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Modeling a Pandemic: Investigating Student Learning about Disease Spread in the Context of Agent-Based Modeling

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MODELING A PANDEMIC: INVESTIGATING STUDENT LEARNING ABOUT DISEASE SPREAD IN THE CONTEXT OF AGENT-BASED MODELING

by

Siyu Wu

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ABSTRACT

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in the Context of Agent-Based Modeling

by

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The COVID-19 pandemic has highlighted a need for students to learn about public health issues, including the transmission of disease and methods for the prevention of epidemics. This study presents data from a project focused on developing computational microworlds to help middle school students learn about these topics. The microworld is designed to help students model and test their ideas about how a disease spreads through a population and how an epidemic can be prevented. I employed a lab-based case study approach to conduct one-on-one 1.5-hour interviews through Zoom with four middle-school students (ages 12-14). During the interview, the student was asked questions about the spread and prevention of disease and then invited to model and test their ideas in the microworld. This study presents an analysis of students' pre and post instructional knowledge of disease spread and prevention, which they shared while constructing their initial and later models. I present student ideas in categories of *disease transmission*, *recovery from disease*, and *disease protection strategies*. The paper also analyzes students' knowledge refinement through the building, testing, and debugging of a disease spread and prevention model. I model student refinement of thinking through steps of building initial models and predicting results, testing initial models, making sense of the results, debugging and retesting models, observing final models, and explaining results, resulting in three types of thinking shifts, and two types of thinking refinements. My findings suggest middle school students can learn about strategies for disease prevention through computational modeling.

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PUBLIC ABSTRACT

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The COVID-19 pandemic has highlighted a need for students to learn about public health issues, including the transmission of disease and methods for the prevention of epidemics. This study presents data from a project focused on developing computational microworlds to help middle school students learn about these topics. The microworld is designed to help students model and test their ideas about how a disease spreads through a population and how an epidemic can be prevented. I employed a lab-based case study approach to conduct one-on-one 1.5-hour interviews through Zoom with four middle-school students (ages 12-14). During the interview, the student was asked questions about the spread and prevention of disease and then invited to model and test their ideas in the microworld. This study presents an analysis of students' pre and post instructional knowledge of disease spread and prevention, which they shared while constructing their initial and later models. I present student ideas in categories of *disease transmission*, *recovery from disease*, and *disease protection strategies*. The paper also analyzes students' knowledge refinement through the building, testing, and debugging of a disease spread and prevention model. I model student refinement of thinking through steps of building initial models and predicting results, testing initial models, making sense of the results, debugging and retesting models, observing final models, and explaining results, resulting in three types of thinking shifts, and two types of thinking refinements. My findings suggest middle school students can learn about strategies for disease prevention through computational modeling.

CONTENTS

Page

LIST OF TABLES

LIST OF FIGURES

CHAPTER I

INTRODUCTION

The COVID-19 pandemic has highlighted a need for a health-literate society. This means enhancing the public's knowledge of public health issues, including the transmission of disease and methods to prevent epidemics. Adolescents in particular have experienced the dramatic effects of the pandemic. They have watched their schools close and move online, and their social contact has been minimal. Their out-of-home leisure activities have been canceled. They also have been exposed to a large amount of information from social media, which can trigger stress (Fegert et al., 2020). As such, students need support in constructing an understanding of the spread of disease to help them promote their and their families' overall wellness.

Epidemiology is a branch of science that studies health-related behaviors and outcomes in populations. This includes subjects such as disease causation and transmission, outbreak investigation, and disease surveillance. At present, learning about epidemiology is primarily limited to graduate and undergraduate students. By comparison, few middle school students have access to epidemiology courses (D'Agostino, 2018). Some scholars and epidemiologists have found that developing epidemiology material for middle school students is challenging and time-consuming (Hlaing, 2014; Hollm-Delgado, 2014). However, learning epidemiology at an early age is essential to help students make informed decisions regarding their health and develop critical thinking regarding public health policy (Bracken, 2014).

One of the most widely-recognized national programs to bring public health sciences into middle school classrooms is the Centers for Disease Control and Prevention's (CDC) Science Ambassador (SA) Program (CDC, 2020), created approximately 20 years ago. The program targets adolescents' public health education by working directly with STEM teachers and educational leaders who develop lesson plans for public health topics (Hamner et al., 2008). Researchers found that many students associated with this program had taken few, if any, epidemiology courses before (Ralph et al., 2017). The program evaluation report reveals factors that prevent middle school students from learning effectively, which diminishes their confidence and interest in learning epidemiology. Some students complained that the teaching and evaluation methods were instructor-centric (i.e., lecture and standardized tests). Additionally, some students were dissatisfied with the curriculum content, stating that some lessons were difficult to understand and unrelated to life (Martinez, 2020). If we do not improve our method of pedagogy, we may create epidemiological courses that overwhelm students and prevent them from learning essential public health topics.

In alignment with the goals of enhancing students' public health literacy and increasing the number of students interested in epidemiology topics, I am designing a student-centered inquiry-based pedagogical approach. This approach uses a computational modeling microworld that allows students to build, test, and debug disease spread models based on their ideas. Microworlds are computer-based interactive learning environments where the prerequisites of domain knowledge are built into the system using program code (Edwards, 1995). In this approach, students develop models of disease spread and prevention at the level of a population by thinking about a single person's behavior and analyzing and predicting the phenomena that result from the interaction of many people. We are investigating what impacts the modeling approach has on students' learning. The more extensive scope of the larger study (of which this thesis is a part) investigates computational modeling as a way of introducing middle school students to scientific theory-building practices.

The larger study is a design-based research project (Collins et al., 2004) designed to create computational agent-based microworlds and associated curriculum to teach middle school science. The larger project is in its initial stages of design-based research. The present work builds on previous research (Swanson et al., 2021; Wu et al., in press a), which investigated student intuitions about the spread of disease and designed a microworld to help students test their intuitions and develop more scientific understanding. As a result, we have developed a computational modeling environment that consciously meets students halfway, by giving students programming blocks that allow them to work with ideas that closely match their intuitions. This work investigates how the computational modeling environment impacts students' learning about disease spread and prevention.

I organize my research questions as three questions, which together help me address my overarching question: "What is the impact of engaging with a series of modeling microworlds on students' thinking about the spread and prevention of disease?" To answer this question, the study will investigate the following research questions.

1. How are students thinking about disease spread and prevention as they construct their initial flu and COVID models?
2. How do students understand disease spread and prevention as they construct their later flu and COVID models?

3. How do their ideas change from their initial to their later thinking in response to their modeling activity?

CHAPTER II

LITERATURE REVIEW

Introduction

The purpose of this research is to investigate young students' prior knowledge about disease spread and prevention and how the computational modeling of microworld will support their learning about the spread of disease. The purpose of this literature review is to delve deeper into research relating to pedagogical approaches that (1) build on students' prior knowledge, (2) utilize computational modeling, and (3) focus on instruction aimed at teaching epidemiology topics to middle school students. This literature review is separated into three sections corresponding to each of these topics.

Article Selection Criteria

Google Scholar and Utah State University's online library resources were used to locate peer-reviewed studies published between 1980 and 2020, with a primary emphasis on those related to prior knowledge pedagogy, computational modeling pedagogy, and pedagogical approaches to teaching epidemiology to middle school students. A variety of search terms were used both singularly and in combination, including, but not limited to, prior knowledge pedagogy, inquiry-based instruction, computational modeling pedagogy, STEM expertise, and grade 7-10 epidemiology pedagogical approaches. Articles were also identified through the recommendation of researchers with expertise in the relevant literature. In the end, 32 articles were identified and selected for inclusion.

Summary of the Literature

I conducted a review of thirty-two articles using a qualitative analysis method. Articles were coded to discuss key themes, particularly on what domain knowledge students are learning about, which pedagogical approaches researchers are utilizing, and what learning outcomes result. This section of the proposal will present the results of this review.

Pedagogical Approaches to Epidemiology

Inquiry-based instruction has been used to instruct students about Epidemiology (D'Agostino, 2019). Inquiry-based instruction involves collaboratively designing curricula that allow for extended investigations and actively inquiring into a scientific phenomenon (Minner et al., 2010). An inquiry-based approach is rooted in constructivism (Shimoda & Borge, 2016) since inquiry-based instruction holds that new knowledge is built upon prior knowledge through experimentation over time. Inquiry-based pedagogical approaches to Epidemiology start by encouraging students to think about health and wellness as they relate to their families, friends, and extended communities, and provide them with opportunities to learn the science through student-led investigations (D'Agostino, 2018).

In her study, D'Agostino (2019) examined what high school epidemiology curricula look like and how they influence students, teachers, parents, policymakers, and the local public. The author argues for a student-centric pedagogical strategy built on students' prior knowledge, experiences, and cultural identities. The author also posits that infusing inquiry-based, authentic learning materials into the high school curriculum can enhance students' critical thinking and problem-solving skills and promote their interest in the health sciences. While her research focuses on high school students, the instructional approach of fostering inquiry-based, authentic learning for epidemiology instruction in high schools may apply to teaching middle school students Epidemiology as well.

Riegelman (2008) has systematically discussed the current state of undergraduate health education. Aligned with the suggestion from the Association of Schools and Programs of Public Health (ASPPH) on the future of public health education, the author named inquiry capstone projects as a critical component of public health education. Such projects serve to integrate, apply, and synthesize knowledge through cumulative and experiential activities. Since this study was restricted to undergraduate students, an opportunity exists to investigate how adolescents learn about epidemiological topics through inquiry-based activities.

In Fraser's (1987) now-classic article on epidemiology as a liberal art, the author argued that epidemiology education is in a range of disciplines that allows the individual to become a problem-solver. The discipline of epidemiology should teach students to inquire into the phenomenon, use intuitive thoughts and critical thinking skills to approach problems, observe and use deductive reasoning, and formulate explanations from evidence.

D'Agostino and Fraser's recommendations contributed to the design of this study. Specifically, the learning environment of this study is consistent with "essential features of inquiry" (Asay & Orgill, 2010). The interview began with the telling of a story of a child who spread an illness to other children after he contacted a sick friend. Then the interviewer asked open-ended questions to probe students' opinions about disease spread and prevention. Students then gather evidence for answering the questions (they build models, test, debug them, and examine their thinking), formulate explanations from the evidence (they explain the results of the models), and relate explanations to scientific knowledge (they determine the best way to protect themselves and their families) and share their explanations with others.

Prior Knowledge Pedagogy

The theoretical model underlying the prior knowledge pedagogy, upon which this research draws, is based on a constructivist view of knowledge called Knowledge in Pieces (KiP; diSessa, 1993). KiP argues that knowledge is a complex system composed of knowledge elements. Knowledge elements are not always productive. Students' intuitive knowledge, for instance, is unstable and often incorrect; I use the term intuitive here to refer to their empirical knowledge before they receive instruction. As students learn a new concept, they cue knowledge elements based on the sense-making context, and the cueing is not always reliable. In contrast, they cue them more effectively and reliably when their understanding is more expert. A central tenet of KiP is that learners build more advanced knowledge from prior knowledge, which is also the premise of constructivism. Therefore, Prior Knowledge pedagogy should be aligned with the constructivist theory of learning that interprets students' prior conceptions as resources for cognitive growth through reorganization and refinement of knowledge systems (Smith et al., 1994).

Research on science learning has debated preconceptions, or ideas held before instruction (Clement et al., 1989), for many years. The perspective of KiP views students' prior knowledge as resources for constructing mature understanding (diSessa, 2014). In contrast, some studies suggest that students' preconceptions are a significant barrier to understanding scientific concepts (Morrison & Lederman, 2003). However, this is a betrayal of the very nature of scientific inquiry (Cohen & Ball, 2001; Hutchison & Hammer, 2010), which values students' arguments. In addition, it violates constructivism, which tells us that new knowledge must be built on the foundation of prior knowledge. The "misconceptions" perspective (Glaser & Bassok, 1989) would have us identify, remove, and replace students' prior knowledge with correct, scientific knowledge. However, removing prior knowledge would mean removing the foundation we must build upon (Smith et al., 1994).

To provide a learning environment that consciously meets students halfway (i.e., learning environments that permit them to test ideas that closely match their intuitions), studies have identified different prior knowledge pedagogies that account for preconceived notions. These include pedagogies such as: students using computational representations to re-invent rules of mathematics and science (diSessa, 2008); instructors using responsive teaching strategies that allow them to tailor their instruction based on what students are thinking about to refine the conceptual and epistemological aspects of students' scientific explanations (Dyer & Sherin, 2016; Hammer et al., 2012, Robertson et al., 2015); teachers and students altering roles and co-developing a discourse community where members make scientific arguments in response to conjectures (Hudicourt-Barnes, 2003; Lampert, 1990; Sherin, 2002); science classes promoting theory-building discussion to support both creative and critical thinking (Swanson & Collins, 2018); teachers guiding student thinking through the "reflective toss," a method where teachers "toss" the responsibility of thinking back to the students (van Zee & Minstrel, 1997).

My study draws upon the literature on prior knowledge pedagogy to design an instructional environment and associated pedagogical strategy. The instructional environment is a learning-by-modeling microworld in which students build, test, and debug computational models to develop an understanding of disease spread and prevention. As the interviewer, I use open-ended questions to elicit students' arguments and probe for additional information after each explanation to gain a deeper understanding of their thinking.

As diSessa believes that preconceptions are crucial to establishing mature understanding, I aim to investigate how intuition affects the way students build their first model, and how their thinking changes from the initial to the later stages as they debug their models and their thinking.

Computational Modeling Pedagogy

Computational modeling pedagogies have been used extensively to support the learning and practice of science (Gautam et al., 2005; Wing, 2006). However, research has suggested that students often face difficulties with learning by modeling (Eidin et al., 2020). For example, students may not be able to relate the behavior of individual entities to aggregated or emergent system behavior (Wilensky & Resnick, 1999). In response to this need for supporting students to learn about complex systems phenomena, such as the spread of disease (Damelin et al., 2017; Wilensky & Reisman, 2006, Wilkerson-Jerde et al., 2015), Wilensky and colleagues developed an agent-based modeling environment called NetLogo (Wilensky, 1999b). The environment involves setting rules on individual elements of a system and their interactions, building models whereby aggregate patterns emerge from the interactions of the elements (Wilensky, 2001). Specifically, young students who know little of computational modeling require a low-threshold modeling language to represent the system under study without requiring them to master complex programming skills (Damelin et al., 2017).

