IMPLEMENTATION OF A DIGITAL APPLICATION FOR SUPPORTING MIDDLE-SCHOOL-AGE LEARNERS' THINKING AND CONCEPTUAL GROWTH IN CLIMATE CHANGE SCIENCE

BY

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DISSERTATION

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ABSTRACT

Until thirty-five years ago, climate change was almost exclusively a topic of domain scientists and deeply serious hobbyists. It was only discussed in science journals and at academic colloquia. Therefore, it should not be at all surprising that many fundamental questions persist about how to teach students about climate change science, including the following.

- *At what age should children start to learn about climate change science?*
- *What should be included in climate change science learning?*
- *What are good sources of climate change science information?*
- *What is a good starting point for teaching or learning climate change science?*

This dissertation addresses these and other issues, but the two overarching questions of this work are the following.

- What do kids think about the science of climate change?
- What are some of the reasons, scientific and otherwise, that children think the way they do about climate change science?

Parents were surveyed to collect pre-participation demographic and socio-cultural information about their children, families, and communities. Such information often influences adults' conceptualizations of climate change, but their effect on children have been very thinly researched. Selected participants were interviewed on three occasions (pre-test, post-test, and delayed-post-test) about their ideas about climate science, as well as underlying attitudes which might influence their ideas. Some of the attitudinal questions are believed to have never been asked of middle-school-age children. For one condition, participants read a compact, systems-oriented text that was developed with the help of national and international experts in climate sciences. The text represented one possible system for relating climate change science concepts to each other. Alternatively, a game in the form of a data-logging digital app was designed and developed for learners of all skill levels (including experts) of at least nine years of age. The

game enabled participants to articulate their thinking about climate change concepts and compare their final responses to those from experts. The app recorded participants' game state changes and proved to be a rich source of questions and possible explanations for their conceptual thinking.

Unlike adults, the small cohort of children selected for this study exhibited few socio-cultural tendencies that often co-conspire with science misconceptions to impede climate change conceptual learning. Participants talked freely about climate science during the study, regardless of if the topic was completely new to them, which many said, or it was something familiar. With very few exceptions, they were receptive and interested to learn more about the concepts. The detail with which participants answered interview questions grew impressively with each successive interview, while the relevancy and accuracy of their responses grew modestly. In terms of children's conceptual alignment with climate experts, there was little difference between summative results from the reading and game conditions. However, participants in the reading condition exhibited a higher degree of confidence in their thinking than participants in the game condition.

Logged data from the digital app provided bases for formative assessments and analysis of conceptual cognition which were impossible with the reading. Logged event sequences provided evidence of learners' confusion, uncertainty, organization, familiarity, and preference related to the science concepts. Two participants featured in the dissertation, Andy and Emily (not their real names), typified this range of responses. In his consecutive uses of the digital app, Andy showed a marked improvement distinguishing concepts for which he had higher confidence and agreement with the experts from those in which he had lower confidence and agreement. Emily exhibited an ability to self-monitor and integrate her responses to different methods, which resulted in her registering substantial gains between sessions. Both formal and informal educators can use such interpretations to positively affect learners' outcomes and foster better alignment with the science.

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It sounds cliché, but I believe it is true, to say that it takes a village to write a dissertation. So many people effected this work in so many ways. They made this dissertation possible by providing me with essential ingredients for success since I started my program in August 2016.

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I want to posthumously thank Dr. David Zola who encouraged me, both as his teaching assistant and as a fellow academic, to work from the base of the self…to make my contributions personal, genuine, and without apologies. I think of him often and how he was simultaneously and unfailingly a dynamic, gentle, wise, and giving soul. I will never forget him.

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My journey to this place in life began shortly after leaving a long career at Oak Ridge National Laboratory and wondering, “What’s next?”. Dr. Mehmet Aydeniz opened the door for me to begin my master’s program in science education at the University of Tennessee, Knoxville. If Mehmet was my initiator, Dr. Barry Golden was my instigator, in that he introduced me to many of the psychological and sociological aspects of climate change science. I still use and refer to many of the source materials that Barry introduced to me.

Family have been immensely important to me in this journey. My mother, Dorothy Annetta (Niederhofer) Toedte, was a lover of all things Nature. That love lives in me today and is one of the main reasons for the topical focus of this work. My wife, Sharon, being a strong yet supremely giving woman, made it possible for me to be a “real” doctoral student nearly 500 miles from home. True love is providing space for those you care for to fulfill themselves. Thanks for giving me that space, Sharon. My children, Blaire and Benjamin, simply by being who they are as inquisitive and bright young people, provided me with substantial motivation. I hope, in a small way, this work will help to improve the quality of their lives, and their children’s lives.

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This dissertation is dedicated to Sharon, Blaire, and Benjamin.

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CHAPTER 1 - INTRODUCTION

Indirectly, a goal of this dissertation is to help resolve a clash of cultures…a clash of perspectives about what is real…a clash between perception and evidence on the topic of climate change. This should not be the case and most people would rather it not be so. From a science standpoint, anthropogenic climate change is a reality, and it will require dramatic changes in how we live and view the world to mitigate its impacts. Studies show that a lack of understanding of climate change science is prevalent in the U.S. public (Leiserowitz, Smith, & Marlon, 2010; Funk & Kennedy, 2016a; Funk & Kennedy, 2020; Leiserowitz, Maibach, Roser-Renouf, Feinberg, & Rosenthal, 2016; Leiserowitz, Maibach, Rosenthal, Kotcher, Wang, Carman, Goldberg, Lacroix & Marlon, 2021). Misconceptions are frequently the root cause of misunderstandings about climate change science. Misunderstandings, in turn, can lead to non-scientific ways of thinking about the problem, doubts about its importance, and inhibition to act. Climate change misconceptions can arise from the most benign of circumstances. Following is an exchange from one such hypothetical, but plausible, situation. Two neighbors are arguing opposing attitudes toward climate change, its existence, who is to blame for it, and what should be done about it.

> Neighbor #1: I'm never going to buy an electric car. The technology is still getting the kinks worked out, climate is not as big a problem as the scientists says, and the cars are freaking expensive!
>
> Neighbor #2: You're wrong. Electric cars are really clean, and the weather is already too hot. Yeah, electrics are more expensive, but they're worth it to help keep the planet habitable.

What if two children observe this hypothetical argument. Suppose one is the 11-year-old daughter of Neighbor #1. The other is the 10-year-old son of Neighbor #2. Which side of the argument will they support? What will be their reasons for picking a side…or not picking a side?

The overarching goal of this work is to help children, no different than the children in this hypothetical scenario, think and act on climate change concepts in ways that are more science-aligned. The scenario presents a realistic case for why this work is important. Climate change is science, but in society it impacts other disciplines including finance, health, and technology. The neighbors' brief exchange illustrates how easily the science and its social implications become intertwined.

1.1 - Motivation

The motivation for this work originated from two sources, both of which are discussed in more detail in Appendix L. The first source was my children, then in elementary school. As a family, we would often engage in outdoor activities like hiking, getting U-pick fruit, and gardening. By engaging nature as a family, I wanted to foster an appreciation and respect for nature in my children at a very young age. What has become apparent since then is it is no longer enough to have an appreciation for nature to understand climate change. It has become necessary to understand the roles of people and their behaviors in relation to nature, and to understand how to affect those relationships in a positive way.

The second source came from my experiences as a science researcher and communicator. I observed many times during public science talks to schoolchildren that they weren't "getting it" when it came to climate change. Having been on teams conducting research related to the work of the Intergovernmental Panel on Climate Change, I became informed about the climate community's thinking on how climate processes interact over different temporal rates and spatial extents, and between major system components such as atmosphere, oceans, and forests.

When I say children weren't "getting it", I mean they weren't interrelating the concepts. I found this is quite common outside the scientific community. Lots of studies show children harbor misconceptions about climate change. The misconceptions include that greenhouse effect has something to do with greenhouses and a bubble around the planet (Sadler, 2004; Niebert & Gropengeißer, 2014), pollution causes global warming, (Boyes & Stanistreet, 1994; Golden, 2011; Koulaidis & Christidou, 1999; Pallant & Lee, 2015; Visintainer & Linn, 2015), and that hot weather over a weekend is an example of climate (Bodzin, Anastasio, Sahagian, Peffer, Dempsey, & Steelman, 2014; Choi, Shepardson, & Charusombat, 2010; Golden, 2011; Lambert, Lindgren, & Bleicher, 2012; McCuin, 2011; Porter, Weaver, & Raptis, 2012; Shepardson, Choi, Nigoyi, & Charusombat, 2011).

1.2 - Problem Statement

The problem of understanding climate change concepts and children not "getting it" is not the fault of children. What is at fault is how children learn about climate change science. There are three ways that children learn. One way that children can learn about climate change science is through institution-directed instruction. School administration in the United States is controlled by state law and implemented at the state and school district levels. The Next Generation Science Standards (NGSS) are not a mandatory national science standard, since such a mandate would be constitutionally forbidden. Rather, the degree to which a state leverages NGSS is determined by their legislature. NGSS 8th grade expectations include knowledge that humans are a major source of climate change. The NGSS even recognizes the importance of climate change as a socio-scientific issue in the statement, "Reducing human vulnerability to whatever climate changes do occur depend on the understanding of climate science, engineering capabilities, and other kinds of knowledge, such as understanding of human behavior and on applying that knowledge wisely in decisions and activities." (NGSS_framework, 2012, p.198). However, the average middle and high school course devotes only four hours to climate change (Plutzer, Hannah, Rosenau, McCaffrey, Berbeco, & Reid, 2016). This leaves little time to discuss conceptual connections beyond the carbon cycle and greenhouse effect.

A second way is teacher-directed learning. Skilled teachers who have the background and inclination to do so can build climate change into their high school (physics, chemistry, biology, and earth science teaching) and middle school (general science) class material (*Ibid.*). However, with experienced teachers leaving the profession at recent rates, few are left that are trained to integrate climate change into their curricula (Will, 2021). Nearly three-fifths of all teachers have no background in climate change science and 89% have never had a class in the subject (Plutzer, et al., 2016).

Finally, there is self-directed learning. This occurs outside the public school system and is a personal choice by the child. Practically speaking, very few children are intrinsically motivated to learn about climate change. For some, peer pressure may inhibit their seeking information or talking about the topic. One of the middle-school-age participants in this dissertation study expressed concern about his friends finding out his interest and labelling him a climate change science 'geek'.

There is a warren of interconnecting resistive factors that inhibit children learning about climate change science. To large extent, the work of this dissertation is to help children to organize information on the topic. In parallel, this dissertation seeks to provide educators and researchers with insights for helping children structure their topical thinking. Most people, regardless of age, find it challenging to access high quality, science-aligned, age-appropriate climate change information. The problem gets progressively harder as one works backward from university to high school to middle school (Plutzer, et al., 2016, Hess & Collins, 2018; Toedte, 2020).

1.3 - Research Questions and Approach

The following research questions were designed to learn more about how children think and grow in their conceptual knowledge of climate change science.

RQ1 - In what ways do the transient data features (haptic event logging) of a digital app reflect learners' underlying comprehension and/or misunderstanding of climate change science concepts.

RQ2 - In what ways does the combination of learners' interactions with a digital app and their interview responses suggest different patterns of change in their climate change thinking?

To answer these questions, a mixed methods strategy was used, involving the combination of a digital app, or game, a topical knowledge text, and structured interviews. The app used a concept map approach centered around three main concepts: weather, climate, and environment. Children were asked to relate 15 sub-concepts to the main concepts. As they did so, their interactions with the game were timestamped and archived in a cloud-based repository. Interviews consisted of a mixture of questions about topical attitudes, topical knowledge, and epistemic practices. Thirty-one participants from six geographically disparate regions of the United States completed all research activities. Participant responses were recorded, transcribed, and coded. Various analyses were conducted to draw insights about the efficacy of the digital tool, the science alignment of the participants' conceptual thinking, and socio-cultural influences on the participants' responses.

1.4 - Dissertation Overview

This remaining chapters of this dissertation are as follows.

Chapter 2, Literature Review, covers the variety of literature that informs this dissertation. It includes some of the current societal conditions in which the study and learning of climate change science is situated, and different philosophies that people use in their thinking about climate change science. This is followed by why climate change is a socio-scientific issue. Next are three sections on different aspects of learning that are relevant to climate change science. Lastly, the unique role of experts in the climate domain and in this study is discussed.

Chapter 3, Methods, articulates the goals of this dissertation and how the research design attained those goals. This is followed by a review of a pilot study, “a new approach”, which was conducted over two years ago and cascaded into the present work. Chapter 3 also discusses the interview structure that accompanied the two conditions, and the participants’ itinerary during the study.

Chapter 4, Analyses, details some, but by no means all, of the different ways of looking at the data collected by the instruments detailed in Chapter 3. Each mini-investigation was intended to respond to a research question or respond to a question from the relevant literature.

Chapter 5, Conclusions and Discussion, summarizes the analyses from Chapter 4, describes what was learned, and offers connections back to the literature where possible.

Chapter 6, Contributions, Limitations, and Future Works, articulates what this work accomplished that improves the state of the field, what aspects of the work could have gone better, and what research topics I would like to pursue going forward.

CHAPTER 2 - LITERATURE REVIEW

In a raucously entertaining segment of *Last Week Tonight* on the topic of climate change, John Oliver declares in his inimitable way, “You don’t need people’s opinions on a fact […] You might as well have a poll asking which number is bigger…15 or five?, […] or, are there hats? […] The debate about climate change should not be whether it exists, it’s what we should do about it. There is a mountain of research on this topic.” (Oliver_Last_Week_Tonight, 2014). The vignette ends with Oliver staging a statistically accurate representation of consensus in the climate science community with ninety-seven climate change accepters crowding onto the stage to argue against three skeptics.

What was likely lost on Oliver’s (*Ibid.*) viewership, because of his cheeky reporting style, was the accuracy of what he reported. First, on the issue of “mountains” of climate change evidence, researchers gather and generate quadrillions of bytes of data from ice cores, readings from ocean buoys satellites, and calculations from climate models that have been developed over decades. The vast majority of this raw data is open to the public and serves as evidential bases for countless research projects. Collectively, this research contributes to the ever-advancing state of the science which is reported in peer-reviewed science journals and periodically collected in nationally- and globally focused compendia (Field, Barrios, & Intergovernmental Panel on Climate Change, 2014; Intergovernmental Panel on Climate Change & Edenhofer, 2014; Stocker, 2014; Reidmiller, Avery, Easterling, Kunkel, Lewis, Maycock, & Stewart, 2018). Climate skeptics’ arguments, on the other hand, are frequently based on overly narrow interpretations of data in terms of location or time, representations of obvious outliers as norms rather than trends, or the impossible expectation that science practice should yield perfectly accurate results with absolutely certainty.

Scientific consensus is very high regarding fundamental climate change questions: How severe is the change? What causes it? How urgently is action needed? What will happen if nothing is done? The scientific consensus is that unnatural climate change is real and significant, humans are the cause, and if people don't dramatically reduce carbon emissions, anthropogenic greenhouse effect will worsen and exacerbate existential threats to most living things on Earth. More than 97% of domain experts speak with a singular voice on these questions (Cook, Oreskes, Doran, Anderegg, Verheggen, Maibach, Carlton, Lewandowsky, Skuce, Green, Nuccitelli, Jacobs, Richardson, Winkler, Painting, & Rice, 2016). Surveys show the general public has little awareness of the high degree of scientific consensus on climate change. Ironically, the perception is that experts are even less in accord than non-experts (Ding, Maibach, Zhao, Roser-Renouf, & Leiserowitz, 2011).

Oliver's demonstration brings attention to the usual and often unfair way that controversy is portrayed in media. If one person is in favor of an issue, then the tendency is another person is needed to be against it. As Oliver puts it in the case of climate change, it's often "Bill Nye [the science guy] versus some dude." (Oliver_Last_Week_Tonight, 2014) Indeed, media does have a penchant for calling a debate "fair" with one person each representing opposing views. While this ploy increases excitement for consuming media, it also risks the perception that debaters' positions and arguments relative to the issue at hand are equally valid. Climate change denialists and skeptics often use non-scientific bases (e.g., economic, religious, political) to defend their arguments. While it is fair to consider these bases *in response to* climate change science (e.g., adaptation is too costly, action conflicts with religious beliefs, or agreement on international policy cannot be achieved), is not fair to *judge* the science through any lens but a scientific one.

Despite this unfairness, people construct what they count as knowledge about climate change from highly variable and personalized mixtures of socio-cultural and scientific bases. It is virtually impossible to entirely disengage one from the other in the practice or public consumption of science (Kuhn, 1996). The literature supporting this work, therefore, cuts across the so-called “soft sciences” such as philosophy, psychology, sociology, and education, as well as the so-called “hard sciences” such as physics, chemistry, and geology. Following are themes from varied literature bases that are important to this dissertation.

2.1 - Social Climate and Climate Change Science in the United States

A significant portion of the general public thinks scientists are evenly split on climate change’s existence and the importance of its mitigation. They assert that scientists are promoting something that doesn’t exist in order to retain their high paying jobs. They say that even if it did exist, there is no evidence humans are the cause. They assert that climate change science is a topic for pro-con debate. All these statements are misconceptions of the perceptual variety, rather than of the understanding variety. These are misconceptions based on an intentionally fostered or unintentionally acquired misperception…errors in perceiving what something *is*. In contrast, much of the conceptual change literature focuses on misconceptions based on misunderstandings…errors in understanding how something *works*.

This dissertation looks at climate change science conceptual thinking in a holistic way because young learners, just like adults, harbor both kinds of misconceptions which interact in pernicious ways that necessitate conceptual change. The first type of misconception that this work examines is unique to conceptual change learning in climate change science and other socio-scientific issues. To address this type of misconception requires an examination of the social roots of climate change misperceptions such as why some people eschew scientific evidence and reject experts' explanations, and instead believe opinions devoid of scientific merit from inferior information sources. The second type of misconception examined here is common to all science learning including climate change science. Factors of this type hew more toward science misunderstandings that, though they initially seem plausible, are ultimately shown to be incorrect in alternative superior conceptual models (Lombardi, Sinatra, & Nussbaum, 2013; Lombardi, Nussbaum, & Sinatra, 2016). To address this type of misconception This dissertation's focus on middle-school-age learners further complicates an already challenging problem, because far fewer climate change educational opportunities exist for this age band compared to university and high-school-age learners. Climate change science domain experts (e.g., atmospheric scientists, meteorologists, and geophysicists) also factor into this work because their consensus thinking serves as a reference point for the thinking of middle-school-age learners. Following are some circumstances that make the present an ideal time to address climate change science thinking in middle-school-age learners.

2.1.1 - Lack of Public Understanding of Climate Change Science

A number of studies show that the U.S. public lacks understanding of important aspects of climate change science. Leiserowitz, et al., (2010) studied more than two thousand American adults and found that 43% were unfamiliar with the greenhouse effect…the key mechanism for atmospheric heating. They also conflated the definitions of weather and climate (50%), didn't know what greenhouse gases were (55-88%, depending on the specific gas), and didn't know how much atmospheric carbon has risen since from pre-industrial levels (>50%). In a study conducted by the Pew Research Center, Funk & Kennedy (2016a) found that a third of those polled did not know that cars produced CO_2 by burning fossil fuels, three-fifths didn't think that human-produced climate change would exacerbate the frequency and severity of droughts and floods, and three-fifths thought that climate change would not affect plant and animal life.

Studies involving children also exposed a limited grasp of climate change science. It is worth noting, however, the aforementioned adult studies were more of a polling variety, whereas children's studies were more classroom oriented. In a study of 225 7th grade students (Shepardson, et al., 2011), no students had a complete understanding of greenhouse effect and only 13% had a substantial grasp of the concept. Sadler (2004) found that only 10% of 84 high-school students understood both the data supporting the relationship between the rise in greenhouse gases and temperature, and the differences between temperature trends due to natural and anthropogenic sources of CO2. Boyes & Stanistreet (1993) found that students aged 11-16 erroneously held the misconception that increased greenhouse effect would result in higher incidence of skin cancer. Niebert & Gropengießer (2014) explored several granularities of interrelated misconceptions that together make up the greenhouse effect. It found that high school students held the misconception that the greenhouse effect is caused by a hole in the ozone layer that lets heat in, increases the temperature of certain layers of the atmosphere, but prevents the heat from leaving. Many studies showed that students also conflated pollution with greenhouse effect because they considered pollution to be a layer of the atmosphere that is to blame for global warming (Boyes & Stanistreet, 1994; Golden, 2011; Koulaidis & Christidou, 1999; Pallant & Lee, 2015; Visintainer & Linn, 2015).

2.1.2 - Non-standard Climate Change Science Education Standards

Perhaps it is not surprising that U.S. adults and children alike lack familiarity with climate change science, considering the lack of consistent education law and standards at national, state, and district levels. Generally speaking, administration of education is the purview of states. State science standards' priorities vary widely and their guidance on teaching climate change science is even more variable. The science standards of three neighboring states…Illinois, Indiana, and Ohio…bear this out. Illinois' standards call for teaching that both natural and anthropogenic climate change (ACC) exist (IL_science_standards, n.d.). Ohio's standards address only natural climate change while failing to mention ACC (OH_science_standards, n.d.). Indiana's standards don't address climate change whatsoever (IN_science_standards, n.d.).

National education standards could play a significant role in climate change instruction by establishing requirements and making recommendations for what should be taught, to whom, and why. However, the U.S. has no national standard. What comes closest is the Next Generation Science Standards, or NGSS, which was crafted by a partnership of education administrators, teachers, business leaders, the National Research Council, the National Science Teachers Association, the American Association for the Advancement of Science, and Achieve, Inc. (NGSS_overview, n.d.). NGSS consists of a framework and topical knowledge standards. The framework is an education model for integrating topical knowledge along intellectual, theoretical, and practical application dimensions (NGSS_framework, 2012). While the partnership also created a set of topical knowledge standards, the framework was intended to be independent of standards, a recognition of states' interests in articulating the topical content for their respective students. To date, the NGSS framework and standards have been adopted by 19 states. Another 21 states have utilized only the NGSS framework, and ten states have adopted neither the NGSS framework nor the standards (Toedte, 2019). The framework elements that apply to climate change science are sparse for 12th grade and are even sparser for 8th grade. The strongest statement the framework makes for 8th grade learners comes from the section ESS3.D, Global Climate Change.

> “Human activities, such as the release of greenhouse gases from burning fossil fuels, are major factors in the current rise in Earth’s mean surface temperature (global warming). Reducing human vulnerability to whatever climate changes do occur depend on the understanding of climate science, engineering capabilities, and other kinds of knowledge, such as understanding of human behavior and on applying that knowledge wisely in decisions and activities.” (NGSS_framework, 2012, p.198)

While there is very little in terms of statutes or direct standards supporting climate change science education, *indirect* standards support exists in the NGSS. Disciplinary core ideas such heredity, ecosystem dynamics, natural selection, and crosscutting concepts including cause and effect, and energy and matter, are essential to learning different facets of climate change science (Sadler, Friedrichsen, & Zangori, 2019). Shepherdson, Roychoudhury, Hirsch, Niyogi, & Top (2014) says climate change science learning falls under the broad topical areas of “…engaging students in scientific activities and thinking that involve: inquiry and investigation, the collection and analysis of evidence, and the reasoning, communication and application of science concepts.” (p.350). In summary, bases exist in educational standards for states and districts to rationalize allocating time, personnel, and curricula to climate change science, if administrators and educators choose to take advantage of them.

2.1.3 - Climate Change Misconceptions in Middle-school-age Learners

I conducted a systematic analysis of climate change misconceptions in middle-school-age learners (Toedte, 2020) during the "modern era" of climate change science, which begins with James Hansen's climate change U.S. Senate testimony (Shabecoff, 1988) and ends with present day. That work showed that most middle-school-age learners' misconceptions were due to misattribution of atmospheric heating to one or more causes from a lengthy list that included artificial fertilizers and changes in Earth's orbit. Over half of the 28 papers that met the study's selection criteria cited ozone holes (71%) and pollution (57%) (see Table 1).

Table 1 - Middle-school-age learners' climate change misconceptions
Table from Toedte, 2020, p.29. See the full-size table in Appendix A.

Study	Misconception Data																															
abbrev-iation	a	b	c	d	e	f	g	h	i	j	k	l	m	n	o	p	q	r	s	t	u	v	w	x	y	z	aa	bb	cc	dd	ee	
B&S, 1993	X	X	X	X	X							X	X							X	X											9
F, ea, 1993		X										X								X												3
K&C, 1993		X	X																			X										3
B&S, 1994		X	X																													2
B&S, 1997		X	X	X																												3
R, ea, 1997		X		X																												2
M&S, 1998	X	X				X	X	X																								5
K&C, 1999		X	X																													2
P, ea, 2001		X	X																				X									3
D, ea, 2004		X	X									X																				3
L, ea, 2007		X	X																													2
B, ea, 2008		X	X																	X			X									4
S, ea, 2009								X																	X	X						4
G, 2011		X	X			X								X																		4
G&Y, 2011		X													X																	2
P, ea, 2011		X	X	X					X																							4
V&L, 2011		X																														1
B, ea, 2013		X	X									X																				3
D&S, 2013																																0
L, ea, 2013	X	X				X				X																						4
B, ea, 2014																											X		X			2
B&K, 2014																								X					X			2
S, ea, 2014																												X	X			2
P&L, 2015			X					X								X												X	X	X	X	7
V&L, 2015	X		X																													2
H, ea, 2016		X																														1
M, 2016	X		X																													2
B, ea, 2017		X	X	X				X			X	X	X				X	X	X													10
	6	20	16	5	1	3	1	4	1	1	1	5	2	1	1	1	1	1	1	3	1	1	2	1	1	1	1	2	4	1	1	
	21%	71%	57%	18%	4%	11%	4%	14%	4%	4%	4%	18%	7%	4%	4%	4%	4%	4%	4%	11%	4%	4%	7%	4%	4%	4%	4%	7%	14%	4%	4%	

Key
...is caused by...
a ---> intensifying sun's rays
b ---> ozone holes
c ---> pollution
d ---> using CFCs
e ---> trapped sun's rays
f ---> volcanoes
g ---> straighter earth rotational axis
h ---> a "dome" over the earth
i ---> earthquakes and tsunamis
j ---> changes in earth's orbit
k ---> artificial fertilizers
l ---> nuclear power production
...causes...
m ---> more incidence of skin cancer
n ---> inceases in CO2
o ---> more incidence of food poisoning
p ---> ozone depletion
q ---> more heart attacks
r ---> earthquakes
s ---> falling sea levels
...is improved by...
t ---> using unleaded petrol
u ---> recycling
v ---> methane production
w ---> using coal and petrol vs nuclear
x ---> hybrid car usage
...is not related to...
y ---> CO2 concentrations
z ---> amount of driving
aa ---> human activity
bb ---> differences in space and time
...miscellany...
cc - is comprised of unrelated factors
dd - involves a list of well-known GHGs
ee - is the same as weather

2.2 - Climate Change as Socio-science

Since one purpose of this dissertation is to help young learners attain a better understanding of climate change science, it is important to understand climate change as a science. Though much remains to be done to understand the problem of climate change science, much *has already* been done. The models that replicate past climate behaviors and project future trends have been developed over the course of decades. Analyses of model and experimental data at the national and international level conclude with very high degrees of likelihood that climate change exists, is causing harm to the planet now, and the harm will only worsen unless prompt action is taken (Stocker, 2014; Reidmiller, et al., 2018). However, it is equally important to understand climate change as a *socio*-science. It belongs to the class of science topics called socio-scientific issues, or SSIs, which includes evolution, immunization, and genetically modified organisms. Because it is an SSI, socially influenced tendencies and dispositions color individuals' perceptions about the science and the scientists that study climate change. Though some of climate change's characteristics are unique, such as its planet-wide influence, others are common to all SSIs, like the complex web of conceptual relationships. This makes SSI science learning more difficult than would be the case with "ordinary sciences" like physics and chemistry that are less inherently issue bound.

Sadler (2004) characterizes SSIs as, "Social issues with conceptual or technological ties to science..." (p.513). Ke, Sadler, Zangori, & Friedrichsen (2020) expands on this, calling SSI's "…complex, ill-defined, critical societal issues…" (p.1) SSIs are, as a class, problems that simultaneously coexist in social and technical spheres. SSI-class problems relate to fundamental human needs, but understanding the problems requires technical thought. Technical discoveries in biological evolution address the fundamental human need to understand "where we came from". Genetically modified organisms, or GMOs, are a technical solution to mitigating the need to feed a growing global human population. Immunization therapy resolves a general health problem, the spread of diseases, by boosting the human body's ability to respond to illnesses. Each of these SSIs also has non-technical responses which are significantly divorced from their technical siblings. These responses, depending on the individual, are seen as competitive and even superior to the technical response. In the case of evolution, a response to "where we came from” is based on creationist interpretations of Judeo-Christian writings that assert that humans were fully created, not evolved from proto humans. In this way of thinking, the age of the universe is less than 6000 years, not billions of years. With immunization therapy, the response is to eschew the treatments because they allegedly harm people and do a poor job of preventing disease. This response is based on the premise that political organizations can’t be trusted and “big pharma” pushes immunizations with the principal goal of boosting business profit margins. Another common characteristic of SSIs is their respective scientific communities are in nearly complete consensus on the scientific perspective. The public, however, persistently thinks there is a thin expert majority that comprises consensus view. For example, Gallup polling since 1983 shows that roughly 40% of Americans unwaveringly believe in the view that humans did not evolve but were created in their present form (Brenan_gallup_creationism, 2019) (see Figure 1). Similarly, Pew polling shows that acceptance of human sourcing of climate change is static at less than half that of domain experts and is strongly biased by political orientation (Funk & Kennedy, 2016b; Funk & Kennedy, 2020) (see Figure 2 and Figure 3).

Figure 1 - Support of creationism

U.S. adults’ support of human creationist view (Brenan_gallup_creationism, 2019).

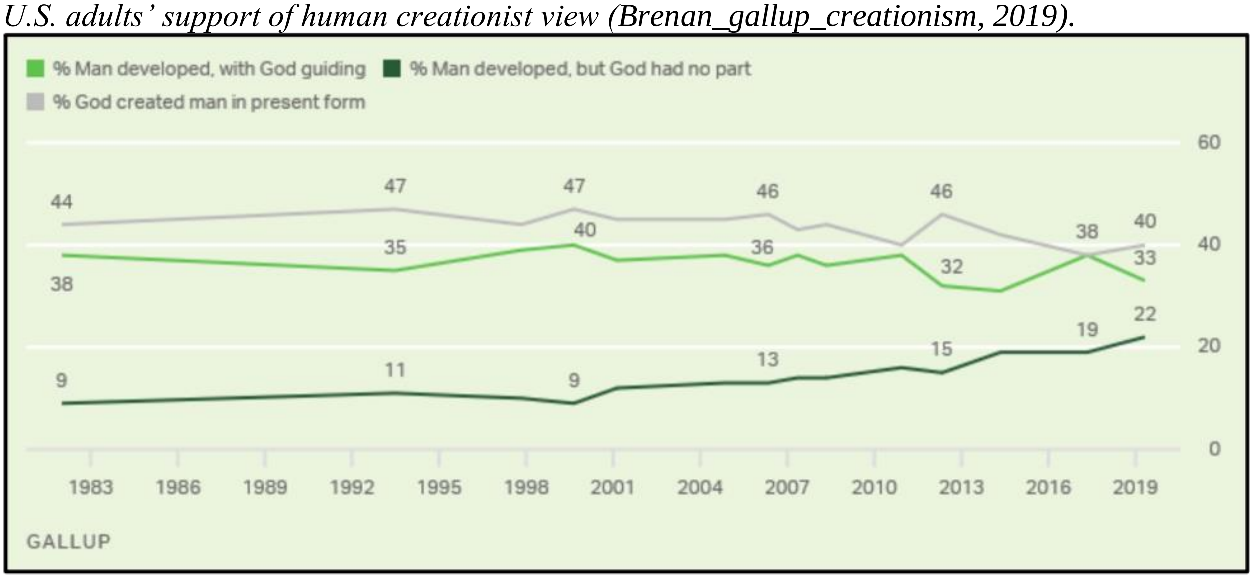
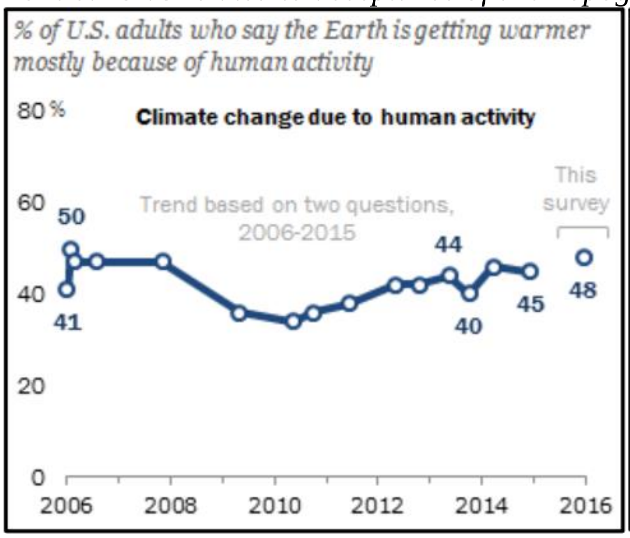
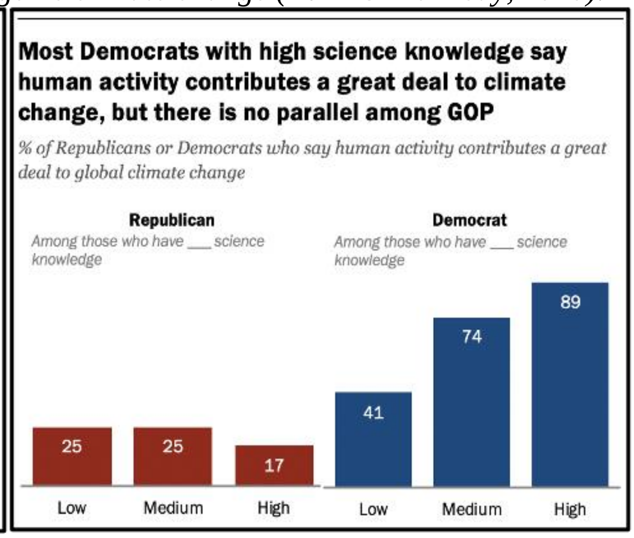


Figure 2 (left) - Support of anthropogenic climate change (ACC)
U.S. adults' support of anthropogenic climate change (Funk & Kennedy, 2016b).
Figure 3 (right) - Political bias related to ACC
Political bias related to acceptance of anthropogenic climate change (Funk & Kennedy, 2020).





A number of authors have identified cognitive tendencies that factor positively in learners' literacy gains in learning SSI topics like climate change. Laius & Rannikmäe (2011), studied the effects on creativity and scientific reasoning skills through a socially driven teaching and learning (STL) strategy with 9th graders. Statistically significant gains were observed for both these literacy proxies which "...enabled the students to solve problems and make well-grounded socio-scientific decisions in their everyday lives" (*Ibid*., p.135). Sinatra, Southerland, McConaughy, & Demastes (2003) studied the relationships between open-minded thinking and science issues with varying levels of controversy ranging from photosynthesis (low controversy) to human evolution (high controversy). The Actively Open-Minded Thinking (AOT) Scale contains Likert-scale questions such as, "Changing your mind is a sign of weakness.", and "A person should always consider new possibilities." (Sá, West, & Stanovich, 1999, p.510). Sinatra, et al. (2003) found that AOT composite scores increased significantly with the topic's level of controversy. Open-minded thinking is widely considered to be a precursor to understanding science concepts, which is necessary for scientific acceptance. Tomas & Ritchie (2012) studied factors which contributed to high school students' self- efficacy in writing projects about socio-scientific subjects. This study found that self- efficacy was driven by positive emotions such as pride, strength, and determination, which translated into student's writing skill and improved depth of SSI topical knowledge.

Acceptance of climate change science has been shown to be affected by learners' goal-oriented cognitive dispositions including need for cognition, cultural cognition, and motivated reasoning. Need for cognition (NfC) is a measure of an individual's need to think effortfully toward the goal of organizing information (Cacioppo & Petty, 1982; Cacioppo, Petty, & Kao, 1984). High NfC has been linked to complex thinking, acceptance of socio-scientific topics (Sinatra, et al., 2003), and inclination to act on reducing ACC (Sinatra, Kardash, Taasoobshirazi, & Lombardi., 2012). Another tendency, cultural cognition, "...naturally imputes socially harmful consequences to behavior that defies their moral norms." (Kahan, 2007). The goal of the culturally cognitive individual is to minimize risk, which is determined by the difference between their behavior and their in-groups' normative behaviors. Individuals' cultural cognition ranges from being very individualistic and status-oriented to very community- and equality-oriented (egalitarianism). High communitarianism and egalitarianism have been linked to acceptance of expert consensus (Kahan, Jenkins-Smith, & Braman, 2011) and support of ACC (Kahan, Peters, Wittlin, Slovic, Ouellette, Braman, & Mandel, 2012). Motivated reasoning measures the application of intrinsic or extrinsic goal orientations in decision-making processes (Kunda, 1990). The continuum ranges from directional goal orientation (a desired conclusion) to accuracy goal orientation (an informed conclusion) in decision making. Motivated reasoning has been linked to polarizing views on ACC policy (Hart & Nisbet, 2012) and support of ACC (Sinatra, Kienhues, & Hofer, 2014).

Socially influenced tendencies and dispositions color individuals' perceptions and confound science learning, especially for SSIs. It is human nature to seek order and sense in the world. A sense-making personal tendency, such as NfC, when it is wedded to logic- and evidence-driven ways of knowing in a science context, results in knowledge that better matches that which is held by scientists. On the other hand, ways of knowing rooted in opinion, fear, and power retention, often lead to misconceptions when used in a science context.

2.3 - Middle-school-age Learning

Three abilities of middle-school-age learners are important to this dissertation. First, their *linguistic ability* allows them to read and hear about climate change science concept names and characteristics, and subsequently articulate their conceptualizations. Second, their *cognitive ability* allows them to understand the important roles and interrelationships of concepts in the climate change science context. Third, their *metacognitive ability* allows them to reflect on their cognitive processes and have ideas about why they know what they know, as well as what they don't know. The studies cited in section 2.1.3 (Toedte, 2020) were chosen because they included children aged 14 and younger. Although middle school age was the principal demographic of interest, studies with younger participants were included to assess whether they contained methods and results which were applicable to older learners.

Children of ages 9-14 have generally acquired the skills necessary to understand the language of climate change science, which is a precursor to conceptual understanding. For children aged less than 9, it is questionable whether this capability exists. I conducted a climate change science study with science center visitors aged 7-13 in which participants were asked if they understood three basic climate change concepts: climate, environment, and weather (Toedte, 2018). Two distinct subgroups emerged from this study. While 64% of participants aged 7-8 did not understand at least one of the concepts, this occurred with only 15% of participants aged 9-13. Anderson and Freebody (1979) found word familiarity was, by far, the main factor (0.8 loading) in children knowing the meaning of words. The authors further asserted that in terms of sentence readability, a two-factor model, with vocabulary once again being the major contributing factor, was sufficient. Furthermore, analysis of interview transcripts from Toedte (2018), showed that participants did not lack the ability to understand climate change science concepts in depth.

In addition to their language skills, children aged 9-14 have the cognitive ability to adequately understand the complex roles and interrelationships in climate change science where younger children may not. Of Piaget's (1964) four stages of cognitive development, the concrete operational stage is the earliest one that equips children to organize the necessary information in climate change science. Operations such as "...classification, ordering, the construction of the idea of number, spatial and temporal operations..." (*Ibid*., p.177) are all essential for understanding climate change science. While children are not automatically able to make the jump from the pre-operational stage to concrete operations, the age of seven is generally seen as when children begin to systematically organize information. According to one measure, 85% of nine-year-old children (up from 75% of eight-year-old children) have at least begun the concrete operational stage (Renner, Stafford, Lawson, & McKinnon, 1976). While the advent of concrete operations varies due to societal and cultural factors (Piaget, 1964), nine is an age that balances cognitive appropriateness with early exposure. Earlier ages risk children failing Piaget's famous conservation experiments (e.g., a tall thin glass does not increase the volume of water poured from a short, fat one) which are fundamental to understanding concepts of quantity.

Finally, children have already developed metacognitive skills by age nine that assist their climate change science learning in ways that both resemble and differ from more traditional science learning. Like traditional science learning, children self-assess their understanding and ask questions about terms and concepts when they feel that their understanding is deficient. On the other hand, climate change science learning, because it is more socially contested, involves additional assessment of knowledge sources, and thus involves different metacognitive skills (Flavell, 1979). Critical thinking, an essential component in source assessment, starts to emerge in early childhood (Kuhn, 1999). Kuhn (2000) pins this development to pre-primary-school age, saying "...the earliest forms of metacognition [occur by] age 3..." (p. 178). Moshman (1998) provides additional support for the early development of metacognitive skills, as early as age six, when young minds start to think about the nature of data in support of their cognition. Children start to consider whether data represent special cases or support broader generalizations and theories. Therefore, the notion that young participants are quite able to reflect on their thinking about climate change science learning is amply supported.

2.4 - Philosophical Paradigms

Philosophical paradigms are important in this work because they address what counts as knowledge, how knowledge advances, and how knowledge is acted upon. Climate change science learning concurrently involves the philosophies of post-positivism and constructivism.

Post-positivism is the paradigm most associated with science practice. This paradigm holds that knowledge is derived from experiments and observations of the physical world and is supported by evidence which is most often quantitative. Post-positivism holds that "absolute truth" is never attainable and that knowledge, or the current state of truth, is a product of consensus among domain experts. Experts weigh, discuss, and challenge the veracity of data or information, from experiments and observations, in the relevant science context. Nature of Science, an approach to science education that is related to post-positivism, calls the process by which held scientific knowledge changes, “tentativeness” (Lederman, 1999; Lederman, Abd-El-Khalick, Bell, & Schwartz, 2002], because it is deemed to be factual at the time it is stated, but subject to future change. In post-positivist philosophy, extreme changes in held knowledge within scientific communities become scientific “revolutions” (Kuhn, 1996). In such revolutions, new information is gleaned by new science theories, processes, and advances in measuring devices. When new information is sufficiently assessed among the scientists in the relevant domain and deemed superior in terms of its robustness and explanatory power, a “paradigm shift” occurs. This shift signals that the new information has become part of the consensus scientifically held knowledge.

Constructivist philosophy holds that knowledge is constructed by the individual using their own observations, assumptions, and rules but within a larger social context of individuals with their own but different observations, assumptions, and rules (Driver, Asoko, Leach, Scott, & Mortimer, 1994; Driver, Newton, & Osborne, 1998). Constructivism is often associated with the so-called “soft sciences” such as psychology and education where advances are largely based on qualitative findings and attention to case-specific application (e.g., individualized education practice), in contrast with case-general application (e.g., laws of gravity). Like post-positivism, the constructivist’s reality incorporates observations of the physical world. However, unlike post-positivism, those observations are not only vetted among domain experts, but also with trusted others. The pool of trusted others for an individual may be wide and can include family, friends, politicians, news sources, textbooks, and social media, all with varying degrees of expertise in the topic at hand. Constructivism is applicable to a wide range of scenarios from the mundane (deciding what clothes to wear) to the weighty (deciding whether and what to do about climate change). When constructivism is used in science learning, the knower epistemically evaluates the trusted other, be it a parent or a textbook, as well as the trusted other's assertions (Smith, Disessa, & Roschelle, 1994). The degree to which this is done is very subjective, increasing the potential for the formation of science misconceptions. Studies have shown that middle school students' misconceptions can originate from a plethora of sources. These include schools and teachers (Boyes & Stanisstreet, 1997; Hestness, McGinnis, & Breslyn, 2016; Rye, Rubba, & Weisenmayer, 1997; Visintainer & Linn, 2015), mass media (Boyes & Stanisstreet, 1997; Boyes, et al., 2008), authority figures such as parents (Golden, 2011; Rye, Rubba, & Wiesenmayer, 1997; Visintainer & Linn, 2015), and textbooks (Golden, 2011; Koulaidis & Christidou, 1999). Any of these categories of sources can produce either conceptually sound or conceptually flawed knowledge. It is the role of the constructivist learner to perform the evaluation.

The contributions of the philosophies of post-positivism and constructivism in this dissertation are not isolated from each other. Both are used by scientists and non-scientists alike. It is impossible for any individual to defensibly assert they use only one or the other exclusively. No scientist re-investigates all established first principles which are deemed to be relevant to their field of study. In this way, scientists invoke a degree of social constructivism because they accept as accurate held knowledge relevant to their discipline. On the other hand, the least scientific among us invokes post-positivism when assessing everyday things like the weather. One might base decisions about what to wear on a particular day on an assessment of collected data (e.g., looking at historical temperatures to find patterns or outliers) or direct experiences with phenomena (e.g., going outside to see if it is raining or windy). These types of evaluation are indistinguishable from analyzing primary data sources or conducting scientific experiments.

Generally speaking, young learners may have been exposed to scientific experimentation, but they tend toward constructivism in how they understand this science domain. Conversely, scientists who work in climate change tend toward post-positivism, conducting their own experiments and running their own models to understand first-hand how climate behaves in different circumstances and on different time scales. As will become evident in Chapter 3, this study is designed to mutually respect and engage the climate change science thinking of young learners and domain experts alike. An emphasis in this work is to understand what young learners and experts think as well as why they think what they do. For young learners, exposure to what experts think and what information they count as held knowledge fosters a range of responses including curiosity, confusion, and motivation. These are natural and necessary ingredients for conceptual change.

2.5 - Epistemic Cognition and Sourcing

Section 2.2 discussed ways that SSI learners' knowledge production can be derailed by tendencies and dispositions that are socially and psychologically influenced. SSI learners also need to be cognizant that sources of information can inadvertently promote misconceptions, or deliberately spread misinformation and disinformation. Therefore, SSI learners need to be selective epistemic consumers by assessing the sources they use to build their knowledge. Epistemic practices can be a vital tool for the learner to choose from among information sources, enabling them to be curators of their own information. Epistemic cognition and source evaluation are especially important in a networked world where anybody can publish unvetted information and potentially make it available to thousands of readers. High quality sources support young learners' scientifically supported conceptions while low quality sources foster misconceptions which become progressively more difficult to correct with the passage of time. Low quality sources can add to preexisting flawed information which, in the case of socio-scientific issues, can further confuse the learner with social opinion rather than credible science.

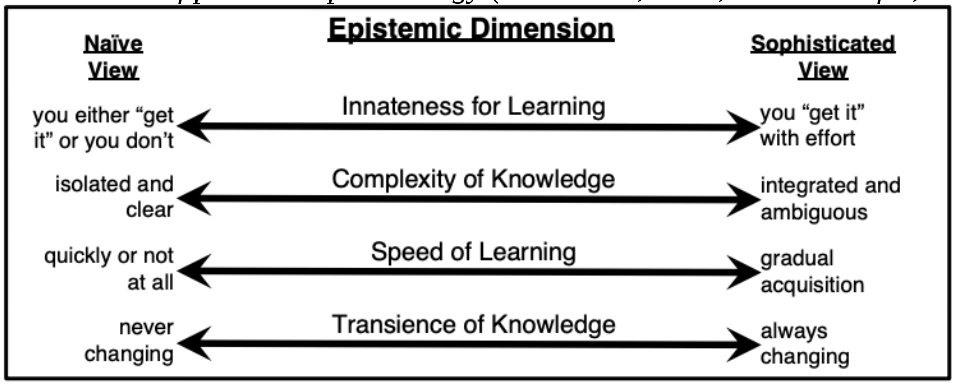
Everyone has personal epistemologies (PE), or rules and systems for selecting, filtering, and culling information in the process of building knowledge. Burr & Hofer (2002) explains PE as "...a metacognitive process that activates epistemic theories, a multidimensional set of interrelated beliefs about knowledge and knowing." (p.43). Each person's personal epistemology is different in terms of sophistication and makeup. Major models of epistemological development from William Perry, Patricia King and Karen Kitchener, and Deanna Kuhn vary in how they define epistemic levels and what drives development from level to level. What is consistent, however, between the models is the following.

- people progress to higher levels of sophistication but don't regress to a prior level
- progression occurs because of maturation, experience, and self-reflection
- individuals "max out" at different levels of sophistication.

Therefore, a 12-year-old may be more epistemically advanced than a 15-year-old.

One can also deconstruct personal epistemologies by considering the important categories of evaluation that might exist within an epistemic model. One such model involves four independent factors that constitute most of the variance in ideas about knowledge and knowing (Schommer, 1990; Burr & Hofer, 2002). (see Fig_4)**.**

Figure 4 - Epistemic dimensions
Dimensions of personal epistemology (Schommer, 1990; Burr & Hofer, 2002).



In addition to these factors, Schommer theorized that "...[o]ther potential influences, such as childhood home life, ethnicity, religion, and the media..." (Schommer, 1998, p.558) may also contribute to a learner's PE. Hofer leverages Schommer's continua while adding others to her personal epistemology model. A learner's PE consists of "...two areas [which] are the nature of knowledge (what one thinks knowledge is), which includes the dimensions certainty of knowledge and simplicity of knowledge; and the nature or process of knowing (how one comes to know), which includes the dimensions source of knowledge and justification for knowing." (Hofer, 2004, p.46)

2.6 - Conceptual Change Learning

Conceptual change learning is science learning that involves a change from a learner's existing inferior conceptualization to a new superior one. A conceptualization may be judged superior for a number of reasons including broader applicability to potential scenarios, better fit with other conceptualizations held by the learner, or new information acquired by the learner. While conceptual change is important across the sciences, it could be argued to be even more important in rapidly evolving fields like climate change science in which understandings of temporal and spatial dynamics are constantly being updated and the complexity of system relationships is growing. Conceptual change learning is a process of transformation that is initiated when the learner encounters information or has an experience related to an object that sufficiently changes their conceptualization of the object (Posner, Strike, Hewson, & Gertzog, 1982; Hewson & Hewson, 1984; Pintrich, Marx, & Boyle, 1993). Piaget's (1964) work with children undergoing conceptual change focused on rational consideration and assimilation, or an integration of the new information with the prior conceptualization. This, in turn, led to equilibration, or a new, balanced conceptualization.

More recent conceptual change literature integrates nuanced descriptions of conceptual change, related cognitive and emotional factors, evaluative terms such as sufficiency and plausibility, and socio-cultural factors which may come into consideration prior to learners modifying or completely overturning their former conceptualizations (Lombardi, et al., 2013; Sinatra, et al., 2014; Lombardi, et al., 2016). This research involves emotions and motivations, which the learner associates with the new information, and that have the potential to become factors in rationalizing the inclusion of new characteristics into an object's conceptualization. Conversely, these same factors could foster rejection of the new characteristics and retention of the old conceptualization. For example, it's a frequent misconception that CO_2 is not a greenhouse gas even though its atmospheric heating properties are well known. A learner may have a conceptualization of CO_2 being "good" because people naturally exhale it. Upon encountering information that CO_2 is one of the "bad" greenhouse gases, the learner could reject reconceptualization because it creates emotional conflict. As a result, the learner might deem it easier to retain the old conceptualization than develop a new nuanced view that CO_2 is both a "good" naturally produced gas as well as a "bad" greenhouse gas.

Chinn and Brewer (1993) explored students' responses to "anomalous data", or new information that does not square with the old but could result in conceptual change. In the following excerpt, the authors refer to old and new conceptualizations as Theory A and Theory B, respectively, in explaining the different potential ways that learners resolve conceptual differences.

> "[...] anomalous data may or may not be accompanied by theory B, which is intended to explain much of the body of data explained by theory A, plus the anomalous data. What are the possible responses of the individual to the anomalous data? We postulate that there are seven basic responses: (a) ignore the anomalous data, (b) reject the data, (c) exclude the data from the domain of theory A, (d) hold the data in abeyance, (e) reinterpret the data while retaining theory A, (f) reinterpret the data and make peripheral changes to theory A, and (g) accept the data and change theory A, possibly in favor of theory B." (Ibid., p.4)

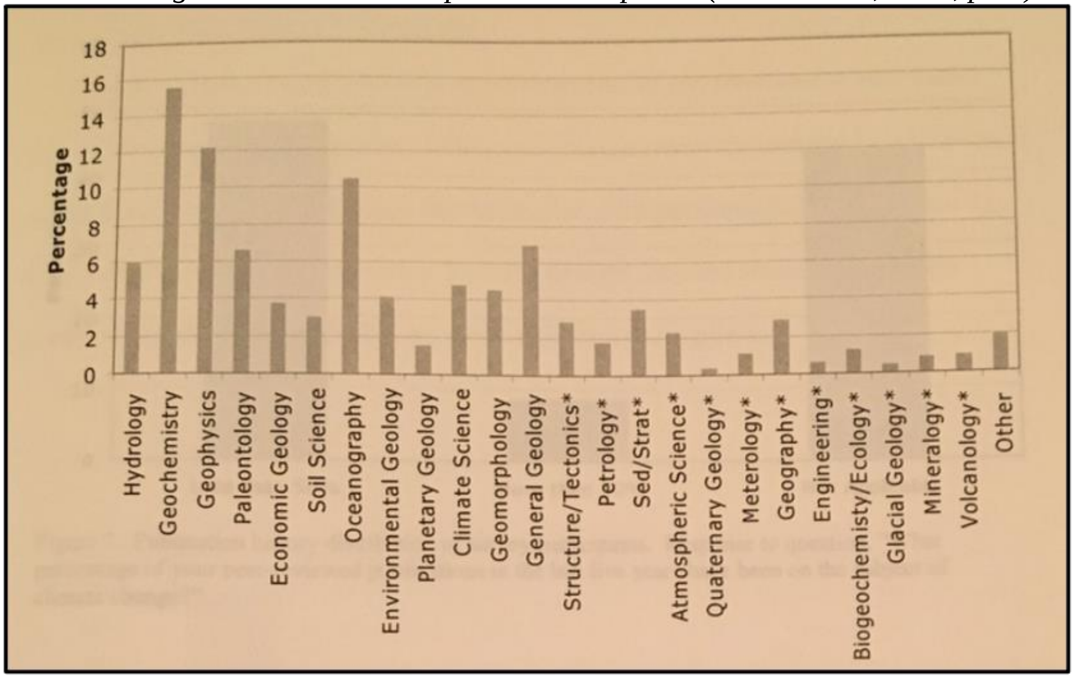
The authors go on to discuss the components of the reconceptualization process: the learner's prior knowledge, the "old" conceptualization, the anomalous data, and processing strategies. Notably the authors did not include irrational processing, including emotional responses and socio-cultural factors, among their list of strategies. Graesser, Lu, Olde, Cooper-Pye, & Whitten (2005) referred to "cognitive disequilibrium" in a study of students' eye movements while diagnosing failures of complex machinery. The authors differentiated learners with weak and strong equilibration drives or varying internal inclinations to resolve conflict through equilibration. Participants with weak drives tended to randomly scan engineering drawings for points of failure, while those with strong drives systematically sought and focused on likely failure points. This had a significant effect on the explanatory potential of the questions the learners asked which were important to their diagnostic processes.

