Epistemic Dispositions in Socioscientific Issues-Based Systems Modeling

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Socioscientific issues (SSI) play a significant role in promoting science literacy among students by fostering active participation in science learning that relates to their personal lives. SSIs are ill-structured problems of society with ethical dilemmas (e.g., climate change, food deserts, gene editing) that can be reasoned about using scientific ideas and evidence (Zeidler et al., 2019). Because there is no simple solution to an SSI, students must be able to coordinate and evaluate multiple dimensions of the problem when negotiating the issue and considering solutions. For instance, when considering the COVID-19 pandemic as an SSI, a decision maker prioritizing the economic ramifications and financial stress of the pandemic may adopt a different position on reopening businesses than someone concerned about availability of hospital beds and guided primarily by a healthcare perspective. For students to construct holistic arguments that address multiple dimensions of an SSI, they need to engage with multiple lines of reasoning and use epistemic practices to form reasoned positions (Ramos & Mendonça, 2021). Epistemic practices are defined as "the socially organized and interactionally accomplished ways that members of a group propose, communicate, evaluate, and legitimize knowledge claims" (Kelly & Licona, 2018, p. 140). Assessing how factors in a complex SSI are linked to one another is difficult for students, particularly when relationships are indirect or nonlinear (Yoon et al., 2018). Students tend to view systems in terms of simple causal relationships and fail to recognize that factors can have multiple causes and indirect relationships (Hmelo-Silver et al., 2007). Modeling is one type of epistemic practice that can support students' sensemaking about complex issues such as COVID-19.

Developing and using models is one of the eight practices envisioned in the Next Generation Science Standards (NGSS) for effective participation in science (NRC, 2012). Models are tools such as diagrams, drawings, computer simulations, or graphical representations (Lehrer & Schauble, 2006). Models can help students demonstrate their knowledge about a system by creating, testing, or revising their models (NRC, 2012). In addition, students can use models to explain and make predictions about phenomena as expert scientists would do (Ke et al., 2021). The majority of research that has explored the use of models to support SSI-based learning has focused on models that are scientific in nature. We refer to scientific models as models that explain how or why natural phenomena occur (Baumfalk et al., 2019; Ke et al., 2021). For example, Peel and colleagues (2022) designed a computational model to support students' science learning of antibiotic resistance and natural selection. Scientific models applied in socioscientific contexts have also been used to help students understand carbon cycling associated with climate change (Zangori et al., 2017) and biological homeostasis to consider policies for regulating e-cigarettes (Peel et al., 2020). It is true that some systems are largely scientific (e.g., an ecosystem can be modeled using a food web). While scientific models are important for developing students' knowledge of science concepts, SSIs encompass many different dimensions including ethics, policy, public health, economics, and politics. One particular modeling approach, systems modeling, can help students identify how science concepts are related to some of these other dimensions (Ke et al., 2021).

Systems models are simplified representations of complex systems that describe how sub-components within a system interact. Systems models can be used to make predictions such as how changes in one part of the system affect other parts of the system. When creating systems models, students use visual representations to show how factors are interconnected through cause-and-effect relationships. Some of these relationships may be scientific in nature—e.g., how viral reproduction rates impact disease spread—while others may require non-science considerations—e.g., how politics influence individuals' decision-making around wearing masks. Systems models help students identify behaviors and interactions of a complex system as a means to better understand patterns, limits, and weaknesses of the system (Yoon et al., 2018). Importantly, NGSS includes systems and system models as a key crosscutting concept in NGSS that facilitates connections across disciplines (NRC, 2012).

This paper presents an exploration of how students engage in systems modeling related to SSIs. We examine students' epistemic dispositions while engaging in a systems modeling task related to COVID-19 to support teaching and learning of SSIs. Establishing a taxonomy of talk is the first step towards being able to identify patterns and characteristics that set high-quality modeling conversations from less productive ones. Doing so can help educators create learning environments and experiences that encourage these high-quality discussions. Our research is guided by the following questions:

1) Which epistemic dimensions do students demonstrate during SSI-based systems modeling?
2) Which epistemic operations do students perform during SSI-based systems modeling?
3) Which interactional operations do students engage in during systems modeling?

