>
</tr>
<tr>
<td>Holistic perspective on impacts of enhanced greenhouse effect</td>
<td>3</td>
</tr>
<tr>
<td>Understanding a map of their own location</td>
<td>3</td>
</tr>
</tbody>
</table>

**Note:** An asterisk indicates items 80 percent or more of the survey participants selected as “Very important.”
Appendix D: The First Draft of the STA-En GreenE Assessment

PART 1: CARBON DIOXIDE EMISSIONS

The map to the right depicts a familiar landscape. This is the West Charleston campus of the College of Southern Nevada, bordered by Charleston Blvd. to the north, Oakley Blvd. to the south, Torrey Pines Dr. to the west, and Jones Blvd.

1. Using the map on the last page, circle everything that you can identify that emits carbon dioxide.

2. Using the same map, put a square around anything that you understand to absorb carbon dioxide from the atmosphere.

3. In the space below, describe any conclusions you come to or observations that you can make by looking at the model that you have created here.
Carbon Dioxide in the Year 1500

1. It is the year 1500. Using the landscape model to the right as your starting point, identify or draw in sources of carbon dioxide as they might have been during this time.

2. Continuing to use the model you are building to the right, represent which of the emission sources you represented are a large emission sources and which are smaller sources of carbon dioxide emissions.

3. It is still the year 1500. Now, identify or draw in the things in the landscape that absorb carbon, as they might have been during this time.

4. Using what you represented as carbon absorbers, represent which of the absorbers you represented absorb large amounts of carbon and which absorb smaller amounts.

5. Represent the relationship between emissions and absorption at this point in history. Which one is bigger, smaller, or are they the same?

6. You have drawn, written about, or represented carbon dioxide emissions and absorption in a year 1500 landscape. Imagine how carbon dioxide is moving around in this system. Now draw or somehow represent how you imagine the carbon dioxide to move around or collect in this world.
Carbon Dioxide in the Year 2000

1. It is the year 2000. Using the landscape model to the right as your starting point, identify or draw in sources of carbon dioxide as they might have been during this time.

2. Continuing to use the model you are building to the right, represent which of the emission sources you represented are a large emission sources and which are smaller sources of carbon dioxide emissions.

3. It is still the year 2000. Now, identify or draw in the things in the landscape that absorb carbon, as they might have been during this time.

4. Using what you represented as carbon absorbers, represent which of the absorbers you represented absorb large amounts of carbon and which absorb smaller amounts.

5. Represent the relationship between emissions and absorption at this point in history. Which one is bigger, smaller, or are they the same?

6. You have drawn, written about, or represented carbon dioxide emissions and absorption in a year 2000 landscape. Imagine how carbon dioxide is moving around in this system. Now draw or somehow represent how you imagine the carbon dioxide to move around or collect in this world.

Based on your representations above, what can you say about carbon dioxide in the atmosphere in 1500 and in the year 2000?
PART 2: RADIATION AND GREENHOUSE EFFECT

For the diagram and questions below, consider the Earth/Sun system in the YEAR 1500.

1. Using the Earth horizon image above (A) as a starting point, represent the Earth’s atmosphere with as much detail as you can.
2. Now, in the model that you have created in image (A), represent greenhouse gases and where they exist in this Earth/Sun system in the year 1500.
3. Imagine the cutout square on the right (B) is a lens that we can use to see greenhouse gases in the atmosphere. In that square, represent greenhouse gases in the atmosphere, as you understand them to be.
4. How does energy move around in the Earth/Sun system? Represent energy in the Earth/Sun system (A), as you understand it. Demonstrate:
   a. All of the places energy might come from and all of the places where it might go.
   b. If it is a lot or a little bit of energy in the place you represent.
5. In the greenhouse gas viewing box (B), represent energy in the presence of greenhouse gas. What is energy doing and how does it move?
6. Using the model that you have created above, what can you say about greenhouse effect in the year 1500? Include in your answer, written below, a discussion of the effects on temperature.
Now, let's consider the Earth/Sun system in the **YEAR 2000**.

