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RESEARCH

Disagreeing softly: Supporting students in managing disagreement in peer critique

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Abstract

Disagreement is often perceived negatively, yet it can be beneficial for learning and scientific inquiry. However, students tend to avoid engaging in disagreement. Peer critique activities offer a promising way to encourage students to embrace disagreement, which supports learning as students articulate their ideas, making them available for discussion, revision, and refinement. This study aims to better understand how students express disagreement during peer critique within small groups and how that affects moving their inquiry forward. It explores 5th-grade students' management of disagreement within a computer-supported collaborative modeling environment. Using conversation analysis, we identified various forms of disagreements employed by students when engaging with different audiences. We observed a tendency for students to disagree softly; that is, disagreement was implied and/or mitigated. Students' resolution of both direct and soft disagreements effectively promoted their collective knowledge advancement, including building shared scientific understanding and improving their models, while maintaining a positive socio-emotional climate. These findings have implications for designing CSCL environments with respect to supporting students in providing and responding to peer critiques at the group level.

Keywords Disagreement · Peer critique · Modeling · Collaborative argumentation · Science education · Inquiry

Introduction

Disagreement is often perceived negatively, whereas agreement tends to be viewed positively (Pomerantz & Heritage, 2013). Consequently, people often prefer to pursue harmony and avoid conflicts or overt disagreements (Chinn & Clark, 2013). This inclination also holds true in classrooms, where students exhibit a tendency to avoid engaging in disagreements, especially with friends, due to concerns about potential negative influence on

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their peer relationships (Bathgate et al., 2015; Nussbaum & Bendixen, 2003; Paulus et al., 2018).

However, it is important to recognize that disagreement can be positive in certain contexts. In decision-making and problem-solving discussions, disagreements are inherent, expected, and valued by professionals, as they are critical for arriving at viable solutions, and have been associated with better quality decisions (Angouri & Locher, 2012; Hüttner, 2014). In argumentation, the preferred action can be disagreeing (Kotthoff, 1993). Moreover, engaging in disagreements is inherent in science practice. Disagreements among different scientists are a major trigger for advancing knowledge, typically spurring new investigations and developments (Longino, 2002). Disagreements may also prove beneficial for learning and doing science, leading learners to explore new ideas, make their thinking visible and open to refinement, and often trigger cognitive conflicts that contribute to conceptual change and collective knowledge construction (Chin & Osborne, 2010; Hmelo-Silver & Barrows, 2008). This ultimately supports "better and more lasting learning" (Nussbaum, 2008, p. 351).

To help students appreciate the value of disagreement, research suggests involving them in practices that foster the consideration of alternative perspectives (Barzilai et al., 2020). One such practice is peer critique, which is perceived as an effective learning practice within the realm of peer learning–a form of collaborative learning (Noroozi & De Wever, 2023). Analogous to the social practice of critique in science, peer critique encompasses the process of evaluating peers' products and revising one's own in responding to critique, ultimately aiming for knowledge advancement. Peer critique intrinsically involves disagreement, as it stimulates students to challenge and question alternative positions and ideas, thus fostering an environment conducive to collective knowledge building (González-Howard & McNeill, 2020; Tan et al., 2023; Tasker & Herrenkohl, 2016; Zhang et al., 2007). Knowledge building refers here to the general practice where students collectively create and improve shared and new-to-the-learners' ideas (knowledge) around a new concept. The long-standing assumption is that knowledge building activities are productive for both collective and individual learning (Scardamalia & Bereiter, 2006).

While there is substantial research on scientific argumentation, with some addressing disagreements or counterarguments (e.g., Asterhan & Schwarz, 2016; Berland & Lee, 2012; Sampson & Clark, 2011; Sandoval et al., 2019), these studies do not focus on the linguistic features of how students manage and resolve disagreements during peer critique at the group level in computer-supported collaborative learning (CSCL) environments for science education. Our study aims to address this gap by exploring the linguistic features of disagreements, with the goal of helping the field understand both how disagreements are managed in knowledge-building activities and how we can foster productive disagreements in future designs. Prior work in math education has suggested that polite disagreements can strengthen social relationships among students and increase creativity (Chiu, 2008a), whereas disagreeing in a direct and confrontational way, can intensify interpersonal conflict, and is less effective in generating new ideas (Chiu, 2008b). However, whether such patterns translate to science learning contexts merits direct investigation.

This study is situated in examining the disagreements that arise as part of peer critique within the Modeling and Evidence Mapping Environment (MEME; Danish et al., 2021; Ryan et al., 2023). MEME is a CSCL tool developed to support students in creating, sharing, and revising scientific models. Using conversation analysis (CA; Sacks, 1992), we explore the forms of disagreements during peer critique and their potential impact on students' progress in modeling practice, including critiquing and improving models, which reflects a socio-cultural approach to learning. We conclude with suggestions for how to design CSCL environments that can promote productive engagement in disagreement and peer critique within groups.