Theoretical Framework

Reforms in science education curriculum have focused on the integration of students' learning how to perform science practices and learning how science knowledge is generated and ultimately accepted through social discourse (Aleixandre & Crujeiras, 2017; Duschl, 2008). Science, like any product of history, is not isolated from culture, identity, language, or values (Gee & Gee, 2007). Drawing from a Vygotskian sociocultural perspective, we posit that students learn through interactions with others which is mediated through language and culture (Vygotsky, 1978). When students participate in groupwork activities such as modeling, they make sense of phenomena and develop meaning through discursive actions with members in their group. As students work together to propose, communicate, evaluate, legitimize, and justify their knowledge claims, they engage in epistemic practice (Kelly & Licona, 2018). Kelly and Licona (2018) argue that epistemic practices are 1) Interactional—constructed among people through concerted activity 2) Contextual—situated in community practices and norms 3) Intertextual—communicated through shared history 4) Consequential—legitimized through power and culture. Systems modeling aligns with this way of operationalizing epistemic practice because students work collaboratively to share what they know about an issue and how they know it using examples from personal and community experiences as sources of evidence to support their sense-making.

Most research on epistemic practices is related to students' interpretation and evaluation of data to develop reasoned arguments (Nussbaum et al., 2008; Ryu & Sandoval, 2012; González-Howard & McNeill, 2020; Kelly & Takao, 2002). Epistemic practices have shown to improve the quality of students' arguments, including the number of factors students use in their thinking (Nussbaum et al., 2008) and their understanding of evidentiary criteria that constitute good argumentation (Ryu & Sandoval, 2012). More recently, González-Howard & McNeill (2020) examined student talk during an argumentation activity and found that critique helped support students' epistemic agency, which they define as students "being positioned, and taking up, opportunities to inform their classroom community's knowledge construction work" (p. 955). During systems modeling, students similarly participate in the generation of individual and shared knowledge which we contend supports their sense-making of complex SSIs. In particular, we unpack student conversations during modeling to understand the ways in which students engage in epistemic practice.

To guide our analysis, we use Kelly and Licona's (2018) framework of epistemic dimensions (i.e., proposing knowledge, communicating knowledge, evaluating knowledge, and legitimizing knowledge) that occur while engaging in science practices like modeling. In addition, we draw from Casas-Quirogas and Crujeiras-Pérez's (2020) coding schema of epistemic operations for student talk in an argumentation activity. Epistemic operations are the types of discursive actions that in summation help students accomplish epistemic practices (Casas-Quirogas and Crujeiras-Pérez, 2020). In Casas-Quirogas and Crujeiras-Pérez (2020), students engage in both argumentation and decision-making as they role-play an emergency situation about food safety. In contrast, students in our study work collaboratively to construct a systems model about a viral pandemic and are less likely to engage in debate. For this reason, we adapted and expanded their coding schema to include the distinct epistemic operations students utilize during a SSI-based systems modeling task.

Methods

We used a qualitative approach to explore student discourse during a SSI-based systems modeling activity. This paper was a pilot study in order to identity the types of epistemic operations students demonstrate while engaging in modeling practices. As such, we document examples of the kinds of epistemic operations students perform as they work with a partner to construct a systems model.

Student Participants

We worked with six students organized in three groups to collect data for this study and used pseudonyms to protect their identity. Avery, Olivia, Leah, and Audrey were high school seniors and two of them planned to study psychology and film in college. Daniela and Brianna were college undergraduates from the same area in the Southeastern U.S. Daniela was an English major with minors in Education and Latino Studies and Brianna was a Psychology major. Both Daniela and Brianna were bilingual in Spanish and English.

Participant Training

We first introduced student participants to systems modeling using an example related to water quality prior to them developing their own models. We emphasized that a systems model is a tool to help better understand the complexity of a societal issue that has both science and social dimensions. Then, we asked student participants to propose one important factor related to the driving question: How does the water quality of a local river impact our life? Next, they described the relationship between their proposed factor and the quality of the river. In addition, we demonstrated modeling conventions for systems maps including the direction of arrows to link two factors (i.e., cause and effect) and the sign of their correlation (i.e., either positive or negative; See Figure 1). By the end of the training activity, the student participants could draw and explain multiple direct and indirect factor relationships in their system maps.