1. Using the Earth horizon image above (A) as a starting point, represent the Earth's atmosphere with as much detail as you can.
2. Now, in the model that you have created in image (A), represent carbon dioxide and where it exists in the Earth/Sun system in the year 2000.
3. Imagine the cutout square on the right (B) is a lens that we can use to see greenhouse gases in the atmosphere. In that square, represent greenhouse gases in the atmosphere, as you understand them to be.
4. How does energy move around in the Earth/Sun system? Represent energy in the Earth/Sun system (A), as you understand it. Demonstrate:
   a. All of the places energy might come from and all of the places where it might go.
   b. If it is a lot or a little bit of energy in the place you represent.
5. In the greenhouse gas viewing box (B), represent energy in the presence of greenhouse gas. What is energy doing and how does it move?
6. Using the model that you have created above, what can you say about greenhouse effect in the year 2000? Include in your answer, written below, a discussion of the effects on temperature.
PART 1: CARBON DIOXIDE IN THE ATMOSPHERE

Carbon Dioxide at Home
The map to the right depicts a familiar landscape. This is the West Charleston campus of the College of Southern Nevada, bordered by Charleston Blvd. to the north, Oakey Blvd. to the south, Torrey Pines Dr. to the west, and Jones Blvd.

1. Using the map, circle everything that you think emits carbon dioxide into the atmosphere. In the space below, describe why you circled the things that you did.

2. Using the same map, put a square around anything that you think absorbs carbon dioxide from the atmosphere. In the space below, describe why you put a square around the things that you did.

3. In the space below, describe any conclusions you come to or observations that you can make about carbon in the atmosphere by looking at the model that you have created here.
**Carbon Dioxide in the Year 1500**

1. Pretend it is the year 1500. Using the landscape model to the right as your starting point, indicate on the model or draw in sources of carbon dioxide as they might have been during the year 1500.

2. Continuing to use the model you are building to the right, place a star next to the biggest source of carbon dioxide emission in the year 1500.

3. It is still the year 1500. Now, indicate on the model or draw in the things in the landscape that absorb carbon, as they might have been during the year 1500.

4. Using the model you have built here, place a star next to the things that you think are the biggest absorbers of carbon dioxide at this time.

5. In the space below, describe the relationship between emissions and absorption at this point in history. Which one is bigger, smaller, or are they the same? Why?

6. You have drawn, written about, or represented carbon dioxide emissions and absorption in a year 1500 landscape. Visualize carbon dioxide moving around in this system. Now, on the diagram, draw how you imagine the carbon dioxide to move around or collect in this atmosphere.
PART 2: RADIATION AND GREENHOUSE EFFECT

For the diagram and questions below, consider the Earth/Sun system in the YEAR 1500.

1. Using the Earth horizon image above (A) as a starting point, represent the Earth’s atmosphere with as much detail as you can.
2. Now, in the model that you have created in image (A), represent greenhouse gases and where they exist in this Earth/Sun system in the year 1500.
3. Imagine the cutout square on the right (B) is a lens that we can use to see greenhouse gases in the atmosphere. In that square, represent greenhouse gases in the atmosphere, as you understand them to be.
4. How does energy move around in the Earth/Sun system? Represent energy in the Earth/Sun system (A), as you understand it. Demonstrate:
   a. All of the places energy might come from and all of the places where it might go.
   b. If it is a lot or a little bit of energy in the place you represent.
5. In the greenhouse gas viewing box (B), represent energy and greenhouse gases. What is energy doing and how does it move?
6. What can you say about greenhouse effect or enhanced greenhouse effect in the year 1500? Write your answer below and include a discussion of the effects on temperature.
Now, let’s consider the Earth/Sun system in the **YEAR 2000**.