Theoretical background

This study is grounded in sociocultural perspectives on learning, which posit that learning occurs through interaction with others while participating in social practices (Danish & Ma, 2022; Engeström, 1987). From this viewpoint, we view students' collective knowledge advancement in face-to-face interaction within groups and asynchronous interaction across groups as both the mechanism for, and evidence of learning. As students develop, identify, and learn new knowledge (concepts and practices), their interactional patterns will shift in observable ways. Linking specific moments in interaction to distal outcome measures, such as tests, is often problematic. For sociocultural theorists, learning is precisely a change in patterns of participation, not what is measured on a sit-down test. Therefore, we focus on the proximal impact of students' interactional moves upon their ongoing activity, given the literature demonstrating that more robust knowledge advancement practices will lead to both collective and individual learning (Scardamalia & Bereiter, 2006). Our goal in this paper is to explore how different forms of disagreement are related to those proximal changes in practice.

When students engage in the kind of collective knowledge advancement that we are focused on, collaborative argumentation is crucial and often requires disagreement to help advance students' collective ideas (Chinn, 2006). Collaborative argumentation refers to discourse in which two or more participants make claims and provide reasons and evidence to support their claims (Chinn, 2006). Participants may disagree with, question, or challenge others' positions and attempt to resolve these disagreements. Extensive research highlights the social and dialogic nature of collaborative argumentation as a practice of knowledge construction (e.g., Berland & Lee, 2012; Chin & Osborne, 2010). In collaborative argumentation, students not only defend their own positions but also must attend to and scrutinize others' thinking in order to succeed (Kuhn, 2015). Their engagement in argumentation allows students to change their opinions, express diverse arguments, and negotiate meanings of concepts, all of which contribute to learning (Baker, 2009). This practice also prepares students to manage complex real-world problems (Noroozi et al., 2012). However, students often face challenges in this process, such as providing justifications for claims, using appropriate evidence, recognizing and responding to peers' alternative positions (i.e., disagreements), and reaching consensus (Berland & Lee, 2012; Fischer et al., 2014). Given these benefits and challenges, providing support to foster collaborative argumentation, especially disagreements, is essential.

Peer critique and disagreement

One way to authentically motivate productive collaborative argumentation is through peer critique (Noroozi et al., 2012). Peer critique naturally immerses students in argumentation, requiring them to identify potential errors or weaknesses in evidence provided for claims or models (Ford, 2008). This practice encourages students to engage deeply with their peers' thinking, question and challenge each other's ideas, and refine their own understanding, which are core aspects of collaborative argumentation. Peer critique in scientific modeling practice involves students in both providing and addressing critiques of one's emerging science model and the argument that the model makes. Providing peer critique allows students to engage in observation and reasoning to explore potential flaws in peers' explanations using relevant knowledge (Henderson et al., 2015). Addressing peer critique, on the other hand, entails reflecting on others' critiques and revising models when appropriate. Note that critiques include comments on potential errors or weaknesses in peer work and different perspectives from peers (i.e., disagreements), but they also include statements highlighting strengths of peer work and specific suggestions for improvement.

In the literature, peer critique and peer feedback are related concepts in the broader context of peer learning (Noroozi & De Wever, 2023). The term "peer feedback" often describes the practice of evaluating and reacting on the quality of peer work. While peer critique may place a stronger emphasis on critical evaluation, both practices can involve constructive criticism and positive statements. Peer feedback has been widely embraced and extensively studied in higher education, especially in disciplines such as writing (Gao et al., 2023). However, there is limited research in K-12 settings, particularly in elementary education, and even less in elementary science (Alqassab et al., 2023). Given this gap, we draw upon literature on peer critique and feedback in various disciplines to gain a comprehensive understanding of this practice while recognizing that peer critique is an important subset of peer feedback.

Providing and addressing peer critique and feedback supports students' science learning and enhances future learning outcomes by fostering their scientific reasoning and enabling them to gain new perspectives and improve their work (Gerard et al., 2019; Henderson et al., 2015; Tsivitanidou et al., 2018). For example, Tan et al. (2023) found that primary school students showed gains in science understanding after giving and receiving peer feedback on each other's concept maps. Similarly, physics students improved their initial models and achieved a deeper conceptual understanding of scientific phenomena through critique activities in model-based learning (Tsivitanidou et al., 2018). Additionally, research drawing on the knowledge building framework (Scardamalia & Bereiter, 2006), which underscores creating and improving ideas collectively within a communal knowledge space, has also explored the significance of critique in supporting students' knowledge building. For example, Zhang et al. (2007) found that using the Knowledge Forum CSCL environment supported students in articulating alternative ideas (e.g., using "I disagree, because") and challenging their peers' ideas, contributing to conceptual advancement. Collectively, these studies and others offer compelling evidence that peer critique promotes generating diverse ideas and refining ideas and work that drive collective knowledge advancement. While there is evidence of learning, our study is in a rich, real-world context, where teasing out the direct impact of individual critiques on learning is challenging, so we limit ourselves to analyzing the way that specific critique moves advance argumentation and collective knowledge.