D'Mello, Lehman, Pekrun, & Graesser (2014) describes confusion as a companion to conceptual change, and a beneficial motivator for many complex tasks. Confusion often

“...[drives] deep learning and inquiry...” (Ibid. p.166) resulting in improved memory retrieval and thoroughness of conceptual descriptive ability by the learners. D’Mello et al. takes care to caution that not all resolutions of confusion are equal. If conceptual conflicts, which D’Mello, et al. calls “impasses”, are overly difficult to overcome, there is a risk of the learner experiencing feelings of frustration rather than accomplishment, resulting in poorer memory retrieval and descriptive ability.

Research discussed in this section presents some of the different interpretations and aspects of conceptual change learning. Some aspects have to do with the magnitude of the difference between former and competing conceptualizations. Other aspects pertain to the nature of the difference. Still others involve background information held by the learner, the presence or absence of which determine a new conceptualization’s acceptance. In the end, what matters is whether conceptual change is applicable to youth, who are the group on which dissertation is focused. Though only Piaget and Chinn & Brewer, of the works cited here, explicitly reference children, there are no indications in the literature that the processes of conceptual change are fundamentally different for younger learners than older ones. The only real differences lie in the complexity of what is being learned.

Figure 5 - Climate change science sub-disciplines
Climate change science domain expert sub-disciplines (Zimmerman, 2008, p.28).



2.7 - Consensus in Climate Change Science

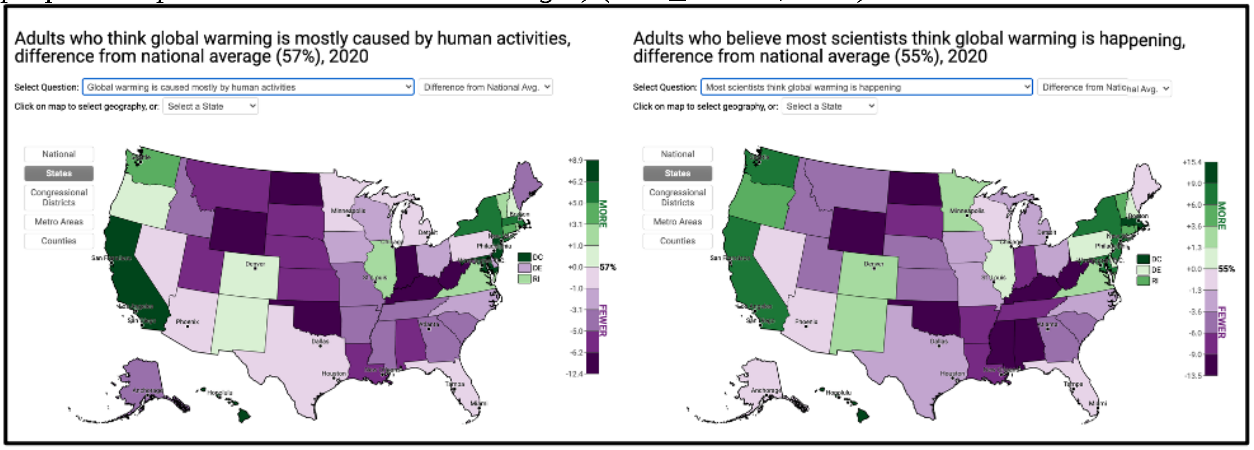
Consensus is an important concept that has been mentioned in several previous sections of this document. There is no consensus definition of, "consensus". Definitions range from "general agreement" to "unanimity" to "judgement arrived at by most" to "wide agreement". In terms of climate change science, 97% is the degree of consensus among domain scientists, which represent more than two dozen sub-disciplines (Zimmerman, 2008) (see Figure 5). They are an international community numbering in the thousands consisting of scientific theorists, experimentalists, and modelers. In the U.S., climate change research is conducted at laboratories such as the National Center for Atmospheric Research, agencies such as the National Oceanographic and Atmospheric Administration, and research universities. The degree of consensus among this community stands up to most of the offered definitions and even comes close to unanimity on several fundamental questions. The number, 97%, comes from two broad analyses of climate change domain experts' assertions that humans bear responsibility for unnatural levels of greenhouse gases and, by extension, anthropogenic climate change. This high level of consensus is based on a 2013 study of 20 years' worth of climate science peer-reviewed literature consisting of nearly 12,000 abstracts (Cook, Nuccitelli, Green, Richardson, Winkler, Painting, Way, Jacobs, & Skuce, 2013), and a subsequent meta-consensus study (literally entitled, "Consensus on Consensus", Cook, et al., 2016),

By contrast, the U.S. public has, at best, a thin majority opinion on anthropogenic climate change. Funk & Kennedy (2016b) reports acceptance of ACC at 48%. The Yale Program on Climate Change Communication (YPCCC) reports a slightly higher number at 57% (Yale_climate, 2020) (Figure 6, left panel). Ironically, the same dataset says that 55% of the U.S. public believe that domain experts think that climate change is happening. In other words, the belief is that experts accept climate change *less* (Figure 6, right panel) than the general public.

The consensus view of climate change that will be used as science bases for this dissertation comes from the global community of thousands of climate change science domain experts. The consensus view is not merely limited to questions of climate change's existence and causation. It extends to the contents of compendium reports produced *by* the community like the National Climate Assessment and the massive reports from the Intergovernmental Panel on Climate Change (Field, et al., 2014; Intergovernmental Panel on Climate Change & Edenhofer, 2014; Stocker, 2014; Reidmiller, et al., 2018). It is especially important to emphasize that these are *consensus reports* that take years to compile and involve hundred if not thousands of researchers who hail from virtually all countries on Earth. Because of the breadth of the underlying science, the international connectedness of the climate research community, and the depth of the analysis from these reports, they represent the most complete snapshots of the state of the science. From domain experts and their reports comes the knowledge of conceptual relationships that are most important from a climate change science standpoint, which should be held by experts and young learners alike.

Figure 6 - Climate change opinion maps

Public acceptance of human causation of climate change (left panel) and public estimate of expert consensus on climate change (right panel). Green both panels - above national averages, purple both panels - below national averages) (Yale_climate, 2020)



2.8 - Literature Review Summary

Climate change science education should be widely accessible, both in terms of availability and understandability. Polls show that large percentages of adults don't know basic conceptual relationships, like between ambient CO_2 levels and atmospheric heating. Children too hold many climate change science misconceptions, but national public school science standards are both nonspecific on the topic and often go unused at state and local school administration levels.

Climate change is a science, but it is often perceived as a socio-science. As a result, people view climate change according to different philosophies which have varying levels of scientific merit. People who adopt less scientific philosophies to understand climate change are more inclined to count opinion as scientific fact, which makes them more prone to science misconceptions.

Middle-school-aged children have historically had few opportunities to learn about climate change science. However, they possess the cognitive skills that are needed to understand it. At a young age, conceptual change learning and an appreciation for consensus of climate change domain experts are extremely useful tools for fostering novice learners' scientifically aligned and durable climate change science understandings.

CHAPTER 3 - METHODS

3.1 - A New Approach to Children's Climate Change Thinking

This section discusses a prior study (Toedte, 2018) in which I developed and implemented a game called the Climate Change Concept Map for Youth and Children, or C^3M_{YC}. As the name implies, The C^3M_{YC} offered children a way of organizing climate change concepts according to how they thought the concepts related to each other. The study employed mixed methods to focus on the interplay between two phenomena: children's climate change topical science knowledge and their engagement of the psychological disposition, Need for Cognition (NfC). The participants were thirty-five children ages 7-13 and six domain experts. The goal of this work was to investigate whether children's NfC was related to the degree of concurrence between their climate change thinking and that of domain experts. The age range of the children was selected in order to establish a minimum suitable age for children to learn about climate change. Suitability of this topic for middle-school-age learners had not previously been determined, from my review of the literature. Climate change learning opportunities are generally rare, and the ones that are available are for high school and college-age learners and are therefore not age-appropriate.

Author's note: Starting in this chapter and continuing for the remainder of the dissertation, a particular notation is used with choices participants make while using the C^3M_{YC}. The notation uses angle brackets, which are typically used in mathematical formulae. Whether the choices are for main concept areas, sub-concept tokens, or questions posed to participants, they are bounded by angle brackets and italicized. Examples are <*Climate*>, <*Greenhouse effect*> and <*Not sure*>.

3.1.1 - Mixed Methods Implementation

This work utilized a rich mixed methods implementation or what might qualify as "mixed methods heavy" (Greene, 2012, p.758) in that mixing occurred on multiple levels and was infused throughout the work. Mixing occurred at the philosophical level in terms of integrating the different thinking processes used by experts and children and what they respectively counted as knowledge. Both groups mixed post-positivist and constructivist thinking though they were weighted differently, as was reflected in the transcriptions of participants 24 and 37 (see section 3.1.4). Greene (2017a) calls this mutual regard for different philosophical perspectives a dialectic paradigmatic stance.

Mixed methods research designs frequently mention the purpose(s) that they embrace. Purpose, in this context, is concurrently a statement about the particular mixed-methods-infused design, the maturity of the line of research, and the researcher's hopes for advancing the line of research (Greene, Caracelli, & Graham, 1989; Greene, 2017b). This work engaged multiple mixed methods purposes of initiation, development, and complementarity. Greene, et al. (1989) describes initiation as yielding better depth and breadth of inquiry, whereas development and complementarity yield better data validity and interpretability, respectively. This work had an initiation purpose given that there were no known existing studies that considered children's thinking on climate change in contrast to that of experts. It had a development purpose because the methods "talked to each other". For example, a participant's response to one instrument (concept map) was used to inform the other instrument (interview) and make it more specific to the participant. Lastly, this study had a complementarity purpose because the synergy of the information gathered by the combined instruments painted a more complete picture of the phenomenon than either instrument did if consider individually.

Finally, this work mixed at the data level. As mentioned in the prior paragraph, the first instrument, the concept map, yielded information from the participant that was used to customize the second instrument, the interview. The first instrument yielded information about the participant that required clarification, elaboration, or precipitated a related line of questioning through the second instrument. The exact nature of the second instrument was therefore dependent on the first instrument's data.

3.1.2 - Science Bases and Concept Selection

The community of climate science domain experts represent dozens of climate sub-disciplines (Zimmerman, 2008; see Figure 5). Through peer-reviewed research and public domain compendium reports such as the periodic assessments of the Intergovernmental Panel on Climate Change (IPCC) and the (U.S.) National Climate Assessment, they establish what counts as held domain knowledge. These reports (Field, et al., 2014; Intergovernmental Panel on Climate Change & Edenhofer, 2014; Stocker, 2014; Reidmiller, et al., 2018) reflect the state of the art in measured and modeled climate change science, assessments of the resulting risks and dangers, and recommendations for responses by governments, corporations, and populations.

Domain experts are represented in this dissertation in two ways. The design of the main instrument used documents derived from the compendium reports to select a manageable yet representative set of science concepts. Several experts, some of whom contributed to the aforementioned reports, used the instrument to establish a consensus conceptual configuration which served as a benchmark against which children's responses were assessed.

Three main concepts *(<Climate>, <Environment>*, and *<Weather>*) were chosen based on their frequent and interconnected usage in the compendium reports. Temperature, rainfall, wind direction and velocity, and precipitation type and quantity, are typical of daily, if not hourly, weather reporting. Climate is generally thought of by domain experts as being the average of these and other weather properties over time. Averages of these quantities over decades or longer time scales are foundational to climate research. Mathematical climate models developed by the climate community over decades are used to estimate past, present and future climate properties. Computational models such as the Community Climate System Model are actually comprised of suites of models. Models, such as the Community Climate System Model, perform calculations of atmosphere, oceans, sea ice, and land surface, respectively (Drake, Jones, & Carr, 2005), which are considered to be the major environmental components. In this way, climate, environment, and weather are intertwined in the science, which is the reason for their selection as the main concepts in the C^3M_{YC} instrument.

A set of 17 sub-concepts was originally selected for inclusion in the instrument. Their names are shown in the leftmost column of Table 2. The sub-concepts were selected from three sources which were chosen based on their science credibility and their applicability to science education for young learners: the Next Generation Science Standards (NGSS, n.d.), Project 2061 from the American Association for the Advancement of Science (Project_2061, n.d.), and youth-oriented material about the IPCC (IPCC_kidzsearch, n.d.). The texts of these sources were analyzed for key science concepts, as well as associated text describing the concept and its connections to other concepts. The product of this analysis was the aforementioned 17 concepts. All the concepts were age-appropriate for young learners and were introduced in the NGSS standards no later than 5^{th} grade (NGSS, n.d.). Some of the original concept names were simplified, such as agriculture became <*Farming*>. Other concepts were combined, such as carbon dioxide and methane were combined in <*Greenhouse effect*>. Still other concepts needed to be split, such as differentiating rates of change which connect to different main concepts. Color codes shown in Table 2 were used in the design of the paper form of the concept map instrument that will be described next.

Table 2 - Topical knowledge sources of C^{3}MYC sub-concepts

Transfer of climate change concepts from topical knowledge sources to concept map instrument.

Selected Concepts from NGSS, Project 2061, and IPCC	Concepts in Sources			Representation in C3MYC	Concept Names in C3MYC	NGSS Connections	
	NGSS	Project 2061	IPCC			earliest NGSS grade	NGSS standards
agriculture	X	X		simplified language	Farming	5	5-ESS3-1
area	X			clarified size	Local area	4	4-ESS1-1
				clarified size	Regional area		
				clarified size	Global area		
atmosphere		X	X	represented in greenhouse effect represented in warming temps represented in cooling temps		5	5-ESS2-1
carbon dioxide	X		X	combined with other concepts	Greenhouse effect		MS-ESS3-5, MS-LS1-6
methane	X		X	combined with other concepts			MS-ESS3-5
glaciers	X		X	represented in warming temps represented in cooling temps			5-ESS2-2
ice		X		represented in warming temps represented in cooling temps		2	5-ESS2, 2-ESS2-3
volcanoes		X		represented in warming temps represented in cooling temps		4	4-ESS2-2
warming world	X		X	clarified temp change direction	Warming temps	K	K-PS3-2, MS-ESS3-5
				clarified temp change direction	Cooling temps		
diversity of species	X	X		combined with other concepts	Plants & animals	3	LS4-1
extinction	X	X		combined with other concepts			MS-ESS3
humans		X	X	simplified language	People	K	K-ESS3
natural resources	X			represented in farming represented in industry		K	K-ESS3-1
industry	X			kept as is	Industry	5	5-ESS3-1
oceans	X	X	X	kept as is	Oceans	4	4-ESS2-2
forests		X		kept as is	Forests	3	3-ESS3.B
rates of change	X			clarified time period	Fast changes	4	4-PS4-1
				clarified time period	Yearly changes	4	4-PS4-1
				clarified time period	Slow changes	4	4-PS4-1

3.1.3 - C^{3}MYC Instrument Design (Paper Form)

The C^{3}MYC used the fifteen climate change concepts listed in the leftmost column of Table 2 (note: the names of some of the concepts were changed in the paper form of the C^{3}MYC). The concepts were described to the participants as "sub-concepts", in contrast to the three "main concepts": <*Climate*>, <*Weather*>, and <*Environment*>. Participants were oriented by the researcher to the C^3M_{YC}'s "base map" showing areas for the main concepts (see Figure 7) and paper tokens (about 2" by 1") for each of the sub-concepts (see Figure 8).

Participants were first asked if they had heard about each of the main concepts, If the participant said they had some idea about the meanings of the main concepts, they were asked to arrange the fifteen sub-concepts on the base map to represent important relationships with the main concepts.

The base map's regions were associated with all combinations of the three main concepts. Circular areas shown in Figure 7 were for single main concepts. Rectangular areas represented pairs of main concepts. A triangular area in the middle represented all three main concepts. Participants were told to represent relationships however they thought was the best, even if that meant placing sub-concepts in the area marked <*Unrelated*>, which would indicate they thought a sub-concept related to none of the main concepts. If the participant was completely unfamiliar with a sub-concept, they were asked to place the token off the base map entirely, since they would be guessing about any conceptual relationships.

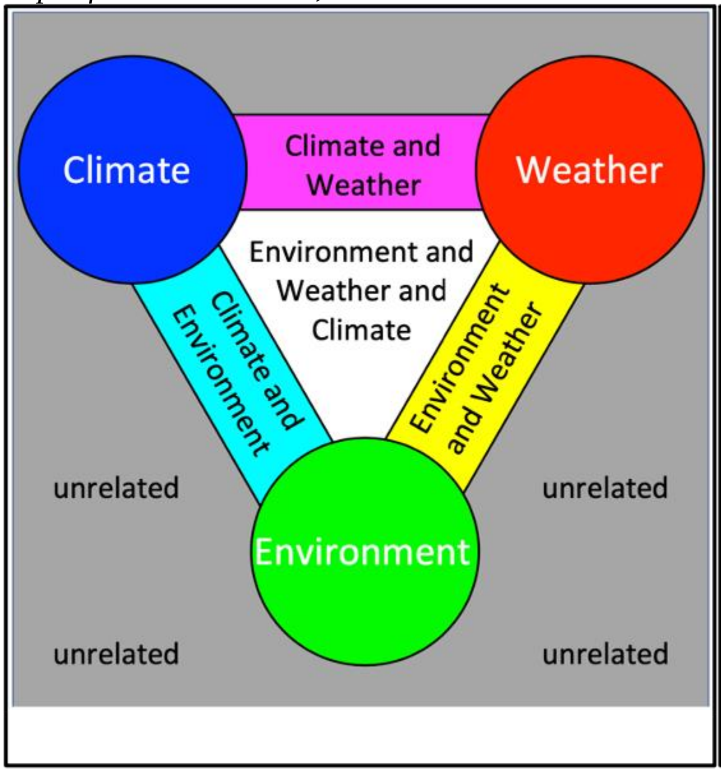
Participants were instructed to indicate their "thinking" rather than their "knowing". This choice of words was deliberate. Climate change science is a very challenging topic. Children may have little exposure to the topic and low confidence in their thinking about it. Some learners associate "knowing" with "correct" and "certainty". This study was much more interested in children's thinking than correctness, even if their thinking was evolving and less than certain.

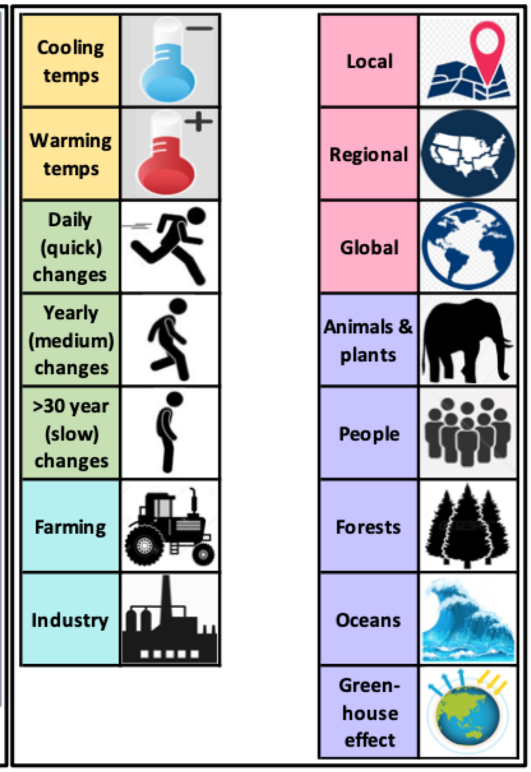
Figure 7 (left) - Base map from C^3M_{YC}

Paper form version 1.71, 2018.06.09.

Figure 8 (right) - Sub-concepts from C^3M_{YC}

Paper form version 1.71, 2018.06.09.



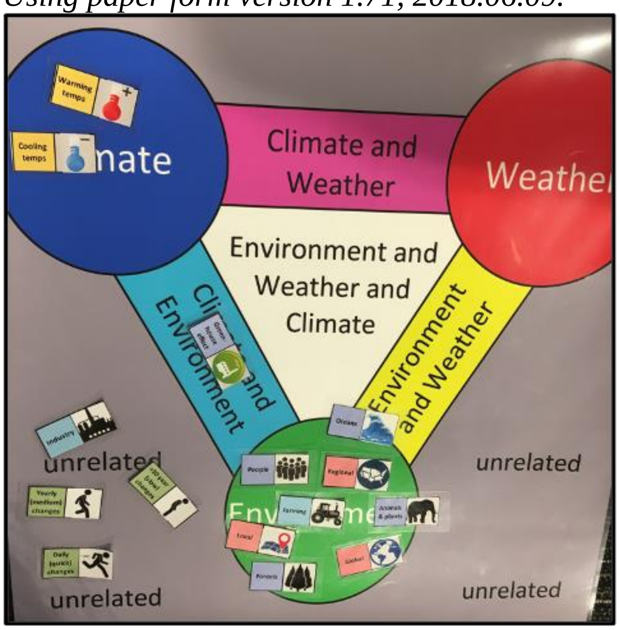


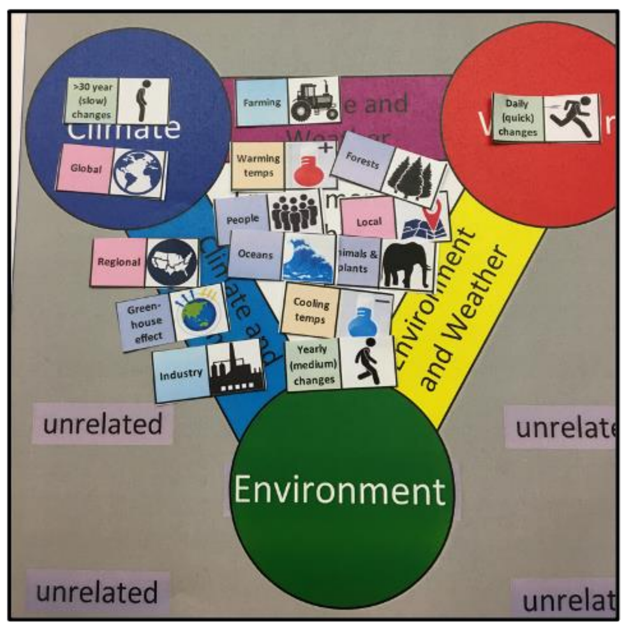
Classic elements of concept maps such as direction of the relationship and the nature of the relationship were not included in the design of the paper form of the C^3M_{YC}. Rather, these aspects of participants' thinking were explored in semi-structured interviews that were conducted immediately after the participants completed their concept map arrangement with the C^3M_{YC}. Whether participants were domain experts or children, the same concept map instrument, interview protocol, and instructions were used.

3.1.4 - C^3M_{YC} Instrument Usage (Paper Form) and Interviews

Thirty-five children aged 7-13 were convenience sampled for participation while attending an urban science museum located in a Midwestern city in February 2018. Twenty-two participants completed concept map constructions and interviews, and their parents completed demographic surveys. Demographic details collected from participants included gender (46% female, 54% male), home community type (72% suburban, 17% rural, 11% urban), parent/guardian's highest level of education (83% had at least a bachelor's degree), language use in the home (80% English only), and ethnicity/race (73% white/Caucasian. 9% black/African, 9% Asian/Pacific islander, 9% other). Eighty percent of participants were aged 7-10 and 20% were aged 11-13. Most (91%) of the children attended public schools. Six domain expert participants were convenience selected from a federal science research lab and a Midwestern R-1 university. Both institutions have historically been involved in climate change science research. Paralleling Zimmerman (2008), all domain experts selected for this project had PhDs, published extensively on different areas of climate change science, and self-identified as, respectively, geophysicist, engineer, ecologist, earth scientist, atmospheric scientist, and meteorologist.

Figure 9 (left) - Example learner's conceptual configuration using C^3M_{YC}
Using paper form version 1.71, 2018.06.09.
Figure 10 (right) - Example expert's conceptual configuration using C^3M_{YC}
Using paper form version 1.71, 2018.06.09.





As expected, experts' and children's responses to the instruments differed significantly in several regards. First, two-thirds of 7- and 8-year-olds did not know at least one of the main concepts with <*Climate*> being the least familiar. Example configurations for children and experts are shown in Figure 9 and Figure 10, respectively. The *Temporal rates of change* sub-concepts, <*Farming*>, <*Industry*>, and <*Greenhouse effect*> were the most unrelatable or unfamiliar sub-concepts to the children. The correlation between age and number of unrelated/unknown sub-concepts was weakly inverse (r = -0.182). The frequency of children associating sub-concepts with only one main concept was more prevalent with younger children (ages 7-9), than with older children (ages 10-13). A moderately inverse correlation between age and single main concept selection was borne out statistically (r = -0.442), indicating that older children built more complicated concept maps involving combinations of main concepts. Experts seldom related sub-concepts to only one main concept (17%).

Table 3 - Color codes for C^{3}MYC sub-concepts
Paper form version 1.71, 2018.06.09.

Main concepts key	
Color/code	**Name**
C	Climate only
E	Environment only
W	Weather only
CW	Climate and Weather
EW	Environment and Weather
CE	Climate and Environment
CEW	All 3 main concepts
U	No main concepts
O	Other/unknown

Sub-concepts key	
Color/code	**Name**
	Temperature changes
	Temporal rates of change
	Human activities
	Spatial extent of change
	Climate system elements

Table 4 shows the most common associations with main concepts for each sub-concept. This is shown for each of three participant groups that completed the C^{3}MYC instrument: experts, all children, and children of at least age 9. Also shown are percentages representing the degree to which these configurations were adopted, representing a rough measure of consensus for each group. Some children's configurations, while the most common, were used by less than half the group. Children of age 9 and higher were considered separately because it was thought that the lack of familiarity that many 7- and 8-year-olds exhibited toward main concepts warranted differentiation from the older children. The experts' view of the sub-concepts was very different from that of the children in the areas of human activities and *Climate change system sub-components*. Experts were nearly unanimous in their view that these sub-concepts related to all the main concept whereas children saw them as only being related to environment. The only sub-concepts that experts thought related to subsets of the three main concepts were those related to *Temperature changes*, *Temporal rates of change*, and <*Greenhouse effect*>. Children were in nearly perfect agreement with the experts with their configurations of the *Temperature changes* sub-concepts. Overall sub-concepts, experts had nearly 87% consensus on their configurations. Children, on the other hand, had less than 65% consensus and their configurations were drastically different from the experts on 7 of 15 sub-concepts. In summary, children's conceptualizations of climate change, framed as they were by the C^3M_{YC} instrument, were different in many ways from those of experts. There were several sub-concept categories where the differences were especially pronounced.

Table 4 - Consensus configurations using C^3M_{YC}

Two-dimensional comparison of consensus by sub-concept and by participant type.

		Intragroup configuration and consensus by sub-concept															
		Temperature changes		Temporal rates of change			Human activities		Spatial extent of change			Climate change system sub-components					
		Cooling Temps	Warming Temps	Daily changes	Yearly changes	30yr changes	Farming	Industry	Local	Regional	Global	Animals & Plants	People	Forests	Oceans	Greenhouse Effect	Composite consensus
Experts (*n* =6)	Consensus configuration	CW	CW	W	CEW	CE	CEW	CEW	CEW	CEW	CEW	CEW	CEW	CEW	CEW	CE	
	Degree of consensus	89%	89%	83%	72%	89%	94%	94%	89%	78%	67%	89%	100%	94%	94%	78%	**86.67%**
Children >= age 9 (*n* =17)	Consensus configuration	CW	CW	CW	CEW	CE	E	E	EW	CEW	CEW	E	E	E	E	E	
	Degree of consensus	88%	90%	37%	41%	41%	71%	55%	63%	59%	63%	76%	75%	82%	69%	49%	**63.92%**
All Children (*n* =22)	Consensus configuration	CW	CW	W	CE	CE	E	E	EW	CEW	CEW	E	E	E	E	CE	
	Degree of consensus	85%	85%	41%	38%	39%	70%	61%	64%	58%	61%	71%	77%	79%	70%	47%	**62.93%**
		Intergroup configuration and consensus summaries by sub-concept type															
		Similar configs, similar consensus		Similar configs, different consensus			Different configs, different consensus		Similar configs, different consensus			Different configs, different consensus					

Immediately after participants completed the C^3M_{YC} instrument, their constructions were used as bases for semi-structured interviews (see Figure 11). For the most part, participants discussed why they placed each sub-concept token in relation to main concepts. Following is a small selection of responses from experts and children with a specific focus on the sub-concept, <*Greenhouse effect*>.

> Participant 18, 10 years old – "Well, I put <*Greenhouse effect*> in climate and the environment because it comes from, like, factories, which are in the environment, and it changes the climate."

> Participant 24, 10 years old – "Oh, greenhouse is like a weather problem, 'cuz I read about it on, like, the computer once and it's like a weather effect."

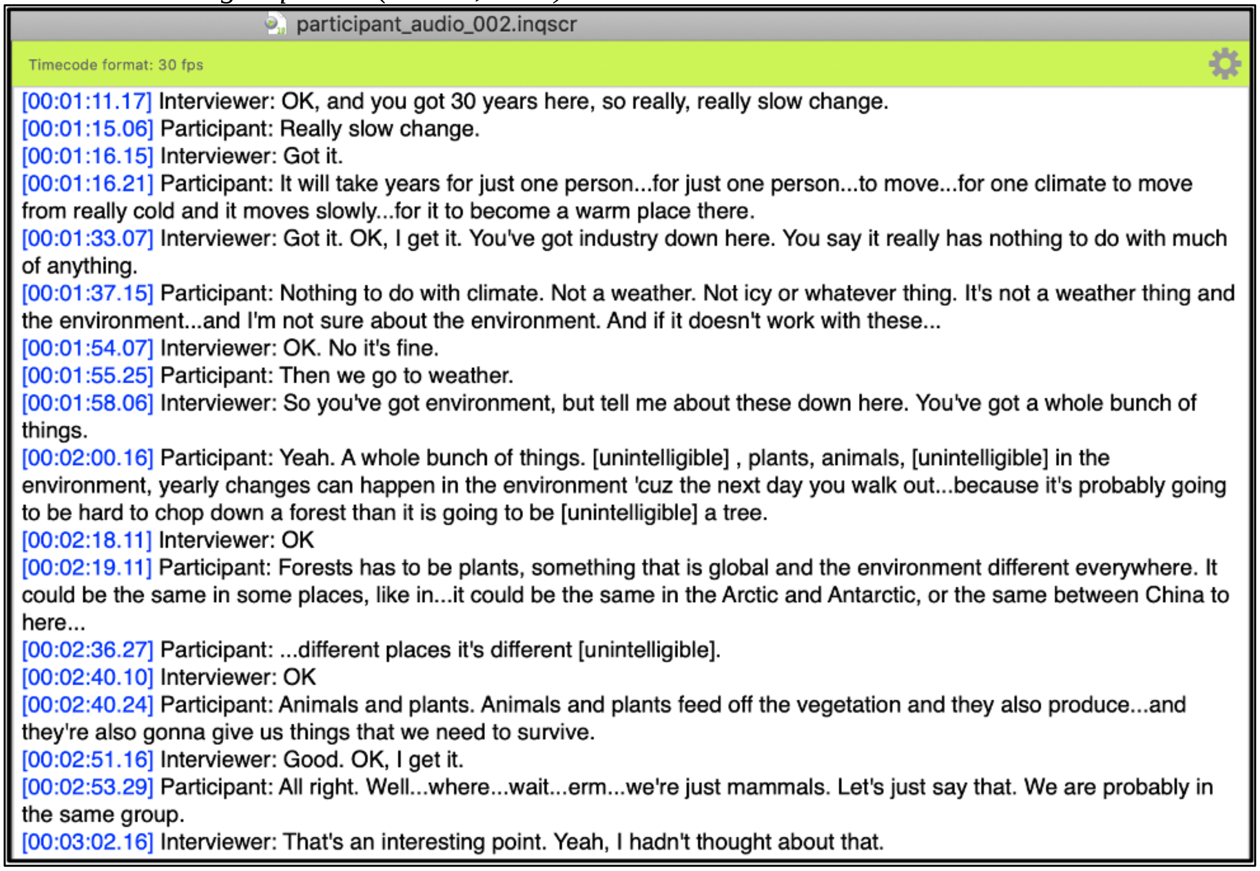
> Participant 25, 11 years old – "... and for climate and weather, I chose the <*Greenhouse effect*>. It's pollution, which affects the weather and climate."

> Participant 37, geophysicist – "OK. So, to me, this is kind of the major connection here, mainly because, you know, what we are really ... all three of those factors are going to impact industry, farms ... they're having global impacts ... forests, and they all kind of come together to impact our greenhouse effect, there is no doubt about it. And there's people influence that. So, as a result, since WE [participant stress] influence the greenhouse effect, and we influence it through our global activities ... forest, farms, and industry... as a result, all of those really need to be in the middle because that's the major driver behind all this."

Greenhouse effect is a challenging concept to understand because it intersects a number of other concepts, which participant 37 incorporated into her discussion. She drew a relationship between <*Greenhouse effect*> and all the main concepts, based on her experiences in climate science research and education. The three children quoted here all made different associations with main concepts using the C^{3}MYC (participant 18 - <*Climate & Environment*>, participant 24 - <*Weather*>, participant 18 - <*Climate & Weather*>). Though none of the children connected <*Greenhouse effect*> with all three concepts, it is noteworthy and encouraging that two of them thought that <*Greenhouse effect*> related to more than one main concept.

Figure 11 - Sample participant interview transcript

Transcribed using InqScribe (Toedte, 2018).



participant_audio_002.inqscr

Timecode format: 30 fps

[00:01:11.17] Interviewer: OK, and you got 30 years here, so really, really slow change.
[00:01:15.06] Participant: Really slow change.
[00:01:16.15] Interviewer: Got it.
[00:01:16.21] Participant: It will take years for just one person...for just one person...to move...for one climate to move from really cold and it moves slowly...for it to become a warm place there.
[00:01:33.07] Interviewer: Got it. OK, I get it. You've got industry down here. You say it really has nothing to do with much of anything.
[00:01:37.15] Participant: Nothing to do with climate. Not a weather. Not icy or whatever thing. It's not a weather thing and the environment...and I'm not sure about the environment. And if it doesn't work with these...
[00:01:54.07] Interviewer: OK. No it's fine.
[00:01:55.25] Participant: Then we go to weather.
[00:01:58.06] Interviewer: So you've got environment, but tell me about these down here. You've got a whole bunch of things.
[00:02:00.16] Participant: Yeah. A whole bunch of things. [unintelligible] , plants, animals, [unintelligible] in the environment, yearly changes can happen in the environment 'cuz the next day you walk out...because it's probably going to be hard to chop down a forest than it is going to be [unintelligible] a tree.
[00:02:18.11] Interviewer: OK
[00:02:19.11] Participant: Forests has to be plants, something that is global and the environment different everywhere. It could be the same in some places, like in...it could be the same in the Arctic and Antarctic, or the same between China to here...
[00:02:36.27] Participant: ...different places it's different [unintelligible].
[00:02:40.10] Interviewer: OK
[00:02:40.24] Participant: Animals and plants. Animals and plants feed off the vegetation and they also produce...and they're also gonna give us things that we need to survive.
[00:02:51.16] Interviewer: Good. OK, I get it.
[00:02:53.29] Participant: All right. Well...where...wait...erm...we're just mammals. Let's just say that. We are probably in the same group.
[00:03:02.16] Interviewer: That's an interesting point. Yeah, I hadn't thought about that.

3.2 - The Present study and Turning the C^3M_{YC} into a Digital App

The present study builds from my early research project which was discussed in the prior section (Toedte, 2018). Some study design elements were retained while others were revised based on the earlier findings. Still other elements were completely reworked based on the affordances of the digital C^3M_{YC}.

3.2.1 - Design Consistencies with the C^3M_{YC} Paper Tool

Some the aspects of the present study retained from the former work have to do with the concept map instrument. The 15 sub-concepts and three main concepts seemed to work well for participants 9-years-old and up, but less well for 7- and 8-year-olds. The game pieces thus remained the same but were used only with the older children. The domain experts' ways of thinking continued to be considered a benchmark of scientific thinking against which young learners' thinking is compared. Nonetheless, this study dismisses the notion of absolute factual knowledge, even from experts, on philosophical and research bases (Kuhn, 1996, Lederman, et al., 2002). In both the present study and the prior one, learners were encouraged to express what they thought rather than what they knew. This was true for their engagements with the concept map tool as well as interviews. An important design consistency between the studies is they followed similar mixed methods mindsets. In fact, some of the changes discussed in the next section are direct responses to findings from the initial study. Therefore, I argue this study extends investigatory strands from the earlier work and demonstrates inter-study sequential mixing (Greene, 2007). The present study, like its predecessor, engages the mixed methods purposes of initiation and complementarity. The purpose of initiation is to "…discover […] paradox and contradiction, new perspectives…" (Greene, 2017b, p.1). Initiation applies to this work because the digital C^3M_{YC} gives the researcher a new perspective on how participants articulate conceptual relationships by logging their interactions with the app. Unlike the paper C^3M_{YC} where only the final conceptual configuration was recorded, the digital version logs state information over time. This work also engages the purpose of complementarity, or "…seek[ing] broader elaboration, enhancement, illustration, clarification of the results from one method with the results from the other method, both measuring different facets of the same construct…" (*Ibid*.) A participant's interview data, the final configuration of their concept map with the C^3M_{YC}, and the logged data collected up to the final state together provide a more holistic picture of the participant's thinking than any single component conveys separately.

3.2.2 - Design Differences with the C^3M_{YC} Paper Tool

Because of differences in the design of the interviews, the present study does not have a purpose of development. Whereas the prior study allowed a participant's concept map configuration to influence questions asked in the interview, the present study does not. The interview was redesigned to be structured rather than semi-structured. As a result, it yielded different and useful responses from the participant, while making the responses more uniform across participants. Though these responses helped inform the reasoning behind a participant's construction, the questions were not altered by the construction. Because the instruments no longer "talked to each other", development is not a purpose in the present study.

Interviews in the earlier study were largely based on the participant's construction of the paper form of the C^3M_{YC}. In the present work, the interview was completely redesigned to ask topical science questions, epistemic practice questions, and attitudinal questions. The purposes of these questions were, respectively, to measure learning in a way customary of formal education, to assess the sophistication of a participant's knowledge curation, and to see where the participant stands on some fundamental climate questions that have been well researched with adults.

Some of the results from the earlier study pointed to areas for improvement in the present study. First, a more heterogeneous cohort of participants was desired. The earlier study's cohort was 74% white, 80% suburban, and 83% had a parent with at least a baccalaureate degree. Next, a participant's pattern of actions during conceptual construction was thought to be at least as important as their final configuration. Capturing only the final configuration, or state, of a participant's interactions with the paper form of the C^3M_{YC} was missing potentially explanatory data. Finally, children's Need for Cognition, or NfC, was left out of the new study. NfC is an important construct in the learning process, and it is especially so with socio-scientific issues. However, other factors, such as social influences, were deemed more central in this new work.

3.2.3 - Reimagining the C^3M_{YC} Paper Tool as a Digital App

Children's interactions with the paper form of the game (Toedte, 2018) substantially informed the digital version. I started each game with the sub-concept paper tiles arranged by category to the side of the sheet printed with the main concepts. After I explained what the tiles and the map main concept areas meant, the child was allowed to proceed with their construction. They picked up each sub-concept tile with thumb and index finger. Then they laid it on the main map where they wanted and then often slid the tile around underneath their index finger until they were satisfied with its position. Their interaction with the game was very much a hands-on, or haptic, experience by moving the tiles around the main map. I wanted to retain this haptic sense in the digital game as much as possible.

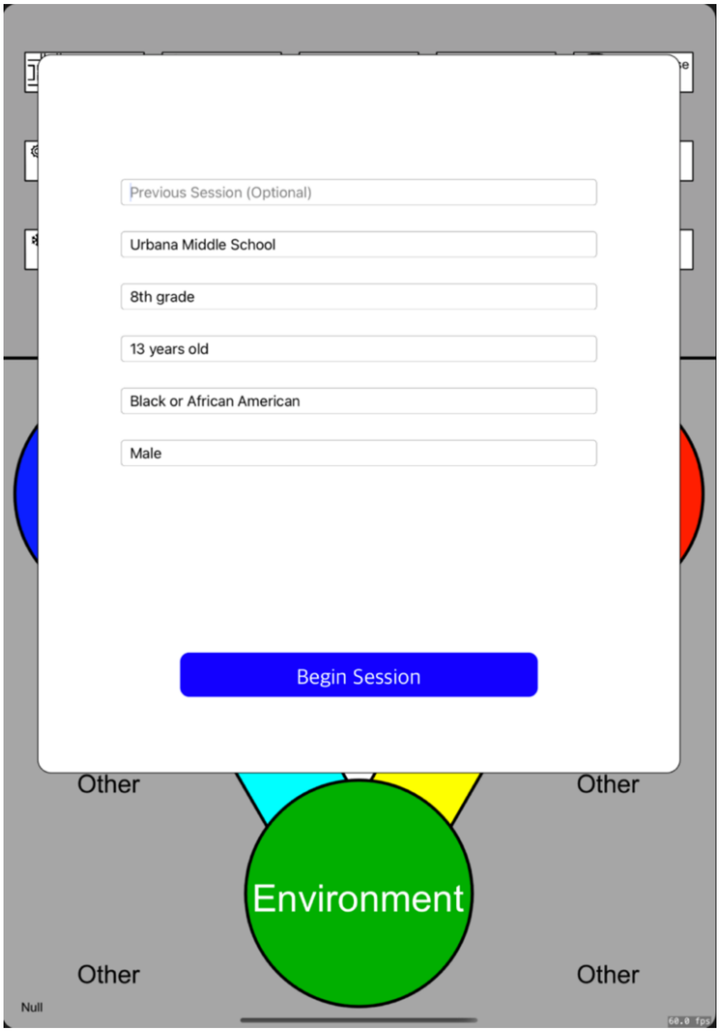
My desire to retain the haptic feel of the game in the digital version disposed the host device to have a touch interface. A computer with a standard keyboard and mouse or trackpad would technically work. However, this was thought to lose some of the sense of a game piece moving under direct control…literally underneath the finger…of the participant. For this reason, a tablet device was originally chosen as the target device for running the digital app. There were two additional reasons for choosing the tablet device. First was cost. Tablet devices cost half to a quarter the price of a laptop. Lowering the price of the platform broadens the potential for organizations and individuals to take advantage of the app. Second was screen size. Phone screen sizes were too small to display the necessary detail of the concept map app. Furthermore, it required too much haptic fidelity…precision of placement…to orient the tiles with required accuracy on such a small screen. Some children took great care when placing sub-concept tiles with the paper form of the game. A small screen would likely create frustration. Tablet devices, on the other hand, have much more screen space than phones and are less bulky than laptops.

As mentioned earlier, a participant's final conceptual configuration with the paper form of the game was recorded, but the sequence of their actions leading to completion was not. As a result, interesting and possibly meaningful actions by the participant were missed. A list of such actions includes the following.

- picking up a sub-concept tile from its initial location, not placing it on any main concepts, and placing it back in its initial place
- picking up a sub-concept tile from atop one main concept and moving it to a different main concept
- taking an unusually long time to place a sub-concept tile
- placing a sub-concept tile last or first of all sub-concepts
- placing a sub-concept differently in successive uses of the game

Though I initially considered capturing game state information at fixed intervals of time, my programmer suggested capturing haptic events when the participant selects a sub-concept tile by pressing their finger against its location on the host device's touch screen or releases a selected sub-concept tile by taking their finger off the host device's touch screen. This would facilitate logging all the actions listed above. All the actions listed above actually occurred with participants using the digital C^3M_{YC} app.

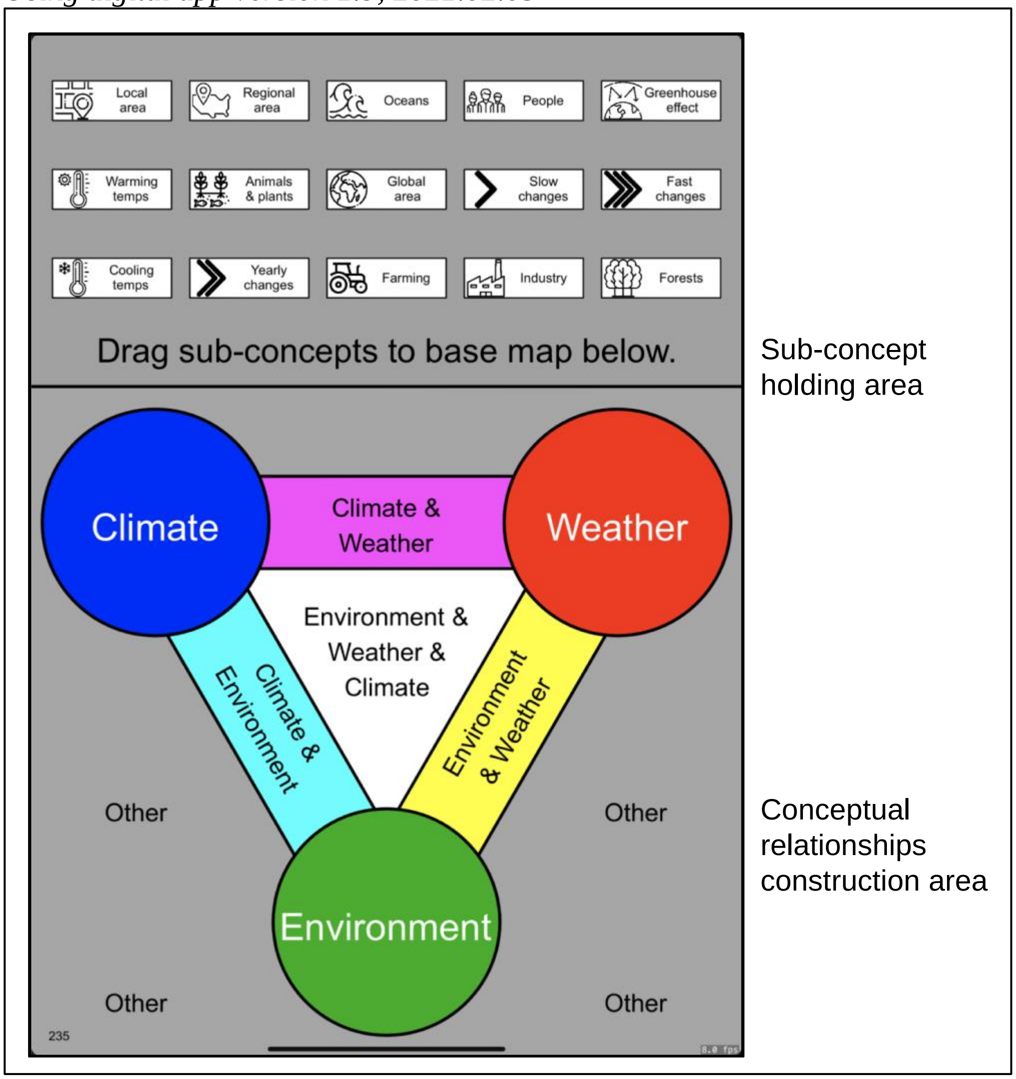
Figure 12 - C³M$_{YC}$ participant data collection screen
Using digital app version 1.9, 2021.02.03



3.2.4 - Developing the C³M$_{YC}$ Digital App

A then-undergraduate computer science major at the University of Illinois programmed the C³M$_{YC}$ digital app based on my design. We jointly made development decisions about the app during 2020 and early spring of 2021. Figure 12 shows the initial screen displayed by the app. The first field is the participant ID, a unique 6-digit random number assigned after completion of the parent survey (see section 3.2.7). The participant's ID is entered each time they use the app. The remaining fields for the participants school, grade, age, race, and gender are entered the first time only. The participant ID is used by the app to match a participant's sessions to facilitate assessments of their learning through multiple uses of the C^3M_{YC} app.

Figure 13 - C^3M_{YC} screen layout at start of gameplay
Using digital app version 1.9, 2021.02.03



Once a participant's information is collected or matched from a previous use of the app, a unique sequential session ID is assigned, the main map area is cleared, and the sub-concept holding area is populated with sub-concept tiles, as shown in Figure 13. The locations of the tiles are randomized to ensure that any patterns of sub-concept placement order are based on the express actions of the participant and not influenced by their position in the holding area.

When participants use the app, they are asked to rate their confidence in their thinking for each sub-concept they place. However, the question is not framed in terms of confidence, but rather how sure the participant is. Participants are asked to choose a response from the list, <*Not sure*>*,* <*Somewhat sure*>*,* <*Very sure*>*,* <*None of these responses work for me*>*,* or <*I don't know*>, to express their state of thinking about the sub-concept. "Sure", in this context, is therefore intended to be synonym of "confidence", and not "self-efficacy". The word, "sure", is more the vernacular of a 9–13-year-old child rather than "confident".

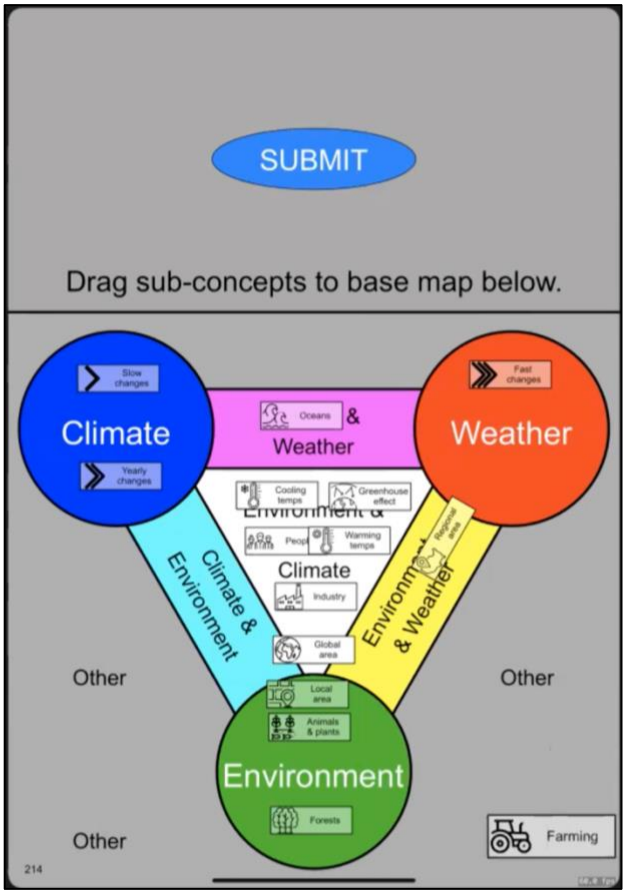
Confidence is a factor in this dissertation because of its role in conceptual growth. James Bruno's (1993) work involving confidence refers to a learner's information base consisting of different information elements, similar to concepts. For each information element, the learner has a level of confidence…a degree of surety…which impacts their ability to learn and remember that information. This dissertation holds a similar attitude about confidence. I am interested in the learner's self-assessment of their thinking about the most recently placed sub-concept because it could have cascading effects on their future learning and thinking. This is especially true if their learning involves conceptual change and conceptual alignment with scientists who have expertise in climate change. Bruno describes an important synergy between a learner's thinking and their confidence. He says, "…if one can build student confidence and fluency in information (informed), not only will this confidence be sustaining, but it can also lead to an acceleration in learning new information to high levels of confidence." (*Ibid*., p. 191).

Figure 14 (left) - A C^{3}M$_{YC}$ submission screen

Using digital app version 1.9, 2021.02.03

Figure 15 (right) - A C^{3}M$_{YC}$ statistical summary

Using digital app version 1.9, 2021.02.03. Note matching with participant's previous game session.



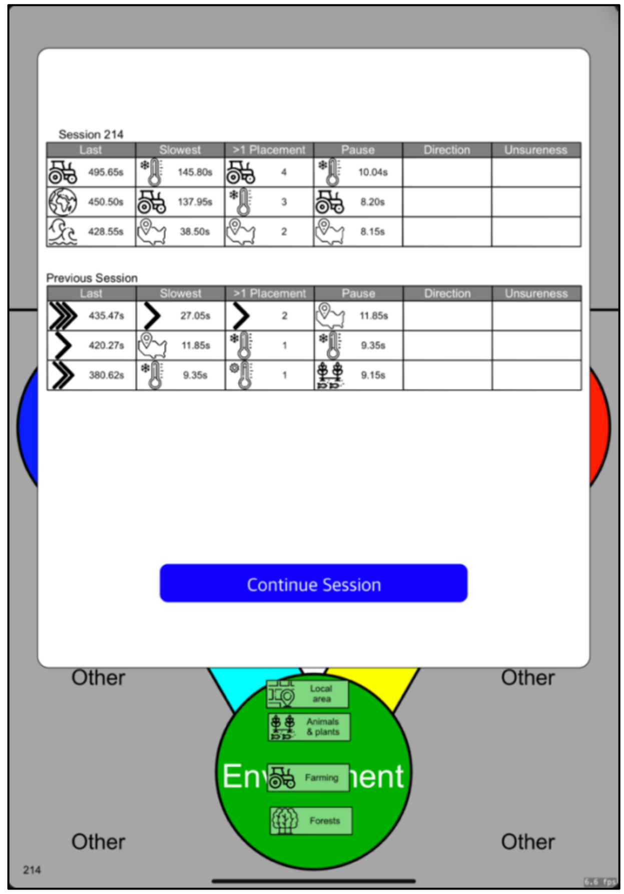


Figure 14 and Figure 15 show two game states from very late in a participant's second session with the app. These figures show screen shots for a participant's initial submission, and their statistical summary, or "stat table", after submission, respectively. After a participant places their last sub-concept, an initial submission screen is displayed similar to Figure 14. The researcher asks the participant if they are satisfied with their conceptual arrangement as shown. The participant can change any sub-concepts they want. If they do so, the questions about relationship direction and confidence are asked again. After last changes are complete, the

<*Submit*> button is selected, any residual event data is uploaded to the repository, and the haptic event log buffers are cleared.