Computational modeling microworlds can be one example of low-threshold, agent-based modeling. Some learning-by-modeling microworld approaches have students use computational models to refine their thinking through building, testing, and debugging models. Microworlds can be effective instructional tools because they encourage learners to articulate their ideas in the program code and refine their thinking as they debug their program. By creating a microworld that consciously meets students halfway, we can engage them in authentic scientific practices through a learning-by-modeling approach.

For example, Wilensky and Reisman (2006) designed a case study to develop an in-depth understanding of integrating agent-based modeling practice to complex biological phenomena curriculum and how this practice influences students' learning. The authors studied the approach of teaching the biological phenomena through computational modeling, described two cases in which an agent-based modeling approach was used (predator-prey model and firefly model), and compared these cases against traditional equation-based approaches. In conclusion, they posited that an agent-based modeling approach helps students understand the connections between different biological levels.

In addition to modeling microworlds that have students building, testing, and debugging models, these approaches also focus on having students modify or extend existing models, as seen in Levy and Wilensky's (2009) study. In this study, the authors conducted several case studies to explore high school students' experiences of investigating and adding extensions to teachers' models of stochastic phenomena. In those cases, students used Gas Lab, a modeling toolkit for connecting micro and macro levels of gasses, to extend the models and run new experiments. The authors claim that allowing students to add extensions to teachers' models can encourage them to extend their knowledge and test their ideas by creating the models.

Similarly, Aslan et al. (2020) describe a novel design process called phenomenological programming to help students build models in NetTango. NetTango features block-based modeling microworlds that allow students to articulate their intuitions of complex phenomena into block codes to support learning by modeling. The NetTango approach lowers the barrier for this type of coding through block-based coding (Horn et al., 2020) and makes NetLogo's (Wilensky, 1999b) computational power accessible to younger modelers by offering a block-based programming language that is tailored for particular phenomena. NetTango blocks are not a full programming language, but domain-specific blocks relevant to the modeled phenomena.

In phenomenological programming, blocks are purposefully designed to meet the intuitive needs of the target group. In this way, students can create custom-designed, domain-specific programming activities. The researchers examined the use of a phenomenological programming language in NetTango to teach students about gas particles. They argue that the phenomenological code blocks accommodate students' intuitive thinking, making block-based agent-based modeling more accessible to students who have little experience in programming.

The above research informs this study's instructional environment. Students will have access to a computational modeling environment that is conscious of meeting them halfway. This means giving students programming blocks that allow them to work with ideas that closely match their intuitions. In order to achieve this goal, our computational microworld of disease spread and prevention design process is human-centered. We began by investigating students' intuitions about how diseases spread and how epidemics can be prevented. Then we incorporated their ideas into the microworlds, as primitive coding blocks. The computational microworld in this study was developed based on our previous study of the larger designed-based research project. Learners can articulate their ideas in the code blocks and evolve their thinking through testing and debugging their models (Swanson et al., 2021; Wu et al., in press b).

Extend Middle-school Epidemiology Pedagogy, Computational Modeling Pedagogy, and Prior Knowledge Pedagogy

Computational modeling microworlds and the value of their application have been described in many research studies (e.g., Dabholkar, Anton & Wilensky, 2018; Edwards, 1995; Eidin et al., 2020), including in studies that specifically examine the impact on students' understanding of scientific phenomena (e.g., Wilensky & Reisman, 2006, Wilkerson-Jerde et al., 2015; Levy & Wilensky, 2009). However, the process of model creation has been less studied (Eidin et al., 2020). To fill this gap, researchers have previously looked at the way students use computational models to understand the spread and prevention of diseases. (e.g., Abrahamson & Wilensky, 2005; Klopfer et al., 2005; Wilensky & Stroup, 1999).

Furthermore, in a study of Epidemiology pedagogical approaches, Castagno et al. (2020) found that computational modeling could support Epidemiology teaching and learning; however, the study was limited to undergraduate and graduate student settings and, therefore, could be extended and deepened to address how adolescents can learn epidemiology concepts through computational modeling.

This study expands research on how to help middle school students learn about disease spread and prevention by investigating how interacting with the microworld impacts that learning. We hope that this research may provide insight into how adolescents may benefit from a computational microworld focused on disease transmission and prevention.

CHAPTER III

THEORETICAL FOUNDATIONS

My research draws on two theoretical frameworks: Constructionism and KiP. I will describe each below.

Constructionism

Constructionism is a theoretical orientation to learning with instructional implications that holds children learn better when they are involved in activities that allow them to construct artifacts. According to constructionism, learning is an active process by which the learner integrates sensory input and constructs meaning (Papert, 1980). Constructing a publicly shareable artifact helps students learn because they can gain knowledge and skills by creating, reflecting on, and discussing artifacts or objects. Creating artifacts can help students understand what they are working on and connect old and new knowledge. Papert talked about how playing with gears helped him learn mathematics as a child. He described this inspiring experience, saying

> the gear can be used to illustrate many powerful advanced mathematical ideas, such as groups or relative motion. But it does more than this. As well as connecting with the formal knowledge of mathematics, it also connects with the 'body knowledge,' the sensor motor scheme of a child. (p. 9)

Constructionist pedagogy has side benefits. Papert, for example, worked with flexible objects like gears that could be disassembled and reassembled to produce different objects, enabling him to create something intuitively engaging and accessible to math. This boosted his intrinsic motivation and ignited his passion for math.

Microworlds are one example of a constructionist learning environment that acts as an object to think with (Edwards, 1995; Olson & Horn, 2011). As mentioned above, microworlds are computer-based interactive learning environments (Olson & Horn, 2011). They can serve as effective instructional tools because they give learners a chance to express their ideas in program code and refine their thinking as they debug their codes (Edwards, 1995). By enabling students to customize a microworld, we also meet their needs for personalized instruction. Students start by creating models of scientific phenomena based on their intuitions, or in other words, they tailor the models to meet their initial thinking. They test and debug the models until the results meet their expectations. When a student runs a model, they may find that the results are unexpected because their old knowledge conflicts with their observation, and the debugging process helps them refine their thinking. This instructional method engages students in student-led investigations that can enhance their intrinsic motivation (e.g., Abrahamson & Wilensky; 2005; Klopfer et al., 2005; Wilensky & Stroup, 1999).

Because my research examines how students' work with a microworld helps them refine their thinking, Papert's (1980) work on the theory of constructionism underpins the theory of my study and my proposed study questions.

Knowledge in Pieces

As my questions relate to intuitive knowledge, I draw upon the theory of Knowledge in Pieces (KiP), which regards knowledge as a complex system consisting of knowledge elements. Learning starts by developing concepts from an unstructured and disjointed collection of naive knowledge elements and develops through the reorganization and refinement of the knowledge networks. Knowledge elements are both phenomenological, in that they are interpretations of reality, and primitive, as they are based on preliminary self-explanations (diSessa, 1993). In my experience as an online learning consultant for some Chinese adolescents talking about the pandemic, for example, the most common problem-solving shortcut knowledge that I have discovered is the notion of "the more, the better"— "The more time I stay at home, the better." Students thought it was best to stay at home to stop the spread of COVID despite feeling depressed by quarantine.

The learning activity from which I drew my research was designed with the theory of KiP in mind. I aim to investigate how students utilize their novice knowledge in building the initial computational modeling microworld and how they refine their thinking by building, testing, and debugging models. In particular, students begin by gaining familiarity with the topic through a series of questions about the spread and prevention of disease and are required to model and test their ideas using the microworld. I begin by sharing the screen and presenting the student with a story about the spread of disease in the context of "folk biology."

"Folk biology" is a name for the everyday thinking of lay people about biological phenomena (Au & Romo, 1999). It holds that young children build their ontology of complex biological concepts through the process of generalization. Even though inductive inferences are not always correct, they are the "prior understanding" of constructing any uniquely biological mechanism. For example, young children would be prone to generalize a property of the cold virus as "a small infectious living organism" primarily based on the reasoning that the virus can transmit from sick people to healthy people and make healthy people sick. "Folk biology" is also aligned with KiP because it regards young learners as "nascent scientists," trying to make sense of the world as scientists do. Learning starts from cueing "everyday thinking" and refines through the reorganization and refinement of the learner's knowledge networks.

KiP instruction is constructivist (Smith et al., 1994) in that it focuses on eliciting and refining students' ideas or memories. In this study, I sought to discover how I could support students in actively constructing an understanding of disease spread based on their intuitions. I accomplished this by investigating how their initial model of disease spread and prevention corresponds to their initial ideas, and how computer modeling impacts their shifts in thinking from the beginning to the end of the interview.

CHAPTER IV

METHODOLOGY

Research Context

As part of our larger project, my research team aims to use design-based research to build computational agent-based microworlds to help middle school students learn about science topics. The purpose of the present study is to instruct students about disease spread and prevention. I offer middle school students block-based modeling microworlds that allow them to create models in a language that makes sense to them. This specific project aims to provide students with a computational agent-based microworld to help students learn about public health issues including the transmission of disease and methods for the prevention of epidemics. The previous study (Wu et al., in press a) examined students' intuitions about disease spread and prevention and used them to design the primitive blocks of the microworld based on their intuitions. The present work investigates how constructing a microworld with these blocks impacts their learning about it.

Table 1 outlines the data collection, sources, analysis, and findings for each of my stated research questions.

Research Design

The study is embedded in a design-based research project, and the microworld is an instructional intervention. I am ultimately interested in understanding if/how it impacts

Table 1

Data Collection, Sources, Analysis, and Findings for the Research Questions

Research question	Data collection	Data sources	Data analysis	Findings
RQ1a. How are students thinking about disease spread and prevention as they construct their initial flu and COVID models?	One-on-one interviews with students responding to think-aloud interview protocol (see p. 80, thesis). Students described microworlds of disease spread and prevention before and as they built the initial models and predicted the model's running results before they tested the initial models.	Video footage and audio recording (transcribed) of students describing micro-worlds of disease spread and prevention before and as they built the initial models and predicted the model's running results before they tested the initial models, as well as screenshots of students' initial models.	I conducted a microanalysis (diSessa et al., 2016) to look at students' smaller ideas in their knowledge systems when they described the microworlds they aim to model, why they built the model the way they did, and their prediction of model running results. I identified the specific elements of students' prior knowledge of disease spread and prevention. I then conducted a cross-case analysis to compare students' knowledge elements (Yin, 2012). My goal was to identify the patterns, similarities, and differences in ideas across cases in order to present the distinct initial ideas that emerged.	Findings are presented as a list of students' prior knowledge elements of the phenomena.
2: How do students understand disease spread and prevention as they construct their later flu and COVID models?	One-on-one interviews with students responding to think-aloud interview protocol (see p.80, thesis). Students described microworlds of disease spread and prevention before and as they built their later models and predicted the model's running results before they tested the later models.	Video footage and audio recording (transcribed) of students describing microworlds of disease spread and prevention before and while they built the later models and predicted the model's running results before they tested the later models, as well as screenshots of students' later models.	I conducted a microanalysis to look at students' smaller ideas in their knowledge systems as they described the improvements that they aimed to make for microworlds, why they built the model the way they did, and their prediction of the model running results. I identified the specific elements of students' later knowledge of disease spread and prevention. I then conducted a cross-case analysis to compare students' knowledge elements. My goal was to identify the patterns, similarities, and differences in ideas across cases in order to present the distinct later ideas that emerged.	Findings are presented as a list of students' later knowledge elements of the phenomena.
RQ3. How do students' ideas change from initial to later in response to their modeling activity?	One-on-one interview with students responding to interview protocol (see p. 80, thesis). Students built models of disease spread and prevention and described why they debugged the models the way they did.	Video footage with screen capture and audio recording (transcribed) of students building models of disease spread and prevention. All models' screenshots.	I conducted a microanalysis to trace over time the development of a student's thinking. Micro means I looked at the whole transcript and tried to identify exactly when their ideas were being elicited (activated) and when they were drawing on new ideas. I looked at the tiny steps that occurred in the student's learning process. I then conducted a cross-case analysis to compare students' shifts in thinking. Across cases, I sought to identify patterns, similarities, and differences in students' thinking shifts.	Findings are written up as a temporal decomposition showing shifts in thinking in response to modeling activity. Specifically, I looked at how their thinking changed throughout the model building, testing, and debugging stages. Each type of shift in thinking was illustrated by one example.

students' learning about disease spread and prevention. Toward this end, I employed a lab-based case study approach (Yin, 1998), conducting one-on-one 1.5-hour interviews through Zoom with middle school students ages 12-14 (see the Interview Protocol in the Appendix). I introduced the students to a story about disease spread and prevention, prepared them to create models in NetTango, and finally invited them to complete tasks, including building, testing, and debugging models, as they discussed them (see Figure 1). As shown in Figure 1, the NetTango microworld interface provides the following interface components:

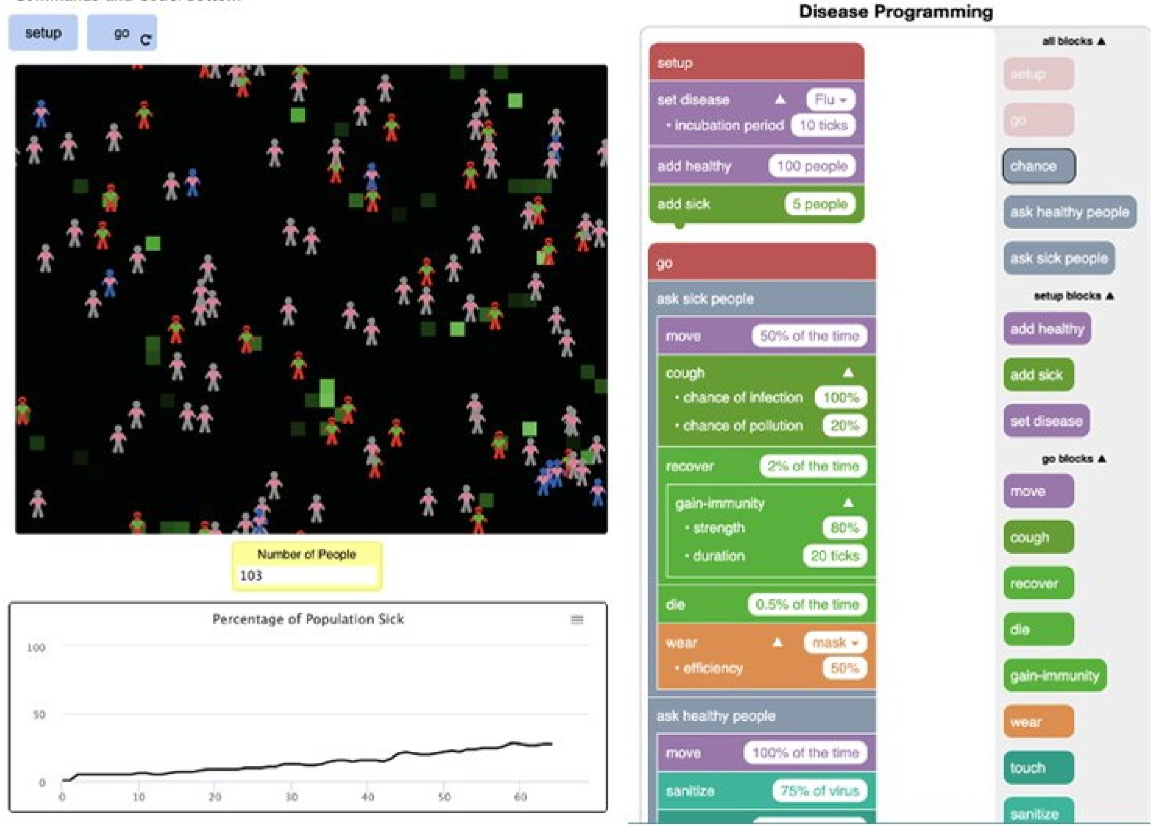
- A display window provides an animated visual depiction of the model as it is run.
- There is a list of blocks and a model construction area. It allows users to drag blocks to a construction area, arrange the blocks, and adjust the parameters to build models.
- A plot window shows graphs of the model's execution (e.g., percentage of sick people over time).

Students used the model in Figure 1 to complete their tasks. This is a model of a NetTango (Horn et al., 2020) microworld. Instead of writing text-based programs, students could use blocks to build and test models and examine how emergent patterns arise from simple rules and interactions at the system level. In this study, students built and tested a model representing the spread of disease and its prevention to explore how the individual-level interactions could give rise to a pandemic, and how the individual's different protection behaviors could make an impact on the overall health of the public.

The microworld is agent-based, meaning each agent is asked to behave, at each tick of the clock, according to the blocks assigned to them in the "go" procedure. For

Figure 1

Screenshot of the NetTango Microworld



example, healthy agents might be asked to move randomly throughout the world and become infected with some probability if they cross paths with an agent who is sick. Sick agents might be asked to die or recover with some probability. The box on the left side of the interface represents a space where people in this microworld interact with each other. The modeling space on the right side of the interface has blocks including “setup,” “go,” “set disease,” “add sick,” “add healthy,” “move,” “chance,” “ask sick people,” “ask healthy people,” “cough,” “recover,” “die,” “gain immunity,” “touch,” and “sanitize.”

Blocks are divided into two groups: *setup* blocks and *go* blocks. *Setup* blocks are connected to a setup procedure through which a student can create agents. *Go* blocks are related to a go procedure, which defines the rules of behavior and interaction between agents.

There are three setup blocks: “add sick,” “add healthy,” and “set disease,” and under “set disease,” students can select flu or COVID and the incubation time for the disease. *Go* blocks include “move,” “chance,” “ask sick people,” “ask healthy people,” “cough,” “recover,” “die,” “gain immunity,” “touch,” and “sanitize.” Students can connect the “chance” block to other blocks to alter the parameters and can use the “cough” block with the option to set infection rate based on air or touch. In particular, the chance of infection means the chance of transmission through air, while the chance of pollution means the chance of virus left on surfaces and transmission through touch. Students can use the “recovery” and “die” blocks to ask a sick person to recover or die a certain percentage of the time. Students have the option of using “gain immunity,” and they can set the strength (out of 100) and ticks of immunity duration (ticks are time units in this microworld) to request that recovered people can be immune for a certain amount of time. Lastly, there is “touch,” which allows them to use a drop-down menu to decide the amount of sanitizing to be applied after touching the object, and “sanitize,” which allows them to set the number of viruses to be removed after sanitizing.”

These blocks can be used to model the spread and prevention of flu or COVID by dragging and arranging them in the modeling space. Students can use this model by placing the *setup* block in the construction area, attaching *add sick* and *add healthy* people blocks, and setting up *disease type*. Then, they can assign a parameter to each block according to the phenomenon they wish to simulate. For example, they can simulate a world full of crowded sick people, or a world with just two people moving around. Then, they can place the *go* block in the construction area and attach blocks from within the *go* blocks group to it in order to simulate the specific agent rules. They can attach blocks of *asking healthy people* and *move* to the *go* block to ask healthy people to move around in the microworld. When testing models, students must click recompile first, then *set up* and *go*.

To investigate students' thinking on how flu would spread and be prevented, I first asked students to create a world where flu spreads and is prevented. To investigate their thinking on how spread and prevention of COVID would differ from that of flu, I asked them to create worlds where COVID spread and was prevented. As part of the interview, and to better understand how they were thinking about effective COVID protection strategies to prevent disease spread, I asked what method would be more effective at protecting people from COVID infections: quarantining sick people or using masks when moving around. After getting their responses, I focused them on two tasks at the end of the interview: "Could you arrange the blocks or modify the parameters of the blocks to create two situations? The first situation is what you have mentioned where sick people stay at home, the second situation is the case where people are free to move with protection." Structured tasks as above could help to investigate students' learning about flu and COVID spread and prevention, along with an emphasis on COVID prevention strategies.

Interview Protocol

To begin the interview, I introduced students to infectious disease spread and prevention, telling a story about the spread of disease, narrating the story according to a script, and asking open-ended questions about it.

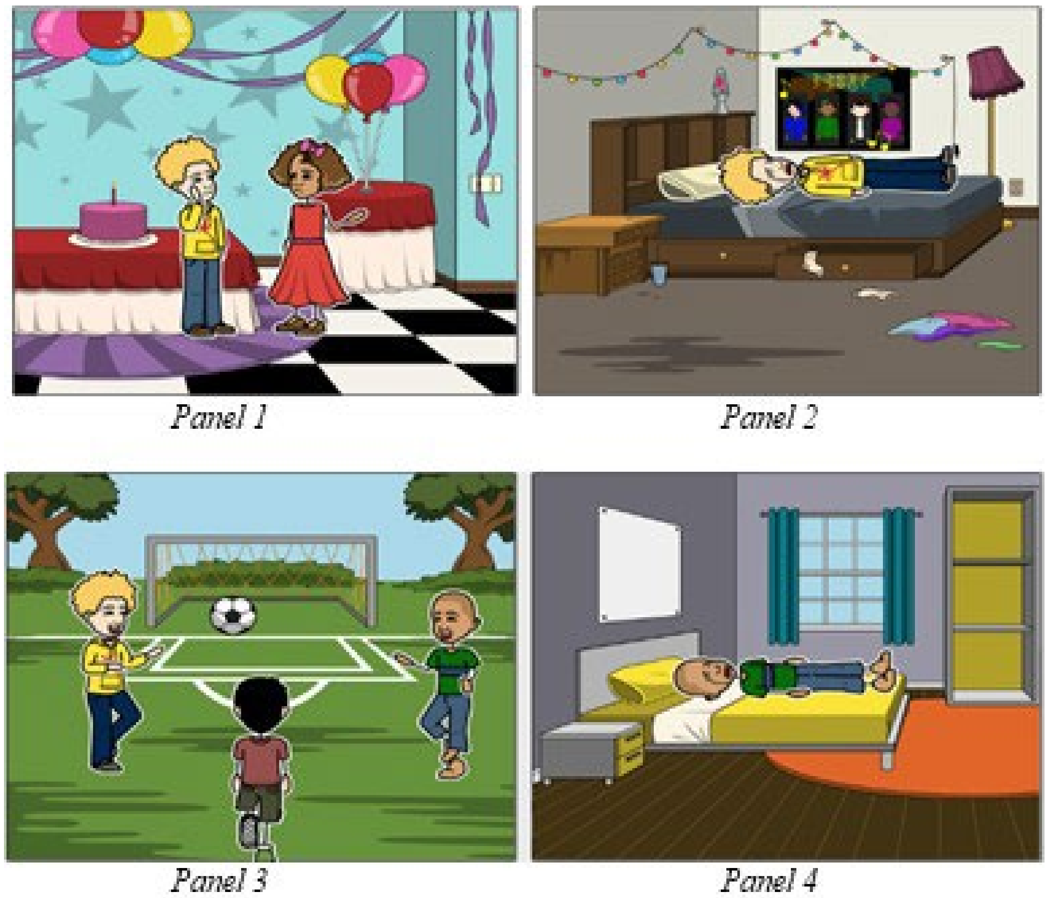
The students were told the story of Jack, who goes to a party and interacts with Mary, who has been sick (see Figure 2, panels 1-2). Jack gets sick the next day, and then, having recovered, goes to play football with his friends. One of the friends gets sick the next day (see Figure 2, panels 3-4). I asked open-ended questions (e.g., “Why do you think Jack got sick even though he seemed fine yesterday?”) and probed for additional information after each explanation offered by a student (e.g., “That’s interesting. Can you explain a little more about how that works?”).

The interview focused on participant thinking. I encouraged interviewees to explain their thinking and limited my comments to avoid stifling their creativity.

After answering the questions, the students were invited to learn how to build NetTango models. Their learning was scaffolded by a sequence of staged microworlds. The microworlds were arranged from zero to four depending on how complex the blocks they contained were. For example, Microworld Zero could be used to create a model with a single rule of setting up the number of sick people and healthy people, while Microworld Four could be used to create the model that students would use to build a world of disease spread and prevention. Microworlds zero through three were used only to introduce students to constructing models in the microworld, whereas microworld four was used to build models of disease spread and prevention.

Figure 2

Screenshots of the Stories, Panels1-4



Note. This figure illustrates the story of Jack, who goes to a party and interacts with Mary (panel 1), who has been sick. Jack gets sick the next day (panel 2), and then, having recovered, goes to play football with his friends (panel 3). One of the friends gets sick the next day (panel 4).

Microworld Zero

Microworld Zero consisted of three blocks: “setup,” “add sick,” and “add healthy.” These blocks defined the setup conditions of the model. This block set was meant to help students learn that *setup* was a procedure that determines the initial agents (kind and number) of the model (see Figure 3).

Figure 3

Screenshot of Microworld with Blocks Set Zero

Microworld One

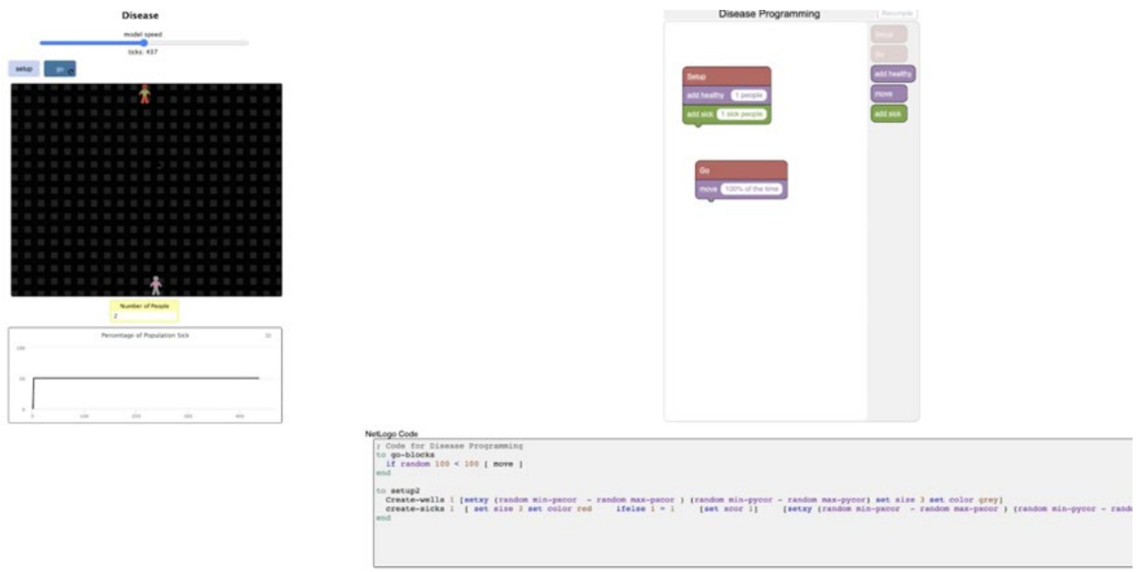
The box on the left side of the interface represents a space where agents interact with each other. The modeling space on the right side of the interface has blocks including “setup,” “add healthy,” and “add sick.” These blocks can be used to model the setup procedure. Compared with Blocks Set Zero, Blocks Set One added “go” and “move” blocks, A “move” block can be attached to a “go” block, which defines the rules for the person moving around. (see Figure 4).