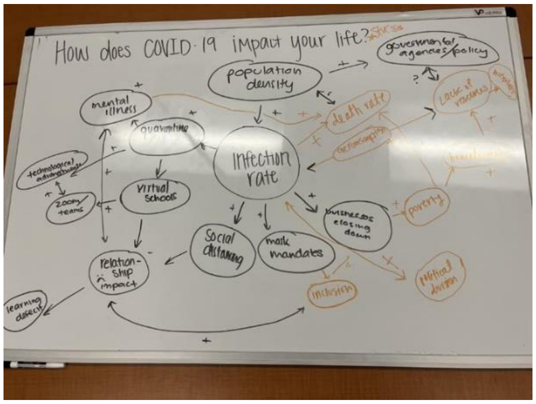
Data Collection

Systems Modeling Sessions

Following the training, pairs of students were asked to create their own systems models on a whiteboard to address the driving question: how has COVID-19 impacted your life? If students needed assistance, we prompted them with one of the following factors: wearing masks, school closure, or the economy. During the session, we video-recorded student pairs as they worked and transcribed the recordings. We also took pictures of their final systems models (See Figure 1).

Figure 1

Student Example of Systems Model



Interviews

After the pairs completed their systems models, we interviewed participants individually using a semi-structured interview protocol as a guide. We videorecorded the interviews and transcribed the students' responses. Some example questions included: How does your model explain how COVID-19 has impacted you, your family, your community, and society? How do you know the relationships between factors in your models are correct? Did you notice any instances where you and your partner had different experiences during the pandemic?

Epistemic Dispositions Analysis

Our analyses were informed by two frameworks: Kelly and Licona (2018) and Casas-Quirogas and Crujeiras-Pérez's (2020). These frameworks were originally developed from studies related to SSI argumentation. Since our systems modeling activity did not involve students constructing arguments or developing scientific explanations based on data from investigations, we did not expect all aspects of the frameworks to be present in our data.

Analysis unfolded in three phases. In the first phase, two members of the research team individually open-coded the transcripts from the systems modeling sessions and compared notes. After three rounds of this open coding and peer debriefing, we narrowed our focus to three primary epistemic dimensions that emerged from the data and aligned with our theoretical framework: proposing knowledge, evaluating knowledge, and legitimizing knowledge. We did not find evidence for Kelly and Licona's epistemic dimension of communicating knowledge.

These three dimensions became our frame of analysis from which we developed codes for the epistemic operations used in the rest of the analysis (Hatch, 2002). In the second phase, two researchers revisited the transcripts and coded for epistemic operations based on our framework. Some codes came directly from Casas-Quirogas and Crujeiras-Pérez's (2020) epistemic operations (e.g., recognizing the value of other positions) while others arose from the participants as in-vivo codes (e.g., proposing a correlation). During the third phase, three researchers looked for overlap and refined the set of codes into a final codebook as shown in Appendix A. In addition, we identified multiple interactional operations students used to accomplish the task which was an emergent finding from the open-coding phase. We clustered these interactional operations into a new dimension which we labeled as coordinating efforts (See Appendix B).

Findings

While participating in a systems modeling task about the COVID-19 pandemic, students engaged in three epistemic dimensions proposed by Kelly and Licona (2018): proposing knowledge, evaluating knowledge, and legitimizing knowledge. For each dimension, we identify the types of epistemic operations (shown in *italics*) students performed which demonstrated epistemic practice. In addition, we provide sub-codes for some of the operations that describe the different ways that students expressed an operation and student examples for these sub-codes in the tables. Lastly, we present examples of interactional operations that students used to support SSI systems modeling.

Proposing Knowledge

Of the three epistemic dimensions, we found that in general students most frequently demonstrated proposing knowledge. When proposing knowledge, students demonstrated the following epistemic operations: *proposing a factor*, *proposing an explanation*, *proposing a correlation*, and *proposing a societal implication*. The operation, *proposing an explanation*, was based on the coding scheme from Casas-Quirogas and Crujeiras-Pérez's (2020). The rest of the operations emerged from the data. Student examples for each of the sub-codes are provided in Table 1.