After a participant picks <*Submit*> with the app, a stat table of their logged haptic events, like that shown in Figure 15, is displayed on the screen of their gameplay device. The stat table is comprised of up to three sub-concepts and related metrics in each of several statistical categories: those sub-concepts that were placed last, those that were replaced the most times, those for which the most time elapsed between first and last placements, those that had longest pauses (the time from a sub-concept's selection to its placement), and those for which the participant rated their confidence as low.

A participant's stat table is potentially very meaningful in terms of conceptual change. If the participant uses the app more than once, the app retrieves and displays both their current and previous stat tables for comparison, as shown in Figure 15. In so doing, differences and similarities between a participant's consecutive stat tables might indicate the need for particular areas of instruction to foster future conceptual growth.

Conceptual change is about shifts, or changes of state, in a learner's thinking about a concept. The app is a tool for recording changes in a learner's state of thinking about the relationships between sub-concepts and the main concepts. However, the stat table can potentially say much more about the learner beyond the existence of a relationship. In terms of conceptual change, the learner might place sub-concepts in an order that is meaningful to them. Considering Chinn & Brewer's (1993) response categories, the learner may choose those sub-concepts which change the least (e.g., they ignore anomalous data) first, and those which change the most (i.e., they accept Theory B) last. If the learner said they had low confidence in a sub-concept placement, they may have had little prior conceptualization of its nature and its relationships. They may have thought, in the moment, that a particular relationship was plausible and so they selected it. Most learners changed several sub-concept placements more than once during a session. However, if a learner changed the relationship for a particular sub-concept six times before finalizing their map, they may be experiencing a high degree of disequilibrium with regard to that sub-concept. This could be caused by a number of alternative conceptualizations having similar strengths. The learner might also be constantly experiencing conceptual impasses, sorting out which of the competing conceptualizations to choose.

The digital C^3M_{YC} app was developed using XCode, a free developer kit for Apple Macintosh computers. The app is programmed in the Swift programming language, a variant of C++. XCode builds executable programs for a wide range of Apple devices, including most models of iPads. This has ramifications for the visual layout of the app because every iPad has different physical screen dimensions and pixel density. The app is programmed to ascertain the model of the iPad and its screen characteristics. These characteristics are then used by the app to scale the sizes of text and graphics for the particular device. Information logged by the app is buffered continually while in use by a participant. Buffers are periodically flushed, and the data uploaded to a cloud-based repository, managed by Amazon Web Services. This limits the risk of the app's storage capacity being exceeded from too much accumulated data. This condition could cause the app to crash. Periodic buffer flushing helps ensure smooth gameplay since data uploads require minimal network bandwidth if they are distributed throughout the time the game is being played. Multiple instances of the game can be played simultaneously with all data being registered by participant ID in the repository. This is beneficial for educators and researchers working with groups of learners. Repository rules can also be written to restrict access by educators and researchers to data for their respective groups of participants. The repository contents, the paper form of the C^3M_{YC}, and the source code of the digital app are all protected under a Creative Commons Attribution-NonCommercial-Share-Alike International license.

3.2.5 - Using the C^3M_{YC} Digital App from the Participant Perspective

Figure 16 through Figure 23 show a gameplay event sequence from a participant placing a sub-concept in the concept construction area, rethinking their choices, and placing it a second time after some reflection. Table 5 shows the corresponding haptic event data in tabular form retrieved from the repository, which are representative of haptic events logged during a C^3M_{YC} digital app session. The collection of all event data from a session is the basis of statistical summaries like that shown in Figure 15.

Figure 16 (upper left) - Start of haptic event with <*Warming temps*> sub-concept
Figure 17 (upper right) - Moving and hovering with <*Warming temps*>
Figure 18 (lower left) - Continued movement and hovering with <*Warming temps*>
Figure 19 (lower right) - Placement of <*Warming temps*>, question prompts

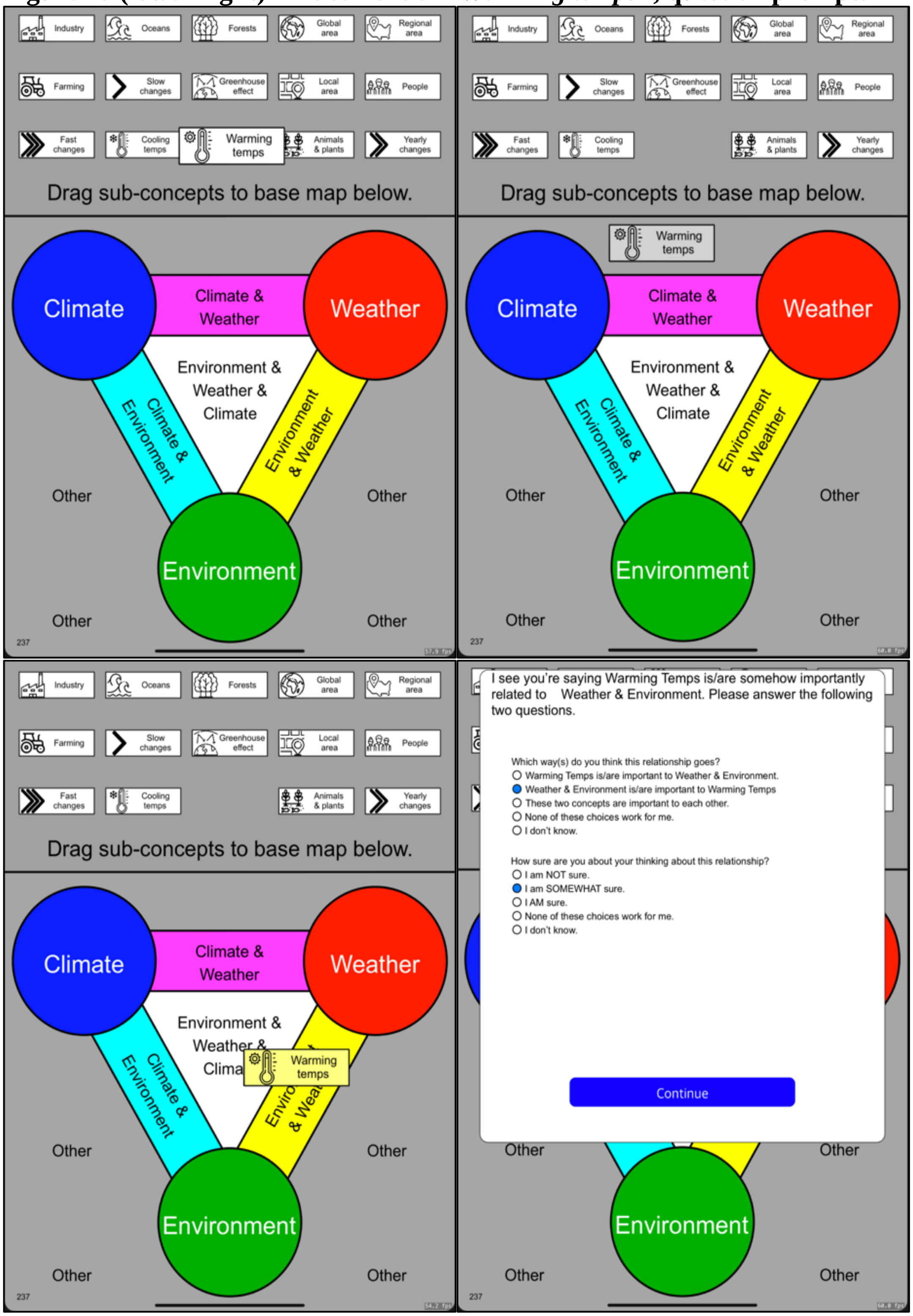


Figure 20 (upper left) - Prompts completed. End of 1st haptic event
Figure 21 (upper right) - Start of new haptic event with <*Warming temps*>
Figure 22 (lower left) - Different placement of <*Warming temps*>
Figure 23 (lower right) - New prompts completed. End of 2nd haptic event

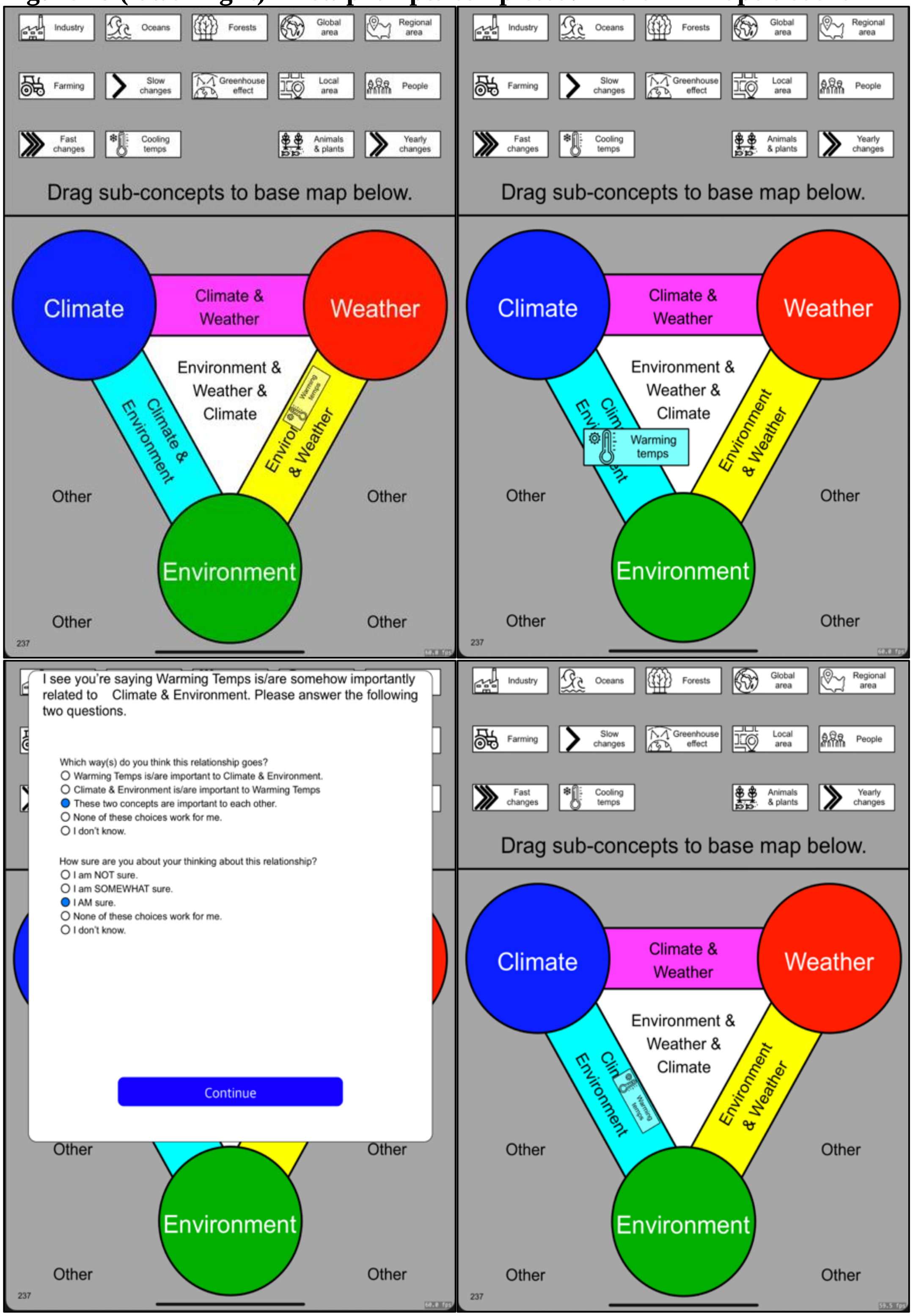


Table 5 shows the event data for the two events depicted in Figure 16 through Figure 23. They were logged and uploaded by the app, and later downloaded by the researcher. The tile index for <*Warming temps*> is 1. The last row is from the participant's next placement, which is for <*Industry*> (tile index 6). The data reflects the beginning and end of each move, and the start, stop, and elapsed times for the event relative to the beginning of the session.

Table 5 - Logged data

Data from events described in Figures 3.13-3.20

Session ID	Tile index	Previous main concept	New main concept	Event duration	Event start	Event end
237	1	Bank	Weather & Environment	8.70	50.11	58.80
237	1	Weather & Environment	Climate & Environment	3.56	58.80	62.36
237	6	Bank	Climate	2.57	62.36	64.93

3.2.6 - Participant Recruitment

Data collection for this study was originally planned to be conducted in-person, after school, and on weekends. However, due to the COVID-19 pandemic, face-to-face participation was not possible during spring semester of 2021 in many school districts and after school programs Furthermore, it was considered generally unwise from a health risk standpoint to conduct face-to-face research regardless of a school district's stance on in-person learning. Therefore, all recruitment and research participation for this study switched to online mode. Over half the participants connected with this study via one of three routes: an electronic research bulletin board maintained by a Midwestern R-1 university, the distribution list for a Southeastern regional science fair, and the distribution list for a science education project managed by a federal agency.

3.2.7 - The Parent Survey

For a child to be a candidate for participation, their parent or guardian completed an online parent survey. The survey was designed and published with the Qualtrics online research platform. The survey details can be found in Appendix B.

Before the survey was made available to candidates' parents and guardians, Institutional Review Board (IRB) approval was requested from the Office for the Protection of Research Subjects (OPRS) at the University of Illinois at Urbana-Champaign. The study was granted exempt status because it posed minimal risk to human subjects. The approval response from OPRS can be viewed in Appendix C.

After a parent or guardian provided consent for their child to participate, they were asked for the following information.

- Demographic information about the child: gender, age, grade, school type, favorite subjects, preferred sources of science information
- Demographic information about the parent or guardian: race, highest education level, political preference
- Demographic information about the child's community: postal code, community type, major employers

The reasons for collecting these data all relate directly or indirectly to the child. The question about sources of science information relates to the epistemic practice questions that were asked in interviews. Highest education level, political preference, and rurality are demographic spectra that have moderate to high correlations with science-aligned perspectives about climate change. Lastly, the question about major employers is relevant because businesses that have more pronounced environmental impacts may use their economic power to locally promote climate-averse products, practices, and attitudes.

3.2.8 - Participant Selection

The participant cohort for the earlier study (Toedte, 2018) was quite homogeneous in several demographic categories, which was an acknowledged shortcoming. No participants from the earlier study were in this cohort. Thirty-two participants were planned for the present study. Fifty-seven parents and guardians completed parent surveys, thus making their children eligible for the study. The rate of parents and guardians completing the survey was uneven and the survey continued to be offered after data collection commenced. It was hoped that the participants in the new study would be more demographically heterogeneous but, initially, this was not the case. Because the planned level of participation was not yet in sight, all eligible children were admitted to the study at first. Therefore, the first part of the participant sample was selected purely out of convenience. More parents completed the survey toward the end of its offering period, which permitted a greater ability to choose participants and achieve better balance in several demographic categories.

Thirty-six of the candidates were selected as participants. Thirty-one of them completed both data collections, three participants did not respond to repeated attempts to contact them to set up the first data collection episode, and two participants abandoned the study before the second data collection episode was complete. Table 6 shows the demographic characteristics of the 33 participants from whom any data was collected. There was good gender, age, and grade balance across the cohort. However, the racial distribution was imbalanced toward white participants.

Table 6 - Participant demographic data from parent surveys

Gender		School Type		Grade level (*n* =33, *M* =5.73, *s* =1.44)		Age (*n* =33, *M* =11.09, *s* =1.26)	
male	51.5%	public	81.8%	3rd grade	12.1%	9 years old	15.2%
female	48.5%	private	3.0%	4th grade	9.1%	10 years old	12.1%
		home	9.1%	5th grade	12.1%	11 years old	36.4%
		other	6.1%	6th grade	33.3%	12 years old	21.2%
				7th grade	27.3%	13 years old	15.2%
				8th grade	6.1%		

Table 7 shows the demographic characteristics of the parents and guardians of the 33 participants that provided data for the study. In at least one way, this was a more heterogeneous group than those that participated in the earlier work because there was good balance between rural and suburban families. The education level remained much higher than national averages. This was partly attributable to two of the communities with significant numbers of participants being hometowns to land grant universities. Political orientation was overall skewed toward liberalism. This was despite nearly half the participant families being from rural communities, which tend to skew toward political conservatism.

Table 7 - Parent and community demographics from parent surveys

Race		Highest education level		Political		Community type	
white	84.8%	**HS**	12.1%	**strong lib.**	24.2%	**rural**	45.5%
black	6.1%	**assoc deg.**	9.1%	**liberal**	18.2%	**suburban**	54.5%
Asian/Pac	3.0%	**bacc. deg.**	12.1%	**slight lib.**	6.1%	**urban**	0.0%
Hisp/LatinX	0.0%	**mast. deg.**	42.4%	**slight cons.**	9.1%		
multi-ethnic	0.0%	**MD/PhD/JD**	15.2%	**cons.**	12.1%		
other	6.1%	**other**	9.1%	**strong cons.**	3.0%		
				other	27.3%		

3.2.9 - Research Questions and Participation Overview

The following two research questions were devised to advance an understanding of middle-school-age learners as they tackle the conceptually difficult topic of climate change.

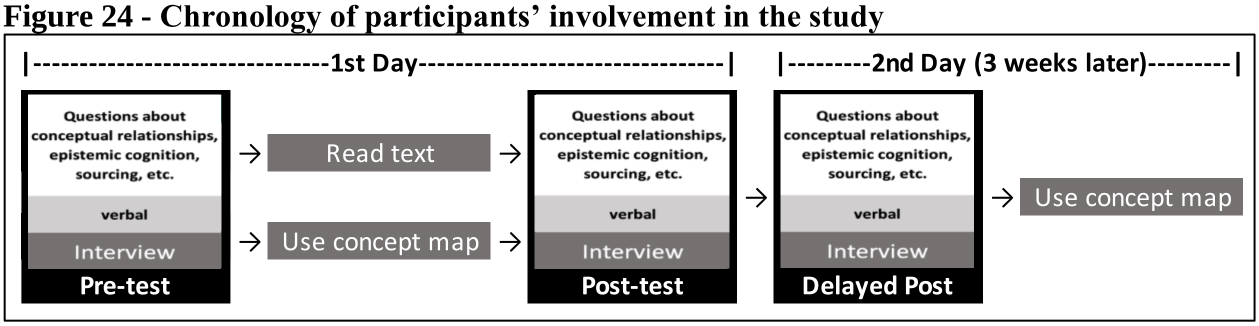
These questions engage the mixed methods purposes of initiation and complementarity and set a course for future research and implementation in educational settings.

> *RQ1 - In what ways do the transient data features (haptic event logging) of a digital app reflect learners' underlying comprehension and/or misunderstanding of climate change science concepts.*

> *RQ2 - In what ways does the combination of learners' interactions with a digital app and their interview responses suggest different patterns of change in their climate change thinking?*

Two participation tracks devised to explore these questions are shown in Figure 24. Two data collection episodes were conducted with each participant with a 3-week interval between the episodes. The first episode took roughly a full hour, and the second episode took roughly half an hour. The participants were divided into two groups. Group 1 used the C^3M_{YC} digital app to complete a concept map which reflected their thinking about a small set of climate change science sub-concepts in relation to three main concepts: <*Climate*>, <*Environment*>, and <*Weather*>. The other half were asked to read a topical text, similar to reading a section of a textbook. All participants used the concept map at the end of their second data collection episode.

Figure 24 - Chronology of participants' involvement in the study



Participants' first data collection episodes lasted no more than an hour for two reasons. A longer episode would be more difficult to arrange with families' schedules, and participants would likely become restless. Following is the general timeline for a participant's data collection episodes.

--- data collection episode 1, scheduled Zoom meeting ---
00:00 - welcome and initial instructions
02:00 - pre-test interview (10-minute max)
12:00 - instructions about the condition (10 minutes max)
22:00 - read text or play C^3M_{YC} app game (15 minutes max)
37:00 - post-test interview (10-minute max)
47:00 - wrap-up including discussion and planning (5 minutes max)
52:00 - participation complete

--- 3 weeks later, data collection episode 1, scheduled Zoom meeting ---
00:00 - welcome and refresher on instructions
02:00 - delayed-post-test interview (10-minute max)
12:00 - instructions about C^3M_{YC} app game (10 minutes max)
22:00 - play C^3M_{YC} app game (15 minutes max)
37:00 - wrap-up including discussion and thanks (3 minutes max)
40:00 - participation complete

3.2.10 - The Interview Protocol and Reading Condition

An interview protocol consisting of 12 questions was used three times with each participant. Detail of the protocol can be found in Appendix D. Seven of the questions were derived from the 5th-grade standards from the NGSS framework (NGSS_framework, 2012) with each question relating to an area relevant to climate change. From here forward in this dissertation, these will be referred to as "the NGSS questions". For example, section ESS1.C refers to knowledge about the history of Earth. This is relevant to climate change because climate change involves "deep time"…millennia or longer…which can be a difficult concept to grasp. Ice cores are an invaluable resource for climate change researchers in that CO_2 concentrations from tens of thousands of years ago can be derived from the cores. Section ESS2D refers to the relationship between weather and climate, one of the most important relationships for learners of climate change science to understand. Two questions dealt with learners' epistemic practices. Models of epistemic cognition look at different aspects of epistemic practice, such as how a learner assesses sources of information (Schommer, 1990; Schommer, 1998, Schommer-Aikins, Mau, Brookhard, & Hutter, 2000; Burr & Hofer, 2002). Learners who use more discerning and sophisticated means to construct knowledge, especially about complex problems like climate change, tend to have a better grasp on the foundational science (Goh, 2015; Roychoudhury, Shepardson, Hirsch, Niyogi, Mehta, & Top, 2017; Ke, et al, 2020). The last three question groups were about fundamental attitudes about climate change, risk perceptions, and social response. The questions are interrelated in many ways and responses are predictive of a participant's future learning and engagement. For example, if someone thinks that climate change exists and that scientists are robustly in consensus about its existence, they are more likely to think it will affect them and that it deserves response from society at large. These questions were derived from opinion studies conducted by the YPCCC (Yale_climate, 2020) and will be referred to in the remainder of this dissertation as "the Yale questions". The standards-based and epistemic questions were each framed two different ways to populate two versions of the interview. This was to avoid asking the same questions in the pre-test and post-test, which were space about 30 minutes apart in the first data collection episode. The Yale questions were kept the same for all interviews.

The reading condition, which can be found in Appendix E, was designed to be like a section from a textbook. The science content for the reading condition is derived from sources including the IPCC 5th Assessment Report (Field, et al., 2014; Intergovernmental Panel on Climate Change & Edenhofer, 2014; Stocker, 2014) and the 2018 National Climate Assessment (Reidmiller, et al., 2018). The final text was vetted by two climate change experts involved in

IPCC and other climate research activities. Many of the concepts mentioned in the text are the same as the sub-concepts used in the C^3M_{YC} game. The wording of the text was analyzed by Readable (Readable.com, n.d.) to have a mean Flesch-Kincaid Grade Level of 6.67 and is therefore considered to be suitable for the participants in this study. The length of the text, including captions, is just less than 1400 words. Children's literacy sources (Beaver & Carter, 2009; Hasbrouck & Tindal, 2006) indicate the mean 6th-grade reading speed is around 160 words per minute. At this pace, the text is readable in less than nine minutes by a 6^{th}-grader. Participants were given 15 minutes to read the text, which matched the estimated time to complete the game task, and to allow time for participants to reread the text. Even though all participants were encouraged to go back and reread the text, few did so, and no participants exceeded the allotted time.

3.2.11 - Relationships Between Research Questions and Participant Data

Answering RQ1 requires comparing the assessment values of a participant's final C^3M_{YC} app configuration and their full sequence of configuration movements using the C^3M_{YC} app. The movements used by each participant in completing a conceptual configuration are considered to be unique to that configuration, that session using the app, and that participant. RQ1 questions the value of the transient data for understanding the participant's thinking *en route to* their final configuration. Moves and their meanings are thus bound together. Potentially meaningful movements include pauses, placements, replacements, and the elapsed time between placements. It is likely that these movements will mean different things with different learners. For example, a pause could reflect a learner's uncertainty about where to place a sub-concept tile. On the other hand, it could indicate the learner considering a wider range of possibilities for placing the token than they did in their prior data collection episode. Movements have meaning in the moment and analyses of movements should consider this.

Answering RQ2 potentially involves all a participant's data…conceptual construction data, topical knowledge data, attitudinal data…and how these data change over the participant's data collection episodes. For example, a learner's changes from simplistic to complex answers about the history of Earth might be meaningful in terms of conceptual change if viewed in parallel with more complex placements of <*Warming temps*> and <*Cooling temps*> with the app. In another scenario, it could be that members of the participant's family believe that climate change does not exist. If the learner has begun to adopt this attitude personally, it may be reflected in their C^3M_{YC} constructions. Yet another example is a learner's responses of high motivation on questions of climate policy and action could help explain conceptual gains from pre-test to post-test and retention of the gains in the delayed post-test. The interview protocol draws from veins of research that have not, to my knowledge, involved youth and children. Asking these kinds of questions of children may help inform how changes in younger learners' attitudes and conceptual ideas relate to each other.

3.2.12 - Notes on Using Zoom for Data Collection

The COVID-19 pandemic has raged worldwide for 20 months, as of November 2021. Starting in February of this year, my team and I started using Zoom meetings exclusively to collect data for this study. We learned a lot about our participants and about interacting with them over Zoom. The experience was mixed, but positive overall.

Among the obvious negatives of Zoom meetings, they are virtual, and they therefore limit what you, the researcher, can learn to what you hear and see of your participant and their surroundings. Sometimes, you know something “else” is going on with your remote correspondent, but you don’t know the extent to which it is important to the research if they don’t tell you. You miss many of the interpersonal communication and environmental clues that surround your participant. Another negative is the non-uniformity of network service. The extent to which the research experience suffers from slow frame rates, frozen video, and garbled audio, is partially a factor of the technology that sits between the researcher and the participant. It is also partially due to the technology that a family can *afford* to purchase or lease. Technology, despite all its advantages, is a tool of inequity. Because network service was unequal across our participants, some had poorer experiences with the C^3M_{YC} app. Selecting sub-concepts didn’t work as well, since it was being performed over the network using Zoom’s remote control feature. Some participants talked about it, but surely others did not. In addition, remote control (RC) via Zoom is disabled on ChromeBooks. Some of our participants’ only platform was a school issued ChromeBook. RC was required for participants to remotely operate the game over Zoom. Rather than interacting directly with the game, those participants who didn’t have access to another platform instructed their research team member to move sub-concepts and answer questions for them. Perhaps their family could not afford a different laptop with which remote control could have been used. Using a different laptop would have enabled them to use the C^3M_{YC} game more directly, personally, and perhaps more impactfully. It will never be known how significantly this affected their experience and, by extension, the data collected from their experience. One final negative about Zoom is that everybody is using Zoom…*a lot*. Maybe people are tired of Zooming, but most people of tired of *having* to use Zoom. For many participants, it was clear that Zoom was a less enjoyable experience than face-to-face communication.

There were many positive aspects of Zooming to collect data. First, the cohort of children for this study was much more geographically diverse. Geographic diversity would likely have limited to a 100-mile radius of Champaign-Urbana if this study depended on face-to-face data collection. As it happened, children from California to Washington, D.C., were in the group. Second, the data quality was very good. A total of about 30GB of video, audio, chat, and transcript, was collected. Not one recording was lost or deleted. The quality always met or exceeded what was required for the research. Particularly surprising was the quality of Zoom's automatic transcription service. No transcription service is perfect, but Zoom's transcriptions were excellent as a first cut. It was surprising how much it got right, even when there was background noise, or the speaker spoke softly. It even got many proper names correct. Zoom transcription likely saved an hour of effort per video for the 70 videos collected.

Zoom also provided a great platform for training research team members to collect data in a fairly uniform way. During training, team members were able to observe interviews with their mics and cameras off and be a "fly on the wall". Similarly, I was able to watch how team members handled data collection once they were trained. In those situations, after a data collection was complete and the participant signed off, we simply extended the meeting to discuss the interview and what could be improved.

3.3 - Methods Summary

I conducted a mixed methods pilot study in 2018 involving a custom concept mapping game using a paper gameboard and tokens for climate change concepts. Concept map configurations from children ages 7-13 were statistically compared to those of climate change experts and served as a representation of their climate science conceptual thinking.

The basic idea of the concept map, children's conceptual configurations, and those of experts were retained in the design of a digital app in the present study. Using the app was one of two conditions used with participants, the other being a short text. Data logging, a new feature of the app, was used to record participants' interactions with the game.

An interview protocol was designed to ask the participant attitudinal questions about climate change, questions about how they learned about climate change, and questions about how climate change related to other sciences. All participant interactions with the game and all interviews were conducted and recorded using Zoom meetings.

CHAPTER 4 - ANALYSES

My team and I collected many kinds of qualitative and quantitative research data for this dissertation. Roughly 48 hours of video and audio were collected from participant interviews, reading tasks, and game tasks, each of which contained multiple data groups. "Data group" is the term used in this work for data collected from multiple participants, with a particular purpose in mind, and of a particular format. Tens of megabytes of haptic event data were logged from participant interactions with the C^3M_{YC} digital app. Haptic event data was just one of the data groups generated by the digital app.

Some of the data groups in this study has not, to my knowledge, previously been collected from middle-school-age learners. In fact, I found that very little prior research about conceptual change in climate change science for middle-schoolers has been conducted (Toedte, 2020). Of the 28 studies since 1988 that met the selection criteria, only ten of them attempted to foster conceptual change. Only three did so with an app and none of them involved concept maps. Among the data groups collected in this dissertation study, the attitudinal and action-oriented questions from the interviews have only been previously asked of adults. Haptic event data, like those collected by the C^3M_{YC} digital concept map app, has not previously been collected from middle-school-age learners.

The following data analyses respond to this study's research questions. Though this work is not a case study, some of the analyses fit that mold. For RQ1 (section 4.1) and RQ2 (section 4.2), respectively, individual participants were selected based on their divergent responses to the methods. In section 4.3, groups of participants were formed based on different demographic and socio-cultural factors. Section 4.4 consists of analyses that span the study cohort but explore different data groups in relative isolation from each other. The reason for this was to objectively consider how the respective data groups inform participants' climate change thinking.

Individual participants featured in this chapter are referred to by their respective aliases to enhance readability and flow. Andy and Bree are the subjects of section 4.1. Emily is the subject of section 4.2.

4.1 - Comparison of C^3M_{YC} Data Groups

The following two mini-analyses address Research Question 1.

RQ1 - In what ways do the transient data features (haptic event logging) of a digital app reflect learners' underlying comprehension and/or misunderstanding of climate change science concepts.

Stated more simply, RQ1 asks, "What is the added benefit from data logging with the C^3M_{YC} digital app?" The C^3M_{YC} digital app logs haptic events. A haptic event starts with a participant picking a sub-concept token by touching their finger to the surface of a touch-sensitive screen, like an iPad. An alternative to this is clicking and holding the mouse button on a device that does not have a touch-sensitive screen. The haptic event continues if the participant keeps touching the screen or holding the mouse button. They can move their finger or mouse anywhere within the game's screen area. A haptic event ends and is complete when the user stops touching the screen or releases the mouse button. For the start and end of the event, the C^3M_{YC} digital app records the time and location within the game's screen area of the participant's finger or mouse. The app, therefore, records what sub-concept was picked, what area of the game screen the sub-concept was picked from (all sub-concepts originate in <*Bank*>, short for "Word Bank", which is the initial location for all sub-concept tokens at the start of gameplay), and what area it was moved to (e.g., <*Climate*>). Events reflect a move of any duration for any sub-concept anywhere within the game's screen area. The patterns of event details surrounding moving a sub-concept can reveal aspects of the participant's conceptual thinking.

The paper form of the C^3M_{YC} was used in such a way that the only data group it collected was the last conceptual configuration, or final state of the game. The digital form of the C^3M_{YC} app collects the sequence of all events leading to the final state. With each event there is the sub-concept that is being moved, a beginning time for the move, an ending time, the main concept area(s) where the touch or cursor started and ended, and responses to the questions after the move. By logging the participant's haptic events with the sub-concept during the game, changes in their thinking may be revealed in the moment. So, yet another way of asking RQ1 is, "What can you tell that is different between knowing the information from the moves compared to just knowing the final configuration?"

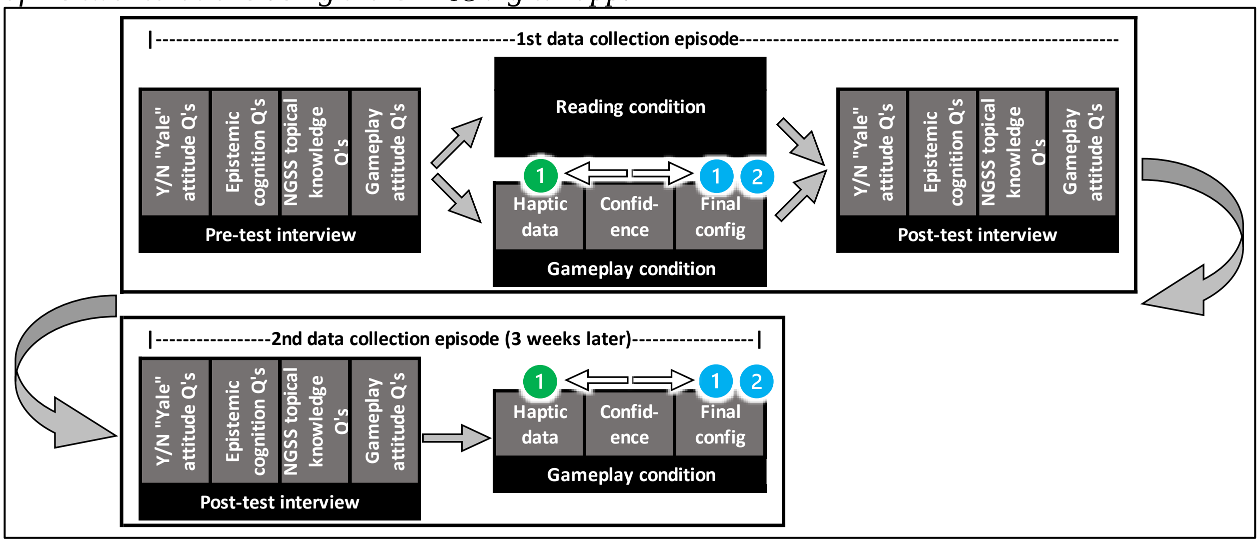
It is these two data groups, the final state and the interim moves, that is the subject of the next two sections. The data groups are discussed in terms of what they reveal about two very different participants. Details about the two data groups will be discussed with each case.

4.1.1 - Andy (Participant 919511): Maintaining Agreement, Gaining Confidence

Andy (not his real name) was a 13-year-old boy who was assigned to the gameplay condition and thus played the game twice. Figure 25 depicts the comparison that this section will discuss. Specifically, the comparison is between what is learned from his final conceptual arrangements, and the combined information from his haptic data and the final arrangements. His final arrangement of sub-concepts for his first session is shown in Figure 4.2.

Figure 25 - Andy's C^{3}MYC logged data

Andy's conceptual arrangement (the blue "1") combined with his haptic event data (the green "1") in comparison to only Andy's final conceptual configuration (the light blue "2") for each of his two iterations using the C^{3}MYC digital app.

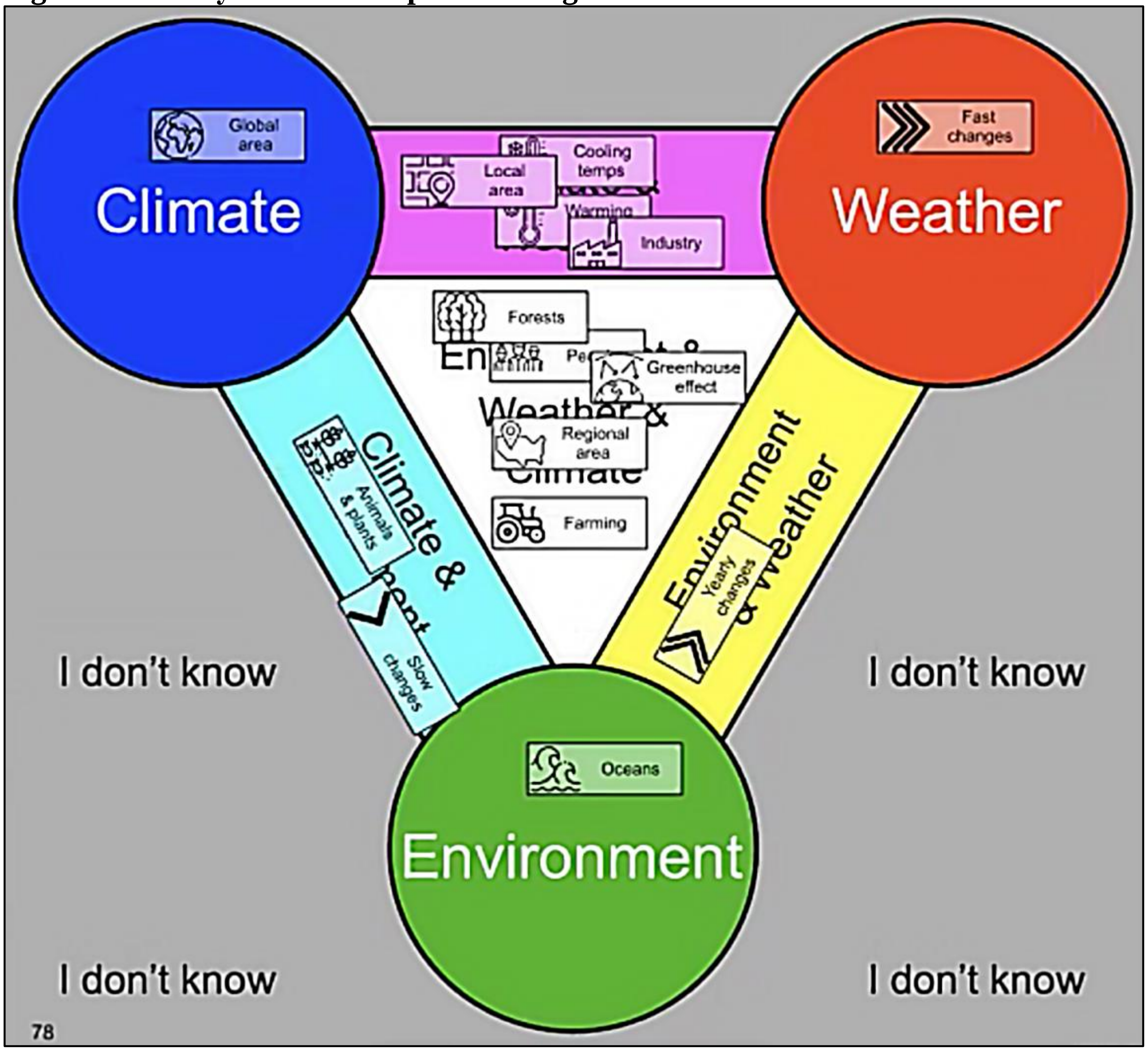


Andy finished his conceptual arrangement in 527 seconds, nearly the average time to finish. A number of ways that experts used the concept map in the earlier study (Toedte, 2018) were consistent with Andy's placements, including the following.

- almost all of them were on more than one main concept
- <*Fast changes*> was related to <*Weather*> and <*Global area*> was related to <*Climate*>
- <*Warming temps*> and <*Cooling temps*> were related to the same main concepts
- most of the *Climate change system sub-components*, such as <*People*> and <*Greenhouse effect*>, were associated with all three main concepts.

Overall, Andy's final arrangement looked similar to that of experts and held no particularly unusual features. However, the logged data captured some unusual features of how he arrived at this arrangement.

Figure 26 - Andy's final conceptual arrangement for session 1



The first thing that stood out from Andy's first session logged data was that he self-rated most of his conceptualizations as <*Somewhat sure*>. He either lacked confidence about his thinking at the time or he was aware that he lacked sufficient knowledge to select <*Very sure*>. He chose <*None of these choices work for me*> as his confidence rating for <*Oceans*>. He placed <*Slow changes*> a second time, but he placed all other sub-concepts only once. Review of the video recording of the session shows that he selected <*Slow changes*> the first time, seemed uncertain where to place it, and returned it to the <*Bank*> (see Table 8). This was not unusual for participants, given that *Spatial extents* and *Temporal rates* are particularly difficult sub-concept categories. They are also the categories where learners' and experts' consensus diverge the most.

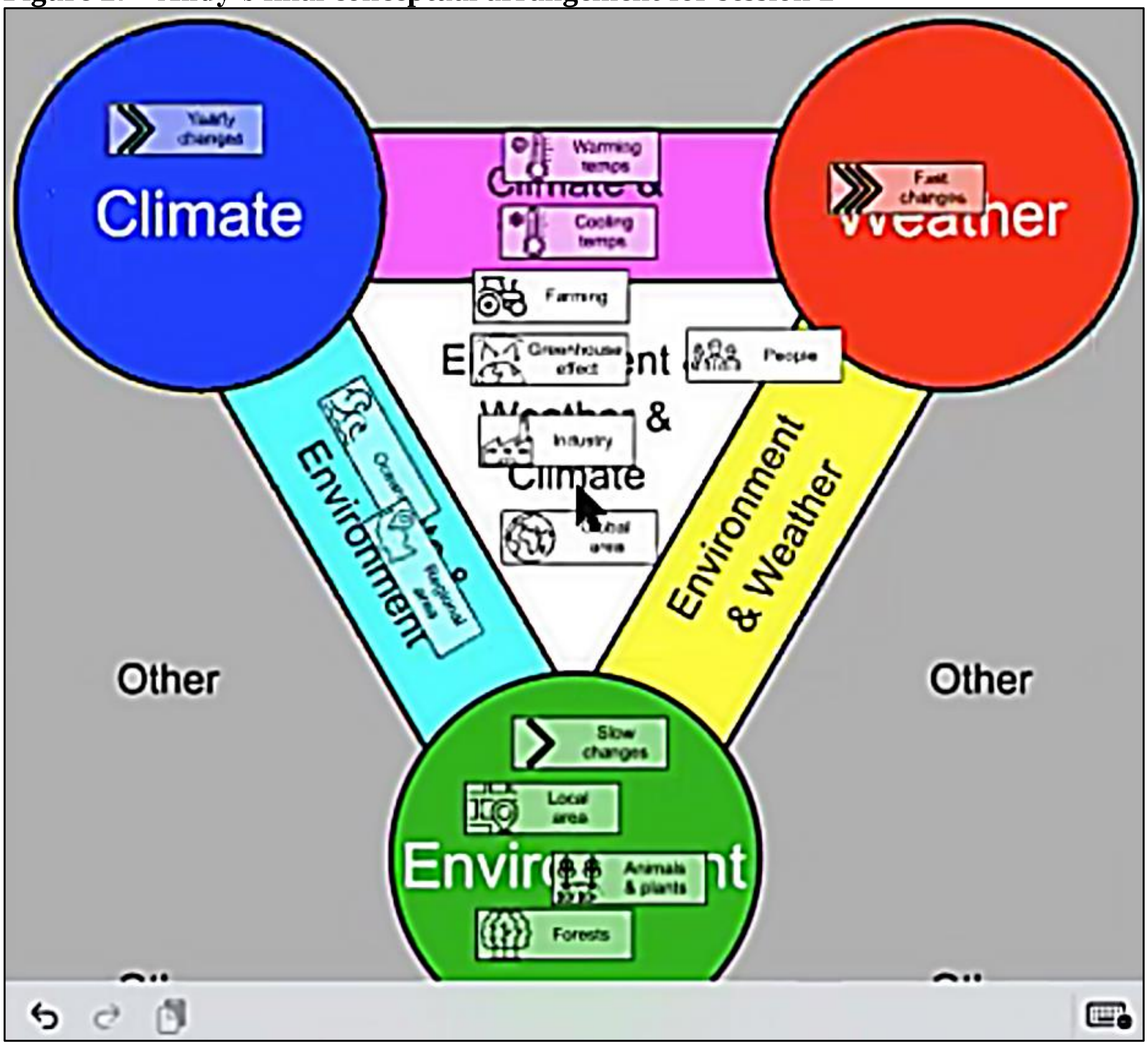
Table 8 - Detail of Andy's logged data for session 1

Move sequence #	Sub-concept	Prior mapping	New mapping	Time spent (s)	Touch # (>1)	Confidence
1	Warming temps	Bank	C & W	3.65		Somewhat
2	Oceans	Bank	Environment	5.11		NA
3	Slow changes	Bank	Bank	5.25		
4	People	Bank	C & W & E	6.40		Very
5	Animals & Plants	Bank	C & E	3.35		Somewhat
6	Regional area	Bank	C & W & E	12.80		Very
7	Farming	Bank	C & W & E	6.25		Very
8	Cooling temps	Bank	C & W	11.15		Somewhat
9	Fast changes	Bank	Weather	5.80		Somewhat
10	Greenhouse effect	Bank	C & W & E	12.00		Very
11	Industry	Bank	C & W	13.10		Somewhat
12	Forests	Bank	C & W & E	8.95		Somewhat
13	Local area	Bank	C & W	3.65		Somewhat
14	Yearly changes	Bank	W & E	3.95		Somewhat
15	Slow changes	Bank	C & E	3.50	2	Somewhat
16	Global area	Bank	Climate	2.05		Somewhat

It would be plausible that learners would tend to hold these categories of sub-concepts to the last because they are the most poorly understood. The last four sub-concepts that Andy placed followed this pattern as they were from the *Spatial extents* and *Temporal rates* categories (see Table 8).

Andy's second session conceptual arrangement is shown in Figure 27. One aspect that struck me was how much more organized it looks than his first arrangement. A number of the sub-concept tiles from the first session were placed so that they overlapped. It appears that, for the second one, he tried to keep everything separated and, thus, readable. A possible reason for this is he found he could think and articulate more clearly about a sub-concept if he could observe the totality of his system of sub-concepts to that point. Another notable point about this second construction is that it took him 342 seconds, or 35% less time to complete. It is likely that some of this is attributable to familiarity with the game. However, one must wonder to what extent reflection on the sub-concepts and how they related to the main concepts were part of Andy's thinking or metacognition during the three weeks between his data collection episodes. Such cognitive processes could have also boosted his confidence in his thinking, and thus his aforementioned self-ratings.

Figure 27 - Andy's final conceptual arrangement for session 2



Andy's second session was marked by a significant boost in confidence. Most sub-concepts garnered a <*Very sure*> self-rating. This included <*Oceans*>, which got a null confidence rating (either <*I don't know*> or <*None of these choices work for me*>) in his first session. This may have indicated a high level of confusion about the sub-concept. However, his confusion seemed to shift to all sub-concepts related to rates of change in his second game session. This comports with the overall low degrees of consensus among children (~40%) and even the relatively low consensus among experts (~80%) for rates of change.

Table 9 - Detail of Andy's logged data for session 2

Move sequence #	Sub-concept	Prior mapping	New mapping	Time spent (s)	Touch # (>1)	Confidence
1	Oceans	Bank	C & E	3.70		Very
2	Local area	Bank	Environment	5.01		Somewhat
3	Regional area	Bank	C & E	3.79		Very
4	Fast changes	Bank	Weather	3.10		NA
5	Cooling temps	Bank	C & W	5.30		Very
6	Warming temps	Bank	C & W	3.30		Very
7	Greenhouse effect	Bank	C & W & E	2.65		Very
8	Yearly changes	Bank	Climate	10.30		NA
9	Slow changes	Bank	Environment	3.35		NA
10	Industry	Bank	C & W & E	7.10		Very
11	Forests	Bank	Environment	8.00		Very
12	Animals & Plants	Bank	Environment	9.50		Very
13	Global area	Bank	C & W & E	9.99		Very
14	People	Bank	C & W & E	5.70		Very
15	Farming	Bank	C & W & E	5.85		Very

Comparing data from Andy's final conceptual arrangements from his two uses of the app produces some interesting observations. First, he changed nine of his 15 sub-concept placements. Of the six sub-concepts that he did not change, five of them were conceptualizations for which he was in complete agreement with domain experts. His changes to <*Yearly changes*> and <*Slow changes*> reduced his agreement with experts on *Temporal rates of change*. Looking at the log data from his first session, he placed temporal sub-concepts in the last half of his move sequence. Two of Andy's final three placements were for sub-concepts in the category, *Temporal rates of change*. In the second session, this changed. He made his first placement at move 4 (of 15) and the last placement at move 9. Sub-concepts placed earlier in the sequence might seem to be ones in which he had more confidence, but this is not borne out by the data, given Andy's confidence self-rating. His addition of <*Environment*> to his conceptualization of <*Industry*> in his second construction brought him into complete accord with the experts on sub-concepts related to *Human activities* and his confidence on this group was 100%. His agreement with experts on spatial sub-concepts in his second session changed on a component basis but were overall the same as his first session. Furthermore, his overall confidence about these sub-concepts rose. His agreement with experts on *Climate change system sub-components* overall went down, but his confidence rose markedly.

Some interesting things happened to Andy's overall confidence in the second session. Andy gave himself null ratings for confidence for one sub-concept (<*Oceans*>) the first session and for three sub-concepts (<*Fast changes*>, <*Yearly changes*>, and <*Slow changes*>) the second session. Despite this, his overall confidence went up nearly 17%. This happened because almost all other sub-concepts' ratings increasing from <*Somewhat sure*> to <*Very sure*>. Ironically, among the unratable sub-concepts in the second session, Andy rated <*Fast changes*> as <*Somewhat sure*> in the first session and its placement did not change.

Table 10 - Comparison of Andy's C^3M_{YC} data

Comparison of Andy's placements, confidence, and consensus across two sessions.

	Temperature changes		Temporal rates of change			Human activities		Spatial scope of change			Climate change system sub-components					
1st app use	Cooling Temp	Warming Temps	Daily changes	Yearly changes	30yr changes	Farming	Industry	Local	Regional	Global	Animals & Plants	People	Forests	Oceans	Greenhouse Effect	
Final placement	CW	CW	W	EW	CE	CEW	CW	CW	CEW	C	CE	CEW	CEW	E	CEW	
Final confidence	0.50	0.50	0.50	0.50	0.50	1.00	0.50	0.50	1.00	0.50	0.50	1.00	0.50	0.00	1.00	**60.0%**
Agreement w/ Experts	1.00	1.00	1.00	0.67	1.00	1.00	0.67	0.67	1.00	0.33	0.67	1.00	1.00	0.33	0.67	**80.0%**
2nd app use																
Final placement	CW	CW	W	C	E	CEW	CEW	E	CE	CEW	E	CEW	E	CE	CEW	
Final confidence	1.00	1.00	0.00	0.00	0.00	1.00	1.00	0.50	1.00	1.00	1.00	1.00	1.00	1.00	1.00	**76.7%**
Agreement w/ Experts	1.00	1.00	1.00	0.33	0.67	1.00	1.00	0.33	0.67	1.00	0.33	1.00	0.33	0.67	0.67	**73.3%**

4.1.1.1 - Andy's Summary

Andy completed the concept map the first time with a high degree of agreement with the experts' configuration. He associated most of the sub-concepts with more than one main concept and he seemed to complete the map in a confident way. He finished the map in average time for the participant cohort. However, the details of his construction indicated he was not very confident in many of his selections and his placement times for the sub-concepts were highly variable, potentially indicating difficulty with some sub-concepts and ease with others.

Andy completed his concept map the second time with high agreement with the experts, though not as high as the first time. However, his overall confidence in his placements was much higher. An irony with his second use of the app was he was confident in many of his choices, but he was unequivocal in his lack of confidence with others. What was especially interesting was the concurrence of his agreement and confidence with his second use of the app. His agreement with the experts was markedly higher for those sub-concepts in which he expressed high confidence than those for which he had middling or low confidence. In another possible indicator of confidence, Andy completed the map much faster the second time and his placement times for the sub-concepts were more uniform.

Without Andy's haptic event data, the interesting ways that his thinking changed from the first to the second concept map would be lost. This sort of information could be very useful for Andy and his teacher to focus on and build his knowledge and confidence about particular sub-concepts.

4.1.2 - Bree (Participant 234293): Organizing and Connecting Knowledge

Bree (not her real name) was a 12-year-old girl who used the app only in her second data collection episode, having had the reading condition in her first episode. Figure 28 illustrates the comparison between her final configuration and her logged haptic event data leading to her final conceptual arrangement in her second data collection episode. Her final arrangement of the sub-concepts is shown in Figure 29.

Figure 28 - Bree's C³M$_{YC}$ logged data

Comparison of Bree's final conceptual construction (the light blue "2") with the combination of her construction and haptic event data (the green and light blue "1") for a single iteration using the C³M$_{YC}$ digital app.