1. Using the Earth horizon image above (A) as a starting point, represent the Earth’s atmosphere with as much detail as you can.
2. Now, in the model that you have created in image (A), represent carbon dioxide and where it exists in this Earth/Sun system in the year 2000.
3. Imagine the cutout square on the right (B) is a lens that we can use to see greenhouse gases in the atmosphere. In that square, represent greenhouse gases in the atmosphere, as you understand them to be.
4. How does energy move around in the Earth/Sun system? Represent energy in the Earth/Sun system (A), as you understand it. Demonstrate:
   a. All of the places energy might come from and all of the places where it might go.
   b. If it is a lot or a little bit of energy in the place you represent.
5. In the greenhouse gas viewing box (B), represent energy and greenhouse gases. What is energy doing and how does it move?
6. What can you say about greenhouse effect or enhanced greenhouse effect in the year 2000? Write your answer below and include a discussion of the effects on temperature.
Appendix F. Final Revisions of the STA-En GreenE Assessment Informed by Cognitive Interview and Pilot Study

PART 1: CARBON DIOXIDE IN THE ATMOSPHERE

Carbon Dioxide at Home
The map to the right depicts a familiar landscape. This is the West Charleston campus of the College of Southern Nevada, bordered by Charleston Blvd. to the north, Oakey Blvd. to the south, Torrey Pines Dr. to the west, and Jones Blvd.

1. Using the map, circle everything that you think emits carbon dioxide into the atmosphere. In the space below, describe why you circled the things that you did.

2. Using the same map, put a square around anything that you think absorbs carbon dioxide from the atmosphere. In the space below, describe why you put a square around the things that you did.

3. In the space below, describe any conclusions you come to or observations that you can make about carbon in the atmosphere by looking at the model that you have created here.
Carbon Dioxide in the Year 1500

1. Pretend it is the year 1500, right around the time that Christopher Columbus made his expedition across the Atlantic. Most work is still done with human and animal energy.

   Using the landscape model to the right as your starting point, indicate on the model or draw in sources of carbon dioxide as they might have been during the year 1500. There is no one correct way to model this, so just model your understanding in a way that makes sense to you.

2. Continuing to use the model you are building to the right, place a star next to the biggest source of carbon dioxide emission in the year 1500.

3. It is still the year 1500. Now, indicate on the model or draw in the things in the landscape that absorb carbon, as they might have been during the year 1500.

4. Using the model you have built here, place a star next to the things that you think are the biggest absorbers of carbon dioxide at this time.

5. In the space below, describe the relationship between emissions and absorption at this point in history. Which one is bigger, smaller, or are they the same? Why?

6. You have drawn, written about, or represented carbon dioxide emissions and absorption in a year 1500 landscape. Visualize carbon dioxide moving around in this system. Now, on the diagram, draw how you imagine the carbon dioxide to move around or collect in this atmosphere.
Carbon Dioxide in the Year 2000

1. Now, pretend it is the year 2000. Using the landscape model to the right as your starting point, indicate on the model or draw in sources of carbon dioxide as they might have been during this time. There is no one correct way to model this, so just model your understanding in a way that makes sense to you.

2. Continuing to use the model you are building to the right, place a star next to the carbon dioxide emission sources that you think are the biggest sources during this time.

3. It is still the year 2000. Now, indicate on the model or draw in the things in the landscape that absorb carbon, as they might have been during this time.

4. Using the model you have built here, place a star next to the ones that you think are the biggest absorbers of carbon dioxide at this time.

5. In the space below, describe the relationship between emissions and absorption at this point in history. Which one is bigger, smaller, or are they the same? Why?

6. You have drawn, written about, or represented carbon dioxide emissions and absorption in a year 2000 landscape. Visualize carbon dioxide moving around in this system. Now, on the diagram, draw how you imagine the carbon dioxide to move around or collect in this atmosphere.

Based on your representations above, what can you say about carbon dioxide in the atmosphere in 1500 and in the year 2000?
PART 2: THE ATMOSPHERE

Using the Earth horizon image BELOW (A) as a starting point, represent the Earth's atmosphere with as much detail as you can.
PART 3: RADIATION AND GREENHOUSE EFFECT
FOR THE MODELING SPACE AND THE PROMPTS BELOW, CONSIDER THE EARTH/SUN SYSTEM FOR A NATURAL GREENHOUSE EFFECT.