For the operation, *proposing a factor*, students suggested a topic to add to their systems model either by providing a factor generally without context, extending a topic previously proposed by their partner, providing a factor from personal experience, or providing a factor from vicarious experience. A few examples of the different factors students added to their systems models included mental health, online learning, inflation rates, import shortages, and jobs. While *proposing a factor*, students often expressed experiences or challenges that they faced which we termed as proposing a factor from personal experience. Daniela asserted that the price of rent went up because she was affected by it. Students also discussed challenges that others may have faced which we termed as proposing a factor from vicarious experience. For example, Avery discussed the consequence of wearing masks for people who are hearing impaired, and Brianna discussed difficulties for unhoused individuals unable to quarantine.

Sometimes students provided reasoning for their factors by *proposing an explanation*. Leah explained her reasoning for adding a factor she labeled "globalization" by stating, "because we're like doing air travel and trading with like other countries." In another instance, Daniela described her factor "enlightenment" by saying, "…a lot of people had that little, uh, enlightenment period where they were like, 'Okay, we're still here, so I'm just gonna do everything I was afraid to do. I'm gonna start that business.'" She then linked this factor to increased mental health discourse and discussed how the pandemic changed individuals' priorities. This was an interesting finding because she considered how individual philosophies changes as a result of the pandemic.

When students discussed causal relationships between factors in their model, they performed the operation *proposing a correlation*. Sometimes the correlation was positive, meaning that the factors changed in the same direction. Other times students proposed a negative correlation when factors changed in opposite directions. We characterized a correlation as neutral correlation if students suggested a relationship between two or more factors without providing directionality of the relationship. They also made connections across different dimensions of the pandemic and recognized the complexity of the issue. For example, Brianna proposed a neutral correlation by linking multiple dimensions when she said, "Like, I was going to say this education issue, this issue with financial, it's just it, [they] both end up connecting to mental health." She recognized the interdisciplinary nature of the SSI and even noted, "I feel like it's all connected."

In addition, students *proposed societal implications* when they expressed the impact of a factor on society. This operation emerged during the coding process and was particularly interesting because students were not prompted to discuss societal implications during the activity. We saw examples of simple societal implications (e.g., factor A is good for society, or factor A is bad for society). We also saw examples of multi-directional reasoning (e.g., factor A is both good and bad for society) which we termed as complex societal implications. For example, Daniela elaborated on her factor called mental health discourse: “I'm going to say that [mental health discourse] is a positive because it did help with the state of mental health research because now they know more teenagers are getting depressed because they cannot see their friends.” Group 1 (Daniela and Brianna), in particular, regularly used their systems model as an opportunity to reflect on the advantages and disadvantages of various COVID-19 policies and outcomes. Furthermore, Leah and Audrey recognized unexpected impacts of the pandemic on the environment such as the water quality improving in Venice, Italy and pollution going down because people were not driving cars as much.

Table 1

Proposing Knowledge Epistemic Dimension

Epistemic Operation	Student Example
Proposing a factor students suggest a topic to include in their model	
General	“Well, also - maybe we could put like education [factor added to model].” (Leah)
Extends idea	“Well, yeah, there was a housing crisis.” (Daniela) “Well, and specifically for *unhoused individuals* not being able to quarantine.” (Brianna)
From personal experience	“And *the price of rent* [factor added to model] did go up.” (Daniela) “It did?” (Brianna) “Because that – [laughs] I was affected by it.” (Daniela)
From vicarious experience	“And that [referring to “relationship” factor] automatically goes to *inclusion* [factor added to model] because like if you have a deaf student in your class, you cannot - um, because it's hard to communicate. If they write on paper or try to show you what they're saying, then you can't see the paper because you're social distanced.” (Avery)
Proposing an explanation students provide reasoning for their ideas	“Globalization [factor added to model], *because we're like doing air travel and trading with like other countries.”* (Leah)
Proposing a correlation students propose the relationship between two or more factors	
Neutral	“Like, I was going to say this education issue, this issue with financial, it’s just it, *[they] both end up connecting to mental health*.” (Brianna)
Positive correlation	“Um, I kinda have something about *rising infection rate, unemployment rose*.” (Daniela)
Negative correlation	“Well, I guess you could also think about like the economy, like with - *when people weren't working, like unemployment rates were higher*.” (Leah)

Proposing a societal implication students suggest the impact of a factor on society	
Simple	"It's [Zoom] created more accessibility, *which is one positive*." (Brianna)
Complex	"I feel like it [budgeting] could be *a good and bad thing*, because for some people who were helped by the emergency grants, they had a little bit more room." (Brianna) "And they probably saved it." (Daniela) "Yeah, but then there's people who were unemployed, and they just – the – even the grants weren't enough to hold them." (Brianna).