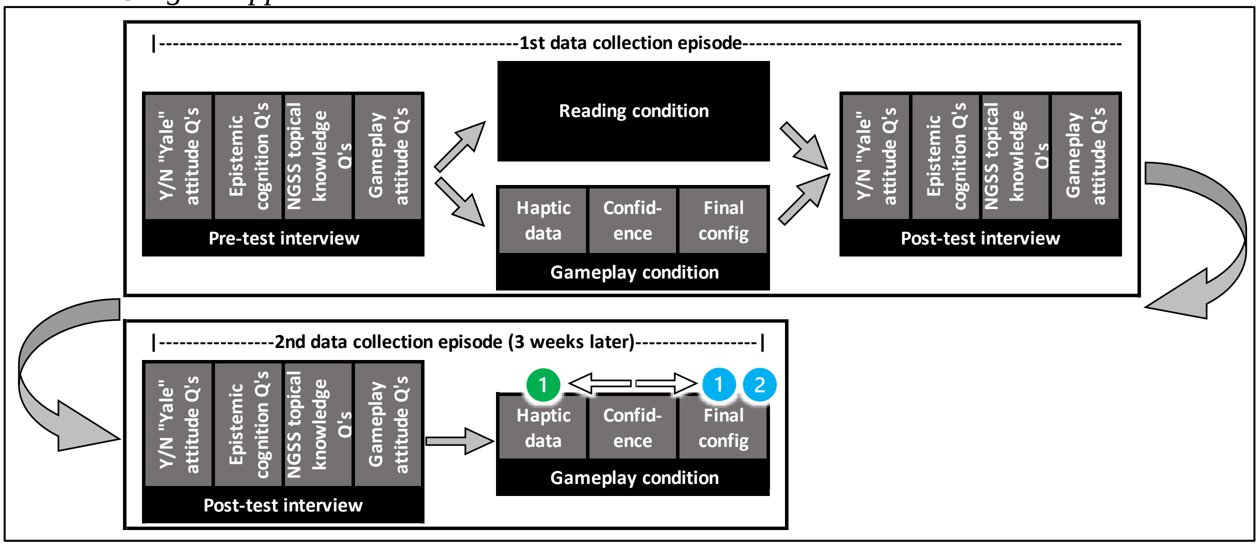
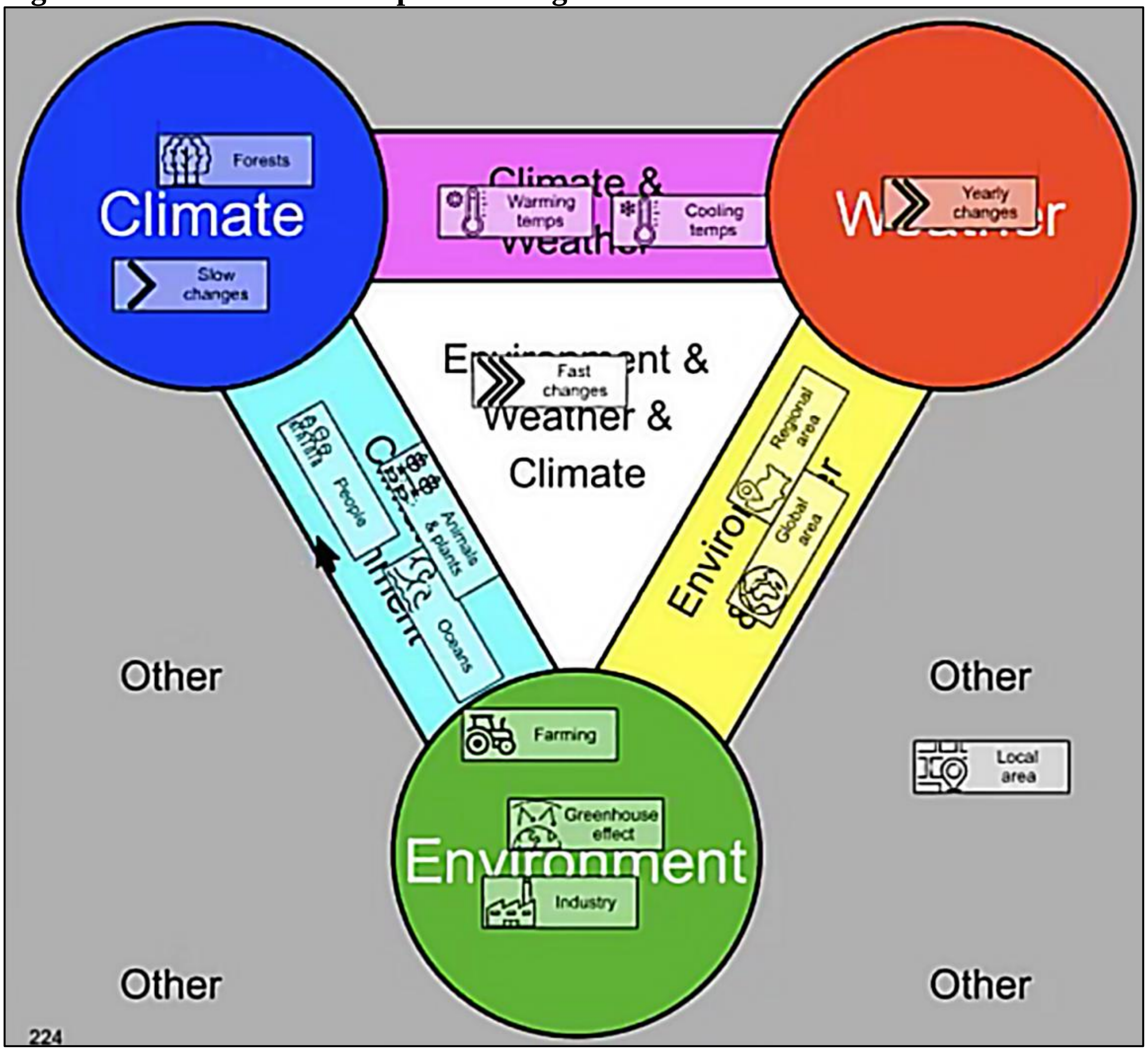


Figure 29 - Bree's final conceptual arrangement



Bree finished her conceptual arrangement in 584 seconds, or a little less than 10 minutes, which was about 15% higher than the average time to finish. She considered *<Local area>* to be unrelated to any of the main concepts, so she left it in the <*Unrelated*> part of the main map. Roughly half of her sub-concepts were associated with more than one main concept. This was consistent with the earlier study (Toedte, 2018) where older learners tended to construe more complex relationships such as those involving multiple main concepts. Bree associated both *<Warming temps>* and *<Cooling temps>* with the same main concepts (*<Climate & Weather>*), consistent with Andy and expert participants (*Ibid*.). An aspect of her arrangement that differed from the earlier study, but not experts, was her association of <*Slow changes*> with only <*Climate*>. Experts draw a clear temporal distinction between weather and climate, which combats common climate misconceptions dealing with long time periods like millennia. Such misconceptions also include the attitude that small but ongoing increases in atmospheric temperatures due to enhanced greenhouse effect are unimportant. The expert consensus is that small increases become very important over long time scales. Bree al so associated <*Yearly changes*> with <*Weather*> only, and <*Fast changes*> with <*Climate, Environment, & Weather*>. Thus, she exhibited a complex mixture of consensus and discordance with both her cohort and experts who used the earlier paper form of the app. While these observations of Bree's data are valuable, they have limited value to educators and educational researchers. That is because they are based only on the end result from a progression of moves. It is difficult, if not impossible, to tell more about her climate change science thinking from only her final arrangement.

The logged data from the digital app helps make sense of Bree's tangle of conceptualizations. They draw attention to details of her conceptual construction *process*. The sequence of events in her interaction with the app is shown in Table 11.

Table 11 - Detail of Bree's logged data

Move sequence #	Sub-concept	Prior mapping	New mapping	Time spent (s)	Touch # (>1)	Confidence
1	Industry	Bank	Environment	2.65		Very
2	Forests	Bank	Environment	8.70		Somewhat
3	Yearly changes	Bank	Climate	4.45		Very
4	Fast changes	Bank	C & E	4.80		Somewhat
5	Global area	Bank	W & E	7.20		Somewhat
6	Oceans	Bank	C & E	6.50		Somewhat
7	People	Bank	C & E	6.90		Very
8	Slow changes	Bank	Weather	3.85		Very
9	Slow changes	Weather	Climate	1.35	2	Somewhat
10	Yearly changes	Climate	Weather	0.95	2	Very
11	Yearly changes	Weather	Weather	1.10	3	
12	Local area	Bank	Other	10.35		
13	Global area	W & E	W & E	0.85	2	
14	Greenhouse effect	Bank	Bank	0.21		
15	Greenhouse effect	Bank	Environment	15.15	2	Somewhat
16	Forests	Environment	Climate	2.25	2	Somewhat
17	Greenhouse effect	Environment	Environment	3.40	3	
18	Industry	Environment	Environment	7.80	2	
19	Farming	Bank	Other	15.90		
20	Fast changes	C & E	C & W & E	1.80	2	Somewhat
21	People	C & E	C & E	1.65	2	
22	Warming temps	Bank	C & W	7.10		Very
23	Cooling temps	Bank	C & W	1.85		Very
24	Regional area	Bank	W & E	9.05		Very
25	Animals & Plants	Bank	C & E	6.85		Somewhat
26	Farming	Other	Other	15.70	2	
27	Farming	Other	Other	8.70	3	
28	Farming	Other	Environment	1.95	4	Very

After moving seven sub-concepts from their initial locations in <*Bank*>, she moves <*Slow changes*> to the <*Weather*> main concept. She followed this with a quick move (1.35 seconds) of <*Slow changes*> to <*Climate*>. What is especially interesting about this was, of these two moves, the second was self-rated by the participant to be less confident than the first. One possible explanation for this is the participant may have felt she was expressing confidence about only her sub-concept placement and not the combination of placement and the direction of the relationship. Thus, she may have had misgivings about the direction of the relationship between <*Slow changes*> and <*Weather*>. As a result, she may have had less confidence about her placement of <*Slow changes*> with <*Climate*>, but a higher unexpressed confidence about the direction of this relationship.

The logged data for Bree show she had three events in excess of 10 seconds apiece where the event ended with placement in <*Unrelated*>. This can be seen in Table 11 for moves 12, 19, and 26. The video recording of her interactions with the app in these instances shows that she picked the sub-concepts and hovered them above different main concepts as if she was doing a visual trial of fit with the sub-concept. She may have been thinking deeply about conceptual relationships in these events and only placed the sub-concept in <*Unrelated*> after ruling out all other possibilities at the time.

Table 12 shows Bree's final sub-concept placements, how her placements compared with the consensus placements of domain experts, and her confidence in her placements. She exhibited the highest confidence as well as the highest agreement with experts' consensus on *Temperature changes* sub-concepts. She had 60% confidence across all other sub-concept categories. With regards to her degree of agreement with experts' consensus, she exhibited the least agreement on *Human activities*, which she related only to <*Environment*>. Domain experts related *Human activities* with all three main concepts at a very high level of consensus (*Ibid.*).

Table 12 - Bree's C^{3}M$_{YC}$ data summary

Comparison of placements, confidence, and consensus for Bree.

	Temperature changes		Temporal rates of change			Human activities		Spatial scope of change			Climate change system sub-components					
	Cooling Temp	Warming Temps	Fast changes	Yearly changes	Slow changes	Farming	Industry	Local	Regional	Global	Animals & Plants	People	Forests	Oceans	Greenhouse Effect	
Final placement	CW	CW	CEW	W	C	E	E	O	EW	EW	CE	CE	C	CE	E	
Final confidence	1.00	1.00	0.50	1.00	0.50	0.50	1.00	0.00	1.00	0.50	0.50	1.00	0.50	0.50	0.50	**66.7%**
Agreement w/ Experts	1.00	1.00	0.33	0.33	0.67	0.33	0.33	0.00	0.67	0.67	0.67	0.67	0.33	0.67	0.67	**55.6%**

With a number of her moves, Bree moved a sub-concept in the app window without changing its main concept association. These instances can be seen in Table 11 in moves 11, 13, 17, and 21. These moves happened more quickly than the average time for a move, often less than two seconds apiece. Looking at the video recording of her session, she did this to adjust the rectangle for a sub-concept within the boundary of a main concept or to move two sub-concepts away from each other if they overlapped significantly. I commented about this to the participant during the session by saying, “You are being tidy.”. At the end of the session, I asked her why she did this and she replied, “Yeah, ‘cuz, like…I don’t know…[laughs]…it just like helps me think about it better, I think. […] It helps me understand it better.” She said she wanted the state of her process with the app to be visible and unambiguous as she continued to execute her conceptual construction.

After placing the last sub-concept, every participant was asked if they wanted to make any final changes. The vast majority declined this offer and said their conceptual construction was good to be submitted as it stood. Bree was one of the rare few that made a change when asked this. She expressed that she was conflicted about whether there was an important relationship between <*Farming*> and <*Environment*>. After I reminded her about her options and how she might resolve the conflict, she said, “I think it’s better to put <*Farming*> in <*Environment*>, because we were learning about the Dust Bowl a couple of weeks ago, and it was caused by farmers [overtilling] the lands and that caused the drought, so I guess if you think about it that way…”. To the two placement-specific questions ask by the app, she subsequently selected <*Farming is important to Environment*> for the direction of the relationship and <*Somewhat sure*> for her confidence in her thinking. Though her attribution of the drought to poor farming practices was not entirely in alignment with the science, she asserted an important connection existed between a human activity and an environmental condition after thinking carefully and supporting her thinking with something she learned in class.

4.1.2.1 - Bree's Summary

Bree was assigned to the reading condition, so she only used the app once. Her conceptual arrangement exhibited both similarities and differences from the experts' consensus arrangement. Overall, her agreement with the experts was somewhat less than the participant cohort average. Looking at the detail of her construction, she seemed to be trying very hard to organize the sub-concepts and concepts into a system. Her number of moves supports this theory, as it was one of the longest sequences of moves among the cohort. She did some curious things, such as "hovering" sub-concepts over different parts of the game, and made minor positional adjustments to her sub-concept placements which did not affect the relationships with main concepts.

A teacher may want to work with Bree to establish the fundamental differences between weather and climate. Bree seems to hold misconceptions about these main concepts, which are negatively affecting her thinking about *Spatial extents* and *Temporal rates of change* sub-concepts. Bree worked hard to conceptualize <*Farming*>. The data seem to indicate this is a meaningful sub-concept to Bree, so it might be a good one to use as a foundation for advancing her understanding of the main concepts and how they intersect other sub-concepts.

Without Bree's haptic event data, educators and researcher have far less evidence to go on to understand how she is thinking. Though the evidence is far from conclusive, the haptic event details improve the opportunities for Bree, either individually or with a teacher, to better align her scientific thinking about climate change concepts.

4.2 - Multi-instrument Data Group Comparison

The following mini-analysis addresses Research Question 2.

RQ2 - In what ways does the combination of learners' interactions with a digital app and their interview responses suggest different patterns of change in their climate change thinking?

In contrast to RQ1, answering RQ2 depends on a learner's responses to both the C^3M_{YC} app and the interview protocol. Exploring data to inform this research question involves a chronological look at a learner's responses rather than skipping from one usage of the C^3M_{YC} app to the next. Learning can occur at any time in the chronology and be informed by any source. Changes in a participant's thinking may occur during their first data collection episode, say between completing the interview and using the digital app. These changes might, in turn, influence their responses in their second data collection episode. This analytical approach allows for more precision in identifying when conceptual change may have occurred.

An illustration of the methods that engage RQ2 is shown in Figure 30. Here, green arrows indicate cognitive continuity from the 1st to the 2nd data collection episodes. This recognizes that a participant may think about climate change during the three weeks between their data collection episodes. Motivated learners may use this time gap as an opportunity to become more engaged with the topic and take charge of their own learning. They may also ask trusted individuals directly or search the internet to inform themselves about how concepts relate to each other.

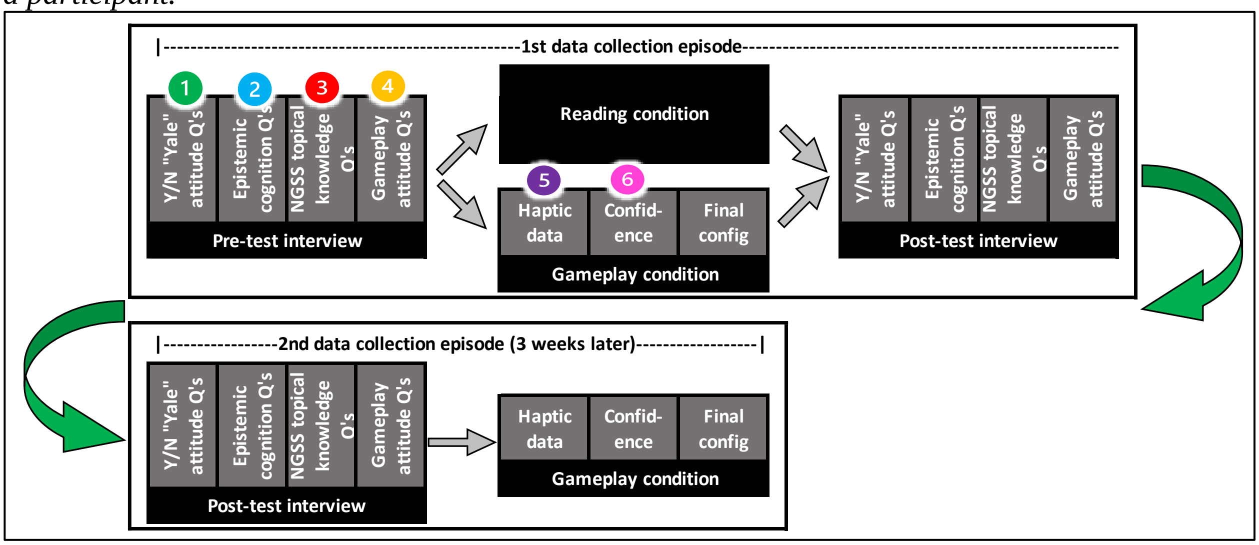
The data groups highlighted in Figure 30 involved different methods that could have synergistic effects that subsequently facilitate learning and knowledge construction for some participants. Using this approach, I looked for indications that a participant combined different ways of thinking about climate change to produce a more integrated, science-informed, systems-oriented way of thinking about the topic. For example, they may have flipped their response to the Yale question about humans affecting climate change from "No" to "Yes" and then added

<*Climate*> to their relationship for <*Industry*> in their second use of the app. This combination of data might indicate that the participant recognized that industrial activities involving people were having a negative effect on climate.

I also looked at consecutive uses of a method for inflection points in a participant's thinking. The lone method that was used only once was the text in the reading condition. Inflection points in interviews were where a participant expressed a change in response from the pre-test to the post-test interview and then retained the new response in the delayed-post-test interview. Examples included flipping from a "No" to a "Yes" response on a Yale question, or changing an initially irrelevant NGSS response to a robustly justified response.

Figure 30 - Responses across multiple data groups

Example of integrating responses from multiple instruments in both data collection episodes for a participant.



4.2.1 - Emily (Participant 224265): Improving Fluency

Emily (not her real name) was an 11-year-old girl whose first data collection episode began with her pre-test interview (see Appendix D). With two exceptions, her responses to the pre-test Yale questions were clear "Yes" responses. See Table 13 for Emily's responses to the Yale questions from all three interviews. Positive responses to Yale questions represent a more accepting, risk acknowledging, and action-oriented mindset toward climate change. She gave detailed answers to the two policy-related questions. Asked if she thought that people were having a big effect on climate change, she thought silently for many seconds, and seemed to be surprised that she was having a difficult time answering the question. She finally said, "I don't know." When I asked her if she thought climate change would harm her, she said, "Harm me? I don't know if it would harm exactly me, but it could harm the world, kind of, like in some places it might get too hot to live like in Africa, maybe, a lot of people would lose their homes and…yeah." To the question, "Should schools teach about climate change?", she said, "Yes, I think they should include a bit more of that because I think some parents, like my parents, my Mom, they tell their kids about stuff like that at home, but not really everybody knows how the world is kind of changing because of climate change."

Table 13 - Emily's responses to "Yale questions"

Cara's responses to yes/no questions from both of her data collection episodes.

	Nature of CC				Rick perception					Policy	
	Happening?	Affected by people?	Scientists?	Affecting weather?	Harm you?	Harm others?	Harm now?	Harm in future?	Harm animals &	Should be taught?	Leaders do more?
Pre	Y	IDK	Y	Y	IDK	Y	Y	Y	Y	Y	Y
Post	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	Y
Delayed post	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y

In her pre-test interview, Emily's answers to NGSS question were mostly on topic and justified at a basic level (see Table 14 and Table 15 for codings of Emily's NGSS responses). Emily's pre-test NGSS response to the question about biodiversity (LS4.D) was the only one considered to be off topic. Basic justification was coded when a participant gave only one brief justification for their response. Robust justification was coded for multiple responses or one elaborate response. Emily's response to the NGSS question about weather and climate (ESS2.D) was coded "Supported" because she said, in alignment with the science, that the main difference between weather and climate is that climate occurs over a long time period. A common misconception is that climate and weather have essentially the same short time scale. On all other questions, she mentioned neither science-supported climate conceptions nor misconceptions.

Table 14 - Emily's coded topical knowledge justifications related to her responses to "the NGSS questions".

	Strength and Appropriateness of Response						
	ESS1.C	ESS2.D	ESS2.E	ESS3.C	ESS3.D	LS2.C	LS4.D
Pre-test	Y-BASIC	Y-BASIC	Y-BASIC	Y-BASIC	Y-BASIC	Y-BASIC	NA
Post-test	Y-BASIC	NA	NA	NA	Y-BASIC	Y-BASIC	Y-BASIC
Delayed-post-test	Y-ROBUST	Y-BASIC	Y-BASIC	Y-ROBUST	Y-BASIC	Y-BASIC	NA

Table 15 - Emily's engagement of science-supported conceptions and misconceptions related to her responses to "the NGSS questions".

	Expressed Climate Science Conceptualizations						
	ESS1.C	ESS2.D	ESS2.E	ESS3.C	ESS3.D	LS2.C	LS4.D
Pre-test	NONE	SUPPORTED	NONE	NONE	NONE	NONE	NONE
Post-test	NONE	SUPPORTED	NONE	NONE	SUPPORTED	NONE	NONE
Delayed-post-test	NONE	SUPPORTED	NONE	SUPPORTED	NONE	NONE	NONE

Emily's first completed concept map was 69% in agreement with experts, and she was 50% confident in her responses, as is shown in Table 16. She recognized all main concepts as having local, regional, and global scope, in agreement with experts. By far, *Spatial extents* was her area of strongest agreement with domain experts. Her overall confidence was relatively low among the participant cohort, and it was especially low on *Temporal rates of change*. However, for several *Climate change system sub-components*, such as <*People*>, <*Animals & plants*>, and <*Forests*>, she had high confidence in her conceptual thinking. Emily skipped around sub-concept categories, placing <*Greenhouse effect*> first, followed by <*Global area*> *Spatial extents*, and <*Forests*>. She then placed the three *Temporal rates of change* sub-concepts,

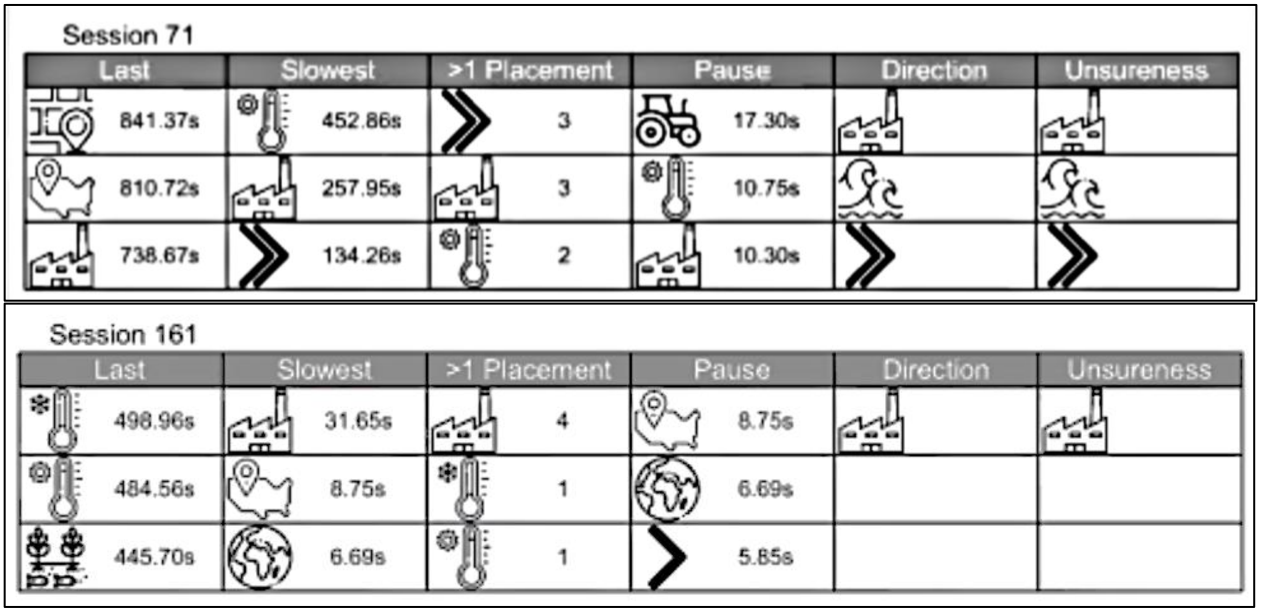
<Oceans>, and the *Temperature changes* sub-concepts. She concluded her first concept map construction by placing the two remaining *Spatial extents* sub-concepts.

Table 16 - Emily's sub-concept placement responses using the digital app.
Comparison of Emily's responses to the digital app from both sessions.

		Temperature changes		Temporal rates of change			Human activities		Spatial scope of change			Climate change system sub-components					overall consensus
		Cooling Temp	Warming Temps	Daily changes	Yearly changes	30yr changes	Farming	Industry	Local	Regional	Global	Animals & Plants	People	Forests	Oceans	Greenhouse Effect	
Experts	Configuration	CW	CW	W	CEW	CE	CEW	CEW	CEW	CEW	CEW	CEW	CEW	CEW	CEW	CE	86.67%
Participant 224265 - 1st app use	Configuration	CEW	CEW	W	C	CE	E	CE	CEW	CEW	CEW	CEW	E	E	E	CEW	68.90%
	Step number	10	9	4	6	5	7	13	15	14	2	12	11	3	8	1	
	Confidence	some	some	none	none	some	some	some	some	some	some	very	very	very	none	some	50.00%
Participant 224265 - 2nd app use	Configuration	CW	CW	W	C	E	CE	CEW	CEW	CEW	E	CEW	CEW	E	E	CEW	75.60%
	Step number	15	14	8	9	7	11	2	5	6	3	13	4	1	10	12	
	Confidence	very	very	some	some	some	very	very	some	very	some	some	some	very	some	very	73.30%

Figure 31 shows the statistical summaries for both of Emily's uses of the digital app. The stat table for session 71, her first use of the C^{3}MYC digital app, corroborates that two of the three sub-concepts placed last were from the *Spatial extents* category. The sub-concepts, *<Yearly changes>*, *<Industry>*, and *<Warming Temps>* were the slowest to be placed. Since slowness is calculated as the elapsed time between first time and last time a sub-concept is touched, it is not surprising that these same three sub-concepts were placed more than once, as shown in the third column. *<Yearly changes>* and *<Industry>* were placed two additional times, and *<Warming Temps>* was placed one additional time. *<Warming Temps>* took more than seven minutes (452 seconds) to place from first initial touch to final placement. *<Industry>* took more than four minutes (257 seconds). In the second to last column, Emily indicated, in response to the app's queries, that she didn't know if the direction of the relationship was from sub-concept to main concept for each of *<Industry>*, *<Oceans>*, and *<Yearly changes>*, or from main concept to sub-concept.

Figure 31 - “Stat tables” from Emily’s first and second uses of the C^3M_{YC} digital app.



After using the digital app and competing her conceptual configuration, I asked Emily the same interview questions as before. This time, in response to the question that asked whether people are having a big effect on the climate change, Emily thought for a few seconds and said, “Yes, kind of.” To the question that asked whether climate change would affect her, she said, “Mmmm. It can, but it’s probably going to harm other people more.”. I took this as mostly a negation of the idea of harming oneself, so I coded it as a *No*. Otherwise, her responses to the Yale questions were consistent with her first interview.

Emily’s post-test responses to the NGSS questions were mostly consistent with those from her first interview, though there were some notable differences. Her responses to ESS2.D (Weather & Climate), ESS2.E (Biogeology), and ESS3.C (Human Impacts on Earth Systems) were off topic. However, she provided a basic justification to her response for LS4.D

(Biodiversity & Humans) where before she had an off-topic response to this in her pre-test interview.

Emily's delayed-post-test interview, which kicked off her second data collection episode three weeks after her first episode, bore a mixture of repeated and new responses to Yale and NGSS questions. Her response to the Yale question which asked if people were having a big effect on climate change, she answered "Yes" quickly and without conditions, unlike the equivocations in her pre-test and post-test responses. To the question that asks if climate change would harm her directly, she said, "Yes, but it will harm more people in bigger groups than just me."

Emily provided on-topic answers to all NGSS questions except LS4.D just as she had in the pre-test interview. The questions for the pre-test and delayed-post-test interviews were identical whereas the post-test questions were worded somewhat differently. Her delayed-post-test answer to ESS1.C (History of the Earth) was robust, whereas her answers in the pre-test and post-test were basic. In the delayed-post-test, Emily talked about dinosaur and plant species extinctions during ice ages where before she had only talked about temperatures during ice ages. Emily's delayed-post-test response to the question about ESS3.C (Human Impacts on Earth Systems) was much more elaborate than in her two prior interviews. She talked about basic needs, like shelter, and how the need was met differently between humans and animals. She also talked about human's unique relationship and negative effects on climate through burning of greenhouse gases. She discussed shelter as a zero-sum battle between humans and animals+plants in that humans provide shelter for themselves without much concern for destruction of environment that includes habitat for animals.

Emily's agreement with the experts' configuration increased to 75% with her second concept map and her confidence in her responses was much higher at 73% (see Table 16). Her new configuration achieved improved agreement with the experts on <*Warming temps*>, <*Cooling temps*>, <*Industry*>, and <*People*>. Agreement was maintained for <*Fast changes*>, <*Local area*>, <*Regional area*>, and <*Animals & plants*>. However, agreement was lost for <*Slow changes*> and <*Global area*>. She had higher confidence for nine of the 15 sub-concepts. Her confidence decreased for only <*Animals & plants*> and <*People*>, for which she expressed the highest confidence in her first construction. The order she used for placing sub-concepts was uncorrelated (r=0.0) to her first construction.

Emily's stat table from her second use of the app was very different from her first use (see Figure 31). She completed her configuration for session 161 more than 30% faster (see the topmost cells in respective first columns of Figure 31). Her slowest sub-concept placements were much faster the second time (respective second columns). She had multiple placements for only <*Industry*> (third column). Among the multiple placements of <*Industry*> she responded that she didn't know about the direction of affect and her confidence in her thinking.

4.2.1.1 - Emily's Summary

Emily showed overall progress in her responses to most of the methods, as is evident from her stat tables (see Figure 31). However, potential evidence of her changes regarding some concepts emerged when her results were viewed in detail. First, Emily developed a more science-aligned perspective of humans in relation to all three main concepts. We see this in the progression of her answers to the Yale question about humans affecting climate change. Emily's responses progressed from "I don't know" to "Yes, kind of" to a straightforward and quick, "Yes". There was also some movement in her answers to the NGSS question about ESS3.C, Human Impacts on Earth Systems. Emily started with a basically justified answer and then moved to an off-topic response before producing a robust and detailed response in her delayed-post-test. In concluding her remarks, she drew connections between humans, greenhouse gases, and infrastructure encroachments on habitats for animals and plants. Using the digital app, Emily went from being very confident about *<People>* being only connected to *<Environment>*, to being somewhat confident with *<People>* being connected to *<Climate, Environment, & Weather>*, thus matching experts' configuration.

A second conceptual change thread that wove through Emily's data was that climate change has consequences for all living things. In her Yale responses, Emily progressed to an admission that climate change could harm her as well as larger groups of people. Her NGSS responses to the question about the History of Earth migrated from just talking about temperature fluctuations to organisms' extinction resulting from the fluctuations. I think this evolution of her thinking contributed to two changes in her second use of the digital app. First, she downgraded her understanding about *<Animals & plants>* while keeping the relationship the same. Also, she moved *<Industry>* four times early in her session, ping-ponging back and forth between *<Climate & Weather>* and *<Climate, Environment, & Weather>*.

4.3 - Participant Sub-group Comparisons

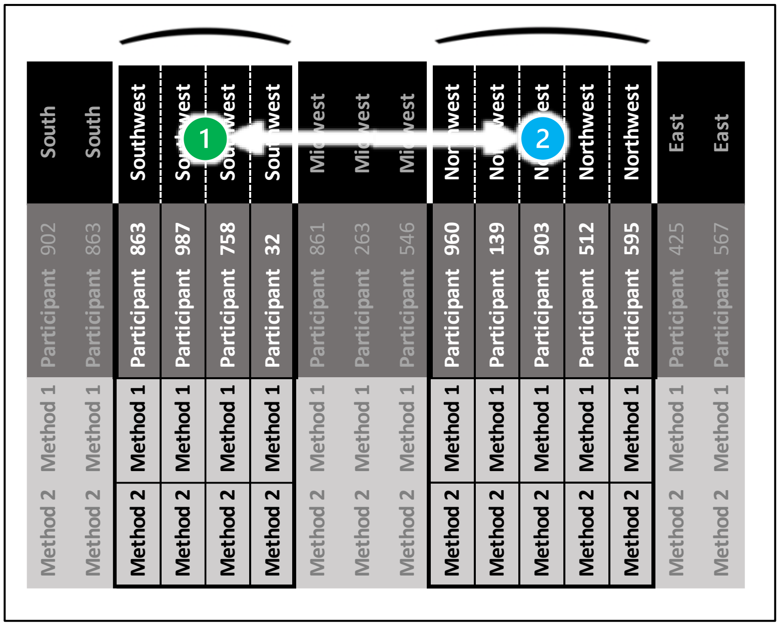
In this section, I focus on sub-groups of study participants with particular demographic or sociographic characteristics or attitudes that have been researched in adults. The purpose is to see if these characteristics or attitudes also exist in children in the context of climate change learning. One example of this, though one that I did not explore in this study, is how parents' political preference on a spectrum from conservative to liberal correlates with children's attitudes that climate change is real and significantly driven by human activities.

A hypothetical example is shown in Figure 32. Here, a group of four participants from the southwest region is compared with another group of five participants from the northwest region. Participants' regions are determinable by their ZIP codes provided in the parent surveys. Coastal parts of the northwestern United States typically experience cooler weather and more rainfall than the southwestern United States. These variations may manifest in differences in children's conceptual thinking as depicted through their constructions of concept maps using the digital app. In turn, the existence of misconceptions provides opportunities for conceptual change. Domain experts think of climate change involving both warming and cooling temperatures. Climate change causes imbalances in atmospheric chemistry that exacerbate both increases and decreases in temperature. A common misconception is that climate change is mostly about rising temperatures. This misconception results partly from the frequent misuse of "climate change" and "global warming" as synonymous phrases.

Table 4 shows that, in my prior study (Toedte, 2018), experts and young learners agree that <*Warming temps*> and <*Cooling temps*> are important features of <*Climate*> and <*Weather*>. Differences in personal experiences with regional weather could result in misconceptions about global weather or climate. This would likely produce a less balanced articulation of the conceptual relationships. If this happened, northwestern participants would show a stronger relationship with <*Cooling temps*> and a weaker relationship with <*Warming *temps*> while southwestern participants would say the relationship with <*Warming temps*> is stronger.

Figure 32 - Participant geographic group comparison

Example of comparing participants from different geographic regions.



Socio-psychological attitudes can play major roles in learners' conceptual ideas, their inclination to consider new information to inform those ideas, and their capacity to reframe those ideas. Following is an exploration of two such attitudes that may affect study sub-groups' climate science conceptualizations.

4.3.1 - Differences between Regional Sub-groups

As previously mentioned, participants hailed from a handful of home communities, some of which had unique demographic and sociographic characteristics. The following discussion will focus on groups from two such communities, whether their sub-concept placements are demonstrably different, and whether their logged data provided clues to why their sub-concept placements differed. All demographic and sociographic information in the following paragraphs was provided by participants' parents when they completed the pre-study survey form.

Group 1 consisted of six participants from rural West Virginia. Two pairs of siblings were in the group. Mining was reported to be the primary supplier of jobs in their respective communities. The children's primary learning interests were science, physical education, and mathematics. Major sources of information for children's learning interests were talking to family members, reading textbooks, talking to educators, searching the Internet, talking to researchers, reading science journals, and watching television shows. Parents' highest educational level ranged from high school graduate to a maximum of bachelor's degree. Parent's political attitudes were mostly self-described as *Other*.

Group 2 consisted of 11 participants from central Illinois who described their home communities variously from urban to rural, but the majority described them as suburban. One pair of siblings was in the group. Primary suppliers of jobs in the respective communities for this group were agriculture, education, and, to a lesser extent, retail businesses. Parents said the children's primary learning interests were art, science, and language arts. Group 2's sources of information were nearly the same as those for Group 1. Parents' highest educational level ranged from a minimum of bachelor's degree up to terminal graduate degree (JD, MD, or PhD). Parents' political attitudes were self-described to be varying strengths of liberal.

Table 17 - Comparison of West Virginia and central Illinois groups

Comparison of West Virginia and central Illinois groups' placements relative to domain experts' consensus.

			Temperature changes		Temporal rates of change			Human activities		Spatial scope of change			Climate change system sub-components					% of total consensus
		Session ID	Cooling Temp	Warming Temps	Fast changes	Yearly changes	Slow changes	Farming	Industry	Local	Regional	Global	Animals & Plants	People	Forests	Oceans	Greenhouse Effect	
Domain experts	Consensus configuration		CW	CW	W	CEW	CE	CEW	CEW	CEW	CEW	CEW	CEW	CEW	CEW	CEW	CE	
	Degree of consensus		89%	89%	83%	72%	89%	94%	94%	89%	78%	67%	89%	100%	94%	94%	78%	86.67%
West Virginia group		207	C	C	CEW	CEW	CEW	E	O	O	CEW	CE	E	E	E	EW	CW	
		224	CW	CW	CEW	W	C	E	E	O	EW	EW	CE	CE	C	CE	E	
		197	O	O	CW	O	O	EW	O	O	O	CEW	E	E	E	O	E	
		200	CW	W	CE	CW	E	CEW	EW	EW	E	C	CE	C	CEW	W	O	
		212	W	CE	CEW	EW	CEW	O	CE	CEW	CEW	CEW	E	CEW	C	C	CW	
		216	C	C	C	E	W	CW	CEW	CE	EW	CEW	CEW	CEW	CE	EW	E	
	WV group consensus		CW	C	CEW	W	CEW	EW	E	E	EW	CEW	CE	CE	CE	EW	E	
	% agree w/ expert config		72%	61%	33%	50%	50%	50%	44%	39%	61%	78%	56%	61%	50%	44%	50%	53.33%
Central Illinois group		145	CW	CW	W	E	C	E	CEW	E	E	CEW	EW	CEW	E	CE	CEW	
		148	C	C	CW	CW	CW	W	CE	E	E	CEW	EW	CE	EW	CE	E	
		155	CW	CW	CEW	CEW	CEW	CE	CE	CEW	CEW	CEW	E	CE	CEW	EW	CEW	
		172	CW	CEW	O	O	O	E	CEW	O	O	O	CEW	CEW	CE	CE	CEW	
		210	CE	CEW	CEW	CEW	CEW	CE	CEW	CEW	EW	CEW	CEW	CEW	E	CEW	CEW	
		214	CEW	CEW	W	C	C	E	CEW	E	EW	CEW	E	CEW	E	CW	CEW	
		221	C	CW	W	CEW	CE	EW	EW	CE	CEW	CEW	EW	CEW	CE	CW	E	
		150	C	C	C	CE	C	EW	E	E	E	E	E	E	CE	E	W	
		163	CEW	CEW	EW	CEW	CEW	O	CEW	O	O	O	CE	CEW	CE	CEW	CEW	
		183	CEW	CEW	CEW	CW	CEW	E	CEW	EW	CEW	CEW	EW	CW	CE	E	C	
		187	W	CW	O	CEW	CE	EW	O	O	E	CEW	E	E	E	EW	O	
	IL group consensus		CW	CW	W	CEW	CE	E	CEW	E	E	CEW	EW	CEW	CE	CE	CEW	
	% agree w/ expert config		73%	79%	64%	70%	67%	45%	76%	42%	52%	76%	61%	79%	58%	67%	58%	64.24%

Table 17 shows the placements of the sub-concepts from gameplay for the West Virginia and central Illinois groups, respectively, compared to the domain experts' consensus view of the relationships between main concepts and sub-concepts. It is important to acknowledge that consensus is not unanimity and that all groups, including experts, exhibit some degree of disagreement. Experts were in 87% agreement on their consensus configuration of the sub-concepts.

The West Virginia group's aggregate agreement with the expert's configuration (53%) differed more widely than did children 9-years-old and older from the earlier study (64%; Toedte, 2018). The West Virginia group's consensus on a per-sub-concept basis (whether the sub-concept related to each of <*Climate*>, <*Environment*>, and <*Weather*>) differed from the experts on 13 of the 15 sub-concepts, with only <*Cooling temps*> and <*Global area*> being viewed the same. <*Fast changes*> was considered to be related to <*Climate, Environment, & Weather*> in contrast with experts' consensus view that it was only connected with <*Weather*>. This resulted in only 33% agreement with the experts on this particular sub-concept. <*Local area*> was the only other sub-concept with less than 40% agreement with experts. This was largely due to half the participants in the group finding no relationship between <*Local area*> and any of the main concepts. <*Local area*> was the sub-concept most often associated with <*Unrelated*>. Notably, this was true of both the West Virginia and central Illinois groups.

The central Illinois group's aggregate agreement with the experts' consensus configuration (64%) was almost identical to that found in children 9-years-old and older from the earlier study (Toedte, 2018). The central Illinois group's sub-concept consensus differed from the experts on seven of the 15 sub-concepts, with most of the difference focused on the *Spatial extents* and *Climate change system sub-components* categories of sub-concepts. Similar to the West Virginia group, the central Illinois group had very low agreement with the experts on <*Local area*>. As previously mentioned, several central Illinois participants related <*Local area*> to <*Unrelated*>, which diminished the level of agreement.

Interesting aspects of this comparison was how the two groups differed with each other, and how they respectively differed from the experts in their conceptualizations in the category, *Human activities*. Table 17 shows that experts had a high degree of consensus that both of the sub-concepts in this category were related to all three main concepts, and thus related them to <*Climate, Environment, & Weather*>. The central Illinois group's aggregate view of <*Farming*> was only 45% in agreement with the experts and only two of the 11 participants had climate (e.g., <*Climate & Weather*>) as part of their response. In contrast to this, eight of the 11 participants had climate as part of their relationship to <*Industry*> and were 76% in agreement with the expert conceptualization. The West Virginia group's view of <*Industry*> was 45% in agreement and their view of <*Farming*> was 50% in agreement with the experts.

Table 18 - *Human activities* comparison
Focus on contrasting conceptualizations of human activities between West Virginia and central Illinois participants.

	Farming	Industry
Experts' consensus config	CEW	CEW
Degree of consensus	94%	94%
WV group consensus config	EW	E
Departure from experts	-44%	-50%
IL group consensus config	E	CEW
Departure from experts	-49%	-18%

To summarize, there are two interesting threads from the analysis of these two groups' placement data. First, the *Human activities* sub-concept conceptualizations of the respective groups are extremely different from those of the experts. Second, as can be seen in Table 18, the groups' respective departures from the expert consensus are very significant. The West Virginia group's departure from the experts is 50% lower (94%-44%) on the sub-concept, <*Industry*>, and 44% lower (94%-50%) on the sub-concept, <*Farming*>. The Illinois group's departure from the experts was 49% lower (94%-45%) on the sub-concept, <*Farming*>.

The logged data from two groups offers some interesting contrasts. First, the central Illinois group times to complete their sessions were relatively tightly clustered whereas the West Virginia's group times included extremely fast and slow instances, as can be seen by the large standard deviation in Table 19. It should be noted that, although there were roughly twice as many participants in the central Illinois group as the West Virginia group, the conditional color mapping used for the "Totals" columns in Table 19 and Table 20 are based on different cutoff values (2 for yellow and 4 for red with the West Virginia group; 4 for yellow and 8 for red with the central Illinois group). Both the West Virginia group's slow placements of <*Regional area*> and the central Illinois group's placements of <*Farming*> stood out as taking inordinate amounts of time.

For the West Virginia group, slow placements of <*Regional area*> were affected by several participants taking relatively long pauses during placement, as shown in the right circle overlay. Oddly, however, unless the participant moved sub-items more than once, this would not, by itself, have radically affected placement slowness. This was not the case, as indicated by the 0 values in the ellipse overlay in Table 19. On closer inspection of the data, one participant in the group had the curious habit of repeatedly picking a sub-concept and returning it to the same area of the concept map. This did not constitute a change of configuration, which is what the 0's in the ellipse overlay of Table 19 indicate. All participants placed <*Regional area*> only once. However, this odd interaction with the app *did* count as handling the sub-concept and thus affected its "end-to-end" time, which was the way of establishing the slowness of its placement. Such behavior with the app is unusual and highly interesting. This is a good example of the app providing information that a skilled educator or researcher can use to connect the participant's behavior with their thinking. The participant's thinking, in turn, may have included new challenges to their existing conceptual thinking…challenges that were facilitated by their use of the app.

Table 19 - Detail of logged data from West Virginia participants

Detail of logged data from the C^3M_{YC} digital app for West Virginia participants (6) from 2^{nd} sessions.

Sub-concept category	Sub-concept index #	Sub-concept name	Sub-concepts placed last				Sub-concepts placed most slowly				Sub-concepts placed additional times				Sub-concepts picked the longest time (MouseUp <---> MouseDown)				Self-rated uncertainty			
			1	2	3	Total	1	2	3	Total	1	2	3	Total	1	2	3	Total	1	2	3	Total
Temps	0	Warming	1	0	1	3	0	0	0	1	0	0	0	1	0	1	0	2	0	0	0	1
	1	Cooling	0	0	1		0	0	1		0	1	0		1	0	0		0	1	0	
Temporal	2	Fast	0	1	0	4	0	2	0	4	0	0	1	4	0	1	0	2	0	0	0	1
	3	Yearly	0	0	1		1	0	0		0	1	1		0	0	0		1	0	0	
	4	Slow	2	0	0		0	1	0		1	0	0		0	1	0		0	0	0	
Activities	5	Farming	1	0	0	1	0	0	1	3	1	1	0	4	1	0	0	2	1	0	0	1
	6	Industry	0	0	0		2	0	0		2	0	0		1	0	0		0	0	0	
Spatial extent	7	Local	0	0	0	2	0	0	0	5	0	1	0	1	0	0	1	5	0	0	0	0
	8	Regional	0	0	2		1	0	4		0	0	0		1	0	3		0	0	0	
	9	Global	0	0	0		0	0	0		0	0	0		0	0	0		0	0	0	
Climate system elements	10	Animals	0	2	0	8	0	1	0	5	0	0	0	2	0	1	1	7	0	0	0	0
	11	People	0	1	0		0	0	0		0	0	0		0	0	1		0	0	0	
	12	Forests	0	1	0		0	2	0		1	0	0		0	1	0		0	0	0	
	13	Oceans	1	0	1		1	0	0		0	0	0		1	0	0		0	0	0	
	14	Greenhouse	1	1	0		1	0	0		0	0	1		1	1	0		0	0	0	
			Mean (seconds)		416.29		Mean (seconds)		86.31						Mean (seconds)		11.31					
			Stdev		175.51		Stdev		99.58						Stdev		5.59					
			Skewness		0.55		Skewness		1.13						Skewness		0.50					

The central Illinois group exhibited similar slowness for their placements of *<Farming>*, but for very different and more straightforward reasons. As the West Virginia group did with placements of the *<Regional area>* sub-concept, this group had several paused placements of *<Farming>*, as indicated by the right ellipse overlay in Table 20. However, unlike the West Virginia group, this group did more replacements of *<Farming>* than for any other sub-concept, as is shown by the left ellipse overlay. This caused bigger time gaps to exist between the start of the first event and the end of the last one, thus corroborating the anomalous count of *<Farming>* slow placements.

Table 20 - Detail of logged data from central Illinois participants

Detail of logged data from the C^3M_{YC} digital app for central Illinois participants (11) in 2^{nd} sessions.

Sub-concept category	Sub-concept index #	Sub-concept name	Sub-concepts placed last				Sub-concepts placed most slowly				Sub-concepts placed additional times				Sub-concepts picked the longest time (MouseUp <---> MouseDown)				Self-rated uncertainty			
			1	2	3	Total	1	2	3	Total	1	2	3	Total	1	2	3	Total	1	2	3	Total
Temps	0	Warming	0	1	0	3	1	0	1	6	0	1	0	5	1	1	0	3	0	0	0	2
	1	Cooling	1	0	1		2	2	0		2	1	1		0	0	1		2	0	0	
Temporal	2	Fast	1	1	1	6	1	2	1	7	3	0	0	5	0	0	1	4	0	0	0	0
	3	Yearly	0	0	2		0	0	1		0	1	0		0	1	0		0	0	0	
	4	Slow	0	1	0		1	0	1		1	0	0		0	1	1		0	0	0	
Activities	5	Farming	2	0	1	4	1	4	0	6	2	2	1	5	1	3	1	8	1	0	0	1
	6	Industry	1	0	0		0	0	1		0	0	0		2	0	1		0	0	0	
Spatial extent	7	Local	2	1	1	13	0	1	2	8	0	2	0	6	1	1	1	10	0	0	0	1
	8	Regional	0	1	3		0	1	1		0	0	1		1	1	2		0	0	0	
	9	Global	2	2	1		3	0	0		2	0	1		0	1	2		0	1	0	
Climate system elements	10	Animals	0	0	0	7	0	0	0	6	0	0	0	3	2	0	1	8	0	0	0	1
	11	People	0	1	0		0	0	1		0	1	1		0	0	0		0	0	1	
	12	Forests	1	1	0		2	0	1		0	0	1		2	0	0		0	0	0	
	13	Oceans	1	0	1		0	1	0		0	0	0		1	1	0		0	0	0	
	14	Greenhouse	0	2	0		0	0	1		0	0	0		0	1	0		0	0	0	
			Mean (seconds)		427.66		Mean (seconds)		68.25						Mean (seconds)		13.61					
			Stdev		11.95		Stdev		73.77						Stdev		9.26					
			Skewness		1.71		Skewness		2.02						Skewness		2.44					

The West Virginia and central Illinois groups' respective conceptual constructions exhibited some very different characteristics, which were corroborated by their haptic event data.

However, perhaps the most interesting aspect of this comparison was their respective placements of the *Human activities* sub-concepts, which will be discussed in Chapter 5.

4.4 - Other Analyses

Prior analyses sections focused on one or more subsets of the participants, selected fields related to those participants, or some selection of data groups from the app. However, in this section, each analysis looks at just one data group. Most of these analyses involve the C^3M_{YC} app only peripherally, if at all.

In each case, an argument can be made that a form of learning is taking place that contributes to conceptual growth. Though novel modes of learning and conceptual growth aren't assumed or expected for all participants, the possibility nonetheless exists and deserves to be discussed as a very real outcome of this work.

4.4.1 - Broadening the Definition of Learning and Conceptual Thinking

Certainly, conceptual change is a foundational element of this work and an important type of learning. However, the topical focus on climate change science and the youth of the participants meaningfully alters, and arguably broadens, the contexts of learning. Thus, what constitutes "learning" extends to factors including the following.

- Learning how to begin to learn about climate change in a personally meaningful way
- Learning what are one's attitudes about climate change
- Learning how climate change concepts interrelate
- Learning how to evaluate and choose sources of climate change information
- Learning how to distinguish opinion from scientifically supported statements about climate change
- Learning how and when to integrate new information with one's current understandings about climate change

4.4.1.1 - Initiation of Thinking about Climate Change

All participants were asked two questions about their epistemic practices, or how they constructed knowledge, in each interview. The first question was about the degree to which they communicated with any sources of climate change information such as people, the internet, books, and videos. The second was how they made choices among sources and curated their list of reliable and trusted sources. The purpose of these questions was to see if evidence of either naiveté or sophistication existed in their answers, as measured against epistemic spectra (see Figure 4).

These questions uncovered a surprisingly common finding. For roughly a quarter of study participants, they had *never* talked with somebody or sought information about climate change, as in this exchange from Participant 787383's post-test.

> Researcher: "How often do you ask people or look online to learn about climate change?"
> Participant 787383: "I can't say I actually ever have."

For other participants, they thought they had talked about it, but hadn't because they lacked vocabulary or conceptual knowledge, as in this example from Participant 771173's pre-test.

> Researcher: Okay, do you talk with people regularly about climate change?
> Participant 771173 : I might in my words but I probably never use 'climate change' but I might have said, like 'the weather is changing a lot' or something.
> Researcher: Okay, yeah, going back to what you said about climate change and weather being pretty much the same right?
> Participant 771173: Mm hmm.
> Researcher: So, you think maybe you use the term, 'weather', more?
> Participant 771173: Yeah, I probably use the term, 'weather', more.

A few participants said that they sought information as they were required to do for assessments or class projects but didn't voluntarily seek information. Fewer than a quarter of study participants sought information voluntarily with frequency of more than once per month. For most participants, this study was the most they had talked about climate change, if they had at all. This study, therefore, provided an initial, if not the first, opportunity for them to think about the topic.

Participant 487967 brought up one final point in their delayed-post-test interview, which is likely an impediment to youth thinking, communicating, and learning about climate change.

> Researcher: So, how often do you communicate or talk to people about climate change.
> Participant 487967: Not at all, because I don't really want to bring up that topic. It's just like you're in, because…I don't really go outside because, you know introverts. This is just like a regular day for them! (Author's note: this was a reference to remote school participation during the COVID pandemic.)
> Participant 487967: So, you don't really find the time and…like school…like when there's breaks, you don't really just want to talk about, "You guys know about climate change?". That's just like weird. They think you're like a climate change professional!