1. Now, in the large model space above (A), represent greenhouse gases and where they exist in this Earth/Sun system for a natural greenhouse effect.
2. Imagine the cutout square on the right (B) is a lens that we can use to see the gases in the atmosphere. In that square, represent gases in the atmosphere, including greenhouse gases, as you understand them to be for a natural greenhouse effect.
3. How does energy move around in the Earth/Sun system? Represent energy in the Earth/Sun system (A), as you understand it. Demonstrate all of the places energy might come from and all of the places where it might go.
4. In the greenhouse gas viewing box (B), represent energy and greenhouse gases. What is energy doing and how does it move?
5. What can you say about greenhouse effect or enhanced greenhouse effect in the year 1500? Write your answer below and include a discussion of the effects on temperature.
NOW, LET'S CONSIDER THE EARTH/SUN SYSTEM FOR AN **ENHANCED GREENHOUSE EFFECT**.

1. Now, in the model that you have created in image (A), represent carbon dioxide and where it exists in this Earth/Sun system for an **enhanced greenhouse effect**.
2. Imagine the cutout square on the right (B) is a lens that we can use to see the gases in the atmosphere. In that square, represent gases in the atmosphere, including greenhouse gases, as you understand them to be for an **enhanced greenhouse effect**.
3. How does energy move around in the Earth/Sun system? Represent energy in the Earth/Sun system (A), as you understand it. **Demonstrate all of the places energy might come from and all of the places where it might go.**
4. In the greenhouse gas viewing box (B), represent energy and greenhouse gases. What is energy doing and how does it move?
5. What can you say about greenhouse effect or enhanced greenhouse effect in the year 2000? Write your answer below and include a discussion of the effects on temperature.
References


Curriculum Vitae

HEATHER SKAZA
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Education
2016 University of Nevada, Las Vegas – Ph.D. in Science Education
   Dissertation: Development and testing of an instrument to measure spatial
   thinking about enhanced greenhouse effect
2010 University of Nevada, Las Vegas – Master of Science in Environmental Policy and
   Management
   Thesis: Assessing the effect of simulation models on systems learning in
   an introductory environmental science course
2006 The Ohio State University – B.S. in Environmental Biology

Employment
2015-present College of Southern Nevada, Department of Physical Sciences
   Full-time Instructor
2012 – 2015 College of Southern Nevada, Department of Physical Sciences
   Part-time Instructor
2007 – 2015 University of Nevada, Las Vegas
   Part-time Instructor; Research/Teaching Assistant

Professional Experience

Research Experience
2013 – 2015 Gaining Early Awareness and Readiness for Undergraduate Programs
   (GEAR UP)
   Design, Development & Implementation of week-long professional
   development for science teachers from underserved schools, using
   argumentation in science teaching, with lessons supporting the Next
   Generation Science Standards.
2012 – 2013 Experimental Program to Stimulate Competitive Research (EPSCoR)
   Education Component
   Design, Development & Implementation of K-12 science curricular units
   based on EPSCoR climate science research.
2010 – 2013 Cyberlearning Climate Change Curriculum Development Research
   Team
   Design, Development & Implementation of Design-based Research
   protocol for multiple climate change curricular units.
2007 – 2011 System Dynamics-based Environmental Education Research Team
   Design, Development, Coordination & Implementation of curriculum
   and assessment related to testing the effectiveness of system dynamics
simulations on undergraduate students understanding of environmental problems.

**Teaching Experience**

2012 – present  
College of Southern Nevada  
ENV 101: Introduction to Environmental Science

2008 – 2010  
University of Nevada, Las Vegas  
ENV 101: Introduction to Environmental Science  
ENV 360: Environmental Assessment Methods  
ENV 460/660: Environmental Modeling

**Curriculum Development**

2015 – present  
Outside Las Vegas Foundation – Environmental Education  
Curriculum for Informal Science Education Providers

2015 – present  
Highroller, Las Vegas – STEM Lessons to Integrate Classroom and Field Experiences

2013 – present  
Gaining Early Awareness and Readiness for Undergraduate Programs (GEAR UP)

2012 – present  
College of Southern Nevada – Introduction to Environmental Science

2015  
The Neon Museum – STEM Lessons to Integrate Classroom and Field Experiences

2013 – 2014  
Cyber-learning Activities to Scaffold STEM Practices (CLASSP)

2013  

2008 – 2010  
University of Nevada, Las Vegas – Introduction to Environmental Science, both online and live classes