Students' participation in peer critique creates opportunities to generate disagreements that can improve scientific reasoning and deepen learning (Henderson et al., 2015). For example, González-Howard and McNeill (2020) effectively illustrated that disagreements during peer critique promoted continued argumentation, collective knowledge construction, and development of epistemic agency. However, those disagreements primarily occurred in teacher-scaffolded whole-class seminars, rather than small groups. Nevertheless, peer critique at the group level may hold greater potential in promoting argumentation and knowledge construction. This potential stems from the enhanced collaborative dynamics in small group settings. Kuhn (2015) argued that when students actively attend to one another's thinking, their collaborations become more productive. During group critique, students not only need to scrutinize models and claims made from other groups but also attend to their groupmates' thinking. This dynamic interaction may lead to more diverse perspectives and extended argumentation, resulting in more constructive critiques and improved work. For instance, when evaluating a scientific model, one student may appreciate its cyclical nature while another challenges the idea that a model should adhere to a cycle. Thus, disagreement arises from contrasting views on models and may become a catalyst for ensuing discussions and explorations, ultimately enhancing their learning experiences. In general, research on collaboration consistently suggests that small group work generally leads to improved problem-solving and learning outcomes (Barron, 2003; Chen et al., 2018).

Regardless of its potential, collaborative critique within small groups remains largely overlooked. In their review, Zheng et al. (2019) found that despite students' frequent engagement in group work for artifact construction, only 5% of studies focused on group-level feedback, which encourages group discussions and increases feedback accuracy. In our experience, many classroom teachers also organize their students into small groups to promote more active engagement in inquiry practices, thus necessitating an understanding of how peer critique works at this grain size. Collaborative learning process can be challenging (Jeong & Hmelo-Silver, 2016). Thus, establishing social norms that promote shared goals and collaboration and value peer critique and disagreement is a prerequisite (Henderson et al., 2015; Sampson & Clark, 2011; Sandoval et al., 2019).

Social norms and disagreement

While disagreements can present students with opportunities to develop deeper disciplinary understanding, they may also introduce socioemotional challenges that lead students to feel attacked (Herrenkohl & Guerra, 1998). Students may perceive engagement in disagreement and critique as a cause of conflict with their peers (Henderson et al., 2015). Additionally, research on collaborative argumentation indicates that students may view disagreements as unpleasant or uncomfortable, particularly with friends (Bathgate et al., 2015). To mitigate these challenges, it is essential to cultivate a CSCL environment where students feel confident and comfortable about managing disagreement and recognize that they can learn from engaging in disagreement (Andriessen & Schwarz, 2009; Nussbaum & Bendixen, 2003). Creating such an environment requires intentional development of shared goals and social norms (Hmelo-Silver & Jeong, 2022). These shared goals should ideally be epistemic aims, such as creating accurate mechanistic models of a phenomenon, or constructing the best possible explanations for a phenomenon (Chinn et al., 2014). When the primary focus is on epistemic goals, students are more likely to embrace overt disagreement, recognizing it as an important pathway to advancing knowledge (Chinn et al., 2014). Villarroel et al. (2019) further supported this notion, finding that emphasizing the goal of consensus-building over persuasion encourages critical evaluation of evidence and consideration of alternative perspectives, enhancing argumentation quality. In contrast, if non-epistemic goals are given greater weight, they can impede knowledge acquisition. For instance, an excessive focus on pursuing group harmony may lead students to avoid overt disagreement. Given these considerations, our design intended to promote the value of advancing knowledge by encouraging students to view disagreements as legitimate objects for discussion aimed at improving their group-consensus models.

Various social norms have been identified as essential for successful collaboration, including building on one another's ideas, holding students accountable to each other, and supporting ideas with reasons (e.g., Hmelo-Silver & Barrows, 2008; Sandoval et al., 2019; Zhang et al., 2011). Research on argumentation emphasizes that resolving disagreements is crucial for knowledge construction (Sandoval et al., 2019). Encouraging students to pursue collective sensemaking and consensus-building can be an effective norm in resolving disagreements (Berland & Lee, 2012). Moreover, González-Howard and McNeill (2020) exemplified how teachers normalized critiquing other students' ideas through using the frame "I disagree because," setting clear parameters for students to agree or disagree with each other, contributing to a more constructive and collaborative learning environment. Overall, fostering social norms can help cultivate a positive climate, where students feel comfortable posing challenging questions to each other and view disagreements as opportunities to construct more accurate scientific knowledge (Berland & Lee, 2012; Borge & Xia, 2023; Herrenkohl & Guerra, 1998; Sandoval et al., 2019). The majority of these studies operate by looking at how specific actions by learners impact subsequent actions within the flow of activity. We aim to do the same by using CA to look at the nuances of how learners take up disagreement in interaction and identify broader patterns from there.

Conversation analysis as an analytical framework for disagreements

CA emphasizes that talk serves as a means to perform actions (Sacks, 1992). Aligning with sociocultural perspectives, CA posits that knowledge is socially constructed and situated, and experiences and perceptions are "mediated culturally, linguistically, and historically" (Lester & O'Reilly, 2019, p. 6). It seeks to understand the mechanism of social interactions and how social norms develop in naturally occurring interaction (Sacks, 1992). CA studies fundamental structures, such as sequence organization, preference organization, and embodied action. In this study, we focus on preference organization, referring to speakers following implicit principles in interaction and responding to prior turns with preferred responses (Lester & O'Reilly, 2019). For example, a preferred response to an invitation to a dinner is to accept: "Sure, I'd love to!" Similarly, agreement is often a *preferred next action* to an assessment such as a responding to "This game is exciting" with "Yes, it's awesome" (Pomerantz, 1984). While conversation in American culture (where this study is situated), generally exhibits a preference for agreement in response to a praise, assertion, or other conversational actions, disagreement is not absent but is often delayed, prefaced, or mitigated (Myers, 1998). By employing CA, we can analyze the forms of disagreements in students' talk-in-interaction and uncover how those disagreements unfold in social context, and how they lead to knowledge production (or not).