Participant 487967's last statement hints at a 'geekiness' factor that might deter some efforts to learn about climate change. It is arguable that socio-scientific issues and complex systems problems such as climate change science require more intrinsic motivation on the part of the learner. The learner may be motivated to learn and, taken further, may be motivated to act based on what they think. The more a learner translates their thinking and knowledge into action, the more intrinsic motivation becomes outwardly apparent to people with whom they interact. The question becomes, "To what extent does internal motivation to learn and act on climate change get stanched by concern about 'geekiness' labeling by external forces?" The question is a good one and may be what Participant 487967 is hinting.

4.4.1.2 - Self-descriptions of Gameplay

After having completed half of the first-round data collection episodes, I updated the interview protocol to include questions about participants' experiences with the app. The questions were very simple, but they yielded some very intricate and interesting responses.

- What did you think about the app?
- What is one thing you liked about the app?
- What is one thing you disliked about the app?
- Did you learn anything by using the app?
    - What do you think you learned?

To the first question, 88% of participants had a positive response, 8% had a negative response and 4% of responses were neutral. The first question was intended to be a warmup to more focused questions, and the participants gave mostly basic, short answers. The most common responses were, "I liked [it/the game].", "It was pretty fun.", and "It was cool." Participant 224265 added, "I would definitely use it for school too." Bree said, "I think it helped me understand it better…like understand environment and climate change and weather." One of the rare negative responses came from Participant 362875: "The game was not the best because it was school related. Yeah, it could be more fun."

Some participants' responses spoke to how they liked the game's open approach to concept associations.

- Participant 668279 - "[What I really liked was] that there was an 'other' [category] so if there's none of the things, there is something you can do […] to show that [the sub-concept] deals with something other than those three things."
- Participant 400940 - " I like how you can choose which [main concept] you want to put [the sub-concept] on and it doesn't like tell you it's the wrong answer or anything."

However, one participant expressed a preference for a more didactic mode of teaching in this response: "[What I didn't like was] at the end, it didn't tell me I was right or wrong." Ironically, this was the same participant who said they didn't like the game because it was "like school".

To other participants, it wasn't the openness that they liked, *per se,* but rather how the game's focus on thinking rather than knowledge or "facts" allowed them to express themselves in different ways and enriched their learning processes.

- Participant 787383 - “Probably [one thing I liked about the game was] being able to say what you think without having to be like a wrong or right answer. I don’t know if it’s really stress, but more like being able to be indecisive. And just questioning whether or not that makes sense or not.”
- Participant 446120 - “I liked how like there were some things that were a little bit challenging. I like a little bit of a challenge. And I like how it gave me the choice.”
- Participant 919511 - “Just the fact that it made me think. Because I consider myself a pretty okay…a pretty good student and school doesn't really challenge me except in the high school courses that I take. But I definitely haven't thought […] that hard in a while.”

Over half the participants said they could not think of anything they wanted to change about the game. Of those that did, two participants said the wording of the questions was a bit confusing and wanted more detail than the general description, “important relationships.” A couple participants were put off by their inability to interact with the game due to the computing platform they used. This was due to the Remote Control (RC) feature of Zoom being disabled for ChromeBooks (see section 3.2.12 for details).

The last question asked if the participant thought they learned something. Only one participant said they did not. This was the same participant that said the game was too much “like school” and also wanted to know if they were “right or wrong” in their responses. Other responses ranged from the general…

- Participant 771173 - “[The game] teaches you that even though you’ve never really thought of that sometimes, but then you, like, finally, think about it and it’s in your brain now.”
- Participant 787383 - “[I think one thing I learned was] that different things can have an impact on multiple things.”
- Participant 919511 - “I definitely [learned something]. I learned that my understanding of these concepts is nowhere near as good as I thought it was.”

…to the specific.

- Participant 722960 - “…I had to think about how like when you put [the sub-concept] in a certain place and they asked you if, for example, farming is important to…I dunno…the environment…or environment is important to farming, you could choose which you thought was more, and you have to think about it, like really think about it, to see what certain aspects of something can affect the other."

- Participant 446120 - "[What I think I learned was] affect like…I'm going to use the example of the glaciers melting. When a glacier melts, not only does it affect it but it's also important to some key survival [aspects]."
- Participant 771173 - "I know what some of the words mean, like 'industry'."

Questions about gameplay yielded some very authentic, personalized responses from the participants. I believe this happened because each participant was encouraged throughout each data collection episodes to openly express themselves. They were told there was no harm, penalty, or negativity to not knowing something. What was of primary important was how they thought about things, so the only requirement was their answers had to reflect how they thought or felt. The participants seemed to really embrace this and were quite at ease during data collection. Many of them said that openness, both in the game and the general conduct of the research experience, was something they really liked. Without having a pervasive "It's all safe and OK." attitude, this part of the interviews likely would not have happened and the participants' rich responses to this simple add-on sub-survey would have been missed.

4.4.1.3 - NGSS Topical Responses

Each participant interview included seven topical questions from the sections of the NGSS standards that related to climate change science. For example, section ESS1.C, History of Planet Earth, discusses Earth processes over very long time scales, which are typical of climate trends. A lack of appreciation for time scales on the order of hundreds of years or more makes it more difficult for a learner to connect historical data with the relatively recent phenomenon of anthropogenic climate change. Evidence of Earth's history comes from experimental information sources, like CO_2 gas bubbles embedded in ice cores. In this way, ice cores help experts establish long term norms for atmospheric concentrations of greenhouse gases. Without these norms, the degree to which current concentrations are abnormal would not be known. The NGSS topical questions can be found in Appendix D.

Participant responses were coded as to whether they contained misconceptions about climate change or contained scientifically supported climate change science conceptualizations. The coding rubric can be found in Appendix F. Two coders were used after achieving a raw interrater agreement of 91%. Coders were given two lists. The first was a list of science-supported conceptualizations from topical science literature sources (Field, et al., 2014; Intergovernmental Panel on Climate Change & Edenhofer, 2014; Stocker, 2014; Reidmiller, et al., 2018). The second list contained climate change misconceptions from a systematic review of middle-school-age conceptual change literature (Toedte, 2020). Both lists are shown in Appendix F. Coders transcribed participant responses and were asked to look for matches between the lists. Participant responses were given one of four codes.

- *None* - no conceptualizations, either science-supported or misunderstood, were present
- *Misconceptions only* - contains misconceptions but no science-supported conceptions
- *Mixed* - contains a mix of misconceptions and supported conceptions
- *Supported only* - contains only science-supported conceptions

Table 21 shows summaries of the codes generated. Most interview responses contained no mention of either scientifically supported conceptualizations or misconceptions. There was a small uptick of scientifically supported conceptualizations from the delayed-post-test interviews in comparison to the post-test interviews.

Table 21 - Participants' coded conceptualizations from interviews

	Pre-test	Post-test	Delayed-post-test
None	94	93	96
Misconceptions only	6	5	4
Mixed	7	10	5
Supported only	5	4	7

The coders were also asked to code participant responses in terms of the degree of justification they provided in their responses to the NGSS questions. This coding rubric can also be found in Appendix F. Two coders were used after achieving a raw interrater agreement of 71%. The participants' responses were transcribed and given one of the following four codes

- *NA* - the participant did not provide a relevant response
- *No* - the participant had a relevant but unjustified response
- *Y-Basic* - the participant provided a relevant and justified response, but their justification was simplistic
- *Y-Robust* - the participant provided a relevant answer with elaborate justification such as more than one example or a single highly detailed example

Table 22 shows summaries of the codes generated. Roughly 50% of each interview consisted of *Y-Basic* responses and 33% *No* responses. The delayed-post-test interview showed a modest reduction in the number of irrelevant responses and a modest increase in the number of robust responses over the post-test interview responses.

Table 22 - Participants' coded support from interviews

	Pre-test	Post-test	Delayed-post-test
NA	13	16	5
No	34	35	39
Y-Basic	63	57	57
Y-Robust	2	4	11

4.4.1.4 - Epistemic Cognition Responses

Each participant interview included two epistemic cognition questions. The first question asked how often the participant sought or received information about climate change. The second question asked how the participant determined the quality of the source or the information from the source.

Participant responses were coded relative to one or more of the four spectra for evaluating personal epistemologies shown in Figure 4. The coding rubric can be found in Appendix F. After training on the epistemic dimension ranges and meanings, coders were asked to rate participants' responses as *NA* (not available), *Naïve*, *Sophisticated*, or *Mixed*. *Mixed* meant the participant's response contained both naïve and sophisticated components. Table 23 shows there was very little difference in aggregate epistemic quality ratings from pre-test to post-test and from post-test to delayed-post-test.

Table 23 - Participants' coded epistemic responses from interviews

	Pre-test		Post-test		Delayed-post-test	
	frequency	sourcing	frequency	sourcing	frequency	sourcing
NA	0	1	1	3	1	0
Naïve	11	6	11	3	10	5
Mixed	4	8	4	9	5	9
Sophisticated	1	1	0	1	0	2

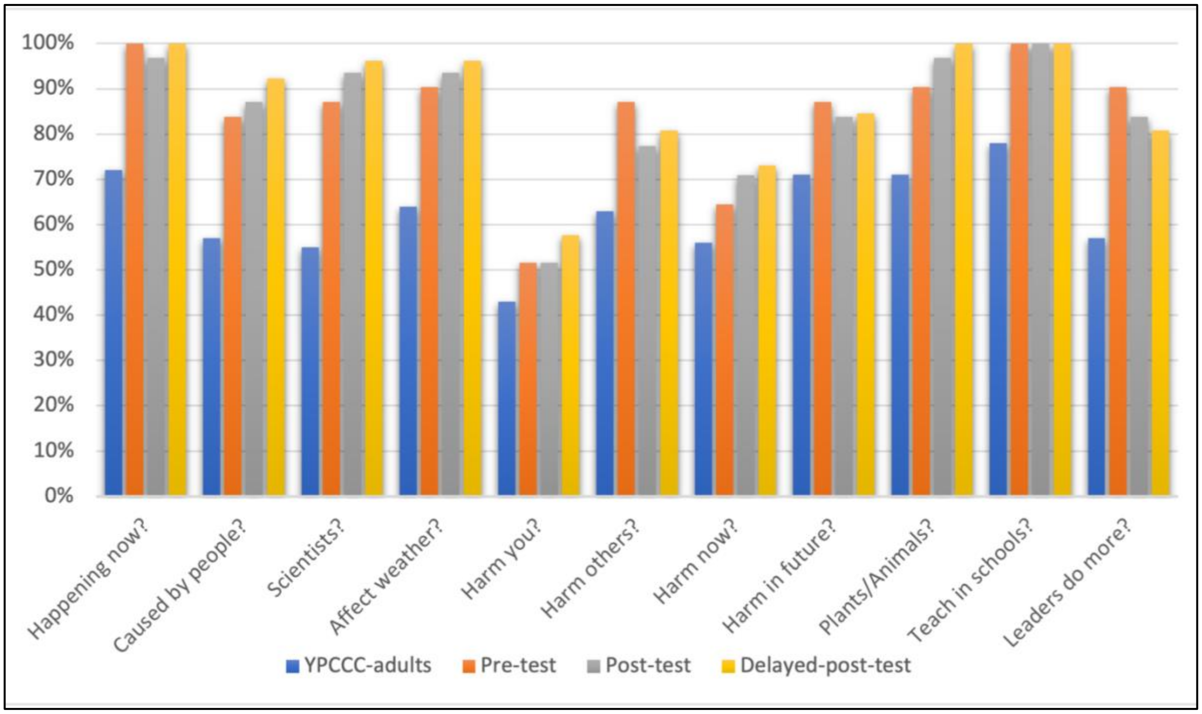
4.4.1.5 - Learners' Attitudes and Opinions

The YPCCC conducts yearly public opinion polls about climate change. A product of this work is their interactive opinion maps (Yale_climate, 2020). The opinion data is in response to roughly 25 questions which can be viewed online. Raw percentages and percentages relative to national averages are explorable on state, congressional district, and county boundaries. The categories of the questions include beliefs about climate change science, attitudes about harm from climate change, climate change policy, and climate change communication. These questions served as bases for the Yale questions which were part of this study's interview protocol. Appendix D shows the questions used in this study's interviews matched with the Yale questions on which they were based. One pronounced difference between the original YPCCC questions and Yale questions used in this study was the usage of the term "climate change" rather than "global warming". "Global warming" is less scientifically accurate, due to the variability and complexities of climate change. Ironically, although "climate change" was once thought to be "… less frightening than 'global warming'" (Luntz, 2003, p.142), the two phrases are now used interchangeably in public communication (Whitmarsh, 2009; Jang & Hart, 2015). The other major difference between the YPCCC and Yale question sets is the number of possible answer choices. Due to the youth of the participants in the present study, some effort was taken to simplify language and reduce response choices. Participants were encouraged to answer with basic responses of "Yes", "No", or "I don't know".

Figure 33 shows how YPCCC adult participants' responses compared to study participants across all three interviews. Across all questions, there is a significant positive difference in that the study participants' scientifically supported attitudes (e.g., climate change is happening now, and climate change is significantly affected by people) were consistently 20% or more higher than the adults in the YPCCC study. The exception to this was the question about personal harm. Like adults in the YPCCC study, the younger participants' responses were the lowest of all questions, but they were still 10% higher than the adults. On a per-question basis, study participants showed modest gains from pre-test to delayed-post-test on questions of human involvement in climate change, scientists' consensus, and climate change affecting the weather. The questions about personal harm and leaders saw modest declines across successive interviews. The question about teaching climate change in schools, the question with the most support among adults, got 100% support from learners across all interviews.

Figure 33 - Cohort Yale attitudinal responses

Percent of scientifically supported attitudes from YPCCC adults and participants from this study.



To tease more information from the Yes/No responses, I considered the extent to which participants' responses might reflect learning and movement toward scientifically supported responses on a per-question basis. Table 24 shows the matrix for all possible combinations of responses from Interview *N* and Interview *N+1*. In the context of the present study, this means stepwise change from the pre-test to the post-test, or from the post-test to the delayed-post-test. A participant changing from a *No* response in the pre-test to a "Yes" response in the post-test was rated a *Very positive* change. The reasoning for rating a change from either "No" or "Yes" to "I don't know" as "Positive" was that they both showed a participant's willingness to question their current attitude, exert cognitive effort, or possibly engage in metacognitive self-evaluation.

Table 24 - Yale question gradient ratings
Ratings for the gradient of question responses across consecutive interviews for all possible participant responses combinations.

Interview *N* questions	Interview *N+1* questions: No	IDK	Yes
No	Negative	Positive	Very positive
IDK	Negative	Neutral	Positive
Yes	Very negative	Positive	Positive

The sequence of gradients was, in turn, used to rate the trajectory (pre-test to post-test to delayed-post-test) of a participant's thinking on each question in terms their movement toward more scientifically supported thinking on the Yale questions. By this measure, *Negative* to *Neutral* was rated as a *Gain* as was *Positive* to *Very Positive*. Both exhibit positive and accelerated change, possibly exhibiting learning built upon prior learning. In contrast, the learner who had consecutive *Positive* gradients would be given a sequence rating of *Same* because there is no acceleration or growth, but rather maintenance of the current attitude.

Table 25 - Ratings of participant response trajectory
Rating the trajectory of participant response gradients across all interviews for all possible gradient ratings.

Pre-post sequence \ Post-delayed-post sequence	Very neg	Neg	Neutral	Pos	Very pos
Very neg	Same	Gain	Gain	Gain	Gain
Neg	Loss	Same	Gain	Gain	Gain
Neu-tral	Loss	Loss	Same	Gain	Gain
Pos	Loss	Loss	Loss	Same	Gain
Very Pos	Loss	Loss	Loss	Loss	Same

Table 26 shows the sequence ratings for fully transcribed study participants (*N*=26) for all Yale questions. Most ratings were *Same*, showing consistency but perhaps not showing learning or conceptual growth. Of the science-related questions, there was some loss of recognition that scientists are in consensus on the existence of climate change, thus reflecting the slight reduction in the steepness of the growth in raw scores shown in Figure 33. Similarly, Table 26 reflects small downturns on all the Risk perception questions, except risks for living things besides people, which showed a small uptick in Figure 33 and little change in Table 26. In fairness, many of the percentages in Figure 33 are near or above 90%. Therefore, calling a slight change in trajectory a *Loss*, may be harsh treatment. The question about personal harm was apparently a difficult question for the participants, given that the gradient of their attitudes changed. This is indicated in Table 26 with half the participants showing either *Gain* or *Loss* for this question.

Table 26 - Participant attitudinal response gradients

Rating the stepwise momentum of participants' attitudinal responses across all interviews

	Science				Risk Perceptions					Political	
participant	Happening now?	Caused by people?	Scientists?	Affect weather?	Harm you?	Harm others?	Harm now?	Harm in future?	Plants/animals?	Teach in schools?	Leaders do more?
116183	Same	Same	Same	Same	Same	Same	Loss	Same	Same	Same	Same
164579	Same	Same	Same	Same	Same	Same	Same	Same	Same	Same	Same
169662	Same	Same	Same	Same	Same	Gain	Same	Gain	Loss	Same	Same
172696	Same	Same	Same	Same	Loss	Loss	Same	Same	Same	Same	Same
211640	Same	Same	Same	Same	Gain	Same	Gain	Same	Same	Same	Same
224265	Same	Same	Same	Same	Gain	Same	Same	Same	Same	Same	Same
234293	Same	Same	Same	Same	Loss	Same	Same	Same	Same	Same	Loss
295319	Same	Gain	Same	Gain	Gain	Gain	Loss	Gain	Loss	Same	Gain
303944	Same	Same	Same	Same	Same	Same	Same	Same	Same	Same	Same
310434	Same	Loss	Same	Same	Loss	Loss	Same	Same	Same	Same	Same
320990	Same	Same	Same	Same	Same	Same	Same	Same	Same	Same	Same
362875	Same	Same	Loss	Same	Loss	Gain	Same	Loss	Same	Same	Loss
367341	Same	Same	Same	Same	Same	Same	Same	Same	Same	Same	Same
395296	Same	Same	Same	Same	Same	Same	Same	Same	Same	Same	Same
400940	Same	Same	Same	Same	Loss	Same	Same	Same	Same	Same	Same
446120	Gain	Same	Same	Same	Same	Same	Same	Same	Same	Same	Same
483686	Same	Same	Same	Same	Loss	Same	Same	Same	Same	Same	Same
487967	Same	Same	Same	Same	Same	Same	Same	Same	Same	Same	Same
577396	Same	Same	Loss	Loss	Same	Same	Same	Same	Same	Same	Loss
578266	Same	Same	Same	Same	Gain	Gain	Gain	Same	Same	Same	Same
668279	Same	Gain	Same	Same	Same	Same	Same	Same	Same	Same	Same
709787	Same	Same	Gain	Same	Same	Same	Same	Same	Gain	Same	Same
722960	Same	Same	Same	Same	Same	Same	Same	Same	Same	Same	Same
771173	Same	Same	Same	Gain	Loss	Same	Same	Same	Same	Same	Same
787383	Same	Same	Same	Same	Gain	Same	Same	Same	Same	Same	Same
860521	Same	Same	Same	Same	Same	Same	Same	Same	Same	Same	Same
874375	Same	Gain	Loss	Same	Gain	Loss	Loss	Same	Same	Same	Loss
907975	Same	Same	Same	Same	Same	Same	Same	Same	Same	Same	Same
919511	Same	Same	Same	Same	Same	Same	Same	Same	Same	Same	Same
945212	Same	Same	Same	Same	Same	Same	Same	Same	Same	Same	Same
946703	Same	Same	Same	Same	Loss	Same	Same	Same	Same	Same	Same

In summary, the study participants' responses were very encouraging. The difference between their responses and those of adults on similar questions indicate they have more scientifically aligned attitudes, even if they may have had little exposure to climate change science. They had a stronger acceptance of the science, a heightened sense of harm, seemed more interested in learning through their schools, and inclined to engage in action and leadership. I believe that such expressed attitudes might be solidified with increased exposure to scientific perspectives on the mechanics and interrelationships of climate change science system components.

4.4.2 - Coarse Grained Analysis of Conceptual Agreement and Confidence

Participants were assigned to either the control condition group, a reading task, or the treatment condition group, using the digital app. The control group also used the app, but only in their second data collection episode after the delayed-post-test interview. The treatment condition group used the app twice: once between the pre-test and post-test interviews, and again after the delayed-post-test interview. Figure 34 shows the average responses from the two condition groups' usages of the game in terms of confidence in their thinking and their agreement with experts' consensus responses to the game. Participants were prompted after they placed each sub-concept token with, "How sure are you in your thinking?". The overall study design embraced the changeability of scientific knowledge, rather than "facts", in accordance with post-positivistic philosophy and Nature of Science. Participants were never asked if they thought their responses were "correct", "facts", or "accurate", because these terms do not reflect perpetual change of scientific knowledge, which is inherent in science practice.

Figure 34 - Comparison of condition groups

Condition groups' normalized means for participants' self-rated confidence in their thinking and agreement with experts' conceptual configuration. (gameplay condition n=17, reading condition n=14).

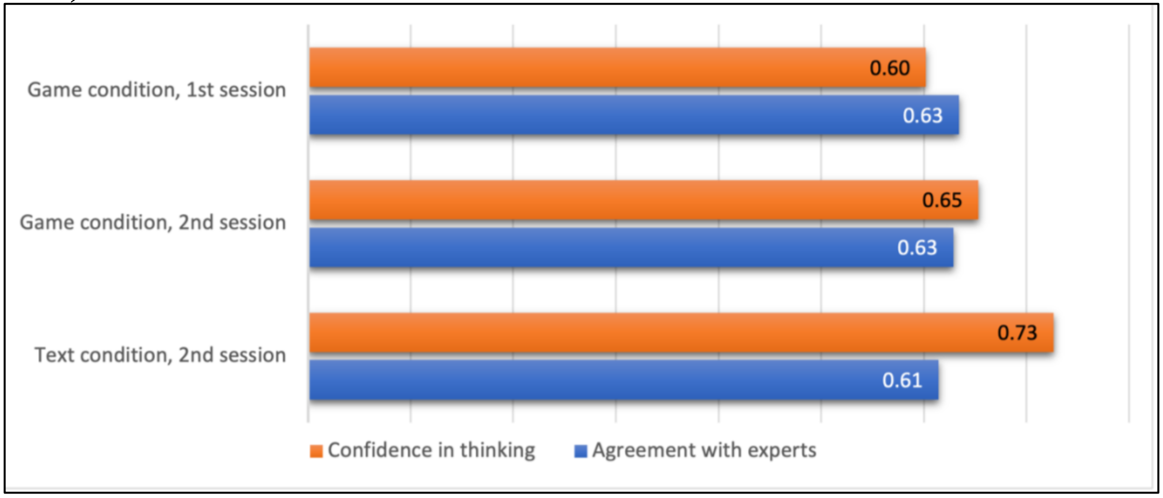
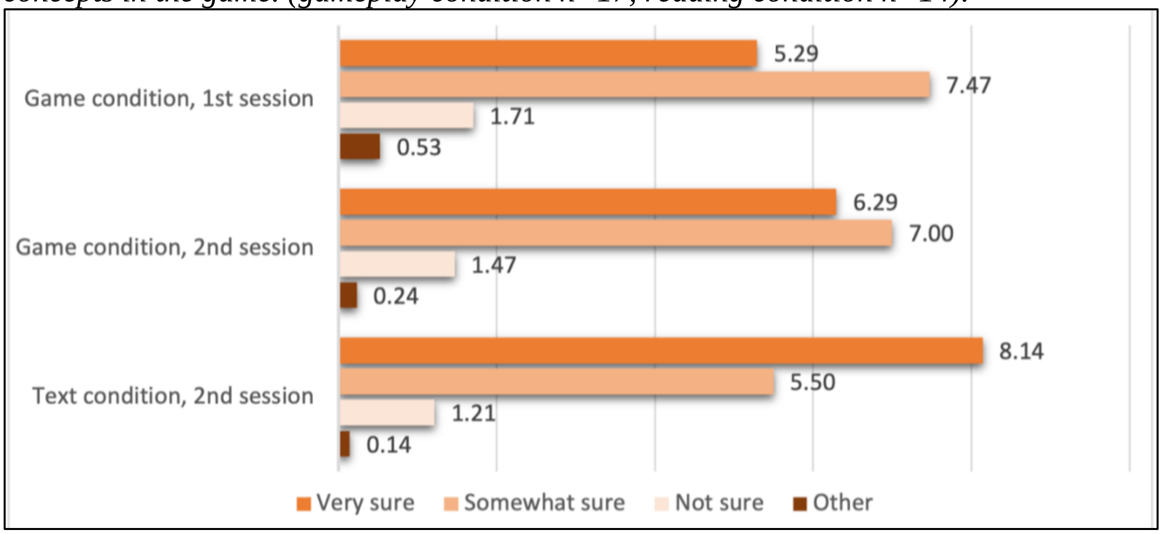


Figure 34 shows that game condition participants' mean confidence increased marginally from their first to their second uses of the app. Their agreement with experts' conceptualizations remained unchanged from their first to their second uses of the app. On the single occasion when participants in the text condition used the app, they exhibited significantly higher confidence than did participants in the game condition. Text condition participants' overall agreement with experts' conceptualizations was nearly the same as that of game condition participants.

The difference in confidence between game condition participants' first and second session may be attributable to residual familiarity with the app. Having completed the game once, participants were more comfortable with it the second time and therefore more confident in their answers. This was not the case with reading condition participants, since they had no prior experience with the app. Reading condition participants' confidence may have evaluated the reading to be a plausible system of climate change science concepts. Many participants said they had never thought about climate change concepts before. Therefore, the conceptual system presented in the reading condition may have filled a conceptual void, or considered superior to a prior weak system. Conceptual change research indicates that credibility is an important factor in assigning plausibility to a source (Lombardi, Seyranian, & Sinatra, 2014; Lombardi, et al., 2016). However, the research team presented the reading to participants without making any assertions about elements of source credibility, such as expertise or trustworthiness.

Figure 35 breaks down participants' responses in terms of the strength of expressed confidence on a per-sub-concept basis. The *Other* category in this table combines participant responses, <*I don't know*> and <*None of these choices work for me*>. Adding the numbers in each condition cluster yields 15, which is the number of sub-concepts in the app.

Figure 35 - Confidence response breakdown by condition group
Group average numbers of participants' self-ratings of confidence in their thinking about sub-concepts in the game. (gameplay condition n=17, reading condition n=14).



A moderate shift can be seen from <*Not sure*> and <*Somewhat sure*> to <*Very sure*> between gameplay condition participants' first and second app usages. This shift is more pronounced in the comparison between the second app usage in the gameplay condition and the reading condition.

The conceptual change process involves a host of factors related to the learner, the subject being learned, the learner's current information on the subject, new information on the subject, and the environment in which the new information is made available to the learner. Whether or not conceptual change actually occurs is highly dependent on the learner (Posner, et al., 1982; Hewson & Hewson, 1984; Pintrich, et al., 1993). One important aspect of the learner is the degree to which they place value in information from trusted others such as science domain experts. This dissertation measured participants' level of agreement with the consensus of domain experts on concepts which were representative of climate change science. By extension, improving agreement between participants and experts on these concepts was considered to be a way of achieving more scientifically aligned domain knowledge held by the participants.

The level of agreement between participants and experts did not vary markedly among the three gameplay scenarios shown in Figure 34. Though this was disappointing, it was not surprising. Participants in the game condition received no expert information…no conceptual configurations were recommended. It was hoped that by sheer dint of getting participants to talk and think about the topic of climate change, their level of agreement with the experts would improve. This did not occur. For the text condition, though expert information was provided to the participants, they did not know the system of concepts was from experts. Participants were entirely justified in thinking it was "just another text" without instruction to point out the differences in content and how the concepts related to each other. Here too, improvement in agreement did not occur.

However, an encouraging data point came from the game participants. Each of them (n=17) played the game twice. The only change in the game the second time was the random order that the 15 sub-concepts appeared in the opening game display. Surprisingly, the average participant changed 61% (9.1 of 15) of their relationships from first use to second. For example, a participant changed <*Greenhouse effect*> from <*Environment*> to <*Climate & Environment*>. The participant who changed the fewest relationships changed 33% (five) of them. In terms of sub-concept relationships that participants changed the least and most between first and second gameplay, <*People*> changed the least at 41% (7 of 17), and <*Industry*> changed the most at 76% (13). My interpretation of this is that participants were trying very hard to organize their climate change conceptual networks and were floundering in the absence of information about how they *should* be organizing them.

4.4.3 - Fine Grained Analysis of Conceptual Agreement and Confidence

Though an argument for learning with the app is possible for all participants, I focused on the 17 participants who had the gameplay condition in their first data collection episode and used the app a second time at the end of their second data collection episode. Comparisons in terms of agreement and confidence across instances of app usage show whether a participant gained or lost ground in these two aspects.

Study participants' climate change sub-concept placements with the C^3M_{YC} app were logged and subsequently compared to the consensus placements by experts who used the paper form of the instrument. All the sub-concepts and main concepts were identical between the paper and digital forms of the app. The comparison yielded the percentage difference between the participant's placement configuration and the experts' consensus configuration. Notably, the experts were not unanimous in their placements, but rather were 87% in consensus. The study participants were 63% in consensus.

In review, a participant asserted a relationship between a sub-concept and main concepts by dragging the sub-concept token to the screen area representing the main concepts. The participant then dropped the sub-concept to assert the existence of a relationship. Next, the participant responded to questions about the direction of the relationship and how much confidence they had in their thinking about the relationship. The participant could say they were not confident, somewhat confident, very confident, or they didn't know.

All responses were recorded in real time by the app and stored for later analysis. As a result, a participant's degree of conceptual agreement with the experts' configuration was recorded for each sub-concept. From this, their overall configuration agreement with the experts was easily calculated. Similarly, a participant's overall confidence in their placements was easily determined based on their per-sub-concept self-described confidence.

To learn more about the game condition participants, I grouped those that showed gains in both agreement and confidence, those that showed losses in both aspects, and those that had mixed gains and losses. Table 27 shows these groupings. The middle columns in color show the percentage gain or loss in agreement and confidence between the two sessions while the columns to the left and right of middle show the agreement and confidence for each of the two sessions for each participant.

Table 27 - Grouped comparison of agreement and confidence

Comparison of agreement and confidence gains and losses for participants who used the C^3M_{YC} *app twice (gameplay condition). Data are grouped, top to bottom, gains in both agreement and confidence (n=4), losses in both agreement and confidence (n=5), and mixed gains and losses (n=8). Conditional formatting: red <-15%, green >15%).*

	Participant ID	1st session agreement with experts	2nd session agreement with experts	Agreement gain/loss	Confidence gain/loss	2nd session confidence	1st session confidence
gains in both agreement and confidence	**722960**	48.9%	53.3%	**4.4%**	**23.3%**	83.3%	60.0%
	224265	68.9%	75.6%	**6.7%**	**23.3%**	73.3%	50.0%
	400940	60.0%	66.7%	**6.7%**	**23.3%**	56.7%	33.3%
	578266	55.6%	77.8%	**22.2%**	**10.0%**	76.7%	66.7%
losses in both agreement and confidence	**164579**	88.9%	86.7%	**-2.2%**	**-10.0%**	46.7%	56.7%
	221640	73.3%	66.7%	**-6.7%**	**-6.7%**	60.0%	66.7%
	310434	60.0%	57.8%	**-2.2%**	**-13.3%**	86.7%	100.0%
	668279	40.0%	33.3%	**-6.7%**	**-10.0%**	20.0%	30.0%
	771173	60.0%	44.4%	**-15.6%**	**-3.3%**	50.0%	53.3%
mixed gains and losses	**295319**	66.7%	75.6%	**8.9%**	**-3.3%**	60.0%	63.3%
	362875	66.7%	57.8%	**-8.9%**	**20.0%**	73.3%	53.3%
	446120	66.7%	64.4%	**-2.2%**	**0.0%**	83.3%	83.3%
	577396	64.4%	55.6%	**-8.9%**	**26.7%**	93.3%	66.7%
	787383	60.0%	66.7%	**6.7%**	**-3.3%**	66.7%	70.0%
	874375	55.6%	55.6%	**0.0%**	**-13.3%**	53.3%	66.7%
	919511	80.0%	73.3%	**-6.7%**	**16.7%**	76.7%	60.0%
	945212	62.2%	57.8%	**-4.4%**	**6.7%**	50.0%	43.3%

Table 27 shows only one participant with double digit changes in both agreement and confidence. Most participants' gains or losses were driven by one factor, since for more than two-thirds of participants, the difference between their agreement and confidence change was more than 5%.

Table 28 and Table 29 show the same gains and losses as Table 27, but at the sub-concept level. Major changes are shown in terms of agreement (Table 28) and confidence (Table 29). Only significant changes are highlighted. In terms of agreement, a significant change happened when at least two of the three main concept associations changed (e.g., from <*Weather*> to <*Climate*, *Environment*, *& Weather*>). Blocks with a red background agreed less with experts' consensus for that sub-concept in the second session. Blocks with a green background agreed more with experts' consensus for that sub-concept in the second session. Looking along the vertical axis of this graphic, the categories with net gains (more green blocks than red ones) were *Human activities* (tiles 5-6) and *Spatial extents* (tiles 7-9). *Temporal rates of change* (tiles 2-4) and *Climate change system sub-components* (tiles 10-14) stayed about the same overall. *Temperatures* (tiles 0-1) showed only losses. Many sub-concepts showed a balance between gains and losses. <*Cooling temps*> and <*Greenhouse effect*> showed mostly losses. *<Farming>*, *<Local area>*, *<Global area>*, and *<People>* showed mostly gains.

Table 28 - Fine-grained changes in agreement

Participants' per-sub-concept change in agreement with experts over two uses of the C[3]*M*$_{YC}$ *app. Red blocks represent declines in agreement. Green blocks represent gains in agreement.*

	Participant ID	Session	tile_0 cooling temps	tile_1 warming temps	tile_2 fast change	tile_3 yearly change	tile_4 slow change	tile_5 farming	tile_6 industry	tile_7 local area	tile_8 regional area	tile_9 global area	tile_10 animals	tile_11 people	tile_12 forests	tile_13 oceans	tile_14 greenhouse effect	Aggregate agreement gain
gains in both agreement and confidence	722960	1st	0.67	0.67	0.67	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.67	0.33	0.67	1.00	4.4%
		2nd	0.33	0.67	1.00	0.33	0.67	1.00	0.67	0.33	0.33	0.33	0.33	0.67	0.33	0.33	0.67	
	224265	1st	0.67	0.67	1.00	0.33	1.00	0.33	0.67	1.00	1.00	1.00	1.00	0.33	0.33	0.33	0.67	6.7%
		2nd	1.00	1.00	1.00	0.33	0.67	0.67	1.00	1.00	1.00	0.33	1.00	1.00	0.33	0.33	0.67	
	400940	1st	1.00	1.00	1.00	0.33	0.67	0.67	0.33	0.00	0.00	0.00	1.00	1.00	0.67	1.00	0.33	6.7%
		2nd	0.67	0.67	0.33	0.33	0.00	0.67	1.00	0.67	0.67	1.00	1.00	1.00	0.67	0.67	0.67	
	578266	1st	0.67	0.67	0.33	0.67	0.33	0.67	0.33	0.33	0.67	1.00	0.33	1.00	0.33	0.33	0.67	22.2%
		2nd	1.00	1.00	1.00	0.33	0.67	0.67	0.33	1.00	1.00	1.00	1.00	1.00	0.33	0.67	0.67	
losses in both agreement and confidence	164579	1st	0.67	1.00	0.67	0.67	1.00	1.00	1.00	1.00	1.00	1.00	0.67	1.00	1.00	1.00	0.67	-2.2%
		2nd	0.67	0.67	0.67	1.00	1.00	1.00	1.00	0.67	1.00	1.00	1.00	1.00	1.00	1.00	0.33	
	221640	1st	1.00	1.00	0.67	1.00	0.67	0.67	1.00	0.33	1.00	1.00	0.33	0.33	0.33	0.67	1.00	-6.7%
		2nd	0.67	0.67	0.33	0.67	0.67	0.33	1.00	0.67	1.00	1.00	0.67	0.67	0.67	0.33	0.67	
	310434	1st	1.00	1.00	0.67	1.00	0.33	1.00	0.33	0.33	0.33	0.33	0.33	0.67	0.33	0.33	1.00	-2.2%
		2nd	1.00	0.67	0.00	0.67	0.67	1.00	0.67	0.67	0.33	0.33	0.67	0.33	1.00	0.33	0.33	
	668279	1st	0.00	0.67	0.67	0.67	0.33	0.00	0.33	0.00	0.00	0.67	0.67	0.33	0.67	0.67	0.33	-6.7%
		2nd	0.33	0.33	0.67	0.00	0.33	0.67	0.00	0.00	0.00	1.00	0.33	0.33	0.33	0.00	0.67	
	771173	1st	0.67	0.67	1.00	0.33	0.67	0.67	0.67	0.67	0.67	0.67	0.33	0.33	0.33	0.33	1.00	-15.6%
		2nd	0.67	0.67	0.33	0.67	0.67	0.67	0.33	0.33	0.33	0.33	0.33	0.33	0.67	0.33	0.00	
mixed gains and losses	295319	1st	1.00	1.00	0.33	1.00	0.67	1.00	0.67	0.67	0.67	1.00	0.33	0.33	0.33	0.33	0.67	8.9%
		2nd	0.67	1.00	1.00	0.67	0.67	0.67	0.67	0.67	0.67	1.00	1.00	1.00	0.33	0.67	0.67	
	362875	1st	1.00	1.00	0.33	0.67	0.67	0.00	0.33	1.00	1.00	0.67	1.00	0.33	0.67	0.33	1.00	-8.9%
		2nd	0.67	0.33	0.33	0.67	0.67	0.00	0.67	1.00	1.00	1.00	0.33	1.00	0.33	0.33	0.33	
	446120	1st	1.00	1.00	1.00	0.33	0.67	0.33	0.67	1.00	0.67	0.33	1.00	0.33	1.00	0.33	0.33	-2.2%
		2nd	0.33	0.67	1.00	0.33	0.67	1.00	0.67	0.67	0.67	1.00	1.00	0.33	0.33	0.67	0.33	
	577396	1st	1.00	1.00	0.33	1.00	0.67	0.33	0.67	0.67	0.67	0.67	0.33	0.67	0.33	0.33	1.00	-8.9%
		2nd	0.67	0.67	0.33	1.00	0.67	0.33	0.67	0.67	0.67	0.67	0.33	0.67	0.33	0.33	0.33	
	787383	1st	1.00	0.67	1.00	0.00	0.33	0.33	0.67	0.33	0.33	0.33	1.00	1.00	1.00	0.67	0.33	6.7%
		2nd	0.33	0.33	0.67	0.00	0.33	0.67	1.00	1.00	0.67	1.00	1.00	1.00	0.67	0.33	1.00	
	874375	1st	1.00	0.67	0.67	1.00	0.33	1.00	0.67	0.33	0.00	1.00	0.33	0.67	0.33	0.33	0.00	0.0%
		2nd	0.67	1.00	0.67	1.00	1.00	0.67	0.00	0.00	0.33	1.00	0.33	0.33	0.33	0.67	0.33	
	919511	1st	1.00	1.00	1.00	0.67	1.00	1.00	0.67	0.67	1.00	0.33	0.67	1.00	1.00	0.33	0.67	-6.7%
		2nd	1.00	1.00	1.00	0.33	0.67	1.00	1.00	0.33	0.67	1.00	0.33	1.00	0.33	0.67	0.67	
	945212	1st	0.67	0.67	0.67	0.00	0.33	0.67	1.00	0.00	0.00	1.00	0.67	1.00	1.00	1.00	0.67	-4.4%
		2nd	0.67	0.67	0.67	1.00	0.67	0.00	1.00	0.00	0.00	0.00	0.67	1.00	0.67	1.00	0.67	

Table 29 shows where major changes in gain or loss occurred at the sub-concept level for confidence in conceptual thinking. Only changes between <*Not sure*>, <*Somewhat sure*>, and <*Very sure*> are shown. Other self-reported scores were unratable. Blocks with a red background showed a loss of confidence in the second session while those with a green background showed a gain in confidence in the second session.

Although the number of per-tile changes in confidence ranged from one to nine, depending on the participant, it was common for a participant to have 5-6 changes. Two participants had only losses in confidence (one and two blocks, respectively), but every other participant had a mix of confidence losses and gains. Looking vertically across this table, roughly half of participants had gains in confidence in the *Spatial extents* category of sub-concepts. Very few had any losses in this category. All other categories were generally balanced between losses and gains. For individual sub-concepts, <*Forests*> mostly showed confidence losses and <*Oceans*> showed mostly gains in confidence.

Table 29 - Fine-grained changes in confidence

Participants' per-sub-concept change in confidence over two uses of the C^3M_{YC} app. Red blocks represent declines in agreement. Green blocks represent gains in agreement.

			tile_0	tile_1	tile_2	tile_3	tile_4	tile_5	tile_6	tile_7	tile_8	tile_9	tile_10	tile_11	tile_12	tile_13	tile_14	
	Participant ID	Session	cooling temps	warming temps	fast change	yearly change	slow change	farming	industry	local area	regional area	global area	animals	people	forests	oceans	greenhouse effect	Aggregate confidence gain
gains in both agreement and confidence	722960	1st	0	1	0	1	0	2	2	1	2	1	2	2	1	1	2	23.3%
		2nd	2	2	1	1	1	2	1	2	2	2	2	2	1	2	2	
	224265	1st	1	1	4	4	1	1	1	1	1	1	2	2	2	4	1	23.3%
		2nd	2	2	1	1	1	2	2	1	2	1	1	1	2	1	2	
	400940	1st	1	1	4	1	0	1	2	0	0	0	1	1	1	1	0	23.3%
		2nd	1	1	1	1	1	2	1	1	1	1	2	1	1	1	1	
	578266	1st	2	1	1	1	1	2	2	1	1	2	1	1	2	0	2	10.0%
		2nd	2	2	1	2	1	1	1	2	2	2	2	1	1	1	2	
losses in both agreement and confidence	164579	1st	1	1	1	1	1	1	2	1	2	1	1	1	1	1	1	-10.0%
		2nd	1	1	0	1	1	1	1	1	1	1	1	2	0	1	1	
	221640	1st	2	2	1	1	2	2	1	1	3	1	2	2	2	1	3	-6.7%
		2nd	1	1	1	1	1	1	1	2	1	1	1	2	1	1	2	
	310434	1st	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	-13.3%
		2nd	2	0	2	2	2	2	2	2	2	2	2	2	2	2	0	
	668279	1st	1	0	0	2	0	0	0	0	0	1	2	1	1	0	1	-10.0%
		2nd	0	0	0	0	0	4	0	0	0	1	1	2	1	0	1	
	771173	1st	1	1	1	1	1	1	1	1	1	1	1	1	1	2	1	-3.3%
		2nd	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	
mixed gains and losses	295319	1st	1	1	2	2	2	1	1	1	1	2	1	1	1	1	1	-3.3%
		2nd	1	2	1	1	1	1	1	1	1	1	1	2	0	2	2	
	362875	1st	1	2	1	0	1	2	1	1	1	1	1	2	1	1	0	16.7%
		2nd	2	2	1	1	1	0	2	2	1	2	2	2	1	1	1	
	446120	1st	2	2	2	2	1	1	2	1	2	1	2	2	2	1	2	0.0%
		2nd	1	2	2	1	1	1	2	2	2	2	2	2	2	2	1	
	577396	1st	1	1	2	2	1	1	2	0	1	2	2	2	1	1	1	26.7%
		2nd	2	2	2	2	2	1	2	2	2	2	2	2	1	2	2	
	787383	1st	2	2	1	0	0	2	2	2	1	1	2	1	1	2	2	-3.3%
		2nd	1	1	2	0	0	2	2	2	1	1	2	2	1	1	2	
	874375	1st	2	2	0	1	1	2	2	2	0	1	2	2	2	1	0	-13.3%
		2nd	2	1	0	1	1	2	0	0	1	1	2	1	2	2	0	
	919511	1st	1	1	1	1	1	2	1	1	2	1	1	2	1	3	2	16.7%
		2nd	2	2	3	3	3	2	2	1	2	2	2	2	2	2	2	
	945212	1st	2	1	0	0	0	2	1	0	4	4	1	2	1	1	2	6.7%
		2nd	2	1	1	0	2	0	2	0	0	0	2	2	1	1	1	

4.4.4 - ANOVA of Conceptual Agreement and Confidence

While participants' responses to the conditions were highly individualized and involved a high degree of detail, two fundamental questions were considered regarding the interactions between the two participant groups and their respective instruments. The first fundamental question was which condition produced more positive results in terms of participants' conceptual agreement and their confidence in their scientific thinking. To test this, between-groups analyses of variance were conducted for each condition and are shown in Table 30.

Table 30 - Between-group ANOVAs

Between-groups one-way ANOVAs for confidence and agreement for the game usage in the second data collection episodes for the gameplay group (second use of the game) and the text group (first use of the game).

Agreement - between groups

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Text	14	8.6	0.61428571	0.01524081
Game	17	10.6888889	0.62875817	0.0172077

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.00160805	1	0.00160805	0.09849637	0.75588805	4.18296429
Within Groups	0.47345368	29	0.01632599			
Total	0.47506173	30				

Confidence - between groups

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Text	14	10.1666667	0.72619048	0.02515873
Game	17	11.1	0.65294118	0.03389706

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.04119289	1	0.04119289	1.37401784	0.25066266	4.18296429
Within Groups	0.86941643	29	0.02997988			
Total	0.91060932	30				

The second fundamental question was which whether participants' conceptual agreement and confidence in their scientific thinking improved with repeated uses of the game. To test this, within-groups analyses of variance were conducted for each condition and are shown in Table 31.

Table 31 - Within-group ANOVAs

Within-group one-way ANOVAs for confidence and agreement for the first and second use of the game by the gameplay group.

Agreement - within game group

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Game - app use #1	17	10.7777756	0.6339868	0.01259985
Game - app use #2	17	10.6888889	0.62875817	0.0172077

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.00023238	1	0.00023238	0.01559187	0.90140967	4.14909745
Within Groups	0.4769207	32	0.01490377			
Total	0.47715307	33				

Confidence - within game group

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Game - app use #1	17	10.2333333	0.60196078	0.0282598
Game - app use #2	17	11.1	0.65294118	0.03389706

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.0220915	1	0.0220915	0.7108307	0.40542632	4.14909745
Within Groups	0.9945098	32	0.03107843			
Total	1.01660131	33				

Given that all four ANOVAs yielded p-values greater than .05, all of them failed to reject their respective null hypotheses. The calculated p-values ranged from a maximum of p=.90 for the agreement variable of the within-group comparison to a minimum of p=.25 for the confidence variable of the between-groups comparison. Post-hoc power analyses were conducted using the PWR package in R for a medium effect size and power level of .80. The within group power analysis showed that the study was underpowered for $n<50.15$. The between group power analysis showed that the study was underpowered for $n<26.14$ per group.

4.5 - Analyses Summary

Three different types of analyses were performed in this chapter, each with a different purpose. The first type was of an individual participant case study variety and was executed to answer the research questions. What was learned by these analyses was that the methods unearthed a good amount of data which provided details about the participants' conceptual thinking about climate change. The second type of analyses was group level case study about potential societal influences on conceptual thinking, given that climate change is a socio-scientific topic. Again, some very interesting data were produced which hint at factors that clearly bear on adult's thinking about climate change and may well be starting to impinge on children's thinking. The third type of analysis considered on a method-by-method basis, what could be argued to be evidence of learning. Given that climate change is a very new topic to almost all children, a liberal definition of "learning" was applied.

CHAPTER 5 - CONCLUSIONS AND DISCUSSION

The conclusions in this chapter relate to the analyses in Chapter 4.

5.1 - Understanding Learners' Conceptual Thinking through Haptic Event Data

Two participants, Andy and Bree, were chosen to explore the first research question:

RQ1 - In what ways do the transient data features (haptic event logging) of a digital app reflect learners' underlying comprehension and/or misunderstanding of climate change science concepts.

All participants used the app at least once to complete their concept maps. Andy and Bree were chosen, in part, because they represent this study's two research conditions. Andy received the gameplay condition with the digital app and Bree received the reading, or control, condition with a text which covered the same topical knowledge as the app. It was previously unknown whether differences in the number of times participants used the C^3M_{YC} app would produce different responses to RQ1.

Andy's conceptualizations were overall closer to the experts than many of the participants. This was true of both of his uses of the app. His agreement with the experts' consensus configuration went down marginally from his first to his second use, but his confidence rose markedly. His approach to the game was logical, for the most part, as evidenced by the fact he consistently used the same relationship for most of the sub-concepts in which he initially expressed high conceptual confidence. For the ones in which he was less confident, he changed his relationship choices. *Temporal rates* and *Spatial extents* categories of sub-concepts made up a majority of the last and most slowly placed sub-concepts across both his app uses. This was common for many participants, as shown in the heat map in Table 32. Placing a sub-concept slowly or delaying its placement could be rationalized to indicate a need for conceptual change learning related to that sub-concept.

Table 32 - Heat map of participants' sub-concept tile placements

All participants' (n=48) frequency distribution of last and slowest tile sub-concept placements by tile index. Conditional tile colors: green=0, yellow=4, red=8.

	Tile Index	Last 3 tiles placed			Slowest 3 tiles placed		
temps	0	4	1	2	5	1	3
	1	1	3	3	3	4	4
temporal	2	7	4	4	1	5	2
	3	2	4	6	2	2	5
	4	5	6	2	3	4	3
activities	5	6	3	2	6	5	3
	6	3	0	2	4	3	1
spatial	7	3	4	4	0	1	7
	8	3	5	7	5	6	8
	9	4	2	6	7	3	1
components	10	1	2	2	1	3	2
	11	1	5	0	2	1	1
	12	2	4	1	3	4	4
	13	4	2	4	4	2	2
	14	2	3	3	2	4	2

An educator working with Andy might consider the following approach. Encourage his approach to the game in that his overall agreement with the experts was high and stable. He also seemed to focus on improving his understanding of the remaining difficult sub-concepts as he considered his conceptual choices in the game carefully. Once he made decisions, he made them quickly, as evidenced by the relatively short event durations. Also, he seldom returned to a sub-concept previously placed. The changes he made with sub-concept placements in his second use of the app were for sub-concepts for which he expressed some uncertainty in his first use. To disambiguate some data collected during the second app usage, an educator could ask Andy why he chose <*None of these choices work for me*> as the best reflection of his confidence. His reasoning could be that the relationship was bidirectional but stronger in one direction, or he could have been thinking about a more complex relationship. Regardless, an educator could encourage better ways for Andy to think about temporal rates of change in a science-aligned way. This includes longer time scales (e.g., <*Slow changes*>) for climate and shorter time scales (e.g., <*Fast changes*>) for weather. Contrasting temperature graphs over hundreds of years for climate with hourly graphs for weather is one way to instill this difference.

Comparing data from both Andy's uses of the app helped me understand the role the app played in his evolving understanding of climate change concepts. The sequence of his configurations exhibited a degree of cold conceptual (Pintrich, et al.,1993) in that he expressed lowered confidence in placing a sub-concept, but followed with a different placement in the next session. His logged data identified particular areas were problematic, such as temporal rates of change, where his conceptualizations could be improved by instruction. The data also identified ambiguities where additional feedback from the participant would have been useful for educational and research purposes. For example, why did Andy rate his confidence about <*Fast changes*> at <*Somewhat sure*> for in his first use of the C^3M_{YC}, but not change it for his second use when he rated his confidence as <*Not sure*>? It turned out that Andy did not rate his thinking as <*Not sure*> but rather <*None of these choices works for me*>, which was scored the same as <*Not sure*>. The research team asked participants to choose this option if their degree of certainty was "strange" or a bad fit with the other choices. This type of response is more typical of Andy's rational approach than <*Not sure*>. Andy was very comfortable sharing what he knew as well as what he didn't know. For <*Fast changes*>, Andy seemed to be experiencing what D'Mello, et al. (2014) would call an extreme state of confusion, which the authors say can facilitate thinking deeply and increasing knowledge about complex tasks. Fortunately for Andy, few areas of conceptual confusion were found in his data and his conceptual understanding progressed well.

Bree, on the other hand, had marginally lower agreement with the experts' configuration, but somewhat higher confidence in her thinking than the average participant. As with Andy's first usage of the app, Bree had low confidence in her thinking about *Temporal rates of change*, *Spatial extents*, and *Climate change system sub-components*. Her levels of agreement with the experts on *Temporal rates of change*, *Spatial extents*, and *Human activities* were all below 50%.

A review of Bree's individual steps toward completion of her concept map showed she revisited most sub-concepts after initial placement. Sometimes she changed their relationships but other times she simply returned them to the same main concept area after a pause as if she reconfirmed her earlier thinking. An example of this was when she picked <*Greenhouse effect*> from <*Environment*> and returned it to <*Environment*>. An exception to this behavior was her placements of *Temperature changes* sub-concepts. Unlike any other sub-concepts, she placed <*Warming temps*> and <*Cooling temps*> once apiece, expressed high confidence in her thinking, and was in complete agreement with the experts.

Bree also exhibited the interesting behavior of revisiting a placed sub-concept after completing several intervening placements of other sub-concepts. For example, she placed <*People*> in steps 7 and 21, and <*Forests*> in steps 2 and 16. She placed <*Yearly changes*> in steps 3, 10, and 11. Just prior to this, she placed <*Slow changes*> with <*Weather*> before she moved it to <*Climate*>. It seemed that she thought that two sub-concepts could not occupy the same concept area and that they could not conceptually overlap. Experts do not see this as a conflict because they understand climate, weather, and environment change exist on multiple time scales depending on the particular nature of the change and relationships with different system components.