2008 – 2010  
University of Nevada, Las Vegas – Environmental Modeling

2008 – 2010  
University of Nevada, Las Vegas – Environmental Assessment Methods

**Professional Development**

2015 – present  
Outside Las Vegas Foundation Next Generation Science Standards-supporting Curriculum Development Workshop  
Developer and Facilitator of a program to introduce informal science educators to the Next Generation Science Standards

2013 – present  
Gaining Early Awareness and Readiness for Undergraduate Programs (GEAR UP)  
Developer, Researcher, and Facilitator for a program for secondary teachers’ development in the practices of science and engineering

2015  
Connecting Hands: Offering Lifelong Learning Adventures (CHOLLA)  
Developer & Facilitator for a program guiding informal science educators in the alignment of environmental education activities to the Next Generation Science Standards.

2010 – 2012  
Cyberlearning Climate Change Curriculum Development (C4D)  
Developer & Facilitator for a program that guided teachers in the development of science and engineering practice-based curriculum.
**Professional Service**

2014 – Present  Informal Science Education Committee for the Nevada STEM Coalition Committee Chair
2013 – Present  CHOLLA-Connecting Hands: Offering Lifelong Learning Adventures Professional Development and Symposium Planning Committee
2010 – Present  System Dynamics Society – Reviewer
2009 – Present  Journal of Science Education and Technology – Springer – Reviewer
2009 – 2012  International Conference of the System Dynamics Society – Conference Volunteer
2012  National Association of Research in Science Teaching – Strand 14 Assessor
2008 – 2009  University of Nevada, Las Vegas President’s Campus Sustainability Taskforce

**Memberships**

System Dynamics Society, since 2009
National Association for Research in Science Teaching, since 2010
National Science Teachers Association, since 2012
North American Association for Environmental Education, since 2013
Connecting Hands: Offering Lifelong Learning Adventures (CHOLLA, Las Vegas), since 2013

**Scholarships and Awards**

2010  Outstanding Graduate Student Award, University of Nevada, Las Vegas, School of Environmental and Public Affairs
2009  Marianne Carpenter Award, for outstanding graduate research in the School of Environmental and Public Affairs – Recipient
2009  Blue Communities Scholarship, awarded to a student researching a topic related to sustainability in arid urban environments – Recipient

**Research & Scholarship**

**Peer-Reviewed Journal Articles**


Research Presentations

International


2014, Skaza, H., Orgill, M., & Crippen, K. University Science Faculty Perceptions of Spatial Thinking for Environmental Literacy. Poster presented at the National American Association of Environmental Education (NAAEE), Ottawa, Canada.

2013, Skaza, H., Crippen, K., & Kern, C. Spatial Understanding as a Means to More Sustainable Decision Making. Poster presented at the National Association of Research in Science Teaching (NARST), San Juan, PR.


2009, **Skaza, H. & Stave, K.A.** *A test of the relative effectiveness of using systems simulations to increase student understanding of environmental issues.* Paper presented at the 27th International Conference of the System Dynamics Society, Albuquerque, NM.

2009, Tabacaru, M., Kopainsky, B., Sawicka, A., Stave, K.A., & **Skaza, H.** *How can we assess whether our simulation models improve the system understanding for the ones interacting with them?* Paper presented at the 27th International Conference of the System Dynamics Society, Albuquerque, NM.

**National**


2012, Carroll, K., **Skaza, H.**, Crippen, K. J., & Kern, C. *Learning about Climate Change in Death Valley with a Four-Part Blended Inquiry.* Paper presented at the National Science Teachers Association (NSTA), Indianapolis, IN.

**State & Regional**

2012, **Skaza, H. & Kern, C. L.** *C4D Cyberinfrastructure.* Presented at the EPSCoR Tri-State Consortium, Sun Valley, ID.

2012, **Skaza, H. & Kern, C. L.** *System dynamics: Developing climate change models.* Presented at the EPSCoR Tri-State Consortium, Sun Valley, ID.

2012, Kern, C. L. & **Skaza, H.** *Design framework for C4D.* Presented at the EPSCoR Tri-State Cyberlearning Summit, Albuquerque, NM.

2010, Schrader, P.G. & **Skaza, H.** *Future Directions for C4D.* Presented at the EPSCoR Tri-State Cyberlearning Summit, Albuquerque, NM.