Conversation analysts have generated many distinct taxonomies concerning forms of disagreements (Netz, 2014). Our study draws on a typical classification introduced by Pomerantz (1984), who delineated strong and weak (or partial) forms of disagreements. A strong disagreement "is one in which a conversant utters an evaluation which is directly contrastive with the prior evaluation" and contains solely disagreement components without any agreement components (Pomerantz, 1984, p. 74). For example, a straightforward "no" to a proposal represents a strong and direct disagreement. Based on politeness theory (Brown & Levinson, 1987), disagreement is often considered "face threatening," with interlocutors perceiving it as "uncomfortable, unpleasant, difficult, risking threat, insult, or offense" (Pomerantz, 1984, p. 77). Therefore, disagreements typically need indirectness or mitigation. Pomerantz (1984) defines mitigated disagreements as weak disagreements, which often include agreement components (e.g., "yeah," "exactly") and may provide qualifications, specifications or exceptions, as well as hedges or delayed devices (e.g., gaps, hesitation). For instance, a weak disagreement might start with "I see your point, but…" or "That's interesting, although…" Other examples include phrases like "maybe," "possibly," "it seems to me." These elements function as "social aligners," enabling the conversation to proceed smoothly without offending the other person (Paulus et al., 2018). In this study, we view direct disagreement as strong disagreement, which is directly and/or explicitly stated, and soft disagreement as weak disagreement, suggesting that it is implied and/or mitigated rather than explicitly stated. We prefer to use the term "soft disagreement" rather than "weak" to avoid a deficit-based characterization of the interlocutors.

Prior research utilizing CA has examined disagreements produced in various contexts and yielded fruitful insights. For example, Muntigl and Turnbull (1998) identified four types of disagreements in everyday argumentation–irrelevancy claim, challenge, contradiction, and counterclaim, each with varying degrees of face threatening potential, with irrelevancy claim being the most face threatening, and counterclaim, often mitigated, is the least face threatening. Netz (2014) analyzed disagreements in gifted classes from grades 5 to 8 in the U.S., categorizing them into five levels from highly aggravated to highly mitigated. Notably, this study found that students often explicitly expressed disagreements, the majority of which were aggravated or non-mitigated, and these disagreements did not undermine students' solidarity. In contrast, Lopez-Ozieblo (2018) studied teachers' disagreements in language education classrooms in Hong Kong and identified three different forms of disagreement–mitigated, aggravated, and unmitigated. The study revealed that teachers used linguistic markers (e.g., hedges) and non-linguistic markers (e.g., laughs, silences, and a deliberate avoidance of negative gestures or head movements) to mitigate 94% of disagreements, which were viewed as negative actions and to be avoided. While these studies have developed various taxonomies for categorizing disagreements, we chose to start with a simpler approach, drawing on Pomerantz's work (1984). This approach was motivated by our aim to establish a foundational understanding of how disagreement unfold within CSCL contexts and their impact on knowledge advancement. To this end, our study addresses three research questions (RQs):

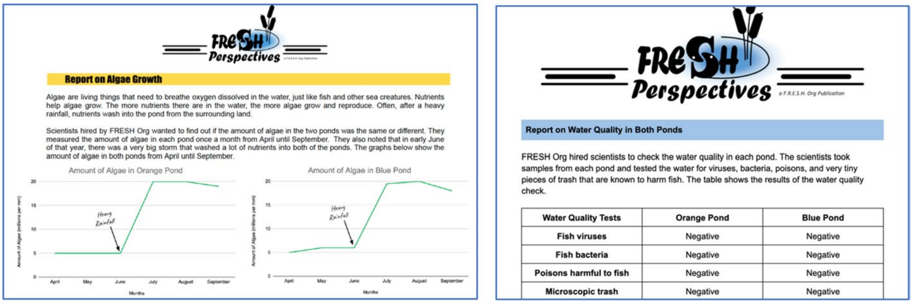
RQ1: How do students manage disagreements in engaging in peer critique activity in a CSCL environment?
RQ2: How do students resolve their disagreements?
RQ3: How do different ways of managing disagreements impact students' collective knowledge advancement?

Methods

The study is part of a larger project that investigates how to support 5th/6th graders' advancing knowledge about complex ecosystems as they engage with evidence in modeling practice (Danish et al., 2021; see https://modelingandevidence.org/). As part of the larger research project, we have developed the MEME CSCL software tool and associated activities to support students as they engage in modeling and inquiry with their peers and the MEME environment.

Instructional materials

We developed an inquiry-based modeling curriculum for the present study to teach students about the phenomenon of eutrophication (a sample can be found at https://modelingandevidence.org/). Specifically, this curriculum aimed to guide students in solving the problem of


FRESH Perspectives

Report on Algae Growth

Algae are living things that need to breathe oxygen dissolved in the water, just like fish and other sea creatures. Nutrients help algae grow. The more nutrients there are in the water, the more algae grow and reproduce. Often, after a heavy rainfall, nutrients wash into the pond from the surrounding land.