From an educator's perspective, Bree's placements of <*Farming*> starting in step 19 were richly detailed. She did her initial placement followed by successive placements in steps 26-28. The app logged a significant pause in step 26 as she held the tile for <*Farming*> and moved it around the screen as she talked with me about her logic. She weighed the importance of the respective relationships with <*Environment*> and <*Unrelated*>. She eventually settled on placing <*Farming*> with <*Environment*> after remembering a connection with a school lesson on the Dust Bowl. An educator would likely be happy to see how Bree integrated this information with her earlier thinking. Given that experts associate <*Farming*> with all three of the main concepts, an educator could subsequently use the opportunity to have Bree think even more deeply about the sub-concept. The direction of the relationship, in which she asserted that <*Farming*> was important to <*Environment*>, could be flipped for her to consider situations where <*Environment*> is important to <*Farming*>. Additional discussions could involve agricultural tilling practices releasing CO_2 (an example of farming affecting climate), and increased frequency of extreme weather events (an example of weather affecting farming) to foster a conceptualization that was more in agreement with the expert's consensus.

Bree's logged data was very complicated and could be interpreted through several conceptual change theories. Despite her numerous changes to the sub-concept placements using the app, she always had at least the same level of confidence in the new relationship. In this way, Bree was following a logical progression of her knowledge and exhibiting "cold" conceptual change (Pintrich, et al., 1993). Bree's placements of <*Farming*> are arguably most representative of different resolutions to anomalous data (Chinn & Brewer, 1993). Though she had initial ideas about the nature of the sub-concepts, she quickly modified her conceptualizations. Her rapid changes likely contributed to the fact she retained only one of her first eight sub-concept placements in her final configuration. We know that placements of <*Farming*> (see Table 11 for moves 19 and 26-28) were difficult for Bree. It was only after integrating the classroom memory about the Dust Bowl that she rated her thinking as <*Very sure*>.

5.1.1 - Summary: Connecting Learners' Haptic Event Data and Conceptual Thinking

The richness of these two analyses would not have been possible without the participants' haptic event data and the data logging features of the C^3M_{YC}. Because of this, the transient data design features of the C^3M_{YC} met their intended purposes. The digital app indicated participants' comprehension and misunderstanding of concepts through event timestamps, placement sequences, and repeated re-placements of sub-concepts. Combining these data with expressed confidence disambiguates participants' conceptual thinking through corroboration and refutation. Educators and researchers should treat the logged data as *potential indicators* of misconceptions which should be confirmed through follow-up discussions with learners. Every learner is different in how and why they build their knowledge. As the differences between Andy's and Bree's progress illustrate, fostering learners' conceptual change and growth is highly individualized.

5.2 - Learner's Patterns of Change

Regarding the second research question, what was learned from Emily, the participant whose interactions were scrutinized in section 4.2. For convenience, here again is the second research question.

> *RQ2 - In what ways does the combination of learners' interactions with a digital app and their interview responses suggest different patterns of change in climate change science thinking?*

In addition to looking at Emily's responses to the C^3M_{YC} app, her responses to the Yale and NGSS question sets were also sources for informing RQ2. Each learner has a unique way of articulating their thinking about climate change concepts. For this reason, all methods are potentially useful pathways for a learner to express themselves. For this reason, a "pattern of change" could take many different forms, depending on the learner. In section 4.2.1.1, two "patterns" are suggested from Emily's data. In both cases, the patterns were identified in multiple methods, multiple data groups from those methods, and even multiple instances of Emily using the methods.

Emily's first pattern of change centers on the sub-concept, <*People*>. In her earlier responses to the methods, Emily seems to regard <*People*> as being simply a part of the environment and therefore experiencing environment just as other living things do. Things start to change in the post-test interview, as is evidenced by her response to the Yale question about people affecting climate in a major way. In Emily's second data collection episode, <*People*> no longer just relate to environment. The sub-concept is related to all three major concepts. Her new conception of <*People*> is that they experience climate, and they also affect weather through climate variations and atmospheric warming exacerbated by human activities. Emily's conceptualization of <*People*> has taken a turn that significantly complicates its web of relationships. Because of this, her conceptualizations come more into alignment with the climate science community.

This conceptual change pattern seems to start during her first data collection. The change is apparent through subtle differences between her pre-test and post-test interviews. Some of her responses in the post-test are more accepting of climate change and others are less ambiguous than in the pre-test. Change also seems to occur during the three weeks between Emily's two data collection episodes. The magnitude of change during this time interval seems much higher than during the first episode. It is less clear which of Emily's information sources fostered the change. One possibility is that she talked with her parents in the interval between data collection episodes. Her mother worked on a sustainability project which would have engaged climate change issues to some degree. Emily mentioned her mother a couple times and she said that both her parents knew a lot about climate science. Another potential source is friends. Emily said that she and her friends talked about climate change every other week. These sources, though, would not have affected Emily's post-test interview responses. The post-test interviews were done immediately after the participants completed the reading or the game, so there would not have been time to talk to anybody. One other possible epistemic source is Emily herself and her own reasoning abilities. She had heard about sub-concepts such as <*Greenhouse effect*>, but perhaps had not previously thought about the activities that lead to the production of greenhouse gases, nor what comes after their production. A number of participants expressed that they had never thought about some of the questions and issues discussed during data collection.

From what she said during interviews, Emily seemed to already have a conceptualization of <*People*> that factored in human activities, greenhouse effect, and temperature changes. Therefore, if she received anomalous data during or between data collections, it didn't completely upend her conceptualization. However, to extend the consequences of climate change to environment and habitat, she may have experienced a "reinterpretation" of <*People*> *a la* one of the resolutions proposed by Chinn & Brewer (1993). Another possible reason for her change in conceptualization could have been the temporal and cognitive proximity of <*People*> with the sub-concept, <*Animals & plants*>. This proximity may have initiated her thinking that a conceptual link with <*People*> was plausible (Lombardi, et al., 2013; Sinatra, et al., 2014;

Lombardi, et al., 2016). Emily's interview responses such as, "I don't think that we should treat other animals that need a shelter or a home or anything any different than we would, if a little boy or little old girl or an adult would like want to find somewhere to sleep or something…", during her pre-test interview, clearly show that she cares for all manner of living things. She may also have been trying to assimilate new information which increased the similarity of basic needs between <*People*> and <*Animals & plants*>. By choosing that <*People*> was related to <*Climate, Environment, & Weather*> in her second use of the app, rather than just <*Environment*>, Emily was able to reflect this assimilation (Piaget, 1964) of new data relating humans and human activity to changes in climate and weather.

Emily's second pattern of change involved the sub-concepts <*Animals & plants*> and <*People*>, and their mutual relationships to the main concepts. As discussed in section 4.2, Emily's responses to the Yale personal harm question progressed from uncertainty to a clear affirmation that she thought climate change could cause her personal harm. Concurrently, her responses to the NGSS question about the history of Earth started with an emphasis on temperature shifts during ice ages, and ended her drawing the connection between temperature shifts leading to species extinctions. In her first concept map construction using the digital app, Emily related <*Animals & plants*> to <*Climate, Environment, & Weather*>. She related <*People*> and <*Forests*> to only <*Environment*>. She rated her thinking about the three sub-concepts as <*Very sure*>. However, with her second use of the app, the relationship for <*People*> changed to incorporate all three main concepts and she downgraded her confidence for both <*People*> and <*Animals & plants*> to being somewhat confident. As she completed the concept map the second time, she placed the sub-concept <*Industry*> four times in total, changing her mind each time before. She settled on a relationship with all three main concepts after multiple changes, having cycled between excluding and including <*Environment*> from the relationship.

As with Emily's first pattern of change, this pattern started with her pre-test interview. The pattern involved the sub-concepts, <*People*> and <*Animals & plants*>, but it also notably engaged <*Industry*>. Logged data reveals that with Emily's three placements of <*Industry*> in her first use of the app, she chose three different configurations of relationships with the main concepts. Each relationship was more complicated than the prior one, a pattern that continued with her second use of the app. As the lower stat table in Figure 31 shows, <*Industry*> was the only remaining sub-concept that presented conceptual challenges for Emily, given that the table shows the sub-concept was placed multiple times, and there was uncertainty about the relationship direction.

I believe that this pattern of change shows evidence of Emily's work to incorporate existential threat from climate change into her conceptualizations of <*Animals & plants*>, <*People*>, and <*Industry*>. Her confidence self-downgrade for <*Animals & plants*> and <*People*> in her second use of the app reflects self-monitoring on her part, which would indicate that she engaged new information and/or new epistemic sources during the three weeks between data collection episodes. From what Emily said in interviews, she seemed to have a robust circle of trusted sources (parents, family, friends) and that climate change was a common subject of discussion. Her self-assessment of her confidence implies that she has not yet achieved a satisfying state of equilibration (Piaget, 1964), though she likely had partly assimilated the new existential threat characteristic at the time of data collection. Emily's frequent changes in conceptualization of <*Industry*> took her from a minimal relationship to the most complex one possible. Her initial placement was from <*Bank*> back to the <*Bank*>. This could be interpreted as not knowing where to start. However, I argue that Emily did not start with a null conceptualization of <*Industry*>. Lombardi & Danielson (2021) emphasize that for conceptual change to occur, the learner must start from *some* prior conceptualization, albeit small. I believe that Emily understood what the term meant from an entirely different context. Her frequent changes to the concept reflected a significant amount of cognitive work, and realizations of its conceptual complexity, as she tried to understand the sub-concept in this new context.

5.2.1 - Summary: Learner's Patterns of Change

Emily exhibited some interesting patterns of change, one of which seemed to continue to assimilate and equilibrate as her former and new conceptualizations combined. The patterns were traceable throughout her data collection episodes. They involved both her interviews and her uses of the C^3M_{YC} app. Notably absent from Emily's research experience was any instruction on conceptual organization. Unlike with the reading condition, no relationships were suggested in the app except for the categorical distinction between main concepts and sub-concepts. Therefore, any patterns of change were affected only by Emily's existing knowledge and her further engagement of sources, be they physical (e.g., books), digital (e.g., websites), or personal (people). All learners make subjective choices when it comes to conceptual change in terms of information quality, quantity, and timing. The epistemic thresholds that Emily employed were not determined in this work. Neither was the extent to which she employed "cold", rational conceptual change and/or "warmer", attitudinal judgements to advance her knowledge. Nonetheless, she seemed to make careful and fruitful epistemic choices which enhanced her understanding of a number of the climate change science sub-concepts used in the digital app.

5.3 - Other Evidence of Learners' Conceptual Growth

The degree to which study participants learned about climate change science was of preeminent importance in this work. Besides the digital app, I employed several other methods to collect evidence of this growth. Of these, the section of the interviews related to the NGSS was arguably the most fruitful. NGSS interview questions were coded two ways: topical argument justification, and science-supported concepts. Little change was found between the three interviews in terms of climate change concepts. However, in terms of topical justification, irrelevant responses decreased by more than half. Concurrently, robustly justified responses nearly tripled. A case can made for learning based on this line of questioning, given more data and a cleaner articulation of the differences between basic justification and robust justification. It should be noted that the improvement in these numbers occurred after a delay of three weeks, which means that other factors could have influenced the gains.

Participants' responses to the NGSS questions, as mentioned earlier, showed small gains in terms of scientifically supported conceptualizations. The main reason for this was that >83% of participants mentioned no climate change conceptualizations at all. A reduction in null responses was expected between the first and second interviews due to topical priming, but this did not occur. Two possible reasons for this are question framing and participants' very early formation of connections between concepts. The NGSS questions focused on the central themes of the respective NGSS sections and thus were quite general. Because of this generalization, it may have been difficult for participants to connect specific climate change science causal agents and their impacts. This is substantiated by many participants who expressed that they had seldom or never thought about climate change. In terms of conceptual connections, this would have an obviously negative effect.

On a positive note, the NGSS questions yielded an uptick in reasoned and justified responses from the participants. These responses are distinguished from those in the prior paragraph in that they justify the participant's response to the topical question, rather than mention a held climate science conception or common misconception. Participants provided responses that were coded as "Y-basic" and "Y-robust" responses 58%, 54%, and 61% in their pre-test, post-test, and delayed-post-test responses, respectively. The decline from pre-test to post-test might have been due to overly similar question framing. The questions in the post-test question set were reframed (see Appendix D) from those in the pre-test. However, given that the two sets were asked within 30 minutes of each other, there may have been a fatigue factor in the decline. The rebound in the delayed-post-test was encouraging, though an increase in unsupported "No" responses to 35%, up from 30% in the pre-test, is concerning.

On what is perhaps the first occasion where children have been asked attitudinal questions *a la* opinion surveys conducted by the Yale Program on Climate Change Communication (YPCCC) (Yale_climate, 2020), participants, compared to adults, exhibited much higher acceptance of the science, higher levels of concern about risk, and higher inclination to act. As was shown earlier in Figure 33, participants' science alignment on most questions rose or stayed consistently high. Only on the question about leadership did their opinions wane. Given the newness of the questions to this age group, it is very likely that the participants were surprised by them the first time they were asked and thought more about them later. The fact that most participants' attitudes increased with successive surveys is very encouraging and hints at their inclination to learn more about the science. In terms of the overall trajectories of learners' attitudes in a stepwise manner across the three interviews, the results (see Table 26) are, again, very encouraging. Table 26 reflects, on per-question and per-participant bases, exponential positive change. “Same” indicates linear change (e.g., “Yes” responses in all three interviews), whereas “Gain" indicates exponential positive change (e.g., “No” in the first and second interviews, and “Yes” in the third interview), and “Loss” indicates exponential negative change (e.g., “Yes” in the first two interviews, and “No” in the third). The abundance of “Same” trajectories in Table 26 means that most participants’ responses were very high and stayed that way or went even higher. Changes in trajectories were few (either “Gain” or “Loss”) and were balanced. These are remarkably positive findings, though that there was a small number of participants.

The questions inspired by the YPCCC produced some encouraging attitudinal trends across the three interviews, all of which contrasted dramatically with YPCCC’s adult opinion data. By themselves, the attitudinal data cannot be counted as learning gains. However, I propose that a complex association between types of rational and attitudinal information may be at play which *would* constitute learning. The participants said in their responses that they had never thought before about many of the questions that were asked. It is also clear from their responses that few learners in this cohort were intrinsically motivated to learn about climate change. I argue that the attitudinal questions about topics of climate change harm, learning in school, and leadership, could kickstart intrinsic motivation to learn about the science. Merely by asking the attitudinal questions, the participant might be more inclined to learn about climate change science in response to perceived hints of personal and near-term harm.

Some of the most interesting responses came from self-descriptions of gameplay. Some of the participants expressed ways of thinking that, while not constituting climate change science learning, have been shown to be conducive to topical learning. For example, Participant 722960 said “…[given the relationship between <*Environment*> and <*Farming*>,] you could choose which you thought was more, and you have to think about it, like really think about it, to see what certain aspects of something can affect the other." Their response indicated they were starting to understand the complex systems nature of climate change. They realized that one change can precipitate changes in a number of other parts of the system (Shepardson, Niyogi, Roychoudhury, & Hirsch, 2012). This response could also be viewed as epistemically sophisticated in that it builds on the knowledge complexity dimension (Schommer, 1990; Burr & Hofer, 2002). Clearly, an epistemic perspective of conceptual isolation and simplicity does not work for SSI's nor complex systems. Learners who utilize such epistemic practices with personally relevant topics have been shown to continue their pursuit of knowledge as the practices bear fruit (Ke, et al., 2020). Therefore, a form of learning occurred that was a precursor to the learning originally envisioned by this work.

CHAPTER 6 - CONTRIBUTIONS, LIMITATIONS, AND FUTURE WORKS

In the first chapter, I said this dissertation was indirectly about a culture clash. In hindsight, I can honestly say that I didn't resolve the clash. Neither perspective "won". However, both the scientific and the social aspects of climate change learning held prominent roles in this work, and they will continue to do so. To do otherwise would seriously degrade the value of this line of research. Rather, what educators and researchers need to do is acknowledge that both "camps" exist in every learner. Their decidedly nontrivial goal is this. They need to understand the individual learner's unique blend of perspectives as they attempt to foster better alignment between the learner's conceptual thinking and experts' currently held view of the science.

I am proud of the diverse Contributions from this study. I certainly hope that others will pick up some of its threads and incorporate them into their own works. Likewise, I hope the listed Limitations can save other researchers and educators time, money, and heartburn/heartache. As for Future Works, they would not be listed here without the directions pointed to by the Contributions discussed in section 6.1 and recalibrations necessitated by the Limitations mentioned in section 6.2. In a way, the entirety of this chapter is about different forms of contributions. Some offer value in their current form. Others offer value by changing the form of future works. The contributions of still others have yet to be established.

6.1 - Contributions

The work of this dissertation produced a number of contributions in which others may find value. I am especially happy with the diversity of the contributions, both in terms of what they are, but also how they came about.

6.1.1 - The app

Possibly the single biggest contribution of this dissertation is the C^3M_{YC} digital app. See section 3.2.3 for its conceptual basis, and section 3.2.4 for its implementation. Just the surface of its potential value has been scratched. The app was originally conceived to be an evaluation tool. However, it has been suggested that the app has significant potential as a teaching tool in addition to its evaluative qualities. The app provides a framework for a learner to complete a semi-structured network diagram, a concept map, from a set of terms. It records participant interactions in real time, and can be used by anybody (9-year-olds were the minimum in the study), with any set of terms, in person or from anywhere over a network. It is a very equitable tool, and its basic structure lends itself to a range of educative settings including formal classes, after school programs, teacher workshops, and museums.

The app is a contribution in the form of a research instrument devoted to the study of conceptual learning in youth. It just happens to be geared toward climate change at present. The app's source code is licensed under a Creative Commons Attribution-NonCommercial-Share-Alike International license, which means that I don't care who uses the app or what they build from it as long as they cite its developers (Patrick Moore and me) and don't financially gain from its use, just as I don't.

6.1.2 - The app data repository

The app data repository should not be confused with the app proper (see the prior section). The app and the repository are only related when a participant session with the app is active, collecting and structuring data, transferring data to the repository, or retrieving a matched prior session from the repository for the same participant (see section 3.2.5). After an app session ends, the data repository and its infrastructure wait patiently for access requests.

The app data repository is a cloud-based, 24/7 on-demand, SQL database which Amazon Web Services (AWS) maintains, and I own. At the present, it is only accessible by the app developer, Patrick Moore, and me. It is web accessible, given the right access credentials, and a SQL database access tool such as PGAdmin. Such standalone access is independent of the app. The repository contains no information which could be used to identify a participant.

The data repository is structured at present to support only this dissertation study and the app in its current state. As such, the structure includes fields that remain constant during a participant session like, [*session_date*], [*session_start_time*], [*session_ID*], and [*participant_ID*]. Other fields many instances of per-sub-concept data such as [*associated_main_concepts*], [*relationship_direction*] and [*degree_of_confidence*]. Most of the tables in this dissertation were produced from data from queries to the app data repository.

The repository currently contains one data structure, but it can contain other data that conform to the existing structure, and data conforming to other structures defined by other research projects. If another researcher wanted to use the app in its current form for their work, app data repository is usable as is. In this case, access rules might be required to keep administrative accesses separate for the respective investigators. Commingling data between investigators would need to be handled before data collection and with the approval of the investigators' respective institutional review boards. Suppose, on the other hand, another researcher wanted to conduct conceptual research on a different SSI, such as evolution, with their own study cohort. Only an additional data structure, like that for climate change data but containing the main and sub-concepts for the evolution study, would be needed.

The app data repository is a contribution to future research activities at the intersection of youth and SSIs. It is most important for youth to be engaged in SSI discussions and actions, since they will likely be included in SSI impacts on society in their lifetimes. A shared data repository such as this will hopefully facilitate more research into SSIs and children.

6.1.3 - Experts' consensus on sub-concepts

Experts matter. In this work, experts matter in terms of what they think and what they produce. Large teams of climate experts produce the annual and multi-annual reports on climate, how it affects the world, and what people should do about it (see section 3.1.2). To produce these reports, there must be consensus, which the scientists have. I discuss climate domain experts and their 97% consensus on the reality of climate change, its anthropogenic sources, and humanity's ability to (still) do something about it in section 2.7. What is unique, however, is that experts who participated in this work did something extremely powerful because they did it exactly the same as the cohort of young learners. They used the app and made decisions about how the set of sub-concepts related to the main concepts. What this produced was an expert consensus of the sub-concepts in the app. Every youth construction of the concept map was mathematically compared to this experts' configuration. Such a comparison is invaluable to learners, researchers, and educators.

Using the same tool to compare middle-school-age learners and world class climate researchers has never been done, from my review of the literature (Toedte, 2020). The experts' consensus configuration of the C^3M_{YC} concept map is kept as part of the app data repository and is updated as new experts weigh in with their configurations. Among adults, knowledge of the existence of an expert consensus is crucial "gateway information" for learning and acting on climate change (Ding, et al., 2011; Lewandowsky, Gignac, & Vaughan, 2012; van der Linden, Leiserowitz, Feinberg, & Maibach, 2014; van der Linden, Leiserowitz, Feinberg, & Maibach., 2015; Cook, et al., 2016; Hamilton, 2016).

The contribution of experts' consensus data specific to the C^3M_{YC} concept map enables, for the first time, studies of "gateway effect" and other phenomena in children related to climate science consensus.

6.1.4 - Children's responses to the Yale questions

The Yale questions were a group of questions included in this study's participant interviews (see section 4.4.1.5). The questions were binary yes-no questions modeled after survey questions used by the Yale Program on Climate Change Communication (YPCCC). YPCCC surveys are conducted nationally on an annual basis with adults (Yale_climate, 2020). The questions are on topics including the nature of climate change, impacts of climate change, and responses to climate change, all of which were included in the interviews with this study's cohort of participants.

These interview responses constitute, to the best of my knowledge, the first-time children have been asked these kinds of attitudinal questions. The value of asking these questions is they indicate participants' knowledge and inclination to act, both of which are precursors to climate-conscious behavior (Frick, Kaiser, & Wilson, 2004; Heimlich & Ardoin, 2008; Otto & Pensini, 2017). Responses to Yale questions were used two ways in this dissertation. First, they individually helped explain responses to other methods. For example, a participant answering "No" to a Yale question (e.g., the one about climate harming animals and plants) may be less likely to relate <*People*> to <*Climate*> and <*Weather*> in the app. To do otherwise might implicate <*People*> in <*Greenhouse effect*> which has negative impacts on <*Animals & plants*>. The second way Yale questions are used in this dissertation is they collectively helped the research team understand relationships between changes in science-aligned attitudes with the Yale questions and conceptual agreement using the app. They tend to improve or regress in tandem.

Children's responses to the Yale questions are an important data contribution for researchers interested in youth and climate change science learning. With adults, the YPCCC opinion surveys reveal many of the attitudes and dispositions that make climate change difficult to teach. Reformulated as they were for the young participants in this study, the Yale questions are easy to incorporate, easy to tabulate, and can serve as bases for semi-structured interviews. Section 4.3.1 explored regional and cultural differences between participants from West Virginia and central Illinois. Whether such differences are significant for children learning about climate change is an open question. The Yale questions are an important contribution for answering it.

6.2 - Limitations

Perhaps the most significant limiting factor in this study was it had too few participants to achieve statistical significance. At the same time, I make no apologies for being underpowered. It was not practical to conduct a larger study in terms of participants, execute the same breadth of instruments, and process and analyzed a larger volume of data in any tractable timeframe. This study produced a number of promising but inconclusive results. As a result, more robust extensions of the work started herein will be the subject of future studies.

A second limitation of this dissertation was it was heavy with 'science-y kids'. An element of the parent survey asked what were the child's favorite school subjects, choosing among art, science, social studies, language arts, physical education, mathematics, and music. Science was the most frequently chosen subject at 81%, followed by art at 64%, then social studies and physical education at 42%. Such a high level of interest in science among the cohort was not surprising, given that the main promotional channels this study used were predisposed to science and math. So, to some degree, engaging kids already interested in science is "preaching to the choir". The hope is that this work impacts *all* middle-school-age students, regardless of their preferred subjects. Involving more children, especially those who do not necessarily like science, is planned for follow-on research projects.

As with the prior study that was overly homogeneous, this cohort was very white (85%), highly educated (67% master's degree and higher), and politically liberal (49% liberal compared to 24% conservative) group. Type of community was balanced (46% rural, 54% suburban). Since a secondary interest of this study was impacts of socio-cultural learning in the context of climate change science, a better demographic mix could have produced better results. In the future, with some studies that are planned, it will be essential to attract a study group that is not just larger, as mentioned earlier, but one that is more balanced demographically and socio-culturally

Time was a limiting factor in this study design in that it prevented exploration of serendipitous things that the participants did or said. We were conscious of the practical limits of available time for the participants and their families, so we limited data collection episodes to an hour. An example of something we were unable to check out in detail was "Cara's" behaviors (see section J.1). I wanted to ask about her traversal of the sub-concepts. Her pattern of revisiting some sub-concepts, but not others, was very interesting. However, time, and the desire to keep data collection episodes as comparable as possible did not permit going down such "rabbit holes”. What was her thinking at particular moments? Her answers could have been meaningful from a conceptual change standpoint and possibly even from a metacognitive standpoint.

Finally, given that this study occurred during the COVID-19 pandemic, Zoom videoconferencing played a noteworthy role in how the work was conducted. I argue that Zoom was more of a benefit than a limitation for this study (see section 3.2.12 for an in-depth discussion about how Zoom was used). Zoom meetings were conducted to collect data from early February to late March of 2021. I mentioned earlier that, for some of the children, data collection was “just another Zoom meeting” and they were tired of it from both school and home. Also, it became increasingly difficult to schedule Zoom data collections with participants in March due to improved weather. A lot of children’s activities were restarting after a one-year hiatus due to COVID-19 and public health protections. Outdoor music rehearsals, sports, outdoor club activities, and planned hikes were beginning to populate participants’ calendars.

6.3 - Future Works

I see future work stemming from this study falling into three categories: “Fixes”, Continuing Operations, and Other Research Directions.

6.3.1 - “Fixes”

“Fixes” refers to aspects of the study which could be improved in design or function.

Two fixes relate to the C^3M_{YC} app. The first fix has to do with the statistical summary shown to the participant between their initial and final configuration. It turned out that session matching based on the participant’s identification number did not work properly, and instead returned two copies of the current initial configuration. The second fix relates to the wording of the “important relationship” question asked after each sub-concept placement. The question asks about the importance and direction of the relationship between main concept and sub-concept. It was hard to explain importance and directionality to participants. Three examples of how a concept might be important to another were told to participants, but many other flavors of “important” are possible. A better way of asking the participant what they think about the nature of the relationship is needed. While providing a type-in response block would certainly produce more diverse responses and be more difficult to assess, it would be more in line with one of the main goals of this work…to find out what the participant genuinely thinks. This approach would also be more in line with the classic design of concept maps.

One last “fix” has to do with the NGSS-related portion of the interview protocol. Given the self-imposed constraint of one hour per data collection session, only one question was asked per NGSS topical area per interview. In hindsight, this was far too limiting an approach to determine if a child had a grasp of a concept related to climate change. What is needed is a redesigned and expanded set of NGSS questions. It is important, in my opinion, to have a way of assessing participants’ conceptual growth and science learning, which is rooted in educational standards, non-standard as they may be. The limitations of the NGSS in terms of formal adoption by states and the lack of direct topical knowledge depth have been noted (see section 2.1.2). However, it has also been shown that robust assertions of *indirect* topical knowledge (e.g., historical climate change, confluences of humans and nature, etc.) can be made (see Table 2). More thought needs to go into the design of the NGSS portion of the interview as well as how/whether it should be in the same study design as the app.

6.3.2 - Continuing Operations

This section pertains to aspects of the study that were fruitful, well-functioning aspects of the work, which I would like to get more utilization, either by me or other educators and researchers.

Educators and researchers interested in the current build of the app may contact me directly for details. To maintain data standards, I will write a user's guide. One purpose of the user's guide is to foster commensurability among data collected by different researchers and educators.

I also intend to build a web site which will include the following.

- Promotional materials related to the app's purposes and community use
- Document licensing, terms, and conditions
- A list of build versions and a version history
- A discussion for vetting educators and researchers who are interested in using the app

Continuing to make the app available to the community goes together with continued access to the app data repository. Hopefully, the existence of the repository will encourage more research and educational applications in this topical space. Metadata tags for researcher identification, app build version, and study details may be added to help make the repository a community resource.

The app data repository will stay open for the foreseeable future. The repository is accessible directly to any credentialed user through Amazon Web Services and indirectly through the app. At present, Patrick Moore and I are the only persons who has credentials for direct access. However, anybody can run the app and have their data stored in the repository.

6.3.3 - Other Research Directions

Following are several future research projects which interest me.

6.3.3.1 - An Exploration of Children's Attitudes toward Climate Change Using Yale Opinion Maps

RQ - To what degrees do children hold scientifically aligned attitudes about the existence, sources, harms, immediacy, and actions related to climate change?

As discussed in section 4.4.1.5, participants' responses to the Yale attitudinal questions were much more aligned with the scientific perspective on climate change than those from adults surveyed by the YPCCC. My suspicion that children had never been asked these questions was confirmed by the director of the YPCCC (A. Leiserowitz, personal communication, July 1, 2021). Because of this, as well as the magnitude of the difference in responses between the two groups, I plan to revisit this question set. I plan to separate these 11 questions from the rest of the interview protocol and ask them with a statistically robust number of participants. If results from an expanded study retain the higher level of scientific alignment, this would imply children hold a smaller plausibility gap (Lombardi, et al., 2013; Lombardi, et al., 2016) regarding climate change and thus possess a greater potential for conceptual change (*Ibid*.). Furthermore, knowing more about children's attitudes toward climate change in areas such as threat perception and scientists as epistemic sources, would have additional implications for research and practice.

6.3.3.2 - Existence of Climate Change Consensus "Gateway" Effect in Children

RQ - To what extent does mere awareness of the existence of scientific consensus about climate change affect middle-school-age children's conceptualizations.

Experts contributed to this dissertation in two ways. First, they contributed directly by using the C^3M_{YC}, which led collectively to the experts' consensus configuration. Second, they contributed indirectly through large science reports that I used to inform design aspects of the app and interview. As mentioned in section 6.1.3, climate experts' consensus exerts a "gateway" effect on adults which facilitates knowledge building and increases propensity to act. I plan to conduct two studies to explore whether this phenomenon exists in middle-school-age children. As with the Yale questions, I am not aware that climate change consensus gateway effect has ever been studied with any but adult cohorts. In the first study, I plan to explore the simple existence of gateway effect. Two conditions will be developed which reuse portions of the control (text) condition from this dissertation. In both conditions, children will first read the text and then use the app to arrange the concepts. No interviews will be conducted with either condition. The experimental condition will include a short introduction to climate change consensus. The text will then be attributed to the consensus community. Thus, the only difference between the conditions will be the absence or presence of the consensus discussion and the attribution.

Consensus Study 1:

Control:	Read text→Arrange C^3M_{YC}
Experimental:	Consensus→Attribution→Read text→ Arrange C^3M_{YC}

6.3.3.3 - Magnitude of Climate Change Consensus "Gateway" Effect in Children

RQ - What differences in middle-school-age children's conceptualizations of climate change are produced by different granularities of scientific consensus knowledge.

If gateway effect in children is shown to exist in the first study, a second study is planned. This second study will use the C^3M_{YC} tool, just as the first one did, but it will not use the text. The power of consensus gateway knowledge will be explored using three conditions involving different levels of information about experts' consensus: no information at all, the short introduction to climate change consensus from the prior study, and verbose information consisting of the short introduction plus a discussion of experts' consensus C^3M_{YC} configuration.

Consensus Study 2:

Control: Arrange C^3M_{YC}

Experimental #1: Consensus→Arrange C^3M_{YC}

Experimental #2: Consensus→Attribution→Experts' config→Arrange C^3M_{YC}

Like previous studies of gateway effect, this one will use the power of consensus knowledge in terms of percentage agreement on issues of climate change's existence and anthropogenic sourcing, However, unlike earlier studies, this one adds instances of specific topical knowledge. I believe combining awareness of consensus with topical knowledge directly from members of the consensus body is a unique approach, based on my reviews of the literature.

6.3.3.4 - Exploring connections between Children's Socio-psychological Dispositions and Climate Change Conceptualizations

RQ - In what ways do children's responses to the C^3M_{YC} tool indicate possible engagement of socio-psychological dispositions which impede topical science learning.

I would like to conduct a broader study exploring the extent to which young learners defend their climate change misconceptions by exercising socio-psychological dispositions. A similar, albeit small scale and inconclusive, exploration of this question appeared in section 4.3.1. It featured small groups of participants from rural regions of the United States where coal mining and agriculture, respectively, are dominant sources of employment and family income. In these communities, families often work for consecutive generations at these businesses and thus the work becomes a key component of local culture and individuals' worldviews. Participants from the respective areas expresses significantly *weaker* relationships existed between the respective dominant industries and environment. In doing so, participants may be resisting a negative connection between the local employers and harms to climate/environment. This could be explained by multiple theories including “backfire effect” (Nyhan & Reifler, 2010), motivated reasoning (Kunda, 1990), and cultural cognition of risk (Kahan, et al., 2011; Kahan, et al., 2012). All such theories involve pushback, rejection, or control of a perceived threat or risk. While political orientation is the strongest correlate with scientifically aligned climate change belief (Kahan, 2015), learners defense of personal attributes including religious beliefs, rurality, and education level can impede climate change science learning. If the aforementioned dispositions exist in children, educators and researchers need to incorporate this awareness into their educative designs.

6.3.3.5 - The Role of a Digital App in Preparation for Future Learning for Climate Change Science

RQ - To what extent does a digital app prepare learners to learn about climate change science?

It has been suggested that the C^3M_{YC} app can serve more than one role in educational research studies. Its role as an assessment tool has been amply demonstrated in this study. However, it also has potential as a teaching tool. Many of this study’s participants said they had never thought about some of the concepts, not been asked about relationships between concepts, nor been asked about confidence in their thinking. Socio-scientific issues, complexly structured topics, and topics undergoing rapid change make it difficult for the novice learner to know where to start learning. These sorts of problems lend themselves to a form of meta-learning called Preparation for Future Learning (Bransford & Schwartz, 1999; Schwartz, Bransford, & Sears, 2005), or PFL. PFL is a novel form of information transfer that is less focused on mapping an earlier learning scenario to a new one, and more focused on the *nature* of the topic being learned.

PFL is especially suited to situations where the learner is starting from sparse conceptual bases on the topic. Such is the case with climate change science.

The following research design seeks to understand whether and how much PFL is derived from the reading and the app, respectively. The difference between the two conditions is the order the learner is exposed to the methods. In the first condition, the learner is first exposed to a structured introduction to the interconnections between climate change concepts. In the second condition, the learner is first exposed to the concepts without structure. They are also required to think about the nature of the concepts, draw relationships between them, and then express their confidence in the asserted relationships. They may also be thinking about what they don't know that would assist future learning. Bransford & Schwartz (1999) stress the importance of metacognitive processes such as monitoring, reflecting, and strategizing in PFL. In this future work, young learners, regardless of condition, are operating with a lack of *a priori* knowledge and structure. A higher level of metacognition at the outset is arguably required with condition #2 to create structure. If PFL is activated by the app, it is expected that condition #2 participants' levels of agreement with their second arrangement of the C^3M_{YC} will be higher than those of participants in condition 1. Furthermore, varying the delay prior to the second use of the app would provide valuable information for educators about the durability of knowledge gains involving PFL.

Experimental #1: Read text → Arrange C^3M_{YC} (delay) Arrange C^3M_{YC}
Experimental #2: Arrange C^3M_{YC} → Read text (delay) Arrange C^3M_{YC}

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APPENDIX A - MIDDLE-SCHOOL-AGE LEARNERS’ CLIMATE CHANGE MISCONCEPTIONS

This is the full-size final table of sources of climate change misconceptions from Toedte, 2020, p.29.

Study	Misconception Data																				
abbrev-iation	a	b	c	d	e	f	g	h	i	j	k	l	m	n	o	p	q	r	s	t	u
B&S, 1993	X	X	X	X	X							X	X							X	X
F, ea, 1993		X										X								X	
K&C, 1993		X	X																		
B&S, 1994		X	X																		
B&S, 1997		X	X	X																	
R, ea, 1997		X		X																	
M&S, 1998	X	X				X	X	X													
K&C, 1999		X	X																		
P, ea, 2001		X	X																		
D, ea, 2004		X	X									X									
L, ea, 2007		X	X																		
B, ea, 2008		X	X																	X	
S, ea, 2009								X													
G, 2011		X	X			X								X							
G&Y, 2011		X													X						
P, ea, 2011		X	X	X					X												
V&L, 2011		X																			
B, ea, 2013		X	X									X									
D&S, 2013																					
L, ea, 2013	X	X				X				X											
B, ea, 2014																					
B&K, 2014																					
S, ea, 2014																					
P&L, 2015			X					X								X					
V&L, 2015	X		X																		
H, ea, 2016		X																			
M, 2016	X		X																		
B, ea, 2017		X	X	X				X			X	X	X				X	X	X		
	6	20	16	5	1	3	1	4	1	1	1	5	2	1	1	1	1	1	1	3	1
	21%	71%	57%	18%	4%	11%	4%	14%	4%	4%	4%	18%	7%	4%	4%	4%	4%	4%	4%	11%	4%

Full size final table of sources of climate change misconceptions (Toedte, 2020, p.29) continued.

u	v	w	x	y	z	aa	bb	cc	dd	ee	
X											9
											3
	X										3
											2
											3
											2
											5
											2
		X									3
											3
											2
		X									4
				X	X						4
											4
											2
											4
											1
											3
											0
											4
						X		X			2
			X					X			2
							X	X			2
							X	X	X	X	7
											2
											1
											2
											10
1	1	2	1	1	1	1	2	4	1	1	
4%	4%	7%	4%	4%	4%	4%	7%	14%	4%	4%	

Key
...is caused by...
a ---> intensifying sun's rays
b ---> ozone holes
c ---> pollution
d ---> using CFCs
e ---> trapped sun's rays
f ---> volcanoes
g ---> straighter earth rotational axis
h ---> a "dome" over the earth
i ---> earthquakes and tsunamis
j ---> changes in earth's orbit
k ---> artificial fertilizers
l ---> nuclear power production
...causes...
m ---> more incidence of skin cancer
n ---> inceases in CO2
o ---> more incidence of food poisoning
p ---> ozone depletion
q ---> more heart attacks
r ---> earthquakes
s ---> falling sea levels
...is improved by...
t ---> using unleaded petrol
u ---> recycling
v ---> methane production
w ---> using coal and petrol vs nuclear
x ---> hybrid car usage
...is not related to...
y ---> CO2 concentrations
z ---> amount of driving
aa ---> human activity
bb ---> differences in space and time
...miscellany...
cc - is comprised of unrelated factors
dd - involves a list of well-known GHGs
ee - is the same as weather

APPENDIX B - PARENT CONSENT AND SURVEY

This is the parent consent and survey that was used with Qualtrics from 2021.01.10 thru 2021.03.05.

English

SURVEY INSTRUCTION

We are from the College of Education at the University of Illinois and we are conducting research about conceptual change learning with middle-school-age participants.

By completing this survey, you are asserting that you are the parent or guardian of a child 9-13 years of age, and you think they would be interested in participating in this research. This survey is a necessary precursor to your child's eligibility to participate.

Children's participation consists of two parts. The first part takes about an hour and the second part takes about 30 minutes. Each part consists of playing an educational game and answering questions about the game play. All participation will be conducted online via Zoom. If your child meets the age requirements, is selected to participate, and completes both parts of the study, they will be eligible to win one of several $100 Amazon gift cards.

Any sharing or publication of the research results will not identify your child by name. The data collected during the study only be used by the researchers for research purposes. The only exception to this is laws and university rules that ensure that research is being conducted in a safe and ethical way.

There are no known risks to participation in this study, beyond those risks that exist during normal activities. Your child's participation in this project is completely voluntary. In addition to your consent, your child will also be asked to assent to participation. This said, your child has the right to withdraw their assent and you have the right to withdraw your consent at any time for any reason. If, at any time, you feel you or your child have not been treated according to these descriptions, or if you have any questions, concerns, complaints, or want to offer input, you may call the University of Illinois research bureau at 217-333-2670 or e-mail them at irb@illinois.edu and reference study #18393.

Please respond to the following two questions. If you respond 'yes' to both questions, you will be asked to respond to a short survey related to the research. Upon completion of the survey, your child will be entered into the pool of eligible participants. Otherwise, if you respond 'no' to either question, we thank you for your time and wish you well.

consent_question

Do you give consent for your child to participate in the research project described earlier?

yes ◯ no ◯

audio_question

Do you give consent for your child to be audio recorded during the interview parts of their participation? Their audio recordings will be transcribed, identified only by random number, and used only for research purposes.

yes ◯ no ◯

child_demographic_questions

What best describes your child's gender?

◯ male
◯ female
◯ [ ] other (specify)

What best describes your child's school?

- public
- private
- home
- ______ other (specify)

What is your child's grade level?

- 3rd grade
- 4th grade
- 5th grade
- 6th grade
- 7th grade
- 8th grade
- 9th grade
- ______ other (specify)

What is your child's age?

- 8 years old
- 9 years old
- 10 years old
- 11 years old
- 12 years old
- 13 years old
- 14 years old
- ______ other (specify)

What are the topic areas your child especially likes to learn? (check all that apply)

- art
- science

- ☐ social studies
- ☐ language arts
- ☐ physical education
- ☐ [ ] other (specify)

What are good information sources for your child's science learning? In other words, which of the following would you recommend to your child for their science learning? (check all that apply)

- ☐ talk to family members
- ☐ talk to friends
- ☐ read textbooks
- ☐ talk with others over social media
- ☐ talk to educators
- ☐ talk to religious leaders
- ☐ search the Internet
- ☐ talk to researchers
- ☐ read science journals
- ☐ watch television channels
- ☐ [ ] other (specify)

parent_demographic_questions

What best describes your race?

- ○ white
- ○ black
- ○ Hispanic / Latin(o/a)
- ○ Asian / Pacific islander
- ○ native American
- ○ multi-ethnic

- ◯ [ ] other (specify) or prefer to not answer

What is your highest education level?

- ◯ high school graduate
- ◯ associate's degree
- ◯ bachelor's degree
- ◯ master's degree
- ◯ JD, MD, or PhD
- ◯ [ ] other (specify) or prefer to not answer

Which of the following best describes your political attitudes?

- ◯ strongly liberal
- ◯ liberal
- ◯ slightly liberal
- ◯ slightly conservative
- ◯ conservative
- ◯ strongly conservative
- ◯ [ ] other (specify) or prefer to not answer

community_demographic_information

What is the postal code of your home community?

[ ]

Which one of the following best describes your home community?

- ◯ rural
- ◯ suburban
- ◯ urban

Which of the following are major employers in your home community? (check all that apply)

- ☐ tech companies
- ☐ mining & materials
- ☐ retailers
- ☐ agriculture & farming
- ☐ energy producers
- ☐ transportation
- ☐ government
- ☐ [ ] other (specify)

participation_summary

If your child is selected for the study, we will contact you during the months of January, February, or March in 2021 to schedule their participation.

Please provide an email address or phone number for us to contact you if your child is selected.

[ ]

Please enter any comments, suggestions, or questions you have related to this survey.

[ ]

How did you find out about this research opportunity?

Thank you for your time!

Click the right arrow below to record your responses and end the survey.

Powered by Qualtrics

APPENDIX C - INSTITUTIONAL RESEARCH BOARD APPROVAL

ILLINOIS

OFFICE OF THE VICE CHANCELLOR
FOR RESEARCH & INNOVATION

Office for the Protection of Research Subjects
805 W. Pennsylvania Ave., MC-095
Urbana, IL 61801-4822

Notice of Exempt Determination

January 8, 2021

Principal Investigator	H. Chad Lane
CC	Ross John Toedte
Protocol Title	*Social Sourcing and Impacts on Children's Early Knowledge about Socio-scientific topics*
Protocol Number	18393
Funding Source	Unfunded
Review Category	Exempt 1
Amendment Requested	Adding survey
Determination Date	January 8, 2021
Closure Date	December 5, 2022

This letter authorizes the use of human subjects in the above protocol. The University of Illinois at Urbana-Champaign Office for the Protection of Research Subjects (OPRS) has reviewed your application and determined the criteria for exemption have been met.

The Principal Investigator of this study is responsible for:

- Conducting research in a manner consistent with the requirements of the University and federal regulations found at 45 CFR 46.
- Requesting approval from the IRB prior to implementing major modifications.
- Notifying OPRS of any problems involving human subjects, including unanticipated events, participant complaints, or protocol deviations.
- Notifying OPRS of the completion of the study.

Changes to an **exempt** protocol are only required if substantive modifications are requested and/or the changes requested may affect the exempt status.

UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN
IORG0000014 • FWA #00008584
217.333.2670 • irb@illinois.edu • oprs.research.illinois.edu

APPENDIX D - INTERVIEW QUESTIONS

This is the interview protocol for NGSS-oriented, epistemic practice, and attitudinal questions.

Primary questions are in red. Additional questions are in black.

Topical area	Question theme	Question framing for pre-test and delayed-post-test	Question framing for post-test
ESS1.C: The History of Planet Earth	Knowledge about the history of Earth and what we can learn from the evidence.	Earth has physically changed over time (make gesture of a sphere). What are some examples of how it has changed? Where have the changes happened, when did they happen, and why?	If you were researching how Earth has changed over time, what would you look for as evidence? What are some things you would need to know to do the research?
ESS2.D: Weather and Climate	Knowledge about climate and weather - what is different and in common between them	How would you describe these two concepts: weather and climate? What is the same and what is different between them?	What kinds of things affect them climate and weather differently. What kinds of things affect them both?
ESS2.E: Biogeology	Knowledge about the affects of living things on the geology of the places where they live	Think about the living things in an environment. What ways that you can think of have they affected their environment over time? What about environments affecting the living things in them?	Think about ways that living things and their environments affect each other. What kinds of changes in living things would you expect from right now to 100 years from now…2121? What about changes in the environment?
ESS3.C: Human Impacts on Earth Systems	Knowledge about humans' unique relationship with our environments	Are people a special case of "living thing" when it comes to our relationship with the environments in which we live? Is our relationship different from fish in the ocean or other mammals on land? Why?	What are some situations where the relationships between people and our environments are helpful? What about harmful? How do you decide if it's helpful or harmful?
ESS3.D: Global Climate Change	Knowledge about the affects of climate change on living things and how to mitigate them	As Earth's average surface temperature increases, how do you expect it to affect people? What about animals and plants? What can be done to change the impact?	What are some things that people are doing that are making the average surface temperature of Earth rise? Is there something that people can do to make temperatures level off or decrease?
LS2.C: Ecosystem Dynamics, Functioning, and Resilience	Knowledge about environments and how they affect the living things in them	What are some physical aspects of environments that change over time? How do physical changes in environments affect the things that live there?	Consider two aspects of an environment: its physical characteristics, and the living things in it. When the environment changes, how do living things in the environment respond?
LS4.D: Biodiversity and Humans	Knowledge about the relationships between humans and environmental resources	Have you every heard about something called an ecosystem? (It is the collection of plants and animals that live in an environment.) Can you tell me what sorts of changes might happen in ecosystems? How would those changes affect humans?	Have you heard about something called diversity? (Explain if not.) Can you tell me what diversity in environments means? Do you have any ideas about how diversity happens?

Topical area	Question theme	Question framing for pre-test and delayed-post-test	Question framing for post-test
Epistemic cognition - frequency of seeking/receiving information	Participant's level of interest in the topic as indicated by frequency of seeking info and depth of questions	How often do you communicate with people about climate change? What ways of communicating do you use?	How often do you ask people or look online to learn things about climate change? What are the best ways you've found to do this?
Epistemic cognition - source selection	Participant's process of vetting and choosing sources of information	Can you tell me some good sources of climate change information that you've found? How did you choose them?	What do you think are some bad sources of information about climate change that I should stay away from? How did you determine they are bad? How can you tell the difference from good ones?
Fundamental domain questions based on Yale Center for Climate Change Communication	Participant's thinking about the nature of climate change	Do you think... ...climate change is happening? ...people are having a big affect on climate change? ...most scientists think climate change is happening? ...climate change is affecting the weather?	NA
Rick perception questions based on Yale Center for Climate Change Communication	Participant's thinking about who or what is at risk and the degree of risk	Do you think climate change will harm... ...you? ...people other than you? ...people living right now? ...future generations of people? ...living things besides people?	NA
Policy and action questions based on Yale Center for Climate Change Communication	Participant's thinking societal response to climate change	Do you think... ...schools should teach about climate change? ...leaders should do more than they are doing about climate change?	NA

APPENDIX E - TEXT READING (CONTROL) CONDITION

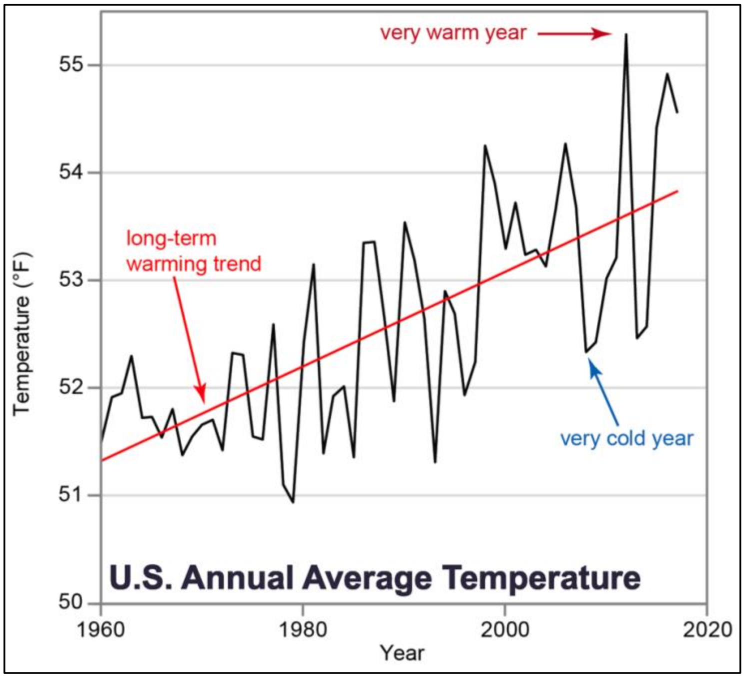
Climate, Environment, and Weather

Climate is changing. It always has. However, scientists know climate is changing more now than ever. They also know why climate is changing and how it is changing differently than before. Lastly, they know how people are playing a role in the recent changes.

First, what is climate? Scientists describe climate as the average of weather. They think of climate being for times of 30 years or more. They also think of climate in areas of multiple sizes. These include local area climate, regional area climate, and global climate. To understand climate, you have to collect a lot of data. For local area climate, you would collect data from locations around your city or county. For regional area climate, you would do it for your state or entire country. For global climate, you would do it for all of Earth.

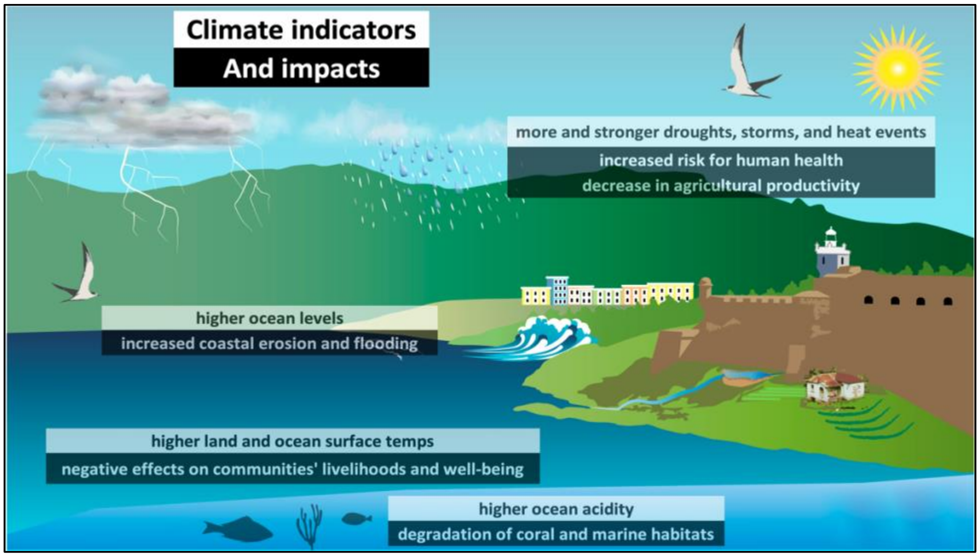
Scientists consider how climate interacts with the surrounding environment. What parts of the environment would you see in a satellite image? You would see bodies of water. You would see mountains, valleys, deserts, forests. You would see things people make and use daily. These include farming areas, cities, roads, and industrial zones. Parts of the environment interact in different ways with climate. But satellite images only show surface features. What is above and below Earth's surface are also parts of the environment. Some examples are in the land like soil and rock layers. Others are in the ocean like trenches and underwater volcanoes. Others go up miles above the land into the atmosphere.

Climate changes at multiple speeds, or rates of change, at the same time. For example, temperatures can change daily, and even hourly. Temperatures can warm or cool quickly. This is fast change. We also call this, "weather". There are also yearly changes in temperature. One example of this is seasonal change. Yearly changes produce different weather for winter, spring, summer, and fall. Finally, there are slow changes. This means temperatures change over long periods of time. "Long" means 30 years or more to climate scientists. Tracking slow changes in climate helps scientists spot trends in temperatures. It also helps them estimate future temperatures. For



This shows the annual average surface temperature for the U.S. (black line) from 1960 to 2017, and the long-term warming trend (red line). Climate change refers to the changes in average weather conditions that last over multiple decades or longer. One cold year or a few cold years in a row does not contradict a long-term warming trend, just as one hot year does not prove it. (Source NCA, 2018, Figure A5-17, p.1475) the past 200 years, temperatures have mostly trended warmer. This trend became more obvious over the last 60 years.