Microworld Two

The modeling space on the right side of the interface has blocks including “setup,” “add healthy,” “add sick,” “go,” and “move.” These blocks can be used to model the setup procedure and go procedure with the “move” block. Compared with Microworld One, Microworld Two added an “if sick, infect” block with an infection rate

Figure 4

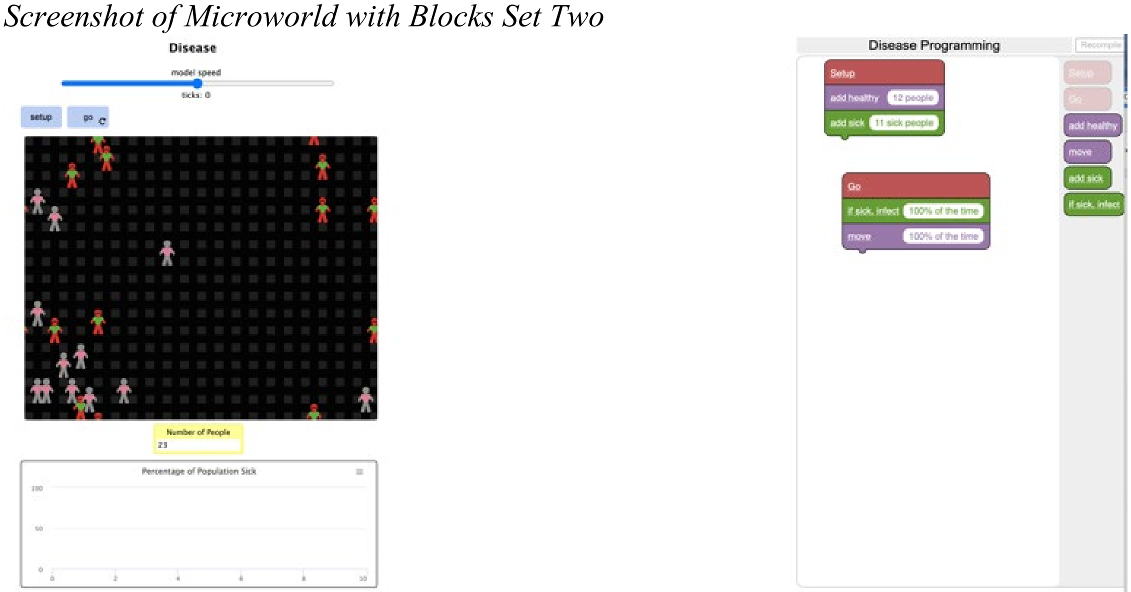
Screenshot of Microworld with Blocks Set One



parameter. Students could attach this block to the "go" block to command the sick people to infect healthy people at a certain rate (see Figure 5).

Figure 5

Screenshot of Microworld with Blocks Set Two



Microworld Three

The modeling space on the right side of the interface has blocks including "setup," "add healthy," "add sick," "go," "move," and "if sick, infect." These blocks can be used to model the setup procedure and command the agents to "move" and "if sick, infect."

Compared with Microworld Two, Microworld Three added "if sick, die" and "if sick, recover" blocks with a rate parameter. Students could attach these two blocks to the "go" block to command the sick people to die or recover at a certain rate (see Figure 6).

Figure 6

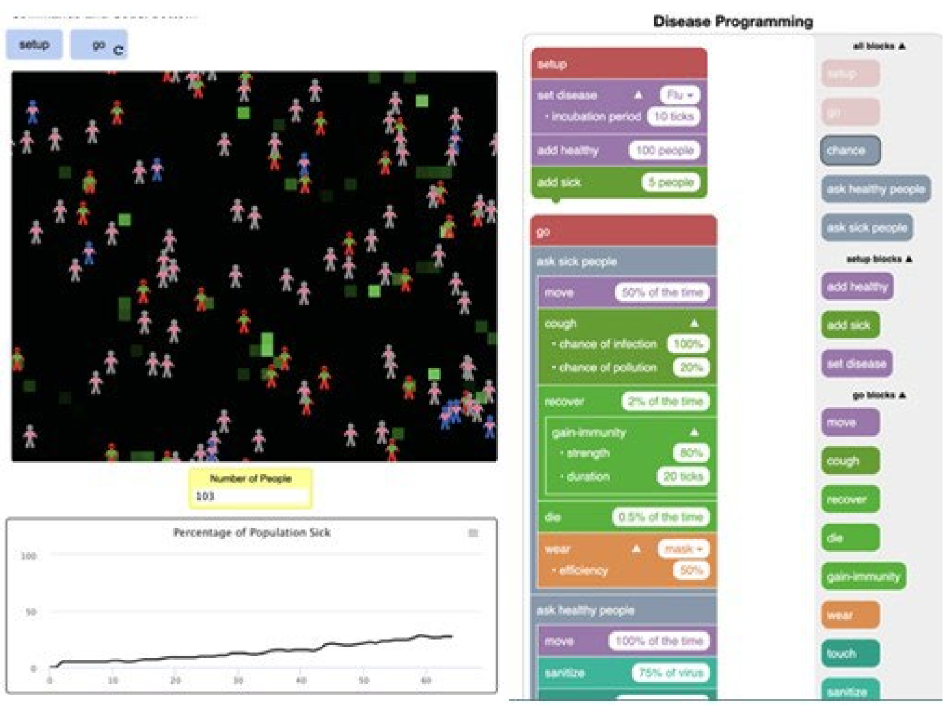
Screenshot of Microworld with Blocks Set Three

Microworld Four

After students used microworlds 0 through 3 to practice building models in NetTango, they were invited to build disease spread and prevention models using Microworld Four. Compared with Microworld Three, Microworld Four added blocks including “set disease,” with the ability to select flu or COVID and set the incubation time for the disease, “gain immunity,” with the option to set immunity strength and duration, “touch,” with the option to set sanitizing rate after touching the objects, “sanitize,” and changed the “if sick, infect” block to “cough” with the option to set infection rate based on air or touch. Those settings enabled this model-to-model flu and COVID spread and prevention scenarios by differentiating the types of diseases and asking for different human behavior across diverse groups (see Figure 7).

Figure 7

Screenshot of Microworld with Blocks Set Four



The modeling space on the right side of the interface has blocks that I have introduced. These blocks can be used to model the flu or COVID setup procedure separately and command the two types of agents to behave differently using “ask sick” and "ask healthy people" blocks.

It was necessary to provide staged microworld scaffolding to students so that they could build complex block-based models without extensive instruction. With the gradual introduction of blocks, students may find it easier to construct a microworld of disease transmission and prevention in Microworld Four.

Participants

Four middle school students aged 12-14 years old were recruited for this study (Malterud et al., 2016). My rationale was that through my study I would develop lists of prior and later knowledge elements and a model of a learning trajectory for middle school students who were learning about the spread of disease and prevention. With four middle school participants, I had a range of ideas and learning trajectories to choose from. I aimed to create knowledge element lists, followed by creating a model of a learning trajectory. My goal was to demonstrate how knowledge could be modeled as a system of tiny elements or individual ideas over time, and how learning could be modeled as tiny shifts in thinking over time. To achieve this, I must look closely at a few cases and four participants was a good number.

I recruited students using a convenient sampling method (Etikan et al., 2016). The method was nonrandom and asks the researcher to select subjects who are easily accessible to them. Easy accessibility—such as availability at a specific time, or willingness to participate—, was an important consideration. Having obtained IRB approval from Utah State University, I posted the recruitment information on the Internet and selected participants who met the studied eligibility requirements (e.g., willing 12–14-year-old middle school students) based on when their applications were submitted, until the four-participant pool was filled. I conducted recruitment through the legal guardian of the participant due to the vulnerability of this population.

I emailed students and their family members inviting participation in the study and provided an informed consent document for the legal guardians to complete. The forms disclosed the nature of the study, outlined the procedures of the study, and described the potential benefits. Guardians were told that consent was voluntary and that the participants could leave the study at any time without penalty.

Upon completion of the informed consent forms, I scheduled each participant for a private ninety-minute interview. Ultimately, four participants took part in this study: Elmo, a 14-year-old public school eighth-grader in the Intermountain West, Susan, a 13-year-old public school seventh-grader in the Intermountain West, Alex, a 14-year-old public school eighth-grader in the Midwest, and Kathy, a 14-year-old public school eighth-grader in the Intermountain West. The students' names have been changed to protect their privacy.

Data Sources

The study was conducted over a 2-week period with two interviews per week. I recorded each interview, using the recording feature of Zoom to capture audio, and images of the student's screen and face. I then transcribed students' interviews using Otter AI.

Data Analysis

To answer the overarching question ("How did modeling microworlds impact students' thinking about preventing disease spread?") I investigated three research questions. To answer RQ1 and RQ2 ("How are students thinking about disease spread and prevention as they construct their initial and later models?"), I first reviewed the audio recordings of the students describing, predicting, building, and making sense of initial and later models, and made note of the times during which they revealed their thinking. I noted those episodes, as well as the screenshots of the models they built, in the transcript, which I examined for indications of their initial and later thinking. In order to investigate their initial thinking, I examined how they described modeled worlds of flu or COVID spread and prevention before and as they built the initial models and how those models would look. I further examined their rationale for building their models in the ways that they did, and how they predicted what the results of the models would be after running them. To investigate their later thinking, I compared those later models with their rationales for modifying the models in the ways that they did.

Research Question 1 and 2

For RQ1 and RQ2, I conducted a microanalysis of the students' knowledge systems as they described the microworlds that they aimed to model, their modeling and debugging processes, and their predictions of what the models' running results would look like. Microanalysis is a method of knowledge analysis that examines reasoning at a fine grain size. In this study, I examine the process of activating particular knowledge elements.

I conducted a microanalytic study (diSessa, Sherin, & Levin, 2016) to identify the specific elements of students' prior knowledge of disease spread and prevention. After that, I conducted a cross-case analysis (Yin, 2012) to identify patterns, similarities, and differences in students' knowledge elements across cases in order to produce a list of distinct initial ideas that emerged. I also produced a list of elements of their later knowledge on the spread and prevention of diseases. My data analysis was driven by the aim of iteratively refining the set of coding blocks used in the microworld, and my intuitions about the appropriate grain size for these blocks. I began by paraphrasing the students' explanations and looking at those ideas for intermediate grain size. I organized the ideas that they identified and incorporated them into the models based on similarities and categories of knowledge that emerged. As for RQ2, I will focus only on reporting the students' later ideas, while RQ3 will address shifts separately. Below, I will use an example to illustrate the data analysis process for RQ1 and RQ2.

Illustration of the Analysis Process

I began by examining closely the interview transcript of each student to identify their individual knowledge elements. After that, I reviewed four cases to identify patterns, similarities, and differences in the knowledge elements in order to produce the pre-instructional ideas across cases. I present segments of the interview transcript below to exemplify students' thinking.

Interviewer: How do you envision a world of infectious disease spread that your model would create?

Alex: If someone touches the surface, they may get the virus on their hands and so on.

Elmo: Throughout the hands? Maybe touch like they're using the same ball to play soccer. And the germs spread to each other.

Kate: It would look like when someone would get it and then they would maybe touch something and then the person next to someone gets it.

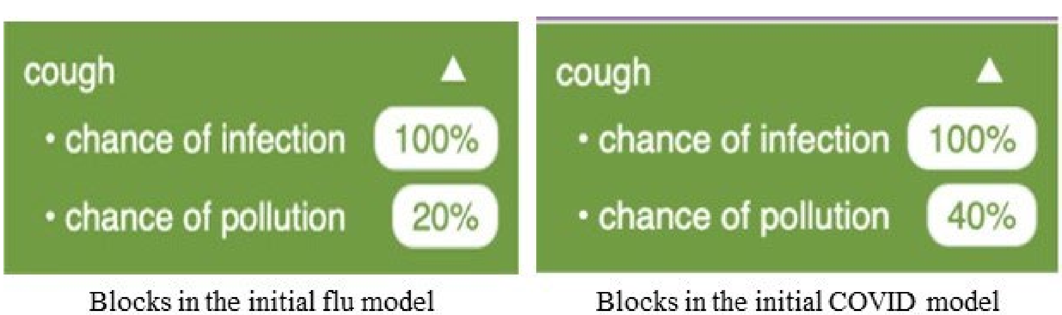
Susan: When you sick and touch something, you kind of leave germs on the stuff and they could spread to other people when they touch it.

Both Elmo and Alex suggested that people could get sick from touching surfaces that are infected with germs, and both Kate and Susan suggested that touching an infected surface with the hands could result in people getting sick. They believed that the virus was transmitted explicitly from objects to hands to stomachs. This was evidence to me that they revealed a similar pre-instructional idea that agents of disease can stay on objects and transfer through touch.

Students' initial models were also examined to identify how their ideas were reflected within the models. Figure 8 shows an example of how I looked at a student's model and examined how he integrated his thinking into it. Using Alex's first flu model and COVID model as examples, I illustrate how I analyze his thinking through models.

Figure 8

Initial Blocks Representing Alex's Thinking That Agents of Disease Can Stay on Objects



As shown in Figure 8, the chance of pollution means that the germs go from the cough to a surface, and someone can touch the surface. Alex's original flu and COVID models had pollution rates of 20% and 40%, respectively, and I interpreted this as evidence that he thought the viruses could be spread by touching infected objects.

Research Question 3

To answer the third research question ("How did their thinking shift from initial to later in response to their modeling activity?"), I recorded and transcribed students while they built models of disease spread and prevention and explained why they built and debugged the models in the ways that they did. I reviewed the whole transcript to identify when their old ideas were being shared and when new ideas were being generated. In this process, I examined the tiny steps that occur in students' learning. I also considered how they made sense of their models' running results and how they debugged the models (if they did so) to identify their thinking shifts.

For RQ3, I conducted a microgenetic (diSessa et al., 2016) analysis to trace the development of students' thinking over time to identify students' thinking trajectories. I documented my findings as a temporal decomposition showing shifts in thinking in response to modeling activity. Specifically, I examined how their thinking changed throughout model building, testing, and debugging, and compared their later thinking to their initial thinking to identify thinking shifts. I also examined why and how they changed their thinking, the categories of those changes, and the relationship between model activity and thinking changes. I then conducted a cross-case analysis to compare students' shifts of thinking (Yin, 2012). My goal was to identify patterns, similarities, and differences between students' thinking shifts across cases and demonstrate each type of shift of thinking with an example.