Note. Italics in the student examples represent the corresponding epistemic operation.

Evaluating Knowledge

We identified three epistemic operations for evaluating knowledge: *evaluating a claim*, *qualifying a claim*, and *acknowledging limited understanding*. *Acknowledging limited understanding* was adapted from Casas-Quirogas and Crujeiras-Pérez's (2020) operation "acknowledging the absence of data." Since students in our study were not provided with sources of data to support their claims, they relied on personal and communal knowledge instead of scientific evidence. However, students did express uncertainty in evaluating claims due to insufficient background knowledge. When discussing financial aspects of COVID-19, the topic of income levels came up and both Daniela and Brianna acknowledged that they did not have enough knowledge about the area to evaluate their claims: "I don't know yet. Just write it down and then we can think about it." Furthermore, we did not discover any examples of Casas-Quirogas and Crujeiras-Pérez's operation, appealing to consistency with previous knowledge, in this study but we felt this operation should be included in our codebook because it is plausible that students in another sample might rely on previous knowledge in their evaluations.

When evaluating knowledge, students assessed the truthfulness of a knowledge claim as either true or false. We saw only a few instances of the evaluating claim operation. This is likely due to the fact that we did not provide students with data sources. Instead, students relied on personal experiences as evidence to support their claims which can be difficult to evaluate without access to additional data to back up their claims.

Table 2

Evaluating Knowledge Epistemic Dimension

Epistemic Operation	Student Example
Evaluating Claim students evaluate the truthfulness of a knowledge claim	
Claim is true	"I was just thinking we could do, um - there's a big like learning deficit [factor added to model] for like kids." (Olivia) "*True*, because of virtual school, because of the lack of relationships with their teachers." (Avery)
Claim is false	[Avery proposes a positive correlation between "mask mandates" factor and "inclusion" factor]

	"*No*, with the mask use then the inclusion goes down." (Olivia) [Student 1 changes correlation to negative]
Acknowledging limited understanding students report a lack of sufficient data	"I don't know yet. Just write it down and then we can think about it." (Avery)

Note. Italics in the student examples represent the corresponding epistemic operation.

Legitimizing Knowledge

Students performed two epistemic operations related to legitimizing knowledge. Both operations, *building consensus* and *recognizing the value of other positions*, came directly from Casas-Quirogas and Crujeiras-Pérez's (2020) codebook. However, we expanded on these operations by including sub-operations used in systems modeling. When *building consensus*, students either expressed consensus by affirming their partner's claim or they requested consensus by asking for input from their partner. To illustrate, Olivia requested consensus from Avery on her claim related to import shortages: "That would be a positive [correlation] then because the less the policy enforcement the less resources, yeah?". Here, Olivia was looking for Avery to legitimize her claim. Avery did express consensus and Olivia added a positive sign to their model. We did not see examples of expressing a lack of consensus, although this operation is plausible and may be seen in a larger dataset so we included in in the final codebook.

The second operation related to legitimizing knowledge that we observed was *recognizing the value of other positions*. This included validating positions and invalidating positions, although we did not see examples of students invalidating positions. By working in pairs, the students had opportunities to affirm each other's ideas. For example, Daniela legitimized Brianna's knowledge claim about her mom's unemployment funding and expanded on that idea using a personal example: "I know you meant the unemployment funding with your mom was more than what we were getting before. I know they gave out a lot of emergency grants that really helped. That was the most money I had really had in a minute". By agreeing with and expanding on Brianna's factor, Daniela legitimized Brianna's position on unemployment grants.

Table 3

Legitimizing Knowledge Epistemic Dimension

Epistemic Operation	Student Example
Building consensus students try to reach consensus in order to decide what to include in their model	
Expressing consensus	"Actually, you could connect those ["lack of resources" factor and "hospitals" factor] then." (Olivia) "*Okay, yeah*." (Avery)
Requesting consensus	"That would be a positive [correlation] then because the less the policy enforcement the less resources, yeah? (Olivia)
Recognizing the value of other positions	

students recognize the usefulness of other perspectives	
Validating positions	[Brianna discusses how unemployment grants helped her mom financially during the pandemic] “I know you meant the unem- like the unemployment with your mom was like more [money] than what we were getting before. I know they gave out a lot of, um, emergency grants that really helped, like that was the most [money] when you had - really had in a minute.” (Daniela)

Note. Italics in the student examples represent the corresponding epistemic operation.