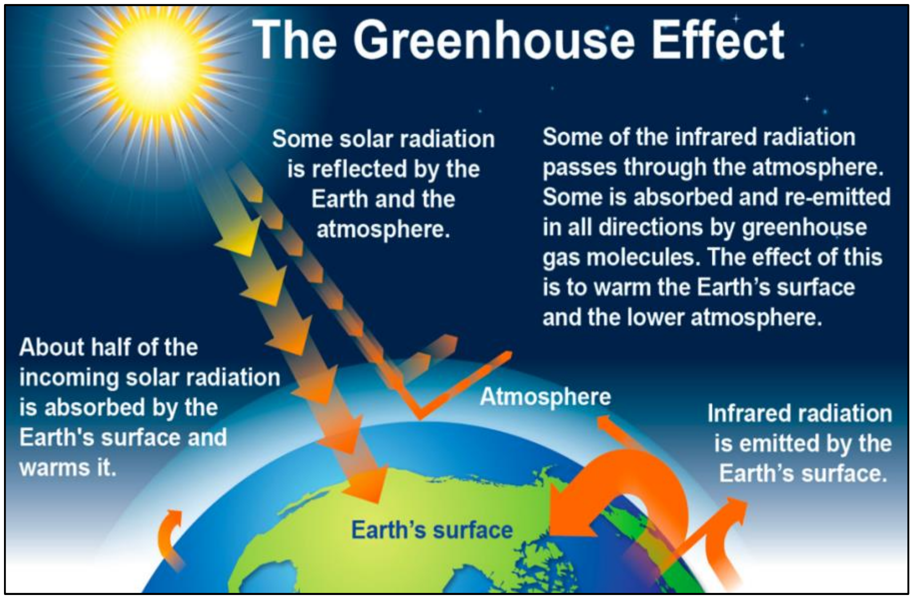
OK, then what is environment? Environment is everything you would experience if you lived in an area. This includes aspects of weather like rainfall, temperature, and humidity. Environment also includes longer term conditions. Think of rainy seasons and multi-year droughts. Environment even includes things that last for thousands of years. Mountains, valleys, rivers, lakes, and oceans are examples of this. An environment is also affected by its location. Latitude, longitude, and elevation above sea level are important. Environment also includes things that live on land and in the oceans. This includes forests, animals & plants, and people. Environments are consistent in type and location. For this reason, environments are local or regional. The Smoky Mountains in the southeastern U.S. are known for their diverse plant life. Death Valley in California is arid, hot, and below sea level. The Atlantic Ocean strongly influences the Outer Banks' environment. Chicago is an example of an urban environment.



Key indicators for climate variability and change in the Gulf coast include sea level rise, ocean temperature and acidity, air temperature, rainfall patterns, frequency of extreme events, and changes in wildlife habitats. Changes in these climate indicators result in environmental and social impacts to natural ecosystems, infrastructure, and society, including degradation of coral and marine habitats, increased coastal flooding and erosion, decrease in agricultural productivity, water supply shortages, negative effects on communities' livelihoods and on human health, as well as economic challenges and decreased tourism appeal. (Source NCA, 2018, Figure 20-2, p.818)

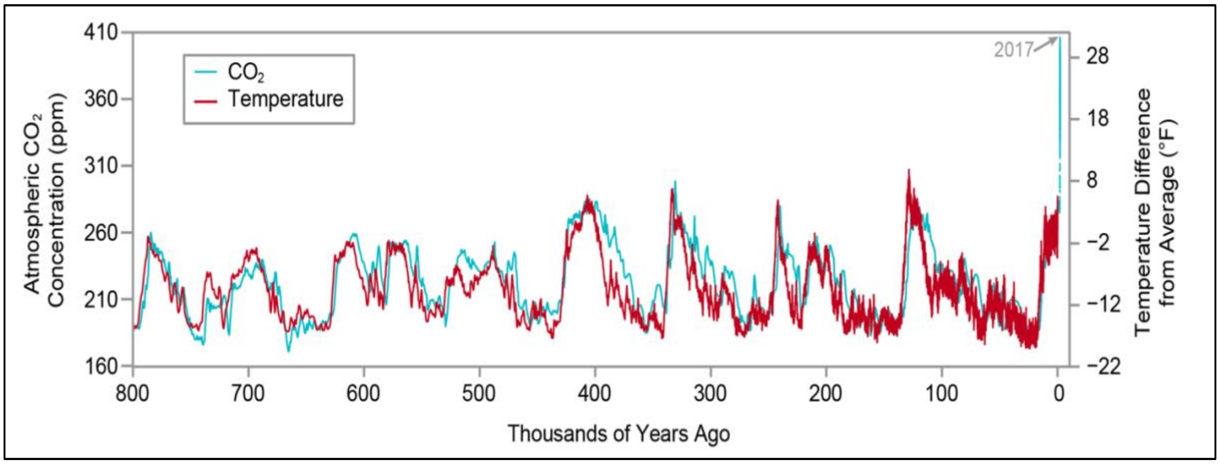
How do temperature trends affect environments? Slowly warming average temperatures make all seasons warmer. They also produce follow-on effects. Warm winter temperatures can affect animal's and plant's annual cycles. Because of this, they might go dormant at the wrong time of year. Warm winter temperatures can also cause some animals and plants to move. They might need to migrate to cooler environments. In this way, migration increases their chances of survival. This is because the new location is more habitable to them. Slowly warming average temperatures can also affect daily weather. Daily weather events include shorter term events like severe storms. They can also include longer term events such as droughts. All these events can harm the environment. Harm does not happen just to lands or oceans. Harm can come to the people, and animals and plants, that live there.

How do we know things are changing? Scientists study temperature trends. They noticed a slow but clear warming trend over the past 60 years. They also identified the cause. Temperatures have gone up because of increasing levels of "greenhouse gases". Carbon dioxide (CO_2) and methane (CH_4) are two important greenhouse gases. They get this name because they are involved in Earth's greenhouse effect. Greenhouse effect is, in some ways, like the warming that happens in a greenhouse. Greenhouse gases exist naturally. They are in the air we breathe and in our atmosphere. They come from numerous sources. Natural sources include living and dead animals and plants. They also come from geologic sources like certain rock formations. Greenhouse gases trap heat in the atmosphere. Without greenhouse effect, all of Earth would be too cold to support life. Instead, natural levels of these gases have kept temperatures stable. It has been this way for thousands of years. This has made Earth habitable for animals and plants and people. They have adapted to survive on land and in the oceans. However, scientists noticed temperatures changed a lot recently. Atmospheric CO_2 and CH_4 levels have increased 60% over the past 60 years. This has resulted in trends of warming temperatures. These trends threaten the climate to which we are adapted.



This shows a simplified representation of the greenhouse effect. Naturally occurring greenhouse gases, including carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), do not absorb most of the incoming visible energy from the sun, but they do absorb the infrared energy re-radiated from Earth's surface. This energy is then re-emitted in all directions, keeping the surface of the planet much warmer than it would be otherwise. Human activities— mostly the burning of fossil fuels (coal, oil, and gas)—are increasing levels of CO_2 and other GHGs in the atmosphere, which is amplifying the natural greenhouse effect and thus increasing Earth's temperature. (Source NCA, 2018, Figure A5-3, p.1452)

Why have atmospheric greenhouse gases increased so much recently? Scientists know the source of most of the increase. It comes from fossil fuels like gasoline and coal. Gasoline is the most common fuel for cars and trucks. Burning gasoline in engines makes cars and trucks move. Coal is often burned to produce electricity. We use electricity in our homes and businesses every day.



This shows atmospheric CO_2 concentrations (left axis, blue line) and changes in temperature (compared to the average over the last 1,000 years; right axis, red line) over the past 800,000 years, as recorded in ice cores from Antarctica. Also shown are modern instrumental measurements of CO_2 concentrations through 2017. Current CO_2 concentrations are much higher than any levels observed over the past 800,000 years. (Source NCA, 2018, Figure A5-4, p.1454)

Burning fossil fuels is a process called combustion. Combustion releases CO_2 trapped in the fuels. Once it is released, CO_2 goes into the atmosphere. CH_4 is a gas and fossil fuel that is trapped in rock formations and soils. Energy companies drill into the rock to extract CH_4. When they do this, some CH_4 leaks into the atmosphere. Farming is another human activity that releases CH_4 and CO_2. Tilling fields for planting crops or during the growing season digs up the soil. Pockets of CH_4 and CO_2 in the soil are disturbed during tilling. The gases are then released into the atmosphere.

APPENDIX F - CODING RUBRICS

These are the coding rubrics for the question groups in the interview protocol.

NGSS

For the seven NGSS questions, see where the participant's response rates in these four areas. Determine how their ratings generally fall, but if they don't provide a complete answer, or justification all parts of their answer, they must be below standard.

	Completeness - answers parts of the question in any form; perhaps not well or correctly	justification- justify the parts of their answer. Can be incorrect, but not opinion.	Accuracy - correct as far as you know	Concepts
Below standard	**N** - **not all** parts of researcher's question were answered	**N - not all** parts of the answer were justified	**N** - **not all** parts of the answer were accurate	**Miscons** - contained **only** CC misconceptions
Meets standard	**Y** - **all** parts of the researcher's question were answered	**Y-basic** - **all** parts of the answer were justified at a **basic** level	**Y** - **all** parts of the answer were accurate	**Mixed -** conceptions **and** misconceptions or **None - no** conceptions **or** miscons were expressed
Exceeds standard		**Y-robust** - **all** parts of the answer were justified at a **robust** level		**Supported** - **only** science-supported conceptions

EPISTEMIC COGNITION

First see if the participant answers everything that was asked. If they do not, score them as naïve. If they do, try to match what they answered to the spectra. Simply score each thing they say as naïve or sophisticated and then take the average of their scores. For example, if they only said one thing and it was sophisticated, they are overall sophisticated. If they said a sophisticated and a naïve thing, they are overall mixed.

MISCONCEPTIONS

Science supported

- Climate is weather over long periods of time (more than a season up to as much as centuries)
- Climate change is caused by…

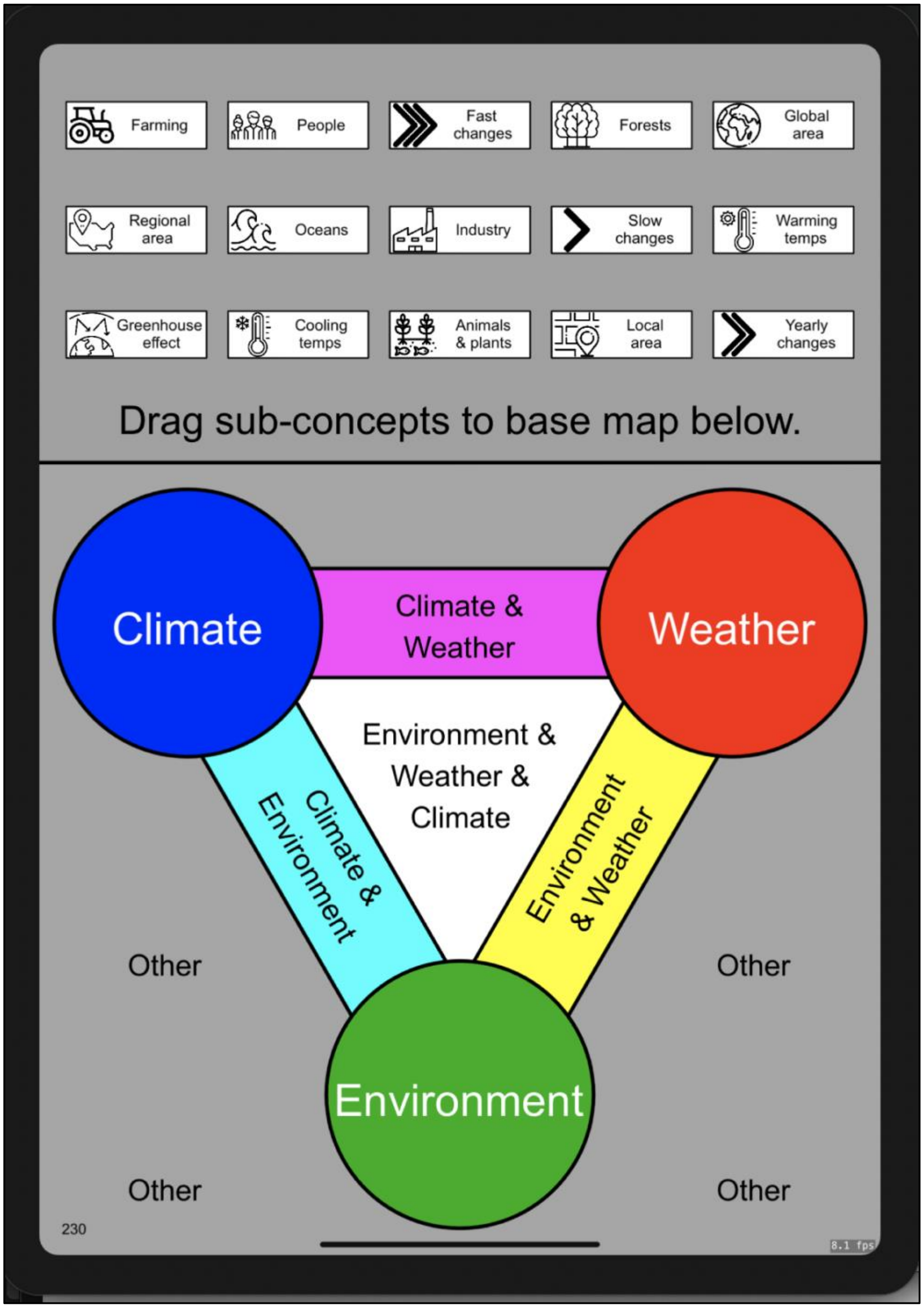
  - Increased levels of greenhouse gases, increased atmospheric CO_2, increased atmospheric methane, burning fossil fuels, people driving, farming practices, etc.
- Climate change causes…
  - Increased incidence of extreme weather, decreased ag production, political instability
- Climate change is lessened by…
  - People driving less

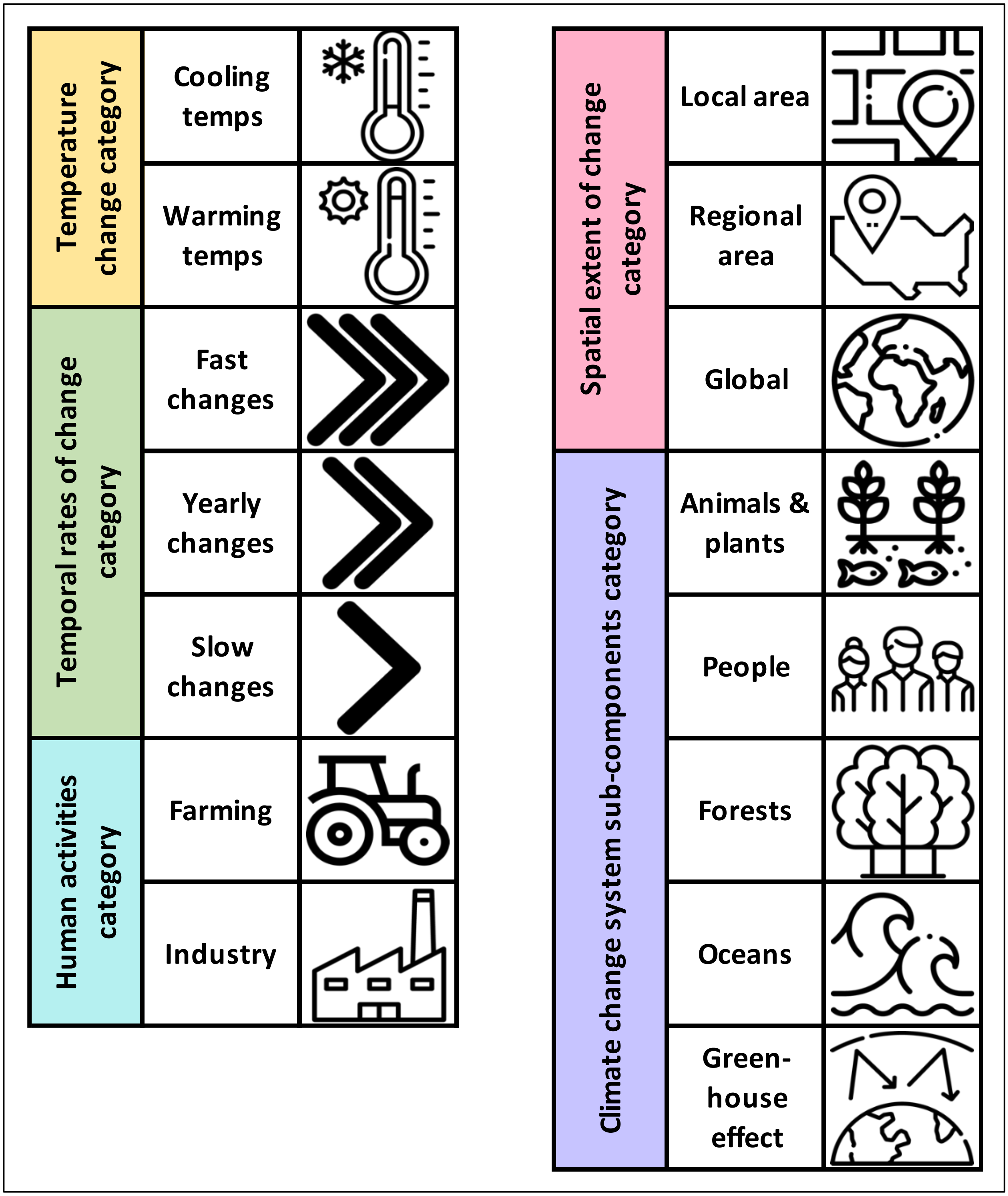
Misconceptions

- Climate is the same as weather
- Climate change is caused by…
  - Intensifying sun's rays, ozone holes, pollution, using CFCs, trapped sun's rays, volcanoes, straighter earth rotational axis, a "dome" over the earth, earthquakes and tsunamis, changes in earth's orbit, artificial fertilizers, nuclear power production
- Climate change causes…
  - more incidence of skin cancer, increases in CO_2, more incidence of food poisoning, ozone depletion, more heart attacks, earthquakes, falling sea levels
- Climate change is improved by…
  - using unleaded petrol, recycling, methane production, using coal and petrol vs nuclear, hybrid car usage

APPENDIX G - ELEMENTS OF THE C^3M_{YC} APP (GAME) CONDITION

This is the start screen for the Climate Change Concept Map for Youth and Children (C^3M_{YC}) digital app as simulated using XCode v12.2 on an Apple PowerBook, followed by the sub-concept categories and icons.




Temperature change category
Cooling temps
Warming temps
Temporal rates of change category
Fast changes
Yearly changes
Slow changes
Human activities category
Farming
Industry
Spatial extent of change category
Local area
Regional area
Global
Climate change system sub-components category
Animals & plants
People
Forests
Oceans
Green-house effect

APPENDIX H - HOW-TO GUIDE FOR RESEARCHERS

This is the guide that the research team used with all study participants. It started as personal notes in November of 2020, evolved from January to March of 2021, and served to significantly normalize our team's data collection process so we could focus on differences in participant responses.

To collect beautiful data for the project, …

…consider these general suggestions as you are working with a participant.

The difference between good data and bad is like the difference between gold and scrap aluminum. You want the very best quality data, and it will save you a ton of work later if you have good data.

- Shut down apps on your computer that you have not been using for a while.
    - PhotoShop, movie editors, and movie players are particular computer resource hogs.
- Close windows that are lying around that you don't need anymore.
    - Every open browser window is actually a separate process running on your computer. I tend to open them and forget to close them when done. Sometimes I shut down my browser and then reopen all the tabs just to kill all the derelict processes.
- If the participant is not speaking up enough, encourage them to speak louder.
- If the participant is not speaking clearly enough, encourage them to speak more clearly.
- If the participant is not paying attention, direct their attention to what they should be doing.

In short, every running app and open window consumes resources that could negatively affect the quality of your exchange with the participant. This could mean fuzzy images, video freezes, etc. A full system reboot is overkill, but do what you can to simplify the state of your computer.

As for participants, do what you need to do to keep them engaged, providing good information about what they are thinking, and doing the things they should be doing in the research context.

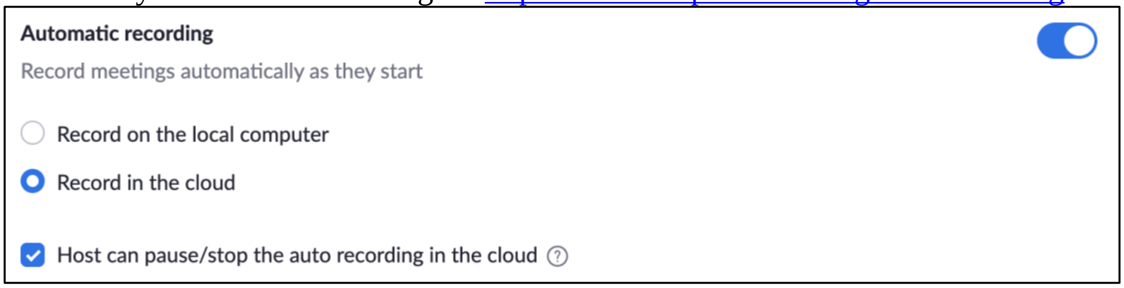
…get the materials you will need.

You will need your laptop and the current versions of all study materials. You can find them in the folder, latest_study_materials, on Box.

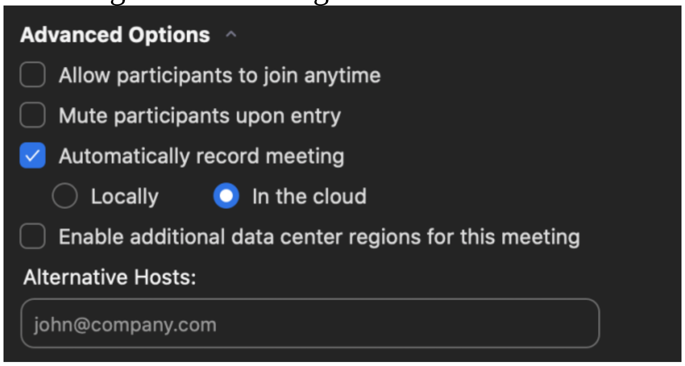
…set up Zoom for recording data.

Our data is audio and video of data collection episodes from our first introduction to the participant to when we say goodbye. There will be portions where there is not much to look at or hear, but it makes the most sense to start recording at the beginning, leaving it on for the whole time, and ending recording at the end. There are several controls that you will need for this work. They are all settings for your Zoom account and they are on the Web.

Enable automatic recording to the cloud. This is a good idea for two reasons. First, you don't have to think about it. You have a lot going on with the data collection episodes and this is one less thing. Also, this avoids the worry that your local system might not have enough disk space for the recording. The only downside is the recordings get scrubbed after 30 days, but hopefully the recordings will have been copied to Box by that time. It is a toggle and checkbox and is located in your web Zoom settings at https://zoom.us/profile/setting?tab=recording.



IMPORTANT: Even though you set automatic recording in your account settings, the Zoom meeting settings override the account settings. It is *very* easy to miss setting automatic cloud recording for the meeting as shown below.



For this reason, make sure when you start your Zoom meeting, that recording is happening, as indicated by the recording icon. It should be in the upper left-hand corner of the viewing window.

Enable audio transcript. Zoom will automatically transcribe audio recordings. We will be using Zoom's transcription as a baseline and edit them by hand to ensure high quality. This is a check box located in your web Zoom settings at https://zoom.us/profile/setting?tab=recording

Enable remote control. This is needed for participants to use their mouse to interact with the concept map condition. It is a toggle and checkbox and is located in your web Zoom settings at https://zoom.us/profile/setting

This does not apply to participants with ChromeBooks as the Zoom package for ChromeBooks does not have the remote control feature. If participants have another non-ChromeBook platform to use, that is preferable, since it gives them direct control of what they are doing. However, if the ChromeBook is their only platform, have them instruct you when and how to use your mouse to express their thinking.

…conduct data collection episode with timing in mind

Each participant will have two data collection episodes. The first one consists of a pre-test, condition, and post-test. The second one consists of a delayed post-test and the concept map condition, which will be discussed later. Generally, here is the timeline for the first and second data collection episodes.

First data collection episode

- 00:00 - welcome and initial instructions
- 02:00 - pre-test interview (10-minute max)
- 12:00 - instructions about condition (10 minutes max)
- 22:00 - read text or play C^{3}MYC app game (15 minutes max)
- 37:00 - post-test interview (10-minute max)
- 47:00 - wrap-up including discussion and planning (5 minutes max)
- 52:00 - participation complete

Second data collection episode (3 weeks later)

- 00:00 - welcome and refresher on instructions
- 02:00 - delayed-post-test interview (10-minute max)
- 12:00 - instructions about C^{3}MYC app game (10 minutes max)
- 22:00 - play C^{3}MYC app game (15 minutes max)
- 37:00 - wrap-up including discussion and thanks (3 minutes max)
- 40:00 - participation complete

…welcome the participant and start a data collection episode. (2 minutes)

Keep a Word document open for every data collection episode for every participant. If anything…and I mean anything…happens that you think might influence the data collection in any way, please make a note of it. Record the participant number, the session number if applicable (shown at the bottom left of the app screen after Begin Session) and the date. After you have shut down the Zoom meeting, upload this file to the participant's data folder on Box along with all the recordings.

This is what you can say. Stay pretty much on script because a lot of this is here for a reason.

> Hi. How are you doing today? Are you feeling good? My name is [your name] and I will be talking with you today. I'm interested in how you learn and your [Dad/Mom] said you wanted to help me do that. I know you can, and it would really help me. I just want to make sure you still want to do that. Do you?

> Good! You won't be graded on anything you tell me. There are no wrong answers. All you need to do is tell me what you think and do your best job at that. Can you do that? Some things you will have thought of before and others will be new. It's OK to say, "I think so." or "I don't know", if that's what you think. This won't take long time. You can quit at any time, but I hope you answer all my questions. If you do help me this time and again in about 3 weeks, there is a good chance you will win $100! How do you feel about that? Finally, if you have any questions, tell your [Dad/Mom/guardian] and they can ask me.
>
> Do you understand everything I've told you so far? Do you still want to help me? Good, let's get going.

… interview a participant.

Each participant will be interviewed 3 times. The interviews are similar in terms of the content, but each interview is unique. The Excel spreadsheet for the interview (see **…get the materials you will need** above) has 12 categories of questions. You will ask questions in each category, so you have about a minute, on average, per category, to get it done in the 12 minutes allowed for this part.

For all interviews, do the Y/N questions in exactly the same way. They are the last 3 in the orange section of the protocol, and each is a multi-part question, they should be the first questions you ask each interview. Also, do them in order, first to last, as they appear in the protocol. To introduce them, you can say.

> For these next few questions, simply answer 'yes' or 'no'.

Now, tell the participant you are going to ask questions that require long answers. You can tell the participant…

> I would like you to answer the following questions as fully as you can. Remember, the answer is whatever you think, there are no wrong answers and there are no grades for this.

This section includes the two epistemic questions (the ones about information sources and communications, in orange.

For the first interview, the pre-test interview, ask questions in column D. The main question is in RED and there are secondary questions in black. Make sure to at least read up to the main question. If you feel you have time, you can ask the secondary question.

For the second interview, the post-test interview, ask questions in column E. The rest of the instructions are just the same as for the first interview.

For the third interview, 3 weeks after the first and second, go back to column D and re-ask those questions. The rest of the instructions are just the same as for the first interview.

…use the text condition with a participant.

The text condition is a PDF that the participant reads. It is about 1000 words with text and should be easily readable in 8 minutes for most middle-school-age learners. We are going to give them 15 minutes so they can go over it more than once It discusses most, if not all, of the sub-concepts mentioned in the concept map tool.

If you got all the research materials (see **…get the materials you will need** above), you have the latest text condition (and it's called, latest_text_condition_layout.pdf) on your local machine. Our new strategy for giving the participants access to this condition is simpler than when we started. Simply open the text condition in a window. Later, you will share that window with the participant through Zoom.

Tell the participant The following.

> Now I have a reading for you. The reading talks about things related to climate, environment, and weather. It probably won't take you long to read and the material may or may not be new to you.
>
> - Note: your "help" should be limited to helping the participant understand the meanings of words or phrases. Do not interpret or editorialize the text. You can often avoid this by asking the participant, "What do you think it means?". They will often have a general sense of what it means, and you can reply by saying something encouraging but unbiased like, "That sounds pretty good to me." If you do provide them with a definition, make sure it is clear and unbiased.
>
> I'm going to share a window with you. (do the share now) Do you see it? Can you read all the text easily…even the captions? Great! Now please read it carefully. If you come across something you don't understand, let me know and I will help you if I can. When you think you have read everything and understand it well, please let me know. Do you have any questions at this time?

When they say they are done…

- …double check with them to make sure they have gotten everything they can from the text.
- …thank them for doing it.
- Start to set them up for what is coming next by saying one of the following.
    - I have a different kind of task for you now. (e.g., the game for the text group in the second data collection episode)
    - I have a task that you may remember from the last time. (e.g., the game for the game group in the second data collection episode)
    - I have a couple small things to take care of with you an then we will be done (e.g., after the post-test interview).

…do the wrap-up

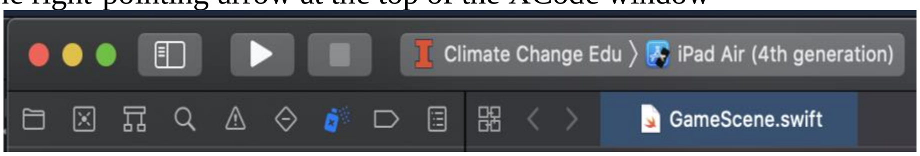
If you are wrapping up after the second interview (first participation), express thanks to the participant and their parent, find out if they have any questions, and set the stage for their second participation.

If you are wrapping up after their second participation, do pretty much the same thing. Use the following as an example.

- Thanks for telling me what you thought about all those questions. And thank you [Mom/Dad] for letting your child work with us. I really learned a lot from you! That's all I wanted to do with you today. Do you have any questions for me? No? If you think of something that you want to ask us or tell us, let your [Mom/Dad] know and send it to me, OK? Well, I look forward to talking to you again in about 3 weeks. Would this same time slot work for you then? If so, I will set it up soon. Otherwise, I will contact you via email.
- Bye!

… prepare your computer to use the concept map tool with a participant

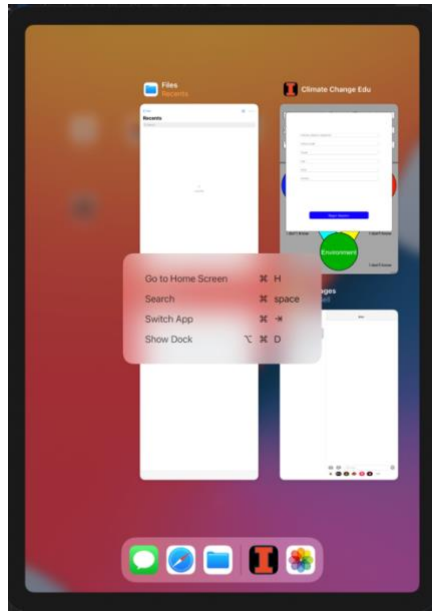
You need to have XCode installed on your computer and the concept map program package downloaded. You also need to get the latest concept map package from the latest_study_materials folder mentioned earlier.

- Launch XCode
- Open the file that ends with ".xcodeproj" that is in the first level of the directory you downloaded with the latest version of the concept map tool.
- Click the right-pointing arrow at the top of the XCode window
    - 

    - This will build the app and start the Simulator. The Simulator should look like an iPad.

- The simulator window will look like this.
- Before the Zoom meeting begins. Do this.
    - If this is the participant's first interview, type their 6-digit participant number into the top box, labeled Previous Session (Optional). Then use the scroll controls to enter the participant's demographic information from the parent_data spreadsheet. For all other interviews, you only need to enter the participant number.
    - Click Begin Session

- At this point, kill the app. To do this, click the Home icon twice. This will bring



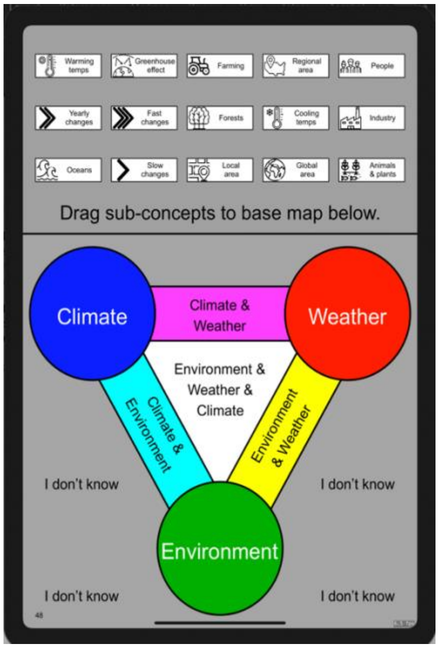
  you to a screen showing all your active apps. Pick and swipe upward the learning app to kill it, since all we wanted to do was get the participant's information and not take time for this during a data collection episode. You can then restart the app by clicking its icon on the Simulator's desktop. (it's the block "I" Illinois logo)

…use the concept map tool with a participant.

The concept map tool is an interactive game that the participant uses to organize sub-concepts in relation to major concepts that are difficult to distinguish from one another.

We need to train the participant before the use it "for real". We do that with a dummy participant number, 987654. Before the participant connects with the Zoom meeting, enter this participant number into the Previous Session field. Then click "Begin Session". You will keep this session running for the duration of your training of the participant.

The concept map app should look like this when the participant starts using it.



Say the following to the participant.

Now I have a game for you to play. The game is about concepts related to the main concepts: climate, environment, and weather. It probably won't take you long to do it. The concepts in this game may or may not be new to you, but that's OK.

- Note: your "help" should be limited to helping the participant understand the meanings of words or phrases. Do not interpret or editorialize the text. You can often avoid this by asking the participant, "What do you think it means?". They will often have a general sense of what it means, and you can reply by saying something encouraging but unbiased like, "That sounds pretty good to me." If you do provide them with a definition, make sure it is clear and unbiased.

I'm going to share a window with you. (do the share now)

- Make sure to turn on remote control for your participant in the sharing control bar.

Do you see it? Can you read all the text easily…even the writing in the white rectangles? Great! Now I'm going to show you how to play the game.

Note: If the participant starts to play the game before instruction is done, stop them and have them wait for all the instructions. If they move a sub-concept, ask them to stop, return the sub-concept to its original location, and make a note of what happened in your session notes. This activity will not count toward their completion of the game.

First, I'm going to tell you what everything is on the screen. I'll start with the bottom of the screen. All the colored areas relate to combinations of the main concepts, climate, environment, and weather. Do you see the circular areas? How many are there? Those are for just climate in blue, just environment in green, and just weather in red. Do you also see colored rectangular areas? How many do you count? They are for combinations of pairs of main concepts. For example, light blue is for climate and environment. There are rectangular areas for all possible pairs of main concepts. There is also a white triangular area in the middle for the combination of all 3 main concepts. Finally, there is a gray area on the outside for concept that relate to none of the main concepts. This is for concepts that don't fit with any of the main concepts…or you simply don't have any idea what they are.

At the top of the screen is an area with 15 white rectangles with names of concepts on them, like people and oceans. You can pick and drag each of these with your cursor. When you play the game, you will drag each of them to the colored area on the bottom of the screen, that best represents how you think about them.

This game is about relationships. You use the game to show what you think are important relationships between the concepts in white rectangles at the top of the screen and the main concepts in the colored areas at the bottom. How would you describe an "important relationship" between concepts? [let them tell you. Make sure they are distinguishing between "important" and "unimportant".]. Now, let's see if you can do that for one of the concepts in the white rectangles. [enable remote control in the options for the shared window.] Pick one of the concepts at the top of the screen and drag it to a colored area that you think represents an important relationship with one or more of the main concepts. If you think there is no important relationship for that concept, drag it to the gray area [have them do it]. Great! The box that opened up when you dragged the concept to the main concept asks two questions. Let me tell you about them.

There are several ways you can think of the direction of an important relationship between concepts. Take, for example, melting glaciers and sea-level rise. like melting glaciers can cause sea level rise. But you would probably not say sea level rise causes glaciers to melt. Would you? Relationships can be two-way, like moisture in the atmosphere and rainfall. Lots of moisture in the atmosphere increases the chances of rain. But did you also know that some rain evaporates and increases atmospheric moisture which could make it rain? That's why this relationship is two-way and they are important to each other about the same.

There can be a lot of different ways concepts can be important to each other. One way a concept can be important to the other by changing it, like we were just talking about with rain and moisture in the atmosphere**.** Another way is one concept can be a part of the other, like a mountain range can be part of a region. Another way is a concept can be a characteristic of the other, like cold temperatures usually happen with winter. There are still more kinds of important relationships too. So, you have to decide if there is some relationship between the sub-concept and main concept(s), if it's an important one, and what the relationship is.

So, the first question asks you if you think the relationship between the main concept(s) and a sub-concept is two-way where each is important to the other, one-way where only one is important to the other, or is a different kind of relationship than one way or two ways, or you don't know what it is. Remember, I've told you, it's totally OK to say, "I don't know." if that is what you really think. The second question asks you how sure you are about what you think about the relationship. It asks if you are not sure, somewhat sure, very sure, a different kind of sureness than the other choices, or you don't know. Does all that make sense? [get them to respond].

Also remember, there are no wrong answers in this. This is about what you think. You can also change your mind as many times as you want in this game. So, you can move the sub-concepts again after you have placed them the first time, to a different main concept area and re-answer the questions.

So, to summarize, I want you to show me, in the best way you can by using the game, what you think are the important relationships between the sub-concepts and main concepts. Does that make sense to you? Can you do that?

If you come across something you don't understand, let me know and I will help you if I can.

Do you have any questions at this time?

- At this point, kill the training instance of the app (the one running with participant 987654).
- Restart the app as described in the prior section.
- Enter the participant's "real" number in the Previous Session field.

You can click on "Begin Session" whenever you want to start.

Please stop when you see the blue SUBMIT button at the top.

- Ask them if there is anything they wanted to change about their conceptual layout. Have them make their final changes or say their answers are good as is.
- Disable remote control.
- Disable screen sharing.
- Be sure to ask them how they liked the game. They are now experts in the game, and we want their expertise. Are there things they especially liked? What would they change?
- Click SUBMIT. It will ask for a code. Type 3-2-1-0 on the screen keypad and click "Continue Session".
    - There will be a delay of about 10 seconds while the app stores the participant's data to the cloud.
- A stats window will appear over the game. You don't need to do anything with this. Click "Continue Session".
- The game will reappear with a blue FINISH button at the top.
- Click FINISH. It will ask for a code. Type 3-2-1-0 on the screen keypad and click "Continue Session".
- Ask the participant four questions about the app.
    - What did you think about the app?
    - What is one thing you really liked about the app?
    - What is one thing you would change about the app?
    - Did you learn anything? (if 'yes') Please tell me about what you think you learned.
- You are done and the game is ready for the next participant.

When you are done with an interview…

- …if it's the pre-test interview for either group…
  - Go to either the concept map or the text section.
- …if it's the post-test interview for either group, say…
  - I have a couple small things to take care of with you an then we will be done (do the wrap-up after the post-test interview).
- …if it's the delayed-post-test interview for the text group, describe the concept map condition, by saying…
  - I have a different kind of task for you now.
- …if it's the delayed post-test interview for the game group, say….
  - I have a task that you may remember from the last time. Do you remember the game?

V10, 2021.03.06

APPENDIX I - A HISTORY OF CLIMATE CHANGE SCIENCE

This is a brief history of the science of climate change. It focuses on significant events, and how and when the events facilitated more visibility for the topic outside its scientific community.

The history of climate change science is long or short, depending on a number of factors including ones' ideas about "long" or "short" time and what constitutes the "beginning" of a research domain. One might consider "Mémoire sur les températures du globe terrestre et des espaces planétaires" ("Thesis on the temperatures of the terrestrial globe and planetary spaces") (Fourier, 1827; R. M. Johnson, personal communication, August 6, 2020) as the beginning. Notably Fourier did not call the phenomenon, "greenhouse effect", in 1827 and measurements at the time would have captured only very small anthropogenic quantities of it, given the Industrial Revolution had just begun. One might also consider John Tyndall who in 1861 referenced Fourier's contribution (Fleming, 1999), and in 1864 conducted experiments on absorption of infrared radiation by species of greenhouse gases (R. M. Johnson, personal communication, August 6, 2020). Additional notables are mentioned in the following paragraphs, but what becomes apparent is there are two parallel histories. Fourier and Tyndall began the history that has been overwhelmingly consumed by scientists in journals, colloquia, and conferences. Others, notably James Hansen, began the science history that has been consumed by the general public in mainstream media.

In the late nineteenth century, Arrhenius provided the chemical theory behind greenhouse effect (Arrhenius, 1896). This theory explained the natural process by which greenhouse gas (GHG) molecules in Earth's atmosphere are heated by capturing infrared radiation energy generated at Earth's surface after its conversion from sun-sourced ultraviolet radiation. At the time, the theory accounted for the sun's energy output, which has been quite stable since the start of the industrial revolution (Phillips, 2013), and the natural abundances of atmospheric chemicals, which have changed historically (and then only negligibly) because of volcanic activity. Without the balance between solar output and natural quantities of GHGs, Earth would be uninhabitable. Earth's population in the year 1900 was 1.6 billion people at a time when there was no commercial availability of combustion engines. Though climate research continued through the early 1900's, it was not until the late 1970's and 1980's that three events established the modern era of climate change research.

Charles David Keeling and colleagues at Scripps Institution of Oceanography and the National Oceanic and Atmospheric Administration started publishing work which provided historical evidence and mathematical algorithms for predicting the effects of anthropogenic carbon buildup in the atmosphere (Keeling, Bacastow, Bainbridge, Ekdahl, Guenther, Waterman, & Chin, 1976; Keeling, Whorf, Wahlen, & van der Plichtt, 1995) This work focused on variations in airborne CO_2 based on data taken from the volcanic Mauna Loa Peak in Hawaii. These variations, known as the Keeling Curve (Figure 36), showed seasonal changes and a steady upward trend since 1950 which were only explainable as human-sourced additions to natural CO_2 concentrations. Changes in temperature follow directly from changes in CO_2 concentrations and their central role in the greenhouse effect. Side-by-side plots of CO_2 and temperature over similar time periods show this nearly lockstep relationship (Figure 37 and Figure 38). This relationship between atmospheric CO_2 concentrations and atmospheric temperatures, including temperatures experienced by people living on Earth's surface, is the essence of the fundamental relationship in climate change science. Keeling's work subsequently influenced two other key events in modern climate change research.

Figure 36 - Keeling curve

"Keeling curve", atmospheric CO_2 at Moana Loa, 2017. Downloaded from Yale Environment 360, https://e360.yale.edu/assets/site/mlo_full_record-copy_trimmed1500.png.

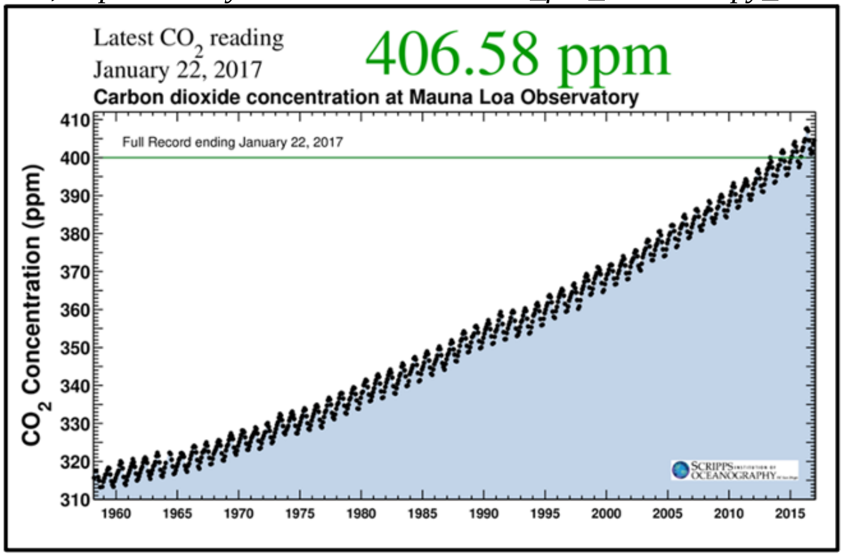
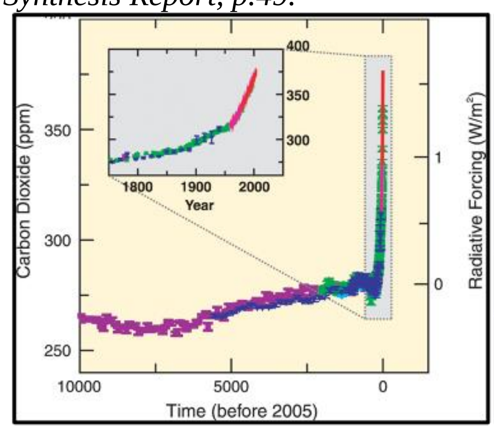


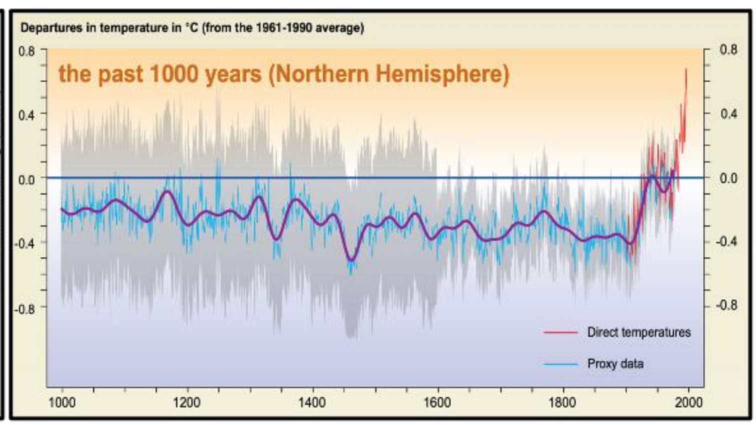
Figure 37 (left) - Historical CO_2 concentrations

Atmospheric CO_2 concentrations from the past 10,000 years and the last 250 years (inset), extracted from Climate Change 2007 Synthesis Report, p.38. Different line segment colors represent different modes of data collection.

Figure 38 (right) - Historical temperature

Atmospheric temperature change from past 1,000 years, extracted from Climate Change 2001 Synthesis Report, p.49.





On June 24, 1988, James Hansen, director of NASA's Institute for Space Studies in Manhattan, testified before the U.S. Senate Energy and Natural Resources Committee (Shabecoff, 1988). Hansen told the committee that sections of the United States could expect to experience higher temperatures and droughts in future decades, and temperatures would rise between three- and nine-degrees Fahrenheit. The reason was increased CO_2 in the atmosphere from humans burning fossil fuels. He expressed that his certainty of this was 99% and further asserted that "…1988 will be the warmest year on record unless there is a remarkable, improbable cooling in the remainder of the year." (*Ibid.*). All the climate experts that testified that day corroborated his warnings, but Hansen is generally credited with "ringing the bell" on climate change.

Also, in 1988, the union of the United Nations Environmental Program and the World Meteorological Association formed a quasi-governmental science organization called the Intergovernmental Panel on Climate Change, or IPCC. The purpose of the IPCC was to conduct research and advise governments on climate change science. In March 1990, the IPCC released the First Assessment Report, or FAR. FAR contained, as have all IPCC's assessment reports, sub-reports on the science, impacts of the scientific findings, and potential responses to those findings (mitigation and adaptation strategies). The IPCC has produced assessment reports on roughly 7-year cycles and is currently writing Assessment Report 6, or AR6. The IPCC has come to be recognized as the preeminent climate change science research collaboration in the world, involving the work of roughly three-thousand researchers in virtually every country. While the relationship between atmospheric CO_2 and temperature is still an important one, the number of fields (discrete computational variables like rainfall, ocean surface temperature, and vegetation type) in climate models now exceeds 300. The analysis of climate model data informs decision-making that has ramifications into the 22^{nd} century.

In 1988, climate change became more than just a science topic. It started to be a *public* science topic, with importance and bearing in everyday conversation. Conversations in both circles continue to this day with large scale climate change science research occurring globally, and daily public news reporting rife with connections to climate change. Science communication about climate change has almost always started with the nature of the phenomena. By contrast, public communication about climate change has almost always been about what it means to material, rather than existential, aspects of humans. The two modes of communication rarely coexist in any single report or media piece, which contributes significantly to climate change being a socio-scientific topic.

APPENDIX J - CARA AND DAVE

Following are detailed longitudinal descriptions of the research experiences of Cara and Dave, who were two participants in the study. Though Cara and Dave's results were not as positive as Emily's, they are included to illustrate the flexibility of the research methods to identify different patterns of progress in terms of scientific thinking about climate change concepts. The methods, therefore, respond well to Research Question #2.

J.1 - Cara (Participant 446120): Experimenting with Conceptual Systems

As was the case with all participants, data collection episode 1 for Cara (not her real name), a 10-year-old girl, I led off with an interview that was front-loaded with the Yes/No questions in Appendix D. One of the first questions I asked her was whether people are having a big effect on climate change. After a long pause, she admitted she had never thought about this question and said, "I'm kind of confused…I think sometimes [climate change] affects people and sometimes it doesn't.". She seemed to have always thought of climate change as something that *affects people*, but never something that is *affected by people*. As a result, she said she really felt most comfortable saying she didn't know the answer. In response to a later question, she said that she thought climate change would not harm her directly but would "probably" harm other people. She furthermore expressed that whether climate change harmed other living things (plants and animals) would "depend". Her responses to the Yes/No questions from all three interviews are shown in Table 33. Except for the question about anthropogenic climate change, Cara's pre-test responses about the nature of climate change were in accord with the climate science community. Her risk perception responses were contradictory in that she indicated that present day climate change would harm others, but not her. She was, however, consistent in her policy responses. She said that leaders and policymakers (framed during the interview as political leaders) should address climate change more than they do presently, and that climate change should be taught in schools.

Table 33 - Cara's responses to "the Yale questions"

Cara's responses to yes/no questions from both of her data collection episodes.

	Nature of CC				Risk perception					Policy	
	Happening?	Affected by people?	Scientists?	Affecting weather?	Harm you?	Harm others?	Harm now?	Harm in future?	Harm plants & animals?	Should be taught?	Leaders do more?
Pre	Y	IDK	Y	Y	N	Y	IDK	Y	Y	Y	Y
Post	N	Y	Y	Y	N	Y	N	Y	Y	Y	Y
Delayed	Y	Y	Y	Y	N	Y	N	Y	Y	Y	Y

Next, I asked her the two epistemic practices questions. Cara's responses to these questions positioned her toward the sophisticated end of several epistemic spectra related to degree and frequency of interest, and evaluation of sources. This participant stated clearly that she sought resources to inform herself about climate change and she did so with some degree of frequency. As she put it, "[I do it] probably every month [because] I noticed that the weather changes." She implied she thinks about the quality of her sources and described her quest for information this way. "[I have not found any good sources] yet. [I have found one bad one]. Wikipedia is not very good information. [It] mainly had things that when I searched for it, they gave me topics that weren't even related." Since she mentioned the plural, "sources", she seemed to not be looking for a single source to tell her what to think. Schommer and others (Schommer, 1990; Burr & Hofer, 2002) call this rejection of omniscient authority in lieu of multiple corroborating sources, which is a trait of sophisticated knowledge curation. Cara evidently had ideas and was looking for sources to support, change, or augment her thinking. She also exhibited epistemic sophistication in her discussion about her different types of sources of climate change information.

Next, Cara answered questions to related to the seven different science topical areas delineated by the Next Generation Science Standards (NGSS, n.d.). In doing so, this participant returned to a couple themes of apparent importance to her. First, she seemed to treat natural environments and human-inhabited environments as being mutually exclusive. She talked about people "…just seeing wildlife from our backyard…" and "…go[ing] hiking and see[ing] some wildlife." In another responses, she said, "…if we try to make a city bigger, we could take out an important environment trying to build more buildings which might be good for the humans, not very good for the environment.". She also said people were, "…harm[ing] the environment by creating buildings."

Second, she showed concern for climate change impacts on plants and animals with responses such as, "Mainly, probably due to weather, the environments could change and that could be bad for the animals living there. […] a drought, it would dry up the water sources and they would not be able to drink the water and they could go extinct." Interesting aspects of this particular response were that she equated ecosystems with environments, implicated weather and not climate as the driver of environmental change, and considered extinction to be species' main response if they couldn't cope with the changes. In another response, she said, "[Rising temps] could affect plants and animals, because if they're sensitive to having too much heat or not enough heat, that could be very dangerous for the plants…"

Third, Cara seemed to struggle with the conceptual differences between weather and climate, and therefore had difficulty in assessing their respective impacts on environments and living things. She indicated that weather had to do with in-the-moment phenomena, especially heat. She didn't explicitly discuss the time aspect of climate. Rather, she said, "…climate is basically where you are, and the climates can change based on how the weather is where you are." From this, it seemed that she saw weather as having power to alter both climate and environments, two terms she tended to use almost interchangeably.

Table 34 Cara's responses

Comparison of Cara's responses to the digital app from both sessions.

		Temperature changes		Temporal rates of change			Human activities		Spatial scope of change			Climate change system sub-components					
		Cooling Temp	Warming Temps	Fast changes	Yearly changes	Slow changes	Farming	Industry	Local	Regional	Global	Animals & Plants	People	Forests	Oceans	Greenhouse Effect	
Experts	**consensus configuration**	CW	CW	W	CEW	CE	CEW	CEW	CEW	CEW	CEW	CEW	CEW	CEW	CEW	CE	**86.7%**
Participant 446120 - 1st app use	**configuration**	CW	CW	W	E	C	E	EW	CEW	CE	C	CEW	E	CEW	W	EW	**66.7%**
	step number	11	5	3	1	2	9	15	14	4	10	8	6	7	13	12	
	confidence	very	very	very	very	some	some	very	some	very	some	very	very	very	some	very	**83.3%**
Participant 446120 - 2nd app use	**configuration**	EW	CEW	W	E	C	CEW	CW	CE	CW	CEW	CEW	C	E	EW	EW	**64.4%**
	step number	1	13	7	4	6	11	12	2	9	3	8	14	15	5	10	
	confidence	some	very	very	some	some	some	very	very	very	very	very	very	very	very	some	**83.3%**

Table 34 shows the order of steps in which Cara placed sub-concepts as she progressed to her final conceptual configurations for both of her uses of the app. Overall, her first configuration concurred 66.7% with that of experts, somewhat higher than the average of all participants. Her confidence in her thinking was one of the highest among the participants. She tackled the three *Temporal rates of change* sub-concepts first. Of these, her conceptualization matched the experts for only <*Fast changes*>. She rated her confidence very high for all but <*Slow changes*>. Her highest degree of categorical matching with the experts was with the *Temperature changes* category of sub-concepts and she was very confident in her thinking about these. *Human activities* was a category where she matched the experts at a relatively low level, and her confidence was lower for these relative to her norm. *Spatial extents of change* garnered the least categorical confidence. Among these, her responses related increasingly to <*Climate*> as the spatial extent of the sub-concept broadened. Finally, she rated her confidence on *Climate change system sub-components* in line with her norm, though her matching with the experts was relatively low. One notable item within this portion of the participant's data is the relationship between her confidence and accuracy. With one exception, she said that she was very confident in her thinking for all the sub-concepts where she matched exactly with the experts.