CHAPTER V

FINDINGS

Findings with respect to RQ1 and RQ2 include pre- and post-instructional ideas belonging to three categories: (1) ideas about transmission of disease, (2) ideas about recovery from disease, and (3) ideas about prevention of disease. Findings with respect to RQ3 include three kinds of shifts in thinking: (1) changes in the relationship between agent rules and aggregate emergent phenomena, (2) changes in the rules of interactions between agents, and (3) changes in the rules of agent behavior. Findings with respect to RQ3 also include reinforcement of student thinking, including (4) reinforcement of thinking about the rules of agent behavior, and (5) reinforcement of thinking on the relationship between agent rules and aggregate emergent phenomena.

Pre-Instructional Ideas

Findings with respect to RQ1 include pre-instructional ideas belonging to three categories: ideas about transmission of disease, ideas about recovery from disease, and ideas about prevention of disease. Students' initial thinking emerged when they described the world of flu or COVID spread and prevention they would like to model, developed their initial models, and predicted the models' run results. Below, I introduce each category of ideas. For each category of ideas, I present a table organizing distinct ideas shared by the four students, belonging to that category.

Disease Transmission

Ideas in this category are about students' initial thinking on the transmission of contagious diseases from an infected individual to the populace. The microanalysis revealed 11 pre-instructional ideas about disease transmission across the four interviews. These ideas are primarily related to how flu and COVID can transmit through air and touch, and how their transmission methods and rates differ. Table 2 summarizes pre-instructional ideas held by the four students about disease transmission.

Disease Recovery

Ideas in this category reflect students' initial thinking about how a person recovers from sickness. The microanalysis revealed 11 pre-instructional ideas about disease recovery across the four interviews. The focus of these ideas was the differences in sickness recovery between flu and COVID. Table 3 summarizes the pre-instructional ideas shared by the four students about disease recovery.

Disease Prevention

Ideas in this category capture students' initial thinking about ways in which an individual can avoid infection. The microanalysis revealed 15 pre-instructional ideas about disease prevention across the four interviews. These thoughts centered on the effectiveness of different flu and COVID protection strategies. Table 4 summarizes the pre-instructional ideas the four students had about disease prevention.

Post-Instructional Ideas

Findings with respect to RQ2 include post-instructional ideas belonging to the same three categories as for pre-instructional ideas: ideas about transmission of disease,

Table 2

Students' Pre-Instructional Ideas About Disease Transmission

Pre-Instructional idea	Transcript
Agents of disease can stay on objects and transfer through touch.	Alex: if someone touches the surface, they may get the virus on their hands and so on.
Agents of disease can transmit through the human mouth and nose when coughing and sneezing.	Susan: I think is a random of sick people spreading it to other people. If they're not careful enough, I guess. When you cough or sneeze, you kind of cough up the like germs and they could spread to other people through the air.
Flu does not spread through the air.	Elmo: Like the flu, I think it's through touch, so somebody that don't wash their hands and they had it that would spread germs to other surfaces and stuff like that. I don't really think it's [flu]that much like through the air, but I could be wrong. I think it's more like through touch.
COVID can spread through coughing, sneezing, and touching.	Kathy: I think it would look like when someone would get it and they would maybe touch something or cough or sneeze and the person next to someone gets it.
COVID is very contagious	Elmo: And cough, the chance of infection is put like pretty as high of 80 around there; More people would get sick.
COVID is a little bit easier to spread than flu.	Susan: For sick people, I think I raised infection a bit more because I guess certain kinds of COVID could be easier to spread maybe.
Flu goes away after a while.	Elmo: The cough I put the chance of infectious under cough is 0 because flu doesn't transfer through air and chance of pollution under cough as 50%; I think the virus is going to just go away after a while.
Flu spreads slower and is not serious	Susan: The chance of sick people infecting only 46.2% of the time sneezing and coughing so it would still spread, but we shall think it might be slower or it's kind of not serious.
COVID is more likely to remain on objects and spread through contact than flu.	Alex: If someone touches the surface, they may get the flu virus on their hands and so on. For COVID, the infection rate from touch is higher compared with flu.
Flu has a lower transmission rate through the air than COVID.	Kathy: I'd say the flu model, for a 50% chance of infection, because a cough might not always cause infection. COVID is more dangerous than flu, so the infection rate through cough should be higher.
COVID has a longer incubation period than flu.	Alex: For COVID, the incubation time for COVID should be longer because I know it takes a long time for someone to realize they have COVID.

Table 3

Students' Pre-Instructional Ideas About Disease Recovery

Pre-instructional idea	Transcript
Flu has a very low death rate.	Alex: For the flu, People will die 0.5% of the time. A lot of people will get infected, but the death rate will still be low.
COVID has a higher death rate than flu.	Alex: For COVID, I increased the chance of death because I believe that's what will happen.
Flu does not cause death.	Susan: People won't die from the flu, so I put this ("die" block) back.
Many people would die because of the flu.	Kathy: I think that they would die because like I read a book and a lot of people die because of flu [she dragged the "die" block into the jaw and set the rate as 17.8%].
COVID has a low recovery rate.	Elmo: For covid, it should only recover 40 % of the time.
Flu has a high recovery rate.	Elmo: For flu, the recovery is about 15 % of the time, no, actually that should be higher, that should be like 80 % time [he dragged the recovery rate from 15% to 80%].
Flu immunity is stronger than COVID immunity.	Elmo: For COVID, it should only recover 40 % of the time and the immunity strength is a little bit lower like 93.6%.
The immunity strength for flu and COVID is the same.	Susan: I think I just left it the same as gain-immunity since once you survive COVID, you often gain the same immunity to it as you do from the flu.
COVID and flu have higher recovery rates than their death rates.	Kathy: I recovered just a little bit bigger than die. I think that's how it would work.
Recovery rates vary from person to person.	Kathy: I think it is because some people are healthier than others and may recover faster, whereas others who are not as strong may not recover fully. I did 34% of the time because it seemed like a fair amount for everyone.

Table 4

Students' Pre-Instructional Ideas about Disease Prevention

Pre-instructional idea	Transcript
Effective protection strategies for flu include sanitizing, wearing masks and resting if sick.	Elmo: For flu, I'll have people sanitize and wear masks, and rest if necessary. This won't be a big deal.
Effective protection strategies for COVID include quarantining while sick, wearing masks when going out, sanitizing, and washing hands.	Alex: Keeping your surroundings and hands clean is important for both COVID and flu. For COVID, make sure to stay in or stay away from other people if get sick. Wear a mask when going out. Or if you don't have a mask, maybe put a cloth around your mouth and your nose.
Sanitizing surfaces is effective to stop the spread of flu.	Elmo: Sanitize environment can kill [*sic*] 90% of the flu virus because flu is transmitted through touch.
Sanitizing surfaces is not effective to stop the spread of COVID.	Elmo: But sanitizing is only 20% effective to kill [*sic*] the COVID virus because COVID is primarily transmitted through the air. So, sanitizing the environment is effective to kill [*sic*] the flu virus, not COVID.
Masks are more effective for sick people.	Elmo: Sanitate [*sic*] environment can kill [*sic*] 90% of the flu virus because flu is transmitted through touch. For flu, healthy people wearing masks is effective 88.9% if they wear them appropriately, while sick people wearing masks is effective 99.3% since most of them take it seriously and wear it appropriately.
Masks have low protection for flu, but higher protection for COVID.	Alex: People don't take masks seriously for flu so the protection is not high.
Masks have higher protection for COVID.	Alex: More people in COVID wear masks properly, so the protection rate is higher.
Handwashing after touching objects would be impractical.	Kathy: And I also did touch because some person touch some time and sanitate [*sic*] 10% of the time because I feel like with a lot of people that when like since we're always touching things and it's not always easy to sterilize everything.
Quarantine is one of the most effective ways to prevent the spread of COVID.	Kathy: The best way would be to quarantine when we get sick. In quarantine, you're just with a few people and you'd go out when everyone is healthy again.
Going out with masks would increase the risk of infection of COVID.	Kathy: If we were still carrying COVID and we were wearing a mask, we would still be touching things and that type of thing. People could still get it.

ideas about recovery from disease, and ideas about prevention of disease. Below, I introduce each category of ideas. For each category of ideas, I present a table organizing distinct ideas shared by the four students. In this section, I only report the students' later ideas and will capture shifts from initial to later thinking separately in RQ3.

Disease Transmission

Ideas in this category are about students' thinking towards the end of the interview on the spreading of contagious diseases from an infected individual to the populace.

The microanalysis revealed four post-instructional ideas about disease transmission across the four interviews. These ideas were mainly about how the flu would be spread from an infected person to others. Table 5 summarizes the four students' post-instructional ideas about disease transmission.

Table 5

Students' Post-Instructional Ideas About Disease Transmission

Post-instructional idea	Transcript
Flu spreads longer.	Elmo: The running result is not as I expected, I thought the graph here (the percentage of sick people over time) would go a little bit longer and a little bit higher.
Flu is more infectious.	Elmo: Flu may be more infectious than I thought, so I set the pollution rate of cough to 70%.
Flu may spread through the air.	Elmo: I now think flu may spread through the air, so I change the infection rate of cough to 4%.
Incubation time for flu is low.	Elmo: I also lower this (flu incubation time) to three ticks.

Disease Recovery

Ideas in this category are students' later thinking about how a person recovers after illness. The microanalysis revealed five post-instructional ideas about disease recovery across the four interviews. These ideas were mainly about how the students later thought about sick people recovering or dying from flu and COVID. Table 6 summarizes the post-instructional ideas the four students had about disease recovery.

Table 6

Students' Post-Instructional Ideas About Disease Recovery

Post-instructional idea	Transcript
Flu has a lower death rate.	Alex: Probably the death rate is even lower.
Flu is more deadly.	Elmo: I think I should lower the recovery rate to lower and the death rate a little higher because the disease should last longer, and I know people would die because of the flu.
People have a shorter period of immunity after recovering from flu.	Elmo: Immunity should be lower, so people should be more likely to get infected by the flu again, which is why we need to get flu shots several times a year.
COVID is more dangerous than Flu.	Elmo: COVID should be more dangerous, I put them 30 (recover rate) because I think 40 percent is still high for COVID. And I need to increase this a little more (if sick die).
When people move around, they do not get enough rest, which makes it harder for them to recover and makes death more likely.	Elmo: I forgot to adjust the rate of recovery and death because moving around would mean not getting enough rest so that sick people would have a harder time recovering and dying easier.

Disease Prevention

Ideas in this category are about students' later thinking about ways in which an individual can avoid infection. The microanalysis revealed four post-instructional ideas about disease prevention across the four interviews. These ideas were mainly about students' later thinking on effective protection strategies for flu and COVID. Table 7 summarizes the post-instructional ideas the four students had about disease prevention.

Table 7

Students' Post-instructional Ideas About Disease Prevention

Post-instructional idea	Transcript
Face shields are not as effective as masks.	Elmo: If you are healthy, you can wear facial shields. Yes, I will change the wear masks to wear facial shields and I will lower the efficiency from 99.3% to 70.4%.
Sanitizing for flu may not be as effective as I thought.	Elmo: So also change this (ask healthy people to sanitize) to 70. So, it might not be able to sanitize all germs because I now think flu can spread though air.
Quarantine may not work as well as I initially thought.	Susan: [after observing the results of everyone wears masks model] 29 people, so only one person died. So I guess that might have been a bit less than the quarantine. I don't know if I actually expected this. I did not, I might have expected maybe like at least a couple of people to be still sick. Well, it kind of shows that masks could still work as quarantine.
Wearing masks may be a useful alternative to quarantine.	Elmo: Last time (strict quarantine model) it had a strong start, then just (disease) died down pretty fast. I think this time (disease spread) was much slower than the other time, MHM. But it actually like virus has completely gone much faster than the other time. Mmm, I feel like I can change the few things I do now. Not moving won't make much difference.

Shifts in Student Thinking

In comparing students' initial ideas with their later ideas, I found that their interactions with the modeling microworld contributed to their shifts in thinking. RQ3 asks whether these shifts occur and how they occur. Findings with respect to RQ3 include three kinds of shifts in thinking: (1) changes in the rules of interactions between agents, (2) changes in the rules of agent behavior, and (3) changes in the relationship between agent rules and aggregate emergent phenomena. Below, I introduce each kind of shift in thinking. I show how each occurred, using results from microgenetic analysis to construct a temporal decomposition of the student's engagement with the modeling microworld.

Shifts One and Two: Changes in Student Thinking About Interactions Between Agents and the Rules of Agent Behavior

Elmo experienced shifts one and two when he built his flu model. I present an episode from Elmo's interview to illustrate how he refined his thinking as he refined his flu model using Microworld Four, and how he experienced shifts one and two due to this activity.

As illustrated by the previous analysis on how Elmo incorporated his initial and later thinking on flu spread and prevention into his initial and later flu models, Elmo initially believed that flu could only be transmitted through touch, that it is not very contagious, and that it would make some people die. However, he developed a sense that the flu can be transmitted both through touch and air and is more infectious and dangerous than he originally thought, after making sense of his later model. The following analysis describes Elmo's thinking shift throughout the modeling activity.

Step 1: Building the Initial Model and Predicting Its Results

Elmo dragged blocks into the programming area and specified agent rules for flu spread and prevention. Based on his initial thinking that flu is only transmitted via touch and is not very contagious, he set the infection rate through air to zero and infection rate for pollution to 50%. He set the sanitation rate at 90% since he believed that sanitizing the object would eliminate most flu viruses. The recovery rate was 80%, and the death rate was 1% because he believed the flu is easily cured but still some people could die. He also put the strength and duration of immunity as 98.9% and 20 ticks separately to show his thinking that after people recover from flu, their immunity should be quite strong and last for a while. Before he tested his model, he predicted that "some people would die but the virus is gonna just go away after a while."

Step 2: Testing the Initial Model and Making Sense of the Results

Upon running his model, Elmo observed that the flu disappeared quickly with no fatalities. He said this result surprised him because he thought the flu would last longer and result in deaths. The reaction was evidence that he modeled the flu with the idea that it could be fatal.