Scientists hired by FRESH Org wanted to find out if the amount of algae in the two ponds was the same or different. They measured the amount of algae in each pond once a month from April until September. They also noted that in early June of that year, there was a very big storm that washed a lot of nutrients into both of the ponds. The graphs below show the amount of algae in both ponds from April until September.

FRESH Perspectives
a F.R.E.S.H. Org Publication

Report on Water Quality in Both Ponds

FRESH Org hired scientists to check the water quality in each pond. The scientists took samples from each pond and tested the water for viruses, bacteria, poisons, and very tiny pieces of trash that are known to harm fish. The table shows the results of the water quality check.

Water Quality Tests	Orange Pond	Blue Pond
Fish viruses	Negative	Negative
Fish bacteria	Negative	Negative
Poisons harmful to fish	Negative	Negative
Microscopic trash	Negative	Negative

Fig. 1 Examples of evidence reports

why more fish died in one fictitious local pond (Orange Pond) compared to another (Blue Pond) by constructing and evaluating models that depict how environmental factors in the pond may impact fish health. The target explanations for the problem were: the fertilizers washed into both ponds triggered algal blooms, depleted dissolved oxygen, and caused fish deaths; in Orange Pond, malfunctioning bubblers disrupted water circulation, leading to more fish deaths than Blue Pond, which had properly functioning bubblers. To aid students in navigating this investigation, we introduced sets of evidence, including reports and simulations, exploring relationships between various factors affecting pond ecosystems, such as algae, nutrients, and dissolved oxygen (see Fig. 1). These evidence resources were introduced sequentially to students, 2 to 3 pieces at a time to help them piece together the puzzle by refining their models.

The modeling and evidence mapping environment: MEME

MEME is a networked collaborative modeling tool, which enables students to create, share, evaluate, and revise visual models within a group (see Fig. 2). Models in MEME are qualitative in nature and visually reminiscent of concept maps. They are organized around *entities*, *processes* (mechanisms), and *outcomes* to help orient students toward the complex system they are modeling across multiple levels crucial for understanding how it works (Hmelo-Silver et al., 2015). Within MEME, students can also access an *evidence library* to explore available evidence in the form of brief reports and simulations as they refine their models. They can use MEME to explicitly link evidence to components of their models and provide rationales for these connections, rate the evidence strength and justify the ratings. An important feature of MEME is commenting, which allows students to access their peers' models and provide comments on any specific components using a comment box similar to popular commercial word processing applications. The comment box also prompts students to select the most relevant criterion for their comment from a menu including options aligned with class-shared criteria for model evaluation. Students can view comments left on their own models and on models from other groups and make corresponding revisions. MEME thus creates a unified and shared space for students' engagement in collective, evidence-based modeling practice with integrated feedback.

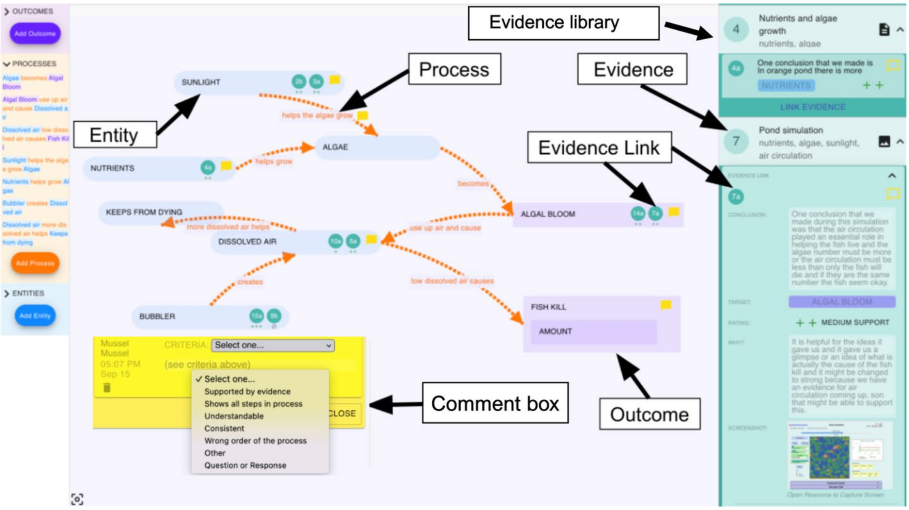


Fig. 2 A screenshot of MEME interface with a student model

Participants

The study was conducted with 11 participants in 2021 in a virtual after-school science club. An after-school club was selected because many students were already in online learning environments, and teachers were already taxed due to COVID-19. While we would have liked a larger group, we also wanted to limit ourselves to students who had some prior experience with each other to minimize the social awkwardness that might arise with unfamiliar students. Students were recruited from two 5th-grade classes in a school located in the Northeastern United States. The school's demographics were 60% White, 22% Asian, 9% African American, 7% Latinx, and 2% other, with 5% eligible for free and reduced lunch. The school is in a well-to-do suburban area and has above-state-average math, reading, and science scores on state tests. These participants were already acquainted with each other and opted in because of an interest in science. Two researchers involved in the project had prior experience collaborating with these two classes. We intentionally assigned the participants to three heterogeneous groups based on gender: Group A (3 girls and 1 boy), Group B (2 girls and 2 boys), and Group C (1 girl and 2 boys). Our approach aligned with the literature suggesting that heterogeneous groups (e.g., gender, prior knowledge) could encourage generating diverse perspectives, thus enhancing the quality of argumentation (Noroozi et al., 2012). In each small group, 2 or 3 researchers were present, with one serving as the facilitator while the others were observing. The facilitators shared their screen to enable students to take turns remotely controlling the screen to manipulate MEME, provided instructions for the tasks, and addressed any technical issues.