In the post-test interview, a couple changes occurred in the participant's Yes/No responses. She changed her response to, "Do you think climate change is happening?", from positive to negative. She is heard in the recording of the episode strongly saying, "No!", to this question, as if she suddenly realized something that completely changed her mind about it. The next question, whether people are affecting climate change, was also asked in the present tense, but the participant nonetheless answered this in the affirmative, which seemed to contradict her response to the prior question. She also changed her response to whether climate change is harming people presently from "I don't know" to "No".

In the long question portion of the post-test interview, this participant visited some of the same themes as she did during the pre-test interview. In her discussion of epistemic questions, she reiterated that she sought information about once per month because "I notice that [climate] is changing". I noted a couple changes in her discussion about sources and how to discriminate between them. She said, "I'm looking things up more because I have some people [that] don't know very much about climate changing, but I know that I could go online and see that some real scientists have put stuff on there that they are thinking about.". With this, she said she is more skeptical of human sources compared to online sources. She also seemed to hold "real scientists" in especially high regard for informing her about climate change.

Her answers to the NGSS questions also offered some subtle changes from the prior interview. This time, in her response to the question about section ESS1.C, The History of Planet Earth, she mentioned animal adaptation. In her response to the question about section ESS2.D, Weather and Climate, she said that weather involves "…particles and things that are in the air and water, because I know that if there is pollution in the air, it could cause the clouds to be bad for us, which effects fog as well." She again discussed separate environments for people and animals by saying "…since [in the future] we're making more buildings at a very fast rate and the environment for the animals is not going too well, I don't think that…environment may not be there and may be replaced by a town." This too seemed to be a contradiction in that she previously responded that she considered areas of human habitation to be environments. She said a major human impact was "…trash buildings where they, like, they have…where they are polluting the air and the ocean." She did not elaborate about how the buildings were polluting. The participant then added, "…that's harmful if [pollution] stays there, but if it's taken away, it will help the environment, a lot." Once she had answered the NGSS questions, I thanked her for her time and ended the first data collection episode.

Three weeks later, I started Cara's 2nd data collection episode with her final interview. The Yes/No portion of the interview saw a reversal back to "Yes" on the question of human causation of climate change. The remainder of her Yes/No responses were the same as for the post-test interview. Her answer to the first epistemic question was somewhat different from what she said to the identical question during her pre-test interview. She called the times she sought out information to be "rare" and occurring only once every two months. She did not cite a reason for seeking the information this time. Her answer to the second question, about sources and their epistemic quality, was very detailed. She discussed what makes a dependable source, and cited a new source of information, her science teacher.

> "…one good source I found is actually a…it's called word World Book and it's actually a website used by Tennessee libraries…that I found. [A bad source] I know I mentioned the last time was that Wikipedia…it's not necessarily bad information, but sometimes it can like lead you off track and sometimes there's like all ads instead of the information

> you asked for. [A good person to talk to] is actually my science teacher. And then, I have a friend who knows a lot about this too. [A person who doesn't know as much] is actually one of my classmates. They haven't learned very much about it. I decide if [something is] a good source or a bad source, one if it keeps me on track for what I searched. For two, if it's actually the information I asked for, instead of like something about a holiday or something. And three, if it has good backup information. Like it has more…it has reasons to back up that information."

During the NGSS part of the delayed-post-test interview, Cara seemed to conflate natural climate change from historical ice ages with mixed natural and anthropogenic climate change in the present, when she said…

> "…if you think about the ice age as the temperatures are warming up and cooling down, the blocks of ice…they're not growing back. They will melt, but when the temperatures get colder than they can't reform again. So eventually, when all of the ice chunks are melted, which is not for a long time…but will eventually…when they're all melted, the ocean levels are going to rise and may cause a flood."

This was the only time during the first interview that this participant discussed historical conditions. She seemed, however, to be thinking of the ice age as a present-day reality, but at the same time, she seemed to think of polar ice melting to be a future long-term process. In her response to the NGSS question about section ESS2.D, Weather and Climate, she differentiated the two concepts by saying,

> "…climate has to do with…kind of like a high point and a low point. The climate, we can change like, very like low changes um very small changes or they can be very big changes. Weather is…it's the things that you see in our atmosphere…the things that you can physically see […] When water from your ocean evaporates it goes up into the clouds, and when there is a lot of water in those clouds that lets it out and it rains.".

The cyclical relationship between evaporation and rain, which she had not mentioned before, was the example of two-way relationships I used during game instructions prior to her first session. She seemed to be talking about a range of temperature readings over a long period of time. She clarified later that she was referring to daily changes, not a range of temperatures over seasons or years, as would be the case with climate. In other responses, just as with prior interview responses, she kept human-inhabited environment conceptually separate from natural environments, saying "…the more we build the more we're basically taking away from the animals and species that live in that environment.". In her response to the question about section ESS3.D (Global Climate Change), she said…

> "[Rising temperatures would affect] people that are used to cold temperatures, but they live closer to where the rising temperature would affect them…that rising temperature could change their…basically, like the outdoors and the climate."

She seemed to be describing differential effects of surface temperature rise depending on how close you are to the equator. Then again, she describes how animals that "…live closer to the center of the earth..." might experience surface temperatures "…heat[ing] up to a high temperature where then cannot live." She mentioned the theme of species adaptation in the context of species migration and as part of broader ecosystem adaptation to temperature increases.

Cara's second use of the app followed a very different process from the first session before arriving at an extremely similar overall product. Her overall agreement with the experts went down slightly over her prior session, but she was just as confident in her thinking this time at 83%. She followed a different order of steps through the sub-concepts. In viewing the video of her gameplay this time, she followed a traditional left-to-right, top-to-bottom traversal of the sub-concepts. This contrasted with her specific selections of sub-concepts, presumably based on their conceptual nature, in the first session. Her traversal of the sub-concepts this time thus preserved the app's random placement of sub-concepts in the Bank at the start of gameplay.

Overall, Cara was very engaged during her both data collection episodes. She took time to compose her responses, communicated them clearly, and projected openness and directness in her responses. She seemed to genuinely enjoy participating in the research. Her responses across the iterations of the Yes/No question set were very consistent. Only three of the 11 questions were answered differently between iterations. Two of the three that did change converted “I don’t know” responses from the first interview to a “No” response for, “Do you think climate change will harm you?”, and a “Yes” response for, “Do you think that people are having a big effect on climate change?”. Her most curious responses were to “Do you think climate change is happening?” which flipped from “Yes” to “No” and finally back to “Yes”. Overall, her responses to the Yes/No questions indicated that Participant 416200 thought that climate change is real, supported by science, affected by human practices, and had a significant impact on the weather. She was concerned about harms, but those harms would come in the future to others and not to her. Her responses were consistent with those of concerned citizenry as measured by YPCCC (Yale_climate, 2020) and the Six America’s Project (Leiserowitz, et. al, 2021).

Her responses to the questions about personal epistemology placed her toward the sophisticated end of the spectrum of overall epistemic quality. Her responses to the question about how often she consulted information sources were consistently positive in that they showed that she consulted them fairly frequently and regularly. She sought information because of personal interest and recognition that she needed or wanted to learn more. Her responses to the question about what sources she used and how she picked them became progressively more elaborate. From her pre-test response in which she touched on why she didn’t like some sources, her post-test response detailed why those sources were bad, and her delayed-post-test response discussed both good and bad sources and the rationale she used to grade them as she did.

Cara's responses to the NGSS questions offered some interesting insights to her thinking. Her responses to the questions about ESS1.C, The History of Planet Earth, were respectively rooted in different lines of potentially useful historical evidence. However, she talked about them only in the present or near-present, not reflecting time over centuries or millennia. Her responses about section ESS2.D, Weather and Climate, increasingly incorporated temporal differences. In the delayed-post-test interview, she talked about temperature ranges related to climate and daily changes related to weather. Her responses to the questions about section ESS2.E, Biogeology, consistently discussed the dichotomy between human environments and natural environments, with humans' building activities being detrimental to the lives of other living things. As such, her focus was always on how humans have affected environments, not how other living things have done so. In her responses related to section ESS3.C, Human Impacts on Earth Systems, she consistently recognized that humans have the ability to hurt or harm habitats and environments. In the pre- and delayed-post-test, she infused her answers with connections to human building activity and how decisions to build or not can have dramatic consequences for living things besides people. Her responses related to section ESS3.D, Global Climate Change, reflected a recognition that rising surface temperatures will have widespread effects on all manner of living things. She seemed to treat temperature as monolithic…that it was the same everywhere…because she talked, in the delayed-post-test, about things "…liv[ing] closer to the center of the earth…" and were therefore more accustomed to high temperatures. Her response to the questions related to section LS2.C, Ecosystem Dynamics, Functioning, and Resilience, contained evidence of an improved trajectory of thinking. In the pre-test, she talked about animals' responding to changing ecosystems by going extinct. In her post-test, she talked about species' numbers being significantly reduced in response to ecosystem challenges. Finally, in the delayed-post-test, she talked about species' adaptation as their principal response. This participant exhibited a similar progression of answers to questions about section LS4.D, Biodiversity and Humans. In the pre-test, she talked about cataclysmic effects on ecosystems with species going extinct. In the post-test, she talked about population balance in ecosystems, with numbers of individual species rising and ebbing over time to achieve overall parity. Her delayed-post-test response discussed the ecosystem as almost a complex living thing, responding to larger and smaller challenges as whole, but variably among its components.

This participant's successive usages of the app were uninteresting if simply viewing the end product, or fascinating if viewed at the detailed level. She placed the *Spatial extents* sub-concepts at very different times in the second sequence than the first. Among the three sub-concepts in this category, the ones previously placed late were placed early and vice-versa. She might have been thinking that she needed to focus on them more the second time, since she said she was *Somewhat sure* about two of the three. There were only four sub-concepts rated *Somewhat sure* in each of the sessions. Her placement of temperatures followed this same pattern to a point. What she placed early the 1st time, was placed late the 2nd time. However, with these sub-concepts, she said she was Very sure for each the 1st time, then changed them both. They were associated with the same main concepts the 1st time and then different main concepts the 2nd.

Cara provided a wealth of well-articulated information about her thinking about climate change. She seemed to have a keen interest in the topic and had lots of ideas, some of which were conceptually congruent with the experts. This was true regardless of the instrument. She was consistent across her interviews in her responses to most of the data groups. For a number of the interview questions, she became increasingly more elaborate in her answers. To what degree that was due to an increased level of comfort with her participation, as opposed to her thinking about the questions in more detail, I cannot say. What is indisputable is that some of her responses as stated came into more agreement with the consensus understanding of the science in her second data collection episode. Her use of the app, however, did not reflect an overall change in confidence or agreement with the experts though there was significant change from how she completed it from first use to the second.

Cara might best be characterized as a bright young person who is struggling to organize in her mind the different elements of the climate change conceptual system. As a result, I saw some responses from her that were consistently held and conceptually agreed with expert consensus. I saw other responses that were consistently held but contained misconceptions. She had some areas in which her conceptualizations became more complex or in more agreement with the experts. Although her use of the concept map exhibited less agreement in some areas, other thinking showed more agreement. Overall, there was practically no net change. It seemed she was trying out some conceptualizations in the app, which would explain why so many of her responses changed, even those for which she expressed confidence.

J.1.1 - Cara's Summary

Cara's responses seemed to exhibit a concern for other living things and a keen interest in learning in her responses to the Yale and epistemic questions in the interviews. She also exhibited some early sophistication in how she should construct her knowledge and her way of looking at climate change as a system.

On the other hand, Cara seemed to wrestle with her ideas about climate change concepts and contradicted herself in her responses to several instruments. She changed her answer back and forth on whether climate change was happening. In her two sessions using the digital app, she changed all but a few relationships between sub-concepts and main concepts. It was interesting that, despite her wholesale configuration changes, her agreement with the experts did not change (in line with the cohort average) and neither did her confidence (much higher than the cohort average).

Cara's struggle with several the sub-concepts could well originate from misconceptions she holds about the main concepts. She said that weather and climate are largely the same. She also indicated that she thinks two separate environments exist for people and animals. Overall, she tended to think of humans as being uninvolved in weather, climate, and environment, in that humans have limited effect on them. This pattern of misconception would have been difficult to see without looking across her responses to the various methods.

J.2 - Dave (Participant 362875): OK with the Status Quo

Dave (not his real name) was an 11-year-old boy who was one of the few participants to respond *No* to the question about scientists' consensus about the existence of climate change. His pattern of responses to other Yes/No questions was interesting in some of responses were flipped from typical patterns. He said that climate change harm was occurring now, but it would not in the future. His response of No to personal harm was not uncommon among participants, but was the minority opinion, nonetheless.

This participant had some interesting misconceptions about life on Earth. First, his long answer about the history of Earth was, "I think there's less water that's in the earth, because we're drinking it and then you can't use it again.", implying that there is simply supply and use of water, rather than a cyclical system that conserves water. This may have played into his response about climate and weather. He said, "Weather is the things that are happening in the environment and it's changing what's growing and what's dying and how humans live. Climate would be the area that you live in…changes from different climates, in which area you live in." He seemed to think of climate as being almost indistinguishable from environment and that weather is the change that happens to a climate/environment.

He talked about people as being unique among living things in that we have "more resources". However, he didn't refer to resources as coming from different environments and rather seemed to mean that humans have ingenuity that they can apply to problems brought about by climate change. However, that ingenuity didn't seem to improve human survivability or adaptability, as he said, "You might get overheated. People will burn up. Animals and plants will be exposed to too much sun."

Dave also had some interesting ideas about ecosystems, in that he seemed to think only humans can instigate change. He said, "An ecosystem is the area basically how the Earth is. It's the system around the earth. No [ecosystems don't change]. Wait, [ecosystems] do change, sorry. If humans are living there, or not, because then they would kill animals like deer and geese. And if they aren't there's and there's going to be more and more and more animals because they're not killing them."

Table 35 - Dave's responses to "the Yale questions"

Dave's responses to yes/no attitudinal questions from both sessions.

	Scientific Nature of CC				Risk perception					Policy	
	Happening?	Affected by people?	Scientists?	Affecting weather?	Harm you?	Harm others?	Harm now?	Harm in future?	Harm plants & animals?	Should be taught?	Leaders do more?
Pre	Y	Y	N	Y	N	Y	Y	N	Y	Y	Y
Post	Y	Y	Y	Y	IDK	N	Y	Y	Y	Y	Y
Delayed	Y	Y	Y	Y	IDK	IDK	IDK	Y	Y	Y	N

Dave's responses to the epistemic questions placed him in the naïve end of the spectra. He was able to cite several sources of information he considered "good", including his Mom, scientists, and Google ("It's always a good source."). However, aside of scientists who are knowledgeable through their research, this participant did not say why his "good" sources were good. Nor did he know any scientists. When asked directly, he said he did not know how to distinguish good from bad sources of climate change information.

Table 36 - Comparison of Dave's app sessions

		Temperature changes		Temporal rates of change			Human activities		Spatial scope of change			Climate change system sub-components					
		Cooling Temp	Warming Temps	Fast changes	Yearly changes	Slow changes	Farming	Industry	Local	Regional	Global	Animals & Plants	People	Forests	Oceans	Greenhouse Effect	
Experts	**consensus configuration**	CW	CW	W	CEW	CE	CEW	CEW	CEW	CEW	CEW	CEW	CEW	CEW	CEW	CE	**86.7%**
Participant 362875 - 1st app use	**configuration**	CW	CW	CEW	CW	C	E	CEW	CEW	CEW	CE	CEW	E	EW	W	CE	**66.7%**
	sequence number	12	14	11	5	15	8	1	6	3	10	13	2	4	9	7	
	confidence	Some	Very	Some	None	Some	Very	Some	Some	Some	Some	Some	Very	Some	Some	None	**53.3%**
Participant 362875 - 2nd app use	**configuration**	W	CE	CEW	EW	CEW	O	CE	CEW	CEW	CEW	E	CEW	C	C	CW	**57.8%**
	sequence number	2	1	9	10	14	15	7	3	8	5	11	4	13	12	6	
	confidence	Very	Very	Some	Some	Some	None	Very	Very	Some	Very	Very	Very	Some	Some	Some	**70.0%**

Table 36 shows the order of steps in which Dave placed sub-concepts as he progressed to his final conceptual configurations for both of her uses of the app. Overall, his first configuration concurred 66.7% with that of experts, somewhat higher than the average of all participants. On *Temperature changes* and *Spatial extents of change*, he matched very well. He seemed to pick, to a degree, the order of his placements in groups, though he did not know the groupings and the sub-concept tiles started in randomized locations. He placed the *Human activities*, most of the *Spatial extents of change*, and most of the *Climate change system sub-components* in the first half, leaving the *Temperature changes*, most of the *Temporal rates of change*, and a couple other sub-concepts to the end.

What Table 36 does not reflect is the number of extra steps it took Dave to arrive at his final configuration. Most participants took a couple extra steps more than the minimum 15. This could be due to reconsidering a prior conceptualization, moving the position of a sub-concepts in subtle ways to make everything more visible, or other reasons. This participant had a habit of picking a sub-concept and returning it to the same location, especially if the location was the sub-concept's original location. Dave did this five times, or with half of the extra steps. In watching the video again, the participant frequently talked to himself and moved his cursor around the main concept map without having picked a sub-concept. It looked like he was figuring out where to put the sub-concept before picking it. This behavior could explain his habit of picking sub-concepts and returning them to their location as indicators that he was not yet ready to place the sub-concept.

Dave's average confidence in his thinking was lower than the overall average of 63%. He had above average confidence for *Temperature changes* and *Human activities*, below average confidence for *Temporal rates of change*, and average for the remaining categories. It is plausible that this participant's behavior of picking, but not moving sub-concepts, would result in higher levels of confidence upon placement. This theory seems to have some merit since two of the three sub-concepts he rated as *Very sure* were ones where he exhibited this behavior. A much larger sample size would be needed to explore this theory fully.

The changes in the Dave's Yes/No responses in the post-test interview from the pre-test moved to better alignment with climate change science. Scientific nature improved with his indication that scientists were in consensus that climate change is happening. Harm indications became more scientifically aligned except for harm to others. Participants frequently responded "Yes" to *Harm to others* but not to themselves. Dave's responses in this category flip this pattern. Future harm became a "Yes", possibly indicating the participant's realization that the problem of climate change is not easily reversed.

In the long question portion of the post-test interview, the participant continued to struggle with differences between climate and weather. He said, "[Weather and climate are] different. Climate can be the temperature and what is going on and in weather usually affects what's happening so climate is based off what weather is so maybe they're similar." This response is like their pre-test in that weather is described as being dynamic. Unlike his prior response, though, the participant indicated in this response that climate is responsive to weather. He identifies similarities between weather and climate, while not being clear about what they are. He seems to be thinking of unspoken sub-concepts as important as inputs and outputs, respectively, of main concepts. In this way, they are climate and weather are similar because they share common important sub-concepts. His response to ESS3.D: Global Climate Change was quite interesting. In response to the question, "What are some things you think people are doing that are making the average surface temperature rise?", he said, "[They are] using more heat and that means the Earth is being heated because the air is staying inside the Earth because of the atmosphere." It is unclear what he means by people "using more heat", but his conceptualization seems to be that heat is trapped inside the Earth and the heating of the surface is coming from within rather than from the atmosphere. He did not say what it was about the atmosphere that was causing heat to stay on Earth's surface. His response to LS4.D: Biodiversity and Humans had similar themes to his pre-test response. Both responses had humans and other animals as members of ecosystems. Other animals like geese, bears, and deer serve as food sources for man, which makes species diversity a good thing, else "…you'd have to kill each other." Without humans killing animals for good, other species' populations would get out of control. In response to the epistemic question about good and bad sources, the participant indicated that familiarity is an important consideration. He says, "[I would go to] Google [for information]. [A bad source would be] a stranger's house [or somebody I didn't know.]"

With Dave's second data collection episode, some of his Yes-No question responses changed, but this time there was a small shift away from scientifically supported positions. His responses to the Scientific nature of CC category stayed the same as before, thus retaining support of the science consensus. The harms category of questions was net no change, though *Harm to others* and *Harm in the present* moved to "I don't know" from "No" and "Yes", respectively. This time, the participant's position on leaders moved to No, indicating his satisfaction they were doing an adequate job.

The long answer portion of Dave's delayed-post-test interview brought out some new themes in his thinking and revisited some previous ones. When asked about evidence of the historical change on Earth, he said, "What has changed is] the flood that God made, started over, what was there. (pause) How humans have evolved…not evolved, but made more buildings and had more technology, which then has changed…and taking more resources out of the planet." He described weather as "…what's happening, what's falling from the sky…" and climate as "…what is there and what the area is…". This was a repeat of what he said in prior interviews with weather as dynamic and climate as static. For the first time in the interviews, however, he mentioned pollution, without explaining how it affects weather or climate. The theme of pollution continued into the ESS2.E: Biogeology question with him saying, “When humans make pollution that can affect the population, what can actually live there. Or when animals can’t live there then humans can’t live there, so, then the humans aren’t there to make more pollution, other things like that.” His response to ESS3.C: Human Impacts on Earth Systems provided clues to what he previously meant with references to technology and resources: “[People] are special because we can think more. And we have more resources to do things about it. Like rockets. Cooling systems. Heating systems if it gets too cold, and yeah.” The extent to which he thought about climate change was revealed in his epistemic responses. In his previous interview, he explicitly said he thought about climate change “once a year”. This time, when pressed, he said he thought about it once a year as part of his home school annual assessment. Except as part of his assessment, he indicated he didn’t think about climate change at all.

Dave’s second use of the concept map app was notable because of how differently he used it from the first time. He kept only three of the fifteen sub-concepts the same. The three were <*Local area*>, <*Regional area*>, and <*Fast changes*> with all three mapping to <*Climate, Environment, & Weather*>. His overall level of agreement with the experts dipped to 57.8%. The three sub-concepts he previously was *Very sure* about all changed. One clear pattern that emerged with this use of the map was he placed all but one of the sub-concepts about which he was *Very sure,* followed by the ones he was *Somewhat sure* about, and finished with the one that he was *Not sure* about. Despite having less agreement, he was surer overall with his placements, moving to above average at 70%. His habit from his first use of the app of picking a sub-concept, but not placing it, was repeated this time. <*Farming*> was the only sub-concepts where he repeatedly exhibited this behavior. Like with his first use of the app, he had 10 “extra” steps in his construction, which was considerably higher than was typical with these participants.

His most interesting answers of the data collection episode were in response to his second use of the app. He said he thought it was a good game, but that it didn’t teach him anything. However, he didn’t think the game taught him anything because “…at the end, it didn’t tell me I was right or wrong.” He also said, “I didn’t really enjoy it because it was [too much like] school.”. Ironically, the thing he really liked about the game was that it gave him choices he could always change his mind.

Dave was quite direct in how he talked about his thinking. Because of this, I learned some things about him that could contribute to designing effective learning. For one, he is not curious about the topic of climate change in that he only seeks out information when he feels he must. He has only general sources to explore his questions and doesn’t really know how to gauge the information he gets from them. He seemed to lack some essential information about Earth systems which would help him discriminate the main concepts of weather, climate, and environment. While he recognizes that there is a dynamic aspect of weather, he sees climate and environment as being interchangeable concepts and static ones at that. He sees the environment is primarily a food source, which would go into an overpopulation spiral without the involvement of people. Being less able to distinguish the nature of the main concepts makes it difficult for him to make placements with the concept map app. The high number of extra steps he required to complete the concept maps speaks to a degree of confusion and indecision to make the sub-concepts “fit”.

J.2.1 - Dave's Summary

Dave's responses were interesting in several regards because they differed from most other participants. Regarding the main concepts, he sees the environment primarily providing food and other resources to humans. He seems to see climate as being an aspect of environments because he thinks climate substantially determines what type of environment exists in an area. He also had difficulty articulating differences between climate and weather.

All but one of Dave's responses to the Yale questions changed over the three interviews. The only question he answered consistently was his assertion that climate change was going to affect animals and plants. With his final interview, he flipped three of his responses, though there was no obvious conceptual connection between the changes.

There may be a clue connecting Dave's responses to the NGSS topical questions and his concept map constructions. When asked how Earth has physical changed over time, he referenced the biblical great flood. Some learners perceive "deep time" as being grounded in biblical references rather than the geologic record. They tend to have difficulty with the long time scales involved in climate change. In Dave's case, he tended to manipulate sub-concepts from the *Temporal rates of change* category later in his sessions with the digital app. He also rated his confidence about these sub-concepts as low. His data from these instruments are coincident and may be related.

Dave's responses to the epistemic questions were consistently scored as naïve. He said that he only thought about climate change once a year. When asked to respond more deeply about this, he said he only sought information about climate change science because it was part of his annual home school evaluation.

Dave is presently unmotivated to learn about climate change science. Clearly, his thinking about climate, environment, and weather needs to be better informed by the science. However, any efforts to address this while he is unmotivated to learn would likely fail. Given Dave's comments that the game "…didn't tell me I was right or wrong.", may mean it will be up to a savvy educator to find him an inspirational source of motivation. Once that source has been engaged, Dave may be able to transfer his locus of motivation to make it more intrinsic than extrinsic and assume more personal control of his climate change science learning.

APPENDIX K - DIFFERENCES BY AGE SUB-GROUP

This dissertation placed importance on participant age and its design process factored age-suitability in its decision-making. It was important that choices considered the full range of ages of the participant cohort. An in-depth exploration was initiated to explore whether this dissertation’s methods were indeed suitable for all participants. This exploration was pursued until two things became clear. First, that such an exploration was an unnecessarily deep dive at this stage, given that the age range for participants had already been well justified. Second, insufficient numbers of participants prevented any statistically defensible conclusions. As a result, this sub-study was placed on hold until a more robust and focused study on this topic could be conducted. However, the present state of the sub-study is presented in this appendix for interested readers.

Several interesting behaviors that seemed to be related to participant age were observed in the preliminary study (Toedte, 2018) and repeated in the current study. The first saw younger participants relating sub-concepts more to only a single main concept than did older participants. The second saw younger participants establishing a relationship between a sub-concept and one or more main concepts, but then undoing it later by drawing a relationship with a different main concept. In essence, they changed their minds about their thinking more than older participants. This section concludes with observations about, and offers explanations for, additional differentiating features between the two age sub-groups’ data.

K.1 - Digital App Response Differences between Age Sub-groups

Children who participated in this study were aged 9 to 13. The low end of this age range allows for most children to have developed critical cognitive, metacognitive, and linguistic skills which are essential for understanding climate change science. The upper end of the range is generally the maximum age for middle school attendance in the United States. A key argument of this dissertation's work is that children need to be exposed to climate change science as soon as developmentally possible.

Having attained cognitive, metacognitive, and linguistic skills, middle school age learners are generally well suited to learning climate change science. That said, children are far from monolithic in terms of the timing of their skill attainment, their degree of development, nor their actual application of the skills. Reading levels for grades 4-6 vary widely. Reading levels at the extremes of the band that meets reading standards, differ by as much as 50% within a grade, as well as 50% between grades (Beaver & Carter, 2009; Hasbrouck & Tindal, 2006). Cognitively, many children have achieved the Piagetian concrete operational stage well before the age of 9 while others have yet to get to this level by age 11 (Renner, et al., 1976). Metacognitive skills are reported to emerge at a range of ages starting at 3 and extending to age 8 and later (Flavell, 1979; Moshman, 1998; Kuhn, 1999; Kuhn, 2000).

To explore what age effects were exhibited through the research methods used in this dissertation, subgroups of 9-to-10-year-olds and 12-to-13-year-olds, respectively, were formed. Only participants assigned to the gameplay condition were chosen because there were more gameplay participants than reading participants. Furthermore, mixing reading condition and gameplay condition participants would have introduced a second variable, where the focus of this particular analysis was age.

One interesting feature was the different levels of complexity exhibited by the respective sub-groups' responses. Table 37 shows conceptual relationships from gameplay drawn by the eleven participants across the two age ranges. Despite the small number of participants, differences between the groups were discernable. First, with the younger group, there are far fewer instances where the participant chose the intersection of all three main concepts, shown in white and labeled "CEW" for <*Climate, Environment, & Weather*>. The younger group of learners more often chose <*Environment*> only, labeled "*E*" in green, as the main concept associated with the sub-concepts. The number of exclusive associations with <*Climate*>, "C" in blue, or <*Weather*>, "W" in red, were roughly equal between the two groups.

This response corresponds to the prior study where an age-related preference to simple associations appeared (Toedte, 2018). In that study, 80.3% of responses from children aged 7-8 were of the simple variety, while only 36.8% of participants aged 9 and higher answered in this way. In the current study, participants (all of which were at least age 9) chose single main concepts for their relationships 34.2% of the time, in line with the earlier study. The current study showed a moderately negative correlation between age and the participants' tendency to answer in terms of simple relationships (r = -.263).

Table 37 - Comparison of placements across age groups

Comparison of placement of sub-concepts with the C^3M_{YC} digital app for two age groups.

	Session ID	Temperature changes		Temporal rates of change			Human activities		Spatial scope of change			Climate change system sub-components				
		Cooling Temp	Warming Temps	Fast changes	Yearly changes	Slow changes	Farming	Industry	Local	Regional	Global	Animals & Plants	People	Forests	Oceans	Greenhouse Effect
9-10 year olds (5)	150	C	C	C	CE	C	EW	E	E	E	E	E	E	CE	E	W
	173	C	C	CEW	CEW	CEW	E	CW	CW	CW	CW	E	CE	E	E	EW
	178	EW	CEW	W	E	C	CEW	CW	CE	CW	CEW	CEW	C	E	EW	EW
	187	W	CW	O	CEW	CE	EW	O	O	E	CEW	E	E	E	EW	O
	200	CW	W	CW	CW	E	CEW	EW	EW	E	C	CE	C	CEW	W	O
12-13 year olds (6)	176	CEW	CW	W	CE	C	CE	CE	EW	CE	CEW	CEW	CEW	E	EW	CEW
	216	C	C	C	E	W	CW	CEW	CE	EW	CEW	CEW	CEW	CE	EW	E
	156	CE	CE	EW	O	O	EW	CEW	CEW	EW	CEW	CEW	CEW	EW	E	CE
	163	CEW	CEW	EW	CEW	CEW	O	CEW	O	O	O	CE	CEW	CE	CEW	CEW
	189	EW	W	W	E	C	CEW	CE	W	E	C	E	CE	E	E	C
	201	CW	CW	W	C	E	CEW	CEW	E	CE	CEW	E	CEW	E	CE	CEW

Another noteworthy feature was sub-groups' differential responses as a function of sub-concept category. The top row of Table 37 identifies different sub-concept categories such as *Temperature changes*, *Human activities*, and *Spatial extents of change*. In terms of main concept associations with *Temperature changes* and *Temporal rates of change* sub-concepts, the two age groups exhibited similar patterns. However, significant age-related differences can be seen in Table 37 for the remaining sub-concept categories, *Human activities* and *Spatial extents of change*. Except for <*Greenhouse effect*>, this was also true of *Climate change system sub-components*. Age-related differences were especially prominent in this sample for conceptualizations of <*Animals & plants*> and <*People*>. The younger sub-group participants equally associated single and multiple main concepts to these sub-concepts. The older sub-group participants, almost as a rule, used multiple main concepts in their conceptualizations. This concurs well with a finding from the earlier study (Toedte, 2018), though the reduced strength of the correlation in this study might suggest a plateauing of this tendency for children aged 9 years and higher.

A closer look at analogous data in the present study yielded a moderate negative correlation across all sub-concepts (*n* = 49, *r* = -0.263) that was somewhat lower than previously found (*Ibid*.). Table 37 shows that 9–10-year-olds' responses for <*Animals & plants*> and <*People*> were dominated by single main concept responses. In contrast, the responses of 12–13-year-olds were overwhelmingly with multiple main concepts. I subsequently reran the correlation for only those two sub-concepts. This yielded a stronger negative correlation (*n* = 49, *r* = -0.431). Finally, I included <*Forests*> and <*Oceans*> in the correlation, which sustained the higher correlation (*n* = 49, *r* = -0.441). The was virtually no correlation between age and tendency to relate single main concepts with all other sub-concepts (i.e., not <*Animals & plants*>, <*People*>, <*Forests*>, or <*Oceans*>) (*n* = 49, *r* = -0.081). It is notable that the earlier work may have had an increased age-related effect, given that five of the 35 participants in the 2018 study were 7- and 8-years-old; ages which were younger than the minimum of 9-years-old for the present work.

Table 38 and Table 39 contain summaries of haptic data collected from the participants of the younger and older sub-groups, respectively. The leftmost of the 5 blocks of data shows elapsed time to place all sub-concepts atop main concepts and to finish using the app. Two differences between the groups are evident. First, the distribution of last placements is different in that the older learners had 4 placements of *Temporal rates of change* sub-concepts, where the younger learners had none. Temporal rates of change are frequently misunderstood for climate and weather, and contribute significantly to their conceptual conflation, especially for younger learners. Therefore, this metric may indicate a lack of awareness that climate is not the same as weather, especially that they occur on very different time scales. However, it is a very good thing if learners' conceptualizations significantly concur with those of experts *and* they exhibit a high degree of confidence. Second, the elapsed time to placing the last sub-concept was roughly 20% less for older learners (430 seconds compared to 532 seconds). Older learners tend to have worked out aspects of many topics, simply by being older and having achieved a higher developmental level. Thus, the shorter time may indicate prior climate change conceptual learning has occurred. However, shorter times may also mean the learners are spending less time metacognitively engaged, and thus not accurately articulating their degree of certainty, which would shorten the total time spent with the app.

Table 38 - Detail for 9–10-year-olds

Detail of logged data from the C^3M_{YC} digital app for selected 9–10-year-olds.

Participants 9-10 years old (5) in their 2nd use of the app

Sub-concept category	Sub-concept index #	Sub-concept name	Sub-concepts placed last				Sub-concepts placed most slowly				Sub-concepts placed additional times				Sub-concepts picked the longest time (MouseUp <---> MouseDown)				Self-rated uncertainty			
			1	2	3	Total	1	2	3	Total	1	2	3	Total	1	2	3	Total	1	2	3	Total
Temps	0	Warming	1	0	1	4	0	0	0	3	1	0	0	3	0	0	0	2	0	0	0	2
	1	Cooling	0	1	1		0	1	2		0	2	0		1	0	1		1	1	0	
Temporal	2	Fast	0	0	0	0	0	1	0	3	1	0	0	3	0	0	0	3	0	0	0	1
	3	Yearly	0	0	0		0	1	1		0	1	1		0	1	0		1	0	0	
	4	Slow	0	0	0		0	0	0		0	0	0		0	1	1		0	0	0	
Activities	5	Farming	0	0	0	1	1	0	0	1	1	0	0	1	1	0	0	2	0	0	0	0
	6	Industry	1	0	0		0	0	0		0	0	0		0	1	0		0	0	0	
Spatial extent	7	Local	0	0	1	4	0	0	2	5	0	1	0	3	1	1	0	4	0	0	0	0
	8	Regional	0	0	1		1	0	0		0	0	0		0	0	1		0	0	0	
	9	Global	1	0	1		2	0	0		0	0	2		0	0	1		0	0	0	
Climate system elements	10	Animals	0	1	0	6	0	0	0	3	0	0	0	2	1	0	0	4	0	0	0	0
	11	People	0	1	0		1	0	0		0	0	0		1	0	1		0	0	0	
	12	Forests	1	0	0		0	1	0		2	0	0		0	0	0		0	0	0	
	13	Oceans	0	0	0		0	0	0		0	0	0		0	0	0		0	0	0	
	14	Greenhouse	1	2	0		0	1	0		0	0	0		0	1	0		0	0	0	
			Mean (seconds)		531.64		Mean (seconds)		40.50						Mean (seconds)		14.65					
			Stdev		141.28		Stdev		27.28						Stdev		8.36					
			Skewness		-0.46		Skewness		0.03						Skewness		1.53					

Table 39 - Detail for 12–13-year-olds

Detail of logged data from the C^3M_{YC} digital app for selected 12–13-year-olds.

Participants 12-13 years old (6) in their 2nd use of the app

Sub-concept category	Sub-concept index #	Sub-concept name	Sub-concepts placed last				Sub-concepts placed most slowly				Sub-concepts placed additional times				Sub-concepts picked the longest time (MouseUp <---> MouseDown)				Self-rated uncertainty			
			1	2	3	Total	1	2	3	Total	1	2	3	Total	1	2	3	Total	1	2	3	Total
Temps	0	Warming	2	0	0	3	1	0	1	2	0	1	0	1	1	0	0	2	0	0	0	0
	1	Cooling	0	0	1		0	0	0		0	0	0		0	0	1		0	0	0	
Temporal	2	Fast	0	1	0	4	0	0	1	3	0	0	0	1	0	0	1	4	0	0	1	3
	3	Yearly	0	0	2		1	0	0		0	0	0		1	0	0		0	1	0	
	4	Slow	1	0	0		1	0	0		1	0	0		1	0	1		1	0	0	
Activities	5	Farming	1	0	0	1	0	1	0	1	0	0	0	1	0	1	0	1	0	0	0	0
	6	Industry	0	0	0		0	0	0		0	1	0		0	0	0		0	0	0	
Spatial extent	7	Local	1	1	0	5	0	0	1	3	0	0	0	0	0	1	0	3	0	0	0	0
	8	Regional	1	1	0		0	0	1		0	0	0		0	0	1		0	0	0	
	9	Global	0	0	1		0	1	0		0	0	0		0	1	0		0	0	0	
Climate system elements	10	Animals	0	0	0	5	0	1	1	9	0	0	0	1	0	1	1	8	0	0	0	1
	11	People	0	2	0		0	1	0		0	0	0		0	1	0		0	0	0	
	12	Forests	0	0	1		1	1	0		0	0	0		1	1	0		0	0	0	
	13	Oceans	0	0	1		2	0	1		0	0	0		2	0	1		0	0	0	
	14	Greenhouse	0	1	0		0	1	0		1	0	0		0	0	0		1	0	0	
			Mean (seconds)		429.53		Mean (seconds)		39.87						Mean (seconds)		15.77					
			Stdev		145.44		Stdev		103.16						Stdev		11.91					
			Skewness		-0.19		Skewness		4.15						Skewness		1.62					

The third and fourth blocks of data show, respectively, which sub-concepts were placed more than once and how long haptic events took to complete. The third block shows that younger learners returned to previously placed sub-concepts much more than older participants, and the sub-concepts they returned to were evenly distributed across the categories. The fourth blocks are, by contrast, similar with one exception. Younger learners spent, on average, 14.6 seconds to place a sub-concept once it was picked. Older learners spent a little longer at 15.8 seconds. However, the difference in standard deviations (8.4s for younger learners, 11.9s for older learners) indicates that there was more uniformity in older children's responses. Taken together, this data could mean that, overall, older children exercised more patience and took more time with their sub-concept placements. The extra time could involve unconscious evaluation as a child thinks to themself, "Does it fit here? How about here? Which is better?". This additional degree of metacognitive monitoring and evaluation could easily result in fewer instances of moving a sub-concept a second or third time.

K.2 - Overall Conceptual Agreement and Confidence Differences between Age Sub-groups

Figure 39 - Response breakdown by age

Group averages of participants' self-rated confidence in their thinking about 15 sub-concepts in the game. (gameplay condition 12-13 YOs n=5, gameplay condition 9-10 YOs n=6, reading condition 12-13 YOs n=4, reading condition 9-10 YOs n=5).

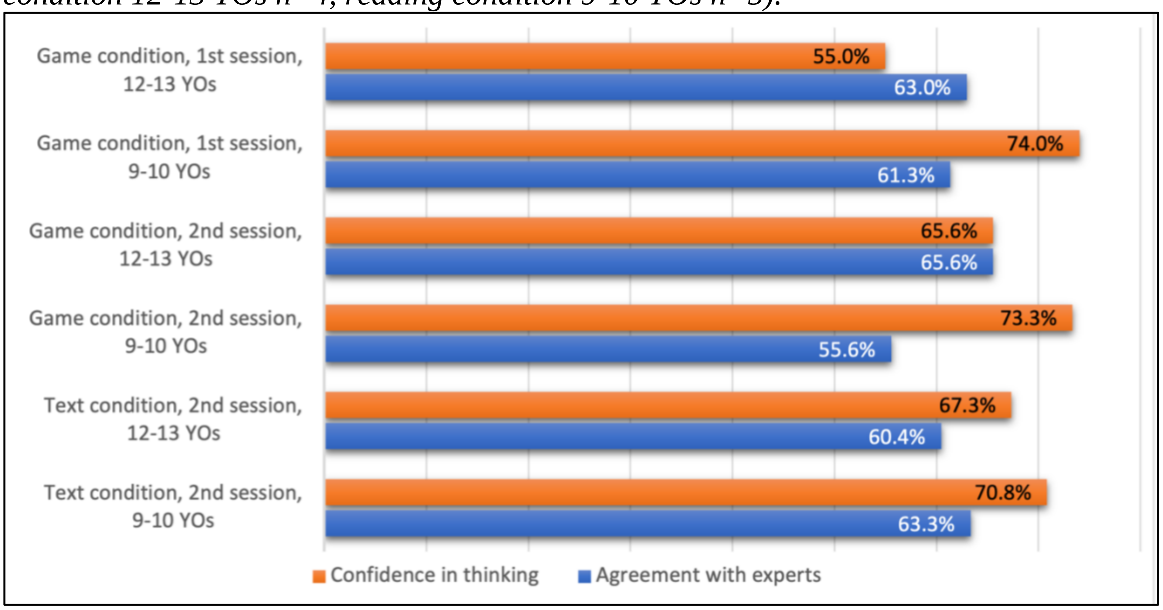
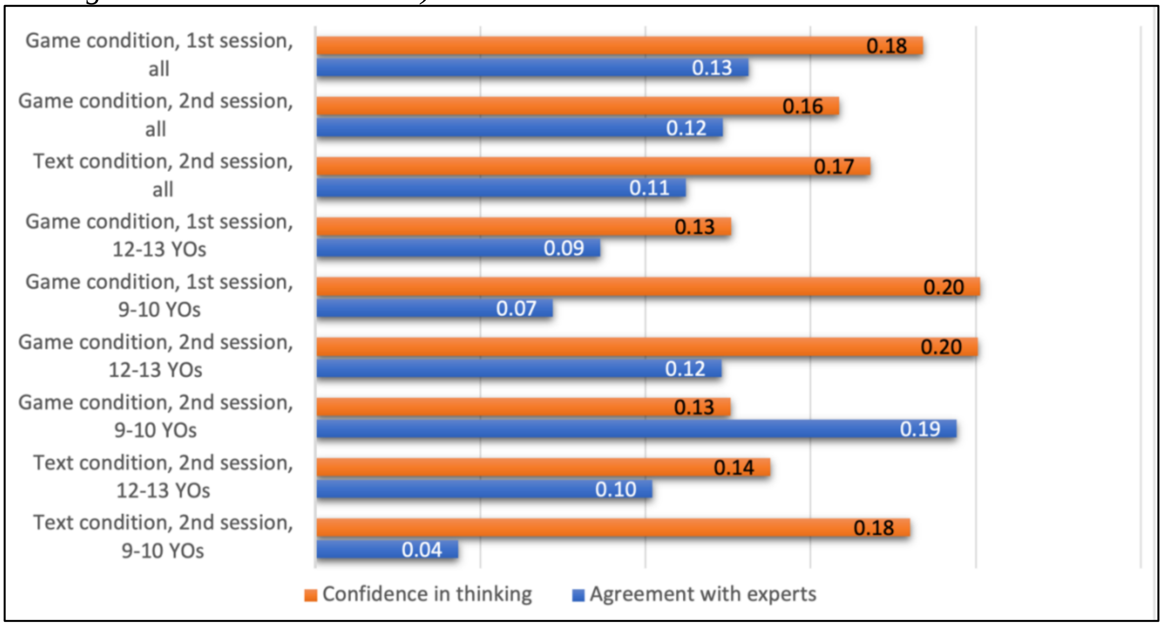


Figure 40 - Response standard deviations

Standard deviations by app data field, and participation groups and subgroups. (gameplay condition 12-13 YOs n=5, gameplay condition 9-10 YOs n=6, reading condition 12-13 YOs n=4, reading condition 9-10 YOs n=5).



APPENDIX L - PERSONAL REFLEXIVITY STATEMENT

Many of the decisions I made in the design and implementation of this dissertation can be traced to my prior experiences, both personal and professional. I feel it is important to mention some of these experiences and the roles they play in my current thinking, including my personal attitudes and dispositions. These, in turn, played roles in the design and conduct of this work. Lincoln, Lynham, & Guba (2011) calls this reflexivity and describes it as follows.

> "Reflexivity is the process of reflecting critically on the self as researcher, the "human as instrument" (Guba & Lincoln, 1981). […] It is a conscious experiencing of the self as both inquirer and respondent, as teacher and learner, as the one coming to know the self within the processes of research itself. Reflexivity forces us to come to terms not only with our choice of research problem and with those with whom we engage in the research process, but with ourselves and with the multiple identities that represent the fluid self in the research setting (Alcoff & Potter, 1993)." (*Ibid*., p.124).

Being reflexive to me means being open about what I think it is about me that affects my decision-making throughout a research activity, even to my reasons for choosing the research topic. While my aspiration is to conduct the perfect research project, it is completely unreasonable to expect that to happen. There will always be something that can be improved. Watt (2007) hints at this unfortunate reality.

> "Although there are guidelines in the literature [about research design, there is] no precise formula on how to proceed. Each project is unique and ultimately it is up to the individual to determine what works best. Since the researcher is the primary "instrument" of data collection and analysis, reflexivity is deemed essential (Glesne, 1999; Merriam, 1998; Russell & Kelly, 2002; Stake, 1995)." (*Ibid*., p.82).

I would append, "…in the moment…", to Watt's statement about, "…determin[ing] what works best…". The researcher makes many irreversible choices during a study. They can only do the best they can in the moment and move on, knowing full well they might realize a better solution later. One example is when the researcher finds an additional information source that tweaks their conceptualization of a term that results in revised interview questions. If half the participants have already been interviewed, the researcher is left with a less than ideal outcome, regardless of if they change the instrument for the second half or keep it consistent. Another is when the researcher finds an additional location where they can conduct research. If the location is found once data analysis is already in full swing, interrupting analysis to add participants is less than completely satisfying to the researcher, just as it is to eschew the new participants.

As you might imagine, these examples are not hypothetical. They actually occurred during this study. Each example represents a junction where a research decision had to be made. In many cases, there was not a clearly better option but, because of my experiences, I was disposed to a particular choice from among good choices. At each junction, a decision was made, and the work continued. In this way, it is impossible to separate the research from the researcher. Following are some of my experiences that have influenced the structure and conduct of this research.

L.1 - Growing Up in Nature

I grew up in southern Illinois, which is almost completely rural. My Mom was a homemaker and my Dad was a farmer. Mom was an avid birder, butterfly collector, and gardener. She and I would often go dewberry or blackberry picking on one of the rare parcels of land not under cultivation. I accompanied Dad working on the farm and, when possible, we hunted and fished together. As a family, we would often go to state parks to picnic and hike. When I got a bit older, we traveled more widely, going to national parks like Great Smoky Mountains National Park near my current home in Knoxville, TN. It seemed that no matter what activity I was doing, it was usually outside. From my Mom, I got an appreciation for the connectedness of nature. When we collected monarch butterfly larvae, we also collected milkweeds for them to feed on and attach their chrysalises. From my Dad, too, I got how nature was intertwined, but with a negative twist. A lot of his farming practices seemed overly destructive. It was hard to miss the fact that the herbicides he used killed the intended weeds, but also many other plants, often with detrimental effects on animals.

I believe my choice of science learning topics, climate change, is connected to my longtime love of nature and recognition of its interconnectedness.

L.2 - Working at "the Lab"

My interests in education and psychology started about twenty-five years ago, in the middle of my computational science career at Oak Ridge National Laboratory. I had no prior formal training in education and only introductory psychology as an undergrad. My professional career started at a national science research laboratory six weeks after getting my baccalaureate degree in computer science. Most of my 32 years at "the Lab" were involved in computational science, and the last half of those years were included public communication of science. Though I worked with a number of different computational science teams, climate modeling took an outsized portion of my effort. Much of the modeling work came under the umbrella of the Intergovernmental Panel on Climate Change. In this role, I learned a lot about the science of climate change, experimentation and modelling projects, and the potential and limitations of climate data analysis and visualization. As I continued working with the climate modeling team, the thought that climate change was a science issue that demanded social response was increasingly at the forefront of my thinking.

I believe that social response must be informed, and climate change is a difficult topic to learn. However, a lot of very credible climate data exists, from computational models and field experiments, that can serve as bases for science thinking for learners of all ages.

L.3 - Visualizing Science and Public Science Communication

My role with the modeling center was to provide visualization support for projects doing simulation runs on our supercomputers. A part of my responsibilities was to run our 1800-square-foot visualization facility with its own computing infrastructure and wall-sized tiled displays for showing visualizations to management, staff, and Lab visitors. The bulk of the results that were viewed in this facility were unclassified, open science. Furthermore, almost anybody could schedule an appointment to come to our facility to see and discuss the visualizations. Roughly a third of the groups that visited were middle school and high school student groups on field trips. I *loved* talking to them because their curiosity and questions were so genuine and individualized. There was also so much for me to learn from them. In some cases, they asked very logical, scientific, yet naïve questions, as you would expect from young children. In other cases, they expressed very unscientific and irrational statements that hinted at social influences. What were the bases for their questions and statements? Why did a particular social or psychological factor take hold with the learner? I wanted to understand both the rational and irrational factors that affected science learning and thinking in children.

An emphasis of this work is the unique ways that climate change is characterized by children. My applied science career told me that no two people said the same about a scientific visualization. Too many variables were involved. Similarly, no two people describe climate change the same way. To what extent do social and psychological factors affect a young learner's thinking about climate change? This study initiates a response to this question.

L.4 - Realizing the Nature of Nature of Science

I was introduced to NoS in my first semester of science education graduate study after having left the Lab. NoS focuses on differences between actual science practices and what non-scientists think scientists do when they "do science". I think NoS, to some extent, pulls back the curtain on science practices and makes them more approachable to science learners. One of the core beliefs of NoS is that the state-of-the-art in science is in a constant state of flux. Science practice is always changing, always evolving, and almost always building on earlier findings, devices, and theories. My experiences both with computational modeling teams and giving public talks about science have allowed me to see two aspects to this NoS tenet. Scientists learn from other scientists in the field and incorporate findings from their community to advance their own ideas. Young learners, similarly, build their thinking through discussion with others whose ideas they deem plausible, reputable, and trustworthy. Therefore, neither young learners nor scientists can ever lay claim to absolute scientific knowledge, regardless of the science domain.

The Nature of Science literature embraces the tentativeness of scientific knowledge. As a result, this study uses the word, "thinking", rather than, "knowledge". The science learners in this study…the middle-school-age children…were asked, "What do you think climate is?", rather than the more challenging and stress-inducing question, "What do you *know* climate is?"

L.5 - Parenting

I am a parent of two amazing people. When I first started thinking about switching from a career in applied science to graduate school in education, they were in middle school. Parents' main job is to prepare their children for life. It is now realistic to say that a child's life will require them to understand and adapt to climate change. Therefore, it seems reasonable that parents will increasingly want their children to understand both the scientific and social aspects of climate change.

Most parents want their children to learn about climate change (Kamenetz, 2019) and most registered voters feel the same way (Leiserowitz, Maibach, Rosenthal, Kotcher, Ballew, Goldberg, Gustafson, & Bergquist, 2019). If the present study is any indication, children as young as 9 years old recognize that climate change poses a threat to them. They also think they should be taught about climate change in school, with the cohort (n=31) saying "Yes" <u>unanimously</u> in the pre-test, post-test, and delayed-post-test.

The unfortunate reality is that many children don't get any climate change education. Those that do, don't get enough of it, or get a version of it tainted with misconceptions (Goldenberg, 2016). In a national study of science teachers (Plutzer, et al., 2016), the mean amount of time spent by middle school teachers on climate change was 4.4 hours. The authors estimated that climate change was being taught in 90% of middle schools in at least one subject. Frankly, these numbers are encouraging. Less encouraging was that 54% of teachers (combined middle school and high school) mixed messages that natural and anthropogenic sources were responsible for the recent rise in atmospheric CO_2. Even less positive was only 11% of teachers said they would prevent climate change from becoming a debate in their classrooms. Eighty-five percent of the teachers said they have or might, if circumstances arose, give natural and anthropogenic sourcing equal weight in class discussion. In terms of teacher preparedness, 57% of teachers reported having no formal education in climate change.

I strongly believe that before one teaches, you need to know *what* to teach. To find out what to teach, it is extremely useful to understand what the learner already thinks and why they think it. The principal goal of this study is to understand children's thinking about a problem that has already begun to affect their lives. In the present study, children talked about climate change, in many cases for the first time. They spoke words they had rarely used and thought new thoughts. Most importantly, the speaking and thinking came directly from *them*. I believe parents should encourage their children's speaking and thinking about topics, *especially* those topics that have profound societal implications.