Interactional Operations

With regards to research question 3, what interactional operations did students engage in during SSI systems modeling?, we found that students accomplished epistemic modeling by *proposing tasks*, *assigning tasks*, *verbalizing tasks*, *seeking advice*, and *coordinating language*. In order to transform ideas into physical representations on their model, they had to determine who was going to do what task (*proposing tasks*), how they were going to communicate their ideas in writing (*coordinating language*), how they would create the model through representations (*verbalizing task*), and how they would divide tasks (*assigning tasks*). We found that epistemic groupwork activities were accomplished via social interactions that involved sophisticated coordination between group members.

While not epistemic, these interactional operations helped students communicate and seek input from their partner in order to coordinate and consolidate their efforts. An example of how students used interactional operations during systems modeling is shown in Excerpt 1. During this interaction, Brianna and Daniela discussed how to incorporate a new factor into their model related to COVID-19 mortality rates. Coordinating roles to co-construct their model and integrating a new factor into their existing model required a series of interactional steps that laid the groundwork for epistemic practice to occur. These are the ways that epistemic practices such as modeling are “interactionally accomplished” through collaborative processes (Kelly and Licona, 2018).

Excerpt 1

Interactional Operations

Student	Discourse	Interactional Operation
Daniela	And so you want another one to be like mortality rates?	Seeking advice
Brianna	Uh, yeah, could you write that?	Assigning task
Daniela	Okay, I don't know where to write in this.	Verbalizing task
Brianna	Just pull it out.	Verbalizing task
Daniela	Yeah. Mortality, okay, what do you want to say about that?	Coordinating language
Brianna	Um, I know that I did have family members who we - who passed away in other countries because, um - and you just - you're not able to - you're not able to, I don't know, travel. So, you can't -	

Daniela	Oh, that could be another one, traveling, and then do you want me to put mortality rates under traveling?	Seeking advice
Brianna	Um -	
Daniela	[Inaudible] there were like a lot of travel bans.	
Brianna	Okay, yeah.	
Daniela	And I'll keep that as a second line too.	Verbalizing task

Discussion

This exploratory study contributes to the field's understanding of how students' epistemic discourse assists their sense-making about a complex socioscientific issue such as COVID-19. We identified three epistemic dimensions from Kelly and Licona (2018) that students used to support modeling in groups and reported the kinds of epistemic operations students performed during their conversations. Recently researchers have studied students' use of epistemic operations during an SSI-based argumentation task (Casas-Quirogas and Crujeiras-Pérez, 2020). As these authors suggest, the types of discursive operations students use varies depending on the nature of the task. In relation to our study, some operations were similar across SSI-based argumentation and SSI-based systems modeling. For instance, when legitimizing knowledge, students in both scenarios demonstrated building consensus and recognizing the value of other positions. On the other hand, proposing knowledge looked different during systems modeling than during argumentation. While both activities included proposing explanations, students who engaged in systems modeling also proposed factors, correlations, and societal implications but did not engage in decision-making or use data as in the argumentation task. Due to these differences, we developed a coding scheme specifically for epistemic systems modeling that can be used for future research (See Appendix A). Although we did not see evidence of all operations represented in the codebook (i.e., invalidating positions, expressing lack of consensus, appealing to consistency with previous knowledge), it is reasonable to assume these operations may emerge in a larger sample or in other SSI contexts since we observed their reverse operations (i.e., validating positions, expressing consensus).

In general, systems modeling supported students in recognizing the complexity of the issue, linking different components of a system, thinking about how science relates to society, and assessing the truthfulness of knowledge claims. These are types of SSI skills that help students achieve science literacy (Ke et al., 2021). Policies such as "stay at home" mandates, school and business closures, and travel restrictions were widespread throughout the nation, yet the impact of these policies on individual experiences drastically differed. Given the open-endedness and interdisciplinary aspect of the activity, students were able to demonstrate their knowledge about multiple dimensions of the pandemic from their own perspectives while also acknowledging and regularly validating the experiences of others.