Instructional context

The curriculum was delivered across six weekly 75-min sessions using videoconferencing software Zoom (see Fig. 3). These sessions comprised whole class discussions held in the main Zoom room and small group work carried out in breakout rooms. In Session

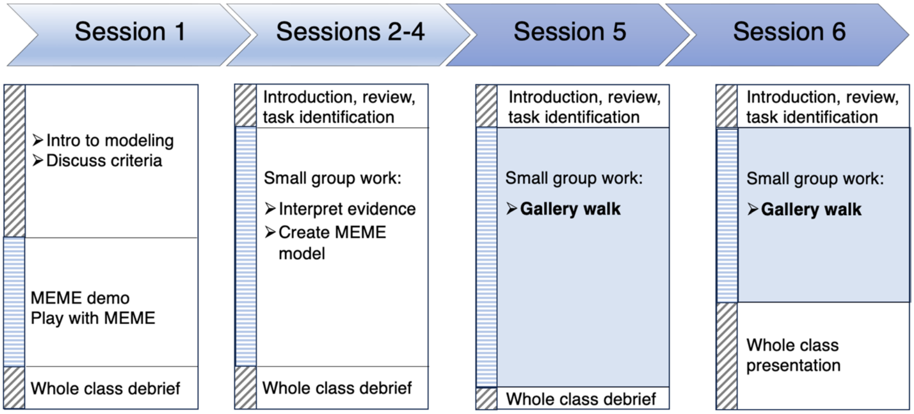


Fig. 3 Timeline of instruction

1, students were introduced to the scientific problem of the fish deaths and modeling practice. They engaged in a whole class discussion about an established criteria list for what counts as a good model, which was expected to guide them to construct and evaluate models. The criteria list emphasized that a good model should be supported by evidence, understandable, consistent, and showing all steps of processes, and these criteria were entered into the MEME commenting feature for selection. From Sessions 2 to 4, students mainly worked in small groups to interpret provided evidence and construct their group models. This study focuses on the last two sessions (5 and 6), where students participated in the peer critique activity called *gallery walk*. Each group was tasked with evaluating other groups' models, providing constructive comments in MEME, and addressing received comments. During the gallery walk, students engaged in synchronous group discussions and asynchronous communication with their "invisible" (not present) out-of-group peers via critiquing models and addressing comments. Disagreements were produced during these moments of exploration of the problem, decision-making, and problem-solving.

To mitigate social discomfort from disagreement that may hinder learning (Andriessen & Schwarz, 2009), we emphasized social norms such as involving everyone in the group discussion, respecting peers' contributions, and showing appreciation of each other's work through whole-class instructions, where researchers explicitly outlined the expectations. Before the gallery walk activity, one of the researchers led a whole-class discussion about the activity's goals, which were to help each other learn and improve their models. We also discussed what constitutes constructive peer critique by having students identify exemplary critiques from a provided set and articulate why some critiques were helpful while others were not. Examples of helpful critiques were specific and actionable, while unhelpful ones were vague or overly negative. Additionally, we demonstrated and emphasized the use of class-shared criteria and evidence to evaluate models. Facilitators were present in each breakout room to model good critique or help with any disagreements as needed, though they aimed to limit intervention as much as possible.

Data collection and analysis

The data sources include all video-recorded meetings conducted in the main room and breakout rooms, associated chats, and models developed by all three groups. This study focused on the video data of breakout rooms of all groups in the gallery walk, during which disagreements were generated, resulting in a combined duration of approximately 300 minutes.

Drawing upon CA, we first reviewed all the class meetings to gain a complete understanding of the data, and then focused our attention on the gallery walk. We transcribed the complete 300-min data corpus verbatim, capturing students' talk and their interactions with MEME (e.g., add a comment). We then segmented the transcriptions into episodes. Each episode was identified as being focused on a specific topic of discussion or a task. For example, an episode could be a discussion about the linked evidence on the reviewed model or a series of actions related to revising a model. An episode may or may not include disagreements, and it could include multiple disagreements. Within the segmented episodes, we identified instances of disagreements. An *instance of disagreement* consists of the initial statement, dissenting turn(s), and the closing, which could be reaching a consensus or shifting to a new topic (Hüttner, 2014). Each instance involves at least two turns. We also followed the Jeffersonian method (2004) to refine the transcription of disagreement instances. Specifically, we added symbols to indicate prosody, including pauses and gaps, intonation, overlapping and latched speech, and changes of speech pace, allowing us to examine both what was said and how it was said.