Step 3: Debugging and Retesting the Model

Elmo began to debug the model to make the model run as he expected. To introduce mortality in his later model, he thought that the likelihood of infection should be higher and started questioning the notion that the flu could only be spread through touch. He suggested that the flu might also be spread through the air. As a result of this later thinking, he increased the infection rate of cough from 0% to 3.9% and its pollution rate from 50% to 70.4%. He reduced the sanitization rate of the flu virus from 90% to 70% because he believed that viruses in the air cannot be eliminated by sanitizing objects. In addition, he lowered recovery rates and increased mortality rates to represent his later thinking that flu can make people ill longer and cause death. Also, he shortened the immunization to ten ticks because he now believes it should be easier for people to get infected again after they recover from the flu. He tested the model again.

Step 4: Observing and Explaining the Results

Elmo observed five people died in his later model, and he said, “This model is probably closer to how flu spreads.”

Summary of Elmo’s thinking shifts on interactions between agents. Based on the previous analysis of Elmo’s thinking trajectory regarding flu spread, the practice of debugging the initial model so that the later model runs as expected can result in changes of thinking about interactions of rules between agents.

Elmo’s thinking shifts on interactions between agents. As illustrated by the previous analysis of Elmo’s thinking trajectory, the ways that Elmo made sense of his initial and later models—and how he debugged his initial models to make his later model run as he expected—show that he changed his thinking from “flu can only be transmitted through touch and is not very contagious” to roughly “flu can be transmitted through the air and is more infectious.” This shift of thinking was that he changed his view of how the flu would spread from a sick person to others. The changes in thinking on how flu would spread from a sick person to a healthy person (flu is more infectious and can be transmitted through the air) falls into the category of changes of interaction rules between agents.

Why and how Elmo experienced those changes of thinking. After Elmo discovered that his later model did not run as he expected, he debugged his flu model to make it run as he expected (i.e., rather than all people recovering as in the initial model, a few would die in the later model). To achieve this, part of the changes included changing the infection rate through the air from 0 to 3.9% and increasing the infection rate through touch. These changes yielded the desired results. In debugging the model to produce an expected result, he changed his thinking to reflect that sick people should be able to infect healthy people through coughing and sneezing, and flu should be easier to transmit.

Summary of Elmo's thinking shifts on agent behaviors. Like Elmo's thinking shifts regarding agent-level interactions, the practice of debugging the initial model so that the later model runs as expected can result in changes of thinking about rules of agent-level behaviors.

Elmo's thinking shifts on agent behaviors. Elmo changed his thinking from "flu is not very dangerous to a person" to roughly "flu is more dangerous than I thought." This shift of thinking came about because he changed his view of how the flu would affect a person. The changes in thinking about how a sick person would recover or die, and how a recovered person would become infected again (flu is more dangerous and has a shorter immunity duration), fit into the category of rules of agent-level behaviors.

Why and how Elmo experienced those changes of thinking. Elmo debugged his flu model to make it run as he expected. To achieve this, he lowered the recovery rate while increasing the death rate, and decreased immunity duration. Those modifications yielded the expected result. In debugging the model to produce an expected result, he changed his thinking to reflect that the flu is more dangerous than he thought.

Shift Three: Changes in the Relationship Between Agent Rules and Aggregate Emergent Phenomena

Elmo, Kathy, and Susan experienced this shift of thinking when they built their two COVID models. I present an episode from Susan's interview to illustrate how she refined her thinking as she refined her COVID model using Microworld Four, and how this activity led to this shift in thinking.

As illustrated by the previous analysis of how Susan built and predicted her two COVID models, she initially believed that asking sick people to quarantine would be the best protection strategy, even at the risk of making people feel depressed. However, she developed a later thinking that asking sick people to wear masks and allowing them to circulate in the general population would be an effective alternative protection strategy. The following analysis describes Susan's thinking shift throughout the modeling activity.

"Sick Stay Home" Model. Step 1: Building the Initial Model and Predicting Its Results

Having built and tested the flu model, Susan built a COVID model in which sick people quarantined. As she inspected her blocks, she dragged the "wear mask" block under the "ask healthy people" block and set its efficiency to 40%, reflecting her belief that masks would slow the spread of COVID. She dragged the "die" block and attached it to the blocks of "ask sick people," setting the death rate to 0.4%, which indicated that she believed COVID would result in a few deaths. Her next step was to lower the sick person's movement rate from 100% to 18% to simulate the rule of sick people staying at home. Before testing the model, she predicted that COVID would spread slightly but not too much. However, if people are already ill, they may die.

Step 2: Testing the Initial Model and Making Sense of the Results

In her model, Susan observed that sick people spread diseases to others, and two sick people died. She said that this was what she expected and that it reflected her initial thinking that COVID is fatal, but quarantine should be effective as a preventive measure.

"Everyone Wears Mask" Model. Step 1: Building the Initial Model and Predicting Its Results

After Susan finished building and testing the model of strict quarantine, she started building a model that represented everyone wearing masks. She dragged the "wear mask" block under the "ask sick people" block and set the protection efficiency also as 40%. Since she believed masks would not be as effective as quarantine, she increased the infection under cough. For the same reason, she also raised the death rate to 0.5%. Her changes indicated that she thought masks would be less effective than quarantine.

Step 2: Testing the Initial Model and Making Sense of the Results

Susan ran her model and observed that no one died in this model. She was surprised by the outcome. She tried to understand what was happening at the agent level that caused the aggregate-level result, particularly why no one died. She checked her model and said that it seemed to be correct. I asked Susan why she thought this was happening and her conclusion. Susan replied. "It kind of shows that masks could still work as quarantine."

Summary of Susan's thinking shifts on the relationship between agent rules and aggregate emergent phenomena. Based on the previous analysis of Susan's thinking shift regarding COVID prevention, allowing students to see how the aggregate-level phenomena can arise from agent level behaviors can result in changes of thinking about interactions between agents and rules of agent-level behavior.

Susan's thinking shift. Based on the previous analysis of Susan's thinking trajectory when she built two COVID models, the way she made sense of her initial models—coupled with her statement that the model of everyone wearing a mask didn't run as she expected and her conclusion that this activity would change her thinking on effective COVID protection strategies—show that she changed her thinking from "in comparison to wearing masks during COVID, quarantine provides greater protection" to "wearing masks may be a useful alternative to quarantine." The shift of thinking was that she changed her view on COVID protection strategies.

Why and how Susan experienced her change of thinking. After Susan observed that her model of wearing masks did not run as she expected, she examined the model and said the model was correct. In viewing the model as a simulation of reality, she observed the aggregate-level phenomena of the level of public health that resulted from each person wearing masks, which changed her perspective on COVID protection strategies. She now believes that wearing masks would be an effective alternative to quarantine. Changes in thinking on COVID protection strategy (e.g., asking each person to wear a mask would impact the level of public health) falls into the category of changes of the relationship between agent rules and aggregate emergent phenomena.

Analysis also revealed two kinds of reinforcement in thinking: (1) reinforcement of thinking about the rules of agent behavior, and (2) reinforcement of thinking on the relationship between agent rules and aggregate emergent phenomena. Below, I introduce each kind of reinforcement in thinking. I show how each occurred, using results from microgenetic analysis to construct a temporal decomposition of the student's engagement with the modeling microworld.

Reinforcement 1: Reinforcement of Thinking About Rules of Agent Behavior

Susan experienced this reinforcement of thinking when she built her flu model. I present an episode from Susan's interview to illustrate how she reinforced her thinking as she built and tested her flu model using Microworld Four and her thinking reinforcement 1 due to this activity.

As illustrated by the previous analysis on how Susan incorporated her thinking on flu spread and prevention into her flu model, Susan initially believed flu would not be fatal. She reinforced this idea when she made sense of her initial model. The following analysis describes Susan's thinking reinforcement throughout the modeling activity.

Step 1: Building the Initial Model and Predicting Its Results.

Susan's first step was to construct a model that showed how the flu spreads and how it might be prevented. Since she believed that the flu was spread by coughing and sneezing and was not very contagious, she set the infection rate under the cough at 46.2%. In addition, she believed sanitizing the environment would effectively eliminate the virus, so she set the sanitation rate to 75%. Due to her belief that the flu would not be fatal, she did not include the "die" block. Before testing her model, she predicted that even with a 46.2% chance of people infecting one another via cough, the flu would spread but there would be no deaths.

Step 2: Testing the Initial Model and Making Sense of the Results

Susan noticed that the flu spread to more people and that people eventually recovered. She said, "Yeah, I like it when it eventually goes away without kill [*sic*] people".

Summary of Susan's thinking reinforcement on agent rules. Based on the previous analysis of Susan's thinking trajectory about flu spread, allowing students to observe that the model runs as expected can result in a thinking reinforcement regarding the agent-level rules.

Susan's thinking shifts. As illustrated in the previous analysis of Susan's thinking trajectory, the way that Susan made sense of her initial model shows that she reinforced her view that flu would not cause death. It was a thinking shift that reinforced her thinking that all people would recover from the flu. The change in thinking on how sick people would all recover from flu (e.g., flu would not cause death) falls into the category of changes of rules of agent-level behaviors.

Why and how Susan experienced those changes of thinking. When Susan realized that her initial model did run as she expected, particularly the fact that taking out the "die" block would result in the predicted result. She ensured that taking out the "die" block was correct, namely that no one would die of the flu.

Reinforcement 2: Reinforcement of Thinking About Relationships Between Agent Rules and Aggregate Emergent Phenomena

Alex experienced this reinforcement of thinking when he built his COVID models. I present an episode from Alex's interview to illustrate how he reinforced his thinking as he built and tested his COVID models using Microworld Four and his thinking reinforcement 2 due to this activity.

As illustrated by the previous analysis of how Alex built and predicted his two COVID models, he initially believed that asking sick people to quarantine would be the best protection strategy. The model activity reinforced this thinking. The following analysis describes Alex's thinking reinforcement throughout the modeling activity.

"Sick Stay Home" Model. Step 1: Building the Initial Model and Predicting Its Results

Alex dragged blocks into the programming area and specified agent rules for strict quarantine. To simulate the behavior of staying in, he lowered the sick people's rate of movement to zero. After that, he raised the pollution rate to 40%, reflecting his belief that COVID is more contagious through touch than flu. Inspecting his blocks, he pondered the "chance" block, placed it under the "ask sick people" block, setting the chance rate to 6%. The "chance" block contained all the blocks that represent the agent rules of disease transmission and recovery. This major change indicated his belief that strict quarantine would greatly impact COVID spread and prevention rules by lowering the chances of disease transmission and recovery. He predicted that the disease would not spread before it was tested, but that it would be fatal if contracted.

Step 2: Testing the Initial Model and Making Sense of the Results

After running his model, Alex observed that the disease spread rapidly and eventually led to the death of fifty-three people. Alex stated that something went wrong with his model. This reaction was evidence that he built this model with the initial idea that strict quarantine would be highly effective to stop the spread of disease.

Step 3: Debugging and Retesting the Model

Alex began debugging the model and began to question the way he used the "chance" block. He explained that the "recovery" block should have been placed outside the "chance" block. He went on to explain that quarantine decreases the probability of infection but will not affect the likelihood of recovery. By placing the "recovery" block inside the "chance" block, he reduced the likelihood of people recovering by eighty percent. He dragged the "recovery" block outside of the "chance" block and tested the model again.

Step 4: Observing and Explaining the Results

In testing the modified parameter, Alex observed that only three people died, which matched his expectations, as he replied, "Yeah, that's what I thought it would look like." This suggests that he expected this modified model to lead to different results resulting in few deaths.

"Everyone Wears Mask" Model. Step 1: Building the Initial Model and Predicting Its Results

Once Alex finished building and testing the model of strict quarantine, he began building a model that represented everyone wearing masks. His first reaction was to delete the "chance" block. He specified agent rules where everyone moved at a rate of 100%, added a "wear mask" block for sick people, and set efficiency to 80%. He kept his other parameters unchanged from the strict quarantine model. Before testing the model, he predicted that more people would die, reflecting his belief that moving around with a mask would increase the incidence of infection.

Step 2: Testing the Initial Model and Making Sense of the Results

According to Alex's model, the disease spread quickly and eventually caused fifty-three deaths. He said this result was exactly what he expected since he thought that moving around would increase infection rates and death rates. This reaction proved that he built this model with the later idea that moving around with masks would increase the risk of infection.

Summary of Alex's thinking reinforcement on agent rules and aggregate emergent phenomena. Based on the previous analysis of Alex's thinking shift regarding COVID prevention, allowing students to observe how the aggregate-level phenomena arise from the agent level behavior can result in the reinforcement of thinking on the relationship between agent rules and aggregate emergent phenomena.

Alex's thinking reinforcements. Based on the previous analysis of Alex's thinking trajectory when he built two COVID models, the way that he made sense of his initial and later models, the way that he debugged his initial strict quarantine model, his statement that the two later models would run as he expected, and his conclusion of how this activity would reinforce his thinking on strict quarantine would be the best protection strategy, all demonstrate that he reinforced his thinking that "strict quarantine would be better than wearing masks when moving around." He reinforced his view on COVID protection strategies. The reinforcement in thinking on COVID protection strategies (quarantine is better than wearing masks) falls into the category of reinforcement of thinking on the relationship between agent rules and aggregate emergent phenomena.

Why and how Alex experienced these thinking reinforcements. Alex was the only participant who used the "chance" block in COVID models. The use of the "chance" block to set the chance rate as 6% lowered the disease transmission as well as recovery rate was only 6% of what he originally set, which made these two rates both extremely low. After Alex observed that his initial model of strict quarantine did not run as he expected, he debugged that model to try to make it run as he expected, i.e., rather than fifty-three fatalities as in the initial model, fewer people would lose their lives when they are moving around in the later model. To achieve this, he checked his model and calculated that including a "recovery" block in the "chance" block had greatly decreased sick person's chance of recovery. After dragging the "recovery" block out of the "chance" block, the model ran as he expected. When he built the model of everyone wearing masks, he decided not to use the "chance" block because it would make it difficult to predict the aggregate outcome, so he removed it. This greatly increased infection rates when compared with the strict quarantine model, resulting in more deaths. Clearly, his understanding of how the blocks work led him to build models in diverse ways, which resulted in a different aggregate-level phenomena, eventually leading him to develop different later thinking on COVID protection strategies.