Regarding research question 3, which addressed interactional operations that occur during SSI-based systems modeling, we identified interactions commonly used by students to help coordinate efforts and accomplish the task. For example, we observed multiple occurrences of students seeking advice from their partner including where to position a factor in a model or how to connect it to other factors. Modeling is a practice learned through social interaction and community norms which entails specialized discourses (Kelly & Licona, 2018). As such, students used interactional conventions in order to bring together ideas and co-construct a model. A key component of appropriate science practice is seeking input from others and receiving feedback (e.g., peer review; Dijk, 2001). Systems modeling provided the opportunity for students to engage in the back-and-forth processes of knowledge generation and become epistemic agents. Typically teachers are seen in the eyes of students as the holders and disseminators of knowledge and classroom discourse is dominated by teacher talk (González-Howard & McNeill, 2020). In contrast, systems modeling provided space where students' ways of knowing were valued and legitimized so they could have authority in sense-making processes.

In politically divided times, where science is often misused or misconstrued to support ideological views, teachers may be hesitant to introduce controversial socioscientific topics in the classroom. Systems modeling is a tool that teachers can leverage to help students evaluate the validity of different knowledge claims, develop shared understanding, and ultimately reach common ground. Instances where students lacked appropriate information to be able to make an assessment could be valuable learning opportunities to engage in further investigation. In addition, disagreement may be useful to showcase how scientific evidence should be used to back knowledge claims and how to determine trustworthiness of science sources (Owens et al., 2017).

In conclusion, this work has demonstrated the importance of epistemic practice such as systems modeling to help students better understand the multidimensional and interconnected components of complex socioscientific issues. Our codebook demonstrates the epistemic operations that students utilize to support their learning. Activities that incorporate these operations can foster epistemic dimensions of proposing knowledge, evaluating knowledge, and legitimizing knowledge which are essential to engage fully in science practices such as modeling.

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Appendix A

Codebook of epistemic operations during systems modeling

Proposing Knowledge (PK)

Epistemic Operation	Code	Description
Proposing a factor	PKF	Students suggest a topic to include in their model
General	PKFG	Factor includes no context
Extends idea	PKFE	Factor expands on previously stated factor
From personal experience	PKFP	Factor includes personal context
From vicarious experience	PKFO	Factor includes secondhand context
Proposing an explanation*	PKE	Students provide reasoning for their ideas
Proposing a correlation	PKC	Students propose the relationship between two or more factors
Neutral	PKCN	Relationship between factors has no directionality
Positive correlation	PKCP	Relationship between factors has positive directionality
Negative correlation	PKCN	Relationship between factors has negative directionality
Proposing a societal implication	PKI	Students suggest the impact of a factor on society
Simple	PKIS	Implication is unidimensional
Complex	PKIC	Implication is multidimensional
Evaluating Knowledge (EK)		
Evaluating Claim	EK	Students evaluate the truthfulness of a knowledge claim
Claim is true	EKT	Students assert claim is valid
Claim is false	EKF	Students assert claim in invalid
Qualifying a claim	EKQ	Students constrain generalizability of knowledge claim
Acknowledging limited understanding*	EKL	Students report a lack of sufficient background knowledge
Appealing to consistency with previous knowledge*	EKC	Students use past experiences or demand arguments that are consistent with their prior knowledge
Legitimizing Knowledge (LK)		
Building consensus*	LKC	Students try to reach consensus in order to decide what to include in their model
Expressing consensus	LKCE	Students communicate agreement
Expressing lack of consensus		Students communicate disagreement
Requesting consensus	LKCR	Students seek agreement from partner
Recognizing the value of other positions*	LKV	Students recognize the usefulness of other perspectives
Validating positions	LKVV	Students value other positions
Invalidating positions	LKVA	Students discredit other positions

Note. *Adapted from Casas-Quiroga & Crujeiras-Pérez (2020)

Appendix B

Codebook of interactional operations during systems modeling

Coordinating Efforts

Interactional Operation	Code	Description
Assigning tasks	CEA	Students coordinate tasks
For self	CEAS	Students assign task to self
For partner	CEAO	Students assign task to partner
Verbalizing tasks	CEV	Students discuss current tasks
For self	CEVS	Students discuss their own task
For partner	CEVP	Students discuss their partner’s task
Seeking advice	CES	Students seek input from partner on how to approach a task
Coordinating Language	CECL	Students discuss how to communicate ideas