The unit of analysis for RQ1 was an individual dissenting turn within each instance of disagreement. We began coding these turns using Pomerantz's framework of strong and weak disagreements (1984) and other existing codes from the literature. We then expanded the framework with new codes that emerged in the data but not yet captured (Table 1 presents all codes, with references provided for those drawn from existing literature). The codes were classified as direct or soft. Direct forms were employed for immediate and overt contradiction with prior statements without delay, emphasizing directness in negative responses. Soft forms were used to imply disagreements rather than overtly contradict others' ideas (Pomerantz, 1984). For each dissenting turn generated by students, we applied one or more codes (see Table 1 for the complete coding scheme). For example, in the turn "*I mean* we don't have to be that picky about that," the code assigned was *hedging*. If a turn encompassed multiple forms of disagreements, we coded each individually. For example, "Yeah, I mean they did write that the entire paragraph, but let's just check it out," the codes were *yes, but partial agreement* and *hedging*. If a turn featured the same code multiple times, we only coded it once. For example, the turn "Well, I wouldn't think this is related to…maybe use like" was coded as an instance of *hedging*.

The first author was the primary coder, segmenting episodes, identifying instances of disagreement, and developing the coding scheme. To establish coding reliability, two additional members of the research team reviewed the disagreement instances, discussed the coding scheme and refined it with the primary coder. In two collaborative coding sessions, the primary coder and the two members independently coded 50% of the disagreement instances and discussed any cases of potential disagreements until reaching full consensus (100%). The first author then coded the remaining 50% of data based on refined codes. Finally, we conducted a frequency distribution analysis of the codes.

To address RQ2 and RQ3, the primary coder categorized the disagreement episodes based on the forms they encompassed: episodes with direct forms (direct negation,

Table 1 Code summary of disagreement forms

Disagreement Type (code source)	Description	Example
Direct disagreement		
Direct negation (Pomerantz, 1984)	Using negative markers, such as "no," "I disagree," "you can't," to contradict a prior turn	Arjun: We already linked the evidence proving that = Priya: = **No**, we need to link another evidence, uh, causing, what causes algal bloom
Challenging rhetorical wh-question (Koshik, 2003)	Using a wh-question like what, why, how, to challenge a prior turn in an established environment of disagreement	Zoe: Comment on the comment? So they realize that we counted on them and they can comment on us. = Rohan: = Well, <u>**why**</u>↑would they want to do that? They're <u>**never**</u> going to see this model again
Sensemaking challenge	Using expressions "It doesn't make sense," "I don't understand" to challenge the sensemaking or reasoning of a prior turn	Sophia: Wait, what? **That doesn't make sense.** Bubbler gives oxygen needed algae (critiquing a peer model)
Soft disagreement		
Hedging (Pomerantz, 1984)	Using expressions like "I mean," "might," "maybe" to soften disagreement and seek agreement	Rohan: We can annotate in these Zoe: Since we **could** annotate, **maybe** it's our note they wanted to see?
Yes, but partial agreement (Pomerantz, 1984)	Using a brief "yes," "yeah" to express agreement, followed by "but" to introduce a contrasting viewpoint	Arjun: Look at 2a, they got it from <u>**2a**</u> (referring to the evidence number) Priya: **Yeah, but** we don't know if that evidence is °actually like°. Let's see. Let's see. It might be there
Posing an alternative idea (Muntigl & Turnbull, 1998)	Presenting a different but not contrasting idea to indicate disagreement with an initial idea	Ethan: Can we quickly look at the pond simulation because I didn't (see it) = Rohan: = Um, maybe we can try for a second Zoe: = **I think we should do that after**
Indirect challenge	Questioning a prior turn or refusing an idea without using explicit negation or direct contradiction	Rohan: Wait, can you press algae and oxygen? I want to see it Zoe: We have seen oxygen <u>**five times. =**</u> Rohan: = But I want to see it one more
Prosody (Pomerantz, 1984)	Pause, gap, intonation, latched speech, overlaps, speech pace change	

challenging rhetorical wh-question, sense making challenge); episodes with soft forms (hedging, yes but partial agreement, posing an alternative idea, indirect challenge); and episodes with both direct and soft forms. Through discussion with the research team, the primary coder then measured variables–the average number of turns and perspectives students expressed in each episode. A perspective here refers to a unique viewpoint a student holds and expresses. Conflicting viewpoints were coded as two distinct perspectives. For instance, if one student agrees with a peer's comment while another disagrees, these are considered two perspectives. Following CA, we analyzed the sequencing of each disagreement instance and subsequent turns that occurred immediately after the disagreements to unfold how disagreements were managed, and what actions were achieved. This allowed us to grasp the influence of different types of disagreements on student engagement and progress in peer critique. Throughout the data analysis process, we frequently reviewed the video data to ground our interpretations and organized data sessions with the research team for further examination.

Findings

Our analysis reveals that during the gallery walk, disagreements were prevalent, occurring in 48 of 72 segmented episodes (2440 turns). Among these 48 episodes of disagreements, 46 were spontaneously initiated by students themselves, with the remaining 2 initiated by facilitators. Additionally, students disagreed with their groupmates (and with or without invisible peers) in 44 episodes and disagreed with only invisible peers in 4 episodes. Notably, these instances of disagreement involved various topics in giving and addressing peer critique (see Table 2).

RQ1: forms of disagreements

The distribution of disagreement forms is shown in Table 3. A total of 185 instances of disagreement forms were identified across 156 dissenting turns, with some turns containing 2 forms. Students employed a substantially higher number of soft forms (64%) compared to direct forms (36%). Given that students worked together to review the models and critiques produced by invisible peers from other groups, we examined those coded turns to determine whether their disagreements differed when directed towards present groupmates versus their invisible peers. Among the 29 turns where students disagreed with invisible peers, 26 (89.7%) were expressed in direct forms. In contrast, when disagreeing with their groupmates, only 44 out of 127 turns (34.6%) were expressed in direct forms. This difference indicates a tendency for students to disagree more directly with invisible peers compared to those who were present. Notably, we did not observe any occurrences of rude behaviors such as insults or shouting during disagreements, highlighting a positive and polite atmosphere within the groups.

Direct disagreements, including direct negation, challenging rhetorical wh-questions, and sensemaking challenge, are expressed in a straightforward way, conveying strong disagreements; however, they can be mitigated by explanations, exceptions, or additions (Pomerantz, 1984). Our analysis reveals that overall, 57% of direct disagreements involved such mitigations, primarily through explanations.

Table 2 Description of students' disagreement topics

Disagreement topic	Description of each topic	Number of episodes
Critique of peer model	Critique of specific components of peer model, discussion of criterion selection for comments, compare and contrast peer model with their own	14
Peer comments	Discussion of comments received from other groups	8
Model revision	Decision-making regarding incorporating or addressing suggestions from peer comment	8
Evidence interpretation	Discussion of interpreting and using evidence when evaluating and revising models, e.g., if the evidence was relevant or accurate to their model, link which evidence to which component of the model	7
Task coordination	Monitoring and regulating task progress and priority	7
Concept discussion	Interpretation of scientific concepts (e.g., relationship between dissolved oxygen and algae)	4
Total		48

Table 3 Distribution of disagreement forms

Disagreement type	*Form*	*Count*	*Percentage*
Direct (67, 36%)	Direct negation	46	24.9%
	Challenging rhetorical wh-question	11	5.9%
	Sensemaking challenge	10	5.4%
Soft (118, 64%)	Hedging	56	30.3%
	Yes, but partial agreement	19	10.3%
	Posing an alternative idea	29	15.7%
	Indirect challenge	14	7.6%
Total		185	100%

Direct negation A prominent form of direct disagreement was *direct negation* ($n=46$), involving straightforward expressions like "no" or "I disagree" without any preface or delay. Students employed direct negation both with their groupmates and invisible peers, to challenge errors on peers' models, scientific misconceptions, misunderstanding of comments, and factual inaccuracies (e.g., whether certain evidence included particular information). They often promptly expressed their disagreements without delay, as evident in latched speech, i.e., no pause between turns (indicated by the symbol "=") and overlapping turns (indicated by "[]"). It is noteworthy that in 72% of the instances, students offered explanations or elaborations for their claims, mitigating the force of strong disagreements. The following example from Group A illustrates this form during their review of Group B's model, specifically regarding the interpretation of bubbler-oxygen-algae relationship (see Fig. 4). During the evaluation, students typically were oriented towards the model together using screen-sharing in Zoom, taking turns to control the screen and read aloud. This shared attention on the model was crucial for uncovering any underlying misunderstandings.

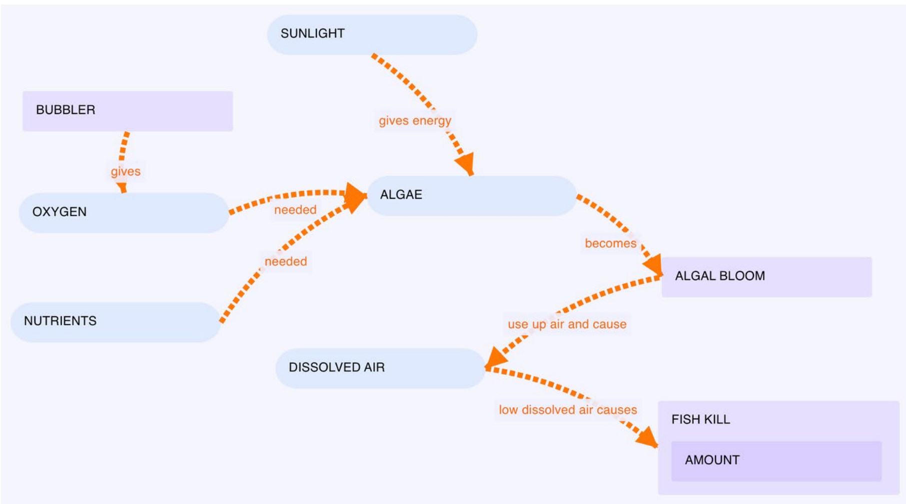
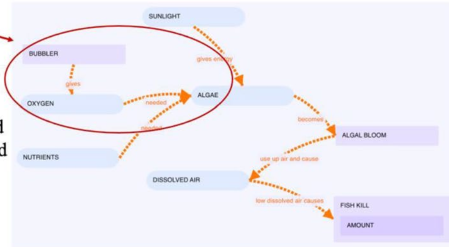


Fig. 4 Group B's model

Excerpt 1

#	S	Utterance	MEME Model
1	Priya	(*Reading aloud the model*) The bubbler increases the amount of oxygen, which then increases, where does it say the oxygen increases the amount of the algae?=	
→ 2	Arjun	=The bubbler <u>de</u>crea::ses the amount of oxygen.=	
→ 3	Priya	=No, [it increases the amount] of dissolved oxygen. The bubbler makes more dissolved oxygen.