High-Level Sketch of Shifts in Student Thinking Supported by the Modeling Microworld

The microanalysis revealed three kinds of shifts in student thinking and two kinds of thinking reinforcement about disease spread and prevention across the four interviews. The analysis also shows students' types of thinking shifts are: (1) changes in the relationship between agent rules and aggregate emergent phenomena, (2) changes in the rules of interactions between agents, and (3) changes in rules of agent behavior. The two types of thinking reinforcement are: (1) reinforcement of thinking about the rules of agent behavior, and (2) reinforcement of thinking on the relationship between agent rules and aggregate emergent phenomena. Students' types of thinking shifts and thinking reinforcement are outlined in Table 8. For each category of thinking shift or reinforcement, I give a description and illustrate it with an example.

Table 8

Categories of Students' Thinking Shifts, Their Descriptions, and Examples

Category of students' thinking shifts	Description	Example
Changes in the relationship between agent rules and aggregate emergent phenomena	The student observes that the agent-level rules have led to a different aggregate emergent phenomenon in the model, which has led her to change her old thinking about the relationship between agent-level rules and aggregate emergent phenomena.	Susan observed that if everyone wore masks, it would have a transformative positive impact on the level of public health. She thought that wearing masks is a good alternative protection strategy to strict quarantine. This is a shift in thinking in the relationship between agent rules and aggregate emergent phenomena.
Changes in the rules of interactions between agents	The student debugs the agent-level rules to make aggregate emergent phenomena run as she predicted, which led her to change her old thinking on the interaction rules between agents.	Elmo debugged his flu model to make his later model results match his prediction, namely that a few people would die from the flu. Through this activity, he developed a later thinking that flu has a higher infection rate. This is a shift in thinking in the rules of interactions between agents.
Changes in the rules of agent-level behaviors	The student debugs the agent-level rules to make aggregate emergent phenomena as she predicted, which led her to change her old thinking on the rules of agent-level behaviors.	Elmo debugged his flu model to make his later model results match his prediction, namely that a few people would die from the flu. Through this activity, he developed a later thinking that people who get infected by flu have a shorter immunity duration than he previously thought. This is a shift in thinking in the rules of agent-level behaviors.
Reinforcement of thinking about agent-level rules	The student tests the model and finds that agent-level rules have led to the aggregate emergent phenomena that she predicted, which led her to reinforce her initial thinking about agent-level rules.	Susan observed that all sick people in her flu model had eventually recovered, and this result was what she expected. Through this activity, she was reassured that people would all eventually recover from flu, which is a reinforcement of thinking on agent-level rules of her flu spread model.
Reinforcement of thinking on the relationship between agent rules and aggregate emergent phenomena	The student tests the model and finds that agent-level rules have led to the emergent phenomena that she predicted, which led her to reinforce her initial thinking on the relationship between agent rules and aggregate emergent phenomena.	Alex tested his two COVID models and observed that more healthy people were left in his strict quarantine model. He was reassured that strict quarantine would be safer than moving around wearing masks, which is a reinforcement of thinking on the relationship between agent rules and aggregate emergent phenomena.

CHAPTER VI

CONCLUSIONS

Discussion

In review, this study addressed the following research questions.

1. How are students thinking about disease spread and prevention as they construct their initial flu and COVID models?
2. How do students understand disease spread and prevention as they construct their later flu and COVID models?
3. How do their ideas change from their initial to their later thinking in response to their modeling activity?

Students' Pre-instructional Ideas About Disease Spread and Prevention

Four case studies revealed patterns of initial knowledge about disease spread and prevention. Each student had knowledge in the categories of disease spread, recovery, and prevention. Some of their perspectives, however, differed. Next, I will discuss their initial thinking with respect to each knowledge category.

Pre-Instructional Ideas on Disease Transmission

As illustrated in Table 2, students' thoughts in this category are focused on how flu or COVID would spread. However, students' knowledge elements on the same topic can differ. For example, Elmo thought the flu could not transmit through the air while Kathy, Alex, and Susan all thought Flu was airborne. Susan, Alex, and Elmo thought COVID was very contagious, but Kathy thought COVID was only slightly easier to spread than flu.

Pre-Instructional Ideas on Disease Recovery

Also, as in Table 3, students' thoughts in this category are focused on how the sickness recovery process would differ from flu to COVID. However, students' knowledge elements on the same topic can differ. For example, Kathy thought many people would die from flu from what she read in the book, while Susan thought flu is not fatal at all. Elmo and Alex thought COVID had a shorter immunity duration than flu, while Kathy thought their immunity durations were the same.

Pre-Instructional Ideas on Disease Protection Strategies

As listed in Table 4, students' thoughts are focused on how sickness protection strategies work for flu and COVID. In contrast to the former two categories, the students expressed similarities of thinking in this category. For instance, they think sanitizing surroundings, wearing masks, and resting are effective ways to stop flu spread, and quarantining and wearing masks when out is effective for COVID. Specifically, they all think that asking sick people to stay in would be more effective than wearing masks and moving around to stop the spread of COVID.

Students' Pre-Instructional Ideas as Reflected in Initial NetTango Models

The findings show that by providing students with programming blocks that could correspond to their intuitions, they could represent their thinking in the initial models. For example, referring to the previous examples of students' different initial thinking on disease transmission, Elmo could set the infection rate through the air for flu to zero using the "cough" block to demonstrate his belief that flu could not spread through the air. In contrast, Kathy could adjust the "cough" block parameters and increase the infection rate under both touch and air to represent her belief that flu could spread both by contact and air. Referring to the previous examples of students' different initial thinking on disease recovery, Susan could remove the "die" block to represent that people did not die from flu. At the same time, Kathy could assign a 17% death rate for her flu model to represent her thinking that flu was dangerous. Referring to the example of students' initial thinking on disease protection strategies, Kathy set up a higher protection rate wearing masks in her COVID model to reflect her belief that masks could help to prevent COVID spread. In contrast, she set up a very low protection rate of handwashing to represent her thinking that handwashing is ineffective.

Students' Post-instructional Ideas About Disease Spread and Prevention

The findings from the analysis of the four cases reveal a pattern of students' later thinking. Students developed their thinking in the categories of disease transmission, disease recovery, and disease prevention strategies, as a result of their interaction with the modeling microworld. Next, I will discuss those later thoughts in each knowledge category.

Post-Instructional Ideas on Disease Transmission

Alex, Kathy, and Susan reinforced some of their initial thinking in this category. However, as illustrated in Table 5, Elmo developed later ideas about how flu would spread. As an example, after Elmo shortened the immunity duration of his initial flu model and got it to run as he expected, he developed the idea that flu immunity is shorter than he originally thought.

Only Elmo changed his thinking about the spread of flu, while others kept their initial ideas. This could be because Elmo's initial thinking about the flu was not sure, so the modeling activity changed his initial thinking quite a bit. However, since flu is quite common in our daily lives, other students might already have their own certain thinking about how the flu would spread, so taking part in the modeling activity would not change their thinking.

Post-Instructional Ideas on Disease Recovery

Susan and Kathy kept their initial thinking on this category while Elmo and Alex developed later thinking on how people would recover or die because of flu or COVID. Elmo, for example, developed the idea that flu has a lower death rate than he had initially thought after he lowered the death rate in his later flu model to make the later model run as he expected.

Post-instructional Ideas on Disease Protection Strategies

Elmo developed later thinking that facial shields are less effective than masks and that sanitizing for flu may be less effective than he thought. Elmo, Kathy, and Susan all developed later thinking that quarantine may not work as well as they initially thought and wearing masks may be a useful alternative to quarantine. Alex kept his initial thinking that quarantine is better than wearing masks.

Students' Post-instructional Ideas as Reflected in Later NetTango Models

Findings show that our representations supported students developing their thinking in two ways. First, they allow students to express their thinking in a language they understand, and second, they enable students to check their thinking by making sense of the model's running result. Next, I will explain those in detail.

Expressing Thinking in Later Models

Recalling back to Elmo's later thinking that flu can also be transmitted through the air, he increased the infection rate from zero to 3.9% to represent this. Susan also represented her later thinking that flu is not dangerous by increasing the recovery rate while lowering the death rate in her later model of flu. Kathy, however, showed her view that flu can be more infectious and deadly by increasing the infection rate and death rate.

Making Sense of their Models as They Develop their Thinking

For example, Elmo, Susan, and Kathy tested their two COVID models and observed that fewer healthy people were left in their strict quarantine model. They developed their thinking to understand that strict quarantine was not as effective as they thought. In contrast, Alex reinforced his thinking that strict quarantine would be more effective by observing that more healthy people were left in his strict quarantine model.

Alex's later thinking on COVID protection strategy is interesting in that he is the only one who did not reverse his thinking about the most effective strategy being strict quarantine. I observed that the use of "chance" blocks changed how he built the model and added a layer of complexity to make sense of the relationship between aggregate-level phenomena and agent-based rules. As he debugged his model, he realized that using "chance" blocks in his initial model of strict quarantine decreased the infection rate by 80% and impacted aggregate outcomes by lowering the infection rate to an extremely low level. Although Alex did not further debug this model and changed the setting of the "chance" block to resemble the real case of COVID infection rate, he was able to realize how aggregate-level phenomena can arise from agent level rules and relate the later model running result to his everyday experience. It would have been worthwhile to have a follow-up interview based on debugging this model to see if his later thinking had changed further.

Thinking Shifts and Reinforcement of Thinking

The findings show that students either developed new thinking or reinforced their initial thinking due to the model activity. Those changes of thinking include three kinds of shifts in thinking: (1) changes in the rules of interactions between agents, (2) changes in rules of agent behavior, and (3) changes in the relationship between agent rules and aggregate emergent phenomena, and two kinds of reinforcement in thinking: (1) reinforcement of thinking about rules of agent behavior, and (2) reinforcement of thinking on the relationship between agent rules and aggregate emergent phenomena. Next, I will discuss this topic by the sequence of what changes of thinking they made, and how and why they changed.

Thinking Shifts and Reinforcements that Occurred

Alex, for example, shifted his later thinking to that the flu would also spread through the air, and strict quarantine of sick people was not as effective as he had thought. In addition, Susan reinforced her belief that flu was not dangerous and would not be fatal, but she shifted her thinking to the idea that wearing masks might be more beneficial than quarantining sick people. Furthermore, Kathy reinforced her belief that flu was dangerous and could cause many deaths, but she also shifted her thinking that wearing masks would be as effective as quarantining sick people. However, unlike the other three, Alex reinforced his thinking that strict quarantine would be the most effective protection strategy.

As we can see, students' changes of thinking are not always correct, nor do they move closer to normative scientific understanding. For example, Susan's reinforcement of thinking that flu is not fatal is factually incorrect. However, the key takeaway is that students are beginning to see the dependence of outcomes on agent behavior. This learning outcome is more evident when we look at students' thinking shifts in modeling COVID spread and prevention.

Why and How They Experienced Those Changes of Thinking

The students' thinking on effective COVID protection strategy changed after they observed that individual behavior, such as wearing masks or staying at home, can affect the aggregate level. Additionally, students changed or reinforced their thinking around how the disease would spread, and how infectious and dangerous it would be after they changed the rules of agent behavior and agent interactions, debugged the models, and got the model to run as expected.

Categories of Changes of Thinking

As illustrated in Table 7, students' thinking shifts on effective COVID protection strategies represent changes in the relationship between agent rules and aggregate emergent phenomena (Elmo, Kathy, and Susan). In comparison, Alex reinforced his thinking on this topic. Besides that, students' thinking shifts around how the disease would spread and how infectious and dangerous it would be changes about the rules of interactions between agents (Elmo) and changes about the rules of agent-level behaviors (Elmo and Alex), while Kathy and Susan reinforced their thinking on the agent-level rules of how flu spreads (Kathy and Susan).

Relationship Between Changes of Thinking and Modeling Activity

As we see in students' activity of modeling flu spread and prevention, making sense of the models and debugging the models to make the model run as expected can help students make changes of thinking in agent behavior rules and interactions. In addition, as we see in students' activity of modeling COVID spread and prevention, allowing students to see the aggregate-level phenomena that arose from the agent-level rules can help students experience changes of thinking on the relationship between agent rules and aggregate emergent phenomena.

Features of Design

Study findings revealed that the design of the modeling microworld supported students' learning, as I observed their thinking shift as they built, tested, observed, and made sense of computational models. For example, in the case of which method of protection would be more effective (requiring sick people to wear masks when moving around or urging them to stay at home), it showed that three students changed their thinking to see wearing masks as effective, while one continued to think that strict quarantine was the best method. Their statements implied that they could make connections between model running results and everyday experiences.

My goal, as explained in the methods section, was to create representational microworlds so that the blocks embodied students' intuitions and allowed them to test, implement, and debug their thoughts. Representational microworlds worked as expected, and there are two reasons for this due to design features. Next, I will discuss these two features one by one.

Blocks Embody Students' Intuitions

The findings of thinking shifts show that students can build models using a language they understand. For example, after Alex's initial misstep, he described the situation appropriately in the modeling language, linking "people wear masks more seriously when they have COVID than when they have flu" with "the protection rate for wearing masks during COVID is higher than flu." Though somewhat abstract, Alex could relate the model's agent rules to his own lived experience of the phenomena he was trying to model.

Models Allow Students to See how Aggregate-Level Phenomena Arise from Agent-Level Rules and Interaction

Findings also show that students can set model rules at the agent level and observe the results at the aggregate level. For example, after Susan built and tested two COVID models, she concluded that even though she does not like to wear masks herself, after seeing the aggregate outcome of everyone wearing masks, she thought everyone should wear masks for the health of society. It is evident that agent models can help students make sense of how behaviors at the agent level affect the aggregate level of health of society.

Contributions

Connections With Prior Work

As stated in Chapter II, there is limited research on teaching middle school students about disease spread and prevention through computational modeling. This study would contribute to the literature on engaging middle students in learning complex systems phenomena, such as disease spread, by providing students with blocks that embody their intuitions and allowing them to refine their thinking through building, testing, debugging, and making sense of computational models.

The findings indicate that students possess various pre-instructional thinking about disease spread and prevention, and that students can customize the blocks used in the model of this study to represent that thinking. As we discussed in the empirical foundation part about prior knowledge pedagogy, block-based modeling practices afford scientific inquiry pathways based on their intuitions in a way that cues pre-instructional thinking as students build their models. Those ways of thinking are reorganized and refined as they test and debug the models.

The findings suggest that agent-based models can help students comprehend how the rules influence the aggregate-level phenomena at the agent level. In public health, students learn how an individual's actions affect the health of the society. Based on the discussion of computational modeling pedagogy in the empirical foundation part, agent-based modeling allows students to fully participate in the scientific inquiry process by setting up the rules of agent behavior and interactions and examining how the emergent phenomena arises from those rules.

Finally, the results indicate that agent-based block-based computational modeling has a positive effect on middle school students' understanding of disease spread and prevention, with a particular benefit in teaching them effective COVID protection strategies. By building, testing, debugging, and making sense of COVID models that use different disease protection strategies, students better understand how an effective protection strategy would be created.

Empirical Contributions

In this study, students had thirty-seven pre-instructional ideas across three categories: disease transmission, sickness recovery, and disease prevention. Computational modeling microworlds help students refine their thinking in four stages: (1) building an initial model and predicting its results, (2) testing the initial model and interpreting its results, (3) debugging and retesting the model, and 4) observing the final model and explaining its results. Due to the modeling activity, students developed twelve types of post-instructional thinking, three types of thinking shifts, and two types of reinforcement in thinking.

Design Contribution

This study presents findings from one iteration of design-based research. Findings show that the current design of the modeling microworld supports students in building, testing, and debugging models of their thinking, and that interacting with the microworld in this way can help students refine their thinking. Moving forward, we can use the identified pre-instructional ideas to help refine the next iteration of the modeling microworld, by adding blocks or parameters. This will make coding primitives more compatible with students' intuitions so that they can build and test models that better represent their thinking. In later implementations, we can create and test instructional supports for interacting with the models, to help students learn more of the science behind disease spread and prevention. For example, we could have students read an article about COVID and an article about the flu to get ideas about agent-level behaviors or aggregate-level outcomes, which they could use in their design and evaluation of models.

Limitations

Consideration of Possible Ethical Issues

Interview activity must be considered in two ways. First, I introduced myself to participants whom I had been interested in observing and interviewing. Second, I did not want to impact the actions of the participants since their actions form the basis of my inquiry. My involvement in their participation was inevitable to some extent, but I intervened as little as possible. Therefore, at the beginning of the interview, I disclosed to the participants that I was a researcher who wanted to understand how they were thinking about things and how I could improve our educational technology to support their thinking and learning about science.

My own sensitivity as an interviewer was around care and justice in facilitation, combined with the desire to work toward improving learning outcomes using the modeling microworld practiced in learning about the spread of disease. Therefore, I could envision being drawn toward moments during the online interview where an interviewee demonstrates thinking I may not expect. However, if I could notice them diligently, such reactions could serve as data since they informed the study and informed me.

Potential Validity Threats

One potential threat to this study was researcher bias. Since this research tended to have been exploratory and was open-ended, I may be prone to "find what I want to find." Researcher bias tends to result from selective observation and selective recording of information and from allowing my personal views and perspectives to affect how data were interpreted and how the research was conducted.

My key strategy to mitigate researcher bias was reflexivity: I actively engaged in critical self-reflection about my potential biases and predispositions. In this way, I became more self-aware and monitored and attempted to control my biases.

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APPENDIX

INTERVIEW PROTOCOL

Interview Protocol

1. Openings

(Greetings and Introduce myself) Thank you for participating in our study. The purpose of the study is to help me and my team develop tools for helping students learn science. As a thank you for your participation today, I will give you a $25 Amazon gift certificate. Today's session will take about an hour and a half. The purpose of the session will be to understand how you are thinking about things, and how we can improve our educational technology to support your thinking and learning about science. The session will work as an interview, with questions and tasks. I will ask you questions to hear your ideas about how things work, and I will ask you to test out our educational technology. Do you have any questions for me?

2. Backgrounds

2.1 Greetings Could you simply introduce yourself? Name, age, where you come from? And which grade are you in? How's your school going?

2.2: Computer backgrounds:

Then some background questions, Do you use computers often? Do you enjoy using computers?

If students say yes, then say:

That's so awesome. Um, what kinds of things do you use those computers or iPads for? (**if students mention programming or Lego or STEM projects, ask "**So when you say programming/ Robo / STEM projects, does that mean that kind of a thing like making a model of the steps? What does that experience look like?

2.2: Use storytelling methods to find intuitions (prior knowledge) about the nature of the infectious disease

I am so glad that you still have had a wonderful school time during the pandemic. Talking about the pandemic, Have you heard much about COVID-19? Students around the world have had to change their lives because of covid. I have dealt with staying at home more of the time and can't take my kids to the playground. Other things are changes in homework approaches, socializing, etc.—what have you most dealt with? Do you know what the word pandemic means? (if they don't explain it means an outbreak of disease).

Next, we will **play a storytelling game together**, and that will be fun!

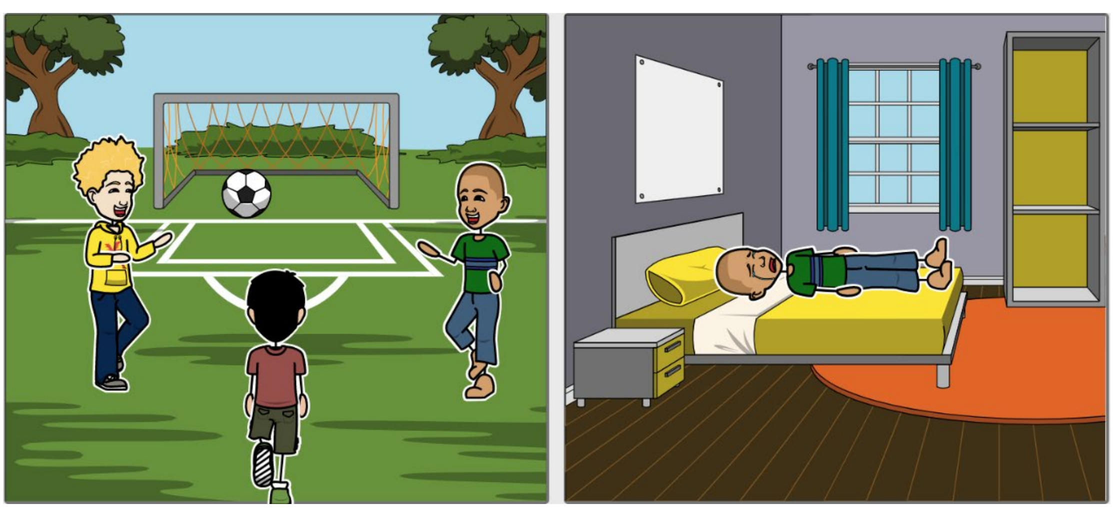
(storyboard is created to facilitate this process)

Scene 1: (Picture: a smiling boy celebrating a birthday party with a girl in her house): "This is a picture of Jack and this is Mary. Jack is visiting Mary today and they are throwing a birthday party. But poor Mary is coughing and sneezing a little bit, but Jack felt fine, and they played for a little while, and then he went home."

Scene 2: (Picture: Jack lying on the bed looking unhappy): "The next day when Jack wakes up, he has a sore throat! Now, remember when Jack was playing with Mary? Yet he felt fine. But the next day, he wakes up with a sore throat. Why do you think that happened? Why might Jack be sick today even though he seemed fine yesterday? (trying to get at their understanding of how the virus spreads from individual to individual)

Scene3 : (Picture: Jack playing football with other boys on a playground): " this is a picture of Jack staying at home resting for a week, he recovers, the sore throat has gone away, he doesn't sneeze, cough or have any other symptoms. He feels healthy again. Today he invite friends to play football on the playground.

Scene4: (Picture: The other boy lying on the bed unhappy): " The next one day the other kid who was playing with Jack found that he had a sore throat! Now, remember when Jack was playing football with them? Yet he felt recovered. But the next day, his friend woke up with a sore throat. What do you think has happened here that caused the friend to wake up with a sore throat? The common flu or Covid-19? (Looking for answers like Covid-19 has a longer incubation period, more contagious compared with flu)?



What conclusions will you make? What are your thoughts about how diseases spread significantly enough to become a pandemic?

That's great thinking. When the vaccine is still in short supply, what strategy would you like to use to protect yourself as well as protect your family and friends? What strategy do you think is the most effective and why? (looking for strategies like wearing masks and washing hands to lower infection probability and staying home in quarantine to lower the probability of infection by reducing the rate of moving)

3. Use sequence stage models to explore the microworld

Cool, Well, hopefully, you enjoy what we have planned for today. Here's the tool (be sure to send the link of **model 0**) we're building to help students think about and learn about disease spread. With the tool, you can use a block-based programming language to build a computational model.

So now you can direct your attention to this page. You know, This box in the interface represents a social space or a space where people interact with each other. Try clicking the Setup button. So what happened when the Setup button was clicked?

Nothing happened, that's intentional, you can think of a setup as a procedure that connects to this Setup button, the procedure is like a command you tell to the box what and how many characters you want to have in this model. What characters do you want to have in this model? (Allow students to respond) try to add those blocks to the setup. You can always test the model by recompiling and pressing the setup button over the box to test whether you have those characters in your model.)

Look, characters show up! Great job! What do you think the green and red characters represent in the world? [People who are green mean they haven't been infected and people who are red mean they are sick].

How do you think you could get there to be more red (sick) or pink (healthy) people in the social space when you hit setup? Check around on the screen and see if there's a way to do that.

Great. you may have noticed that the system has been frozen when you finish building the blocks. I think you need to press the recompile, it's like a refresh button when your computer freezes, and after you press the recompile, the system can come back to life, then you can press the setup above the box to see what will appear in that box.

Next, here is model 1 which adds the go button (sent the link to the student at the same time)

Remember what you have done in model 0? Try to arrange the blocks and make some healthy people and sick people show on the screen? (IF students are confused when selecting the blocks and arranging them, say " remember setup is a procedure that connects to this Setup button, the procedure is like a command you tell to the box what and how many characters you want to have in this model. What characters do you want to have in this model? (Allow students to respond) try to add those blocks to the setup. You can always test the model by recompiling and pressing the setup button over the box to test whether you have those characters in your model.)

Try dragging the Go button into the block building space, clicking the Go button. What do you notice happening?

Nothing happened. That's intentional. You can think of Go as a procedure that connects to the Go button. The procedure likes commands that you can ask the characters you have set up, in this case, healthy and sick people to behave. Do you think you could rearrange the blocks and let people move around?

If the people don't move and the students question whether the model is running or not, reply "yeah, people don't move but those ticks**,** the tick count is going up and the ticks **represent ticks on a clock in this fictional world. We can adjust tick speed to make it faster or slower**. So they can happen as fast and slow as you would like. Now they're happening pretty fast. so there are more than one a second maybe, maybe there's like 10 a second. But there are a lot of ticks happening so that means time is going by. It means the model is running.

Then why are the people not moving, can you guess? Do you want to rearrange the model and try again? (allow students to try)

Great, Next I will give you a model 2 with infect button

How do you think you can arrange the blocks to get the people to move around and have sick people infect healthy people when you press the go button? Try it.

Great job, how do you modify the blocks and parameters to make people get sick faster or slower? Try it.

Great job, next I will send you the model 3 link. With this model, you can model sick people, recover, or could die.

The rate of if sick, die means sick people dying at the rate of X, and the rate of if sick, recovery means sick people recovery are the rate of X. The denominator when we calculate the rate is time, and in this microworld, the time is tick. As you remembered before, you can drag the tick bar above the box to make ticks happen faster and slower.

When someone is sick, and this disease is infectious and deadly, do you know what happens to the size of a population in a certain place over time?

Oh, that's a really good observation. Let's just see if you can use some of the blocks in your exploration to make the population either increase or decrease.

That's good, I think you are ready and now let's move on to model 4, compared with model 3, this model has an additional chance block so that you can modify the parameters to create a variety of virus spread situations. Would you like to arrange the blocks and modify the parameters to create a situation that represents the outbreak of pandemic?

Great thinking, then I will send you a link to model 5, and with this model, you can modify the blocks and parameters to create microworlds that represent people using different protection strategies in Pandemic. Here we have a little challenge for you. Could you arrange the blocks, modify the parameters of the blocks to create models that represent four situations in a pandemic, predict the result, and test them?

Task 1:

The first task is to try to model the people in this world in a strict quarantine situation where everyone stays at home. Are there any blocks or parameters you could use to model all people staying at home more of the time? [After students build the model and before they test the model, ask them: Would you predict the model running result?]

Task 2:

The second task is to model the people in this world in a normal quarantine situation where sick people stay at home and quarantine, while healthy people wear masks and keep normal activity. How would you modify the code? Try it. [After students build the model and before they test the model, ask them: Would you predict the model running result?]

Task 3:

The third task is to model the people all wearing masks while still keeping the essential activity time, for example cuts off some leisure activities and still keeps the normal school, work, and grocery activities. How would you modify the code? Try it. [After students build the model and before they test the model, ask them: Would you predict the model running result?]

Task 4:

The fourth task is to model the people all wearing masks and keep normal activity. How would you modify the code? Try it.[After students build the model and before they test the model, ask them: Would you predict the model running result?]

When they model each scene, ask "Based on anything you know about prevention measures and whatever you just read, how would you make an approximate guess on the infectivity rate when everyone wears a mask/ no one wears a mask, and how would you like to adjust the parameter in the infect block? (If students say they don't know, encourage them to google the answer.)

What conclusion would you draw? which prevention measure is more effective, according to your model results? Is this what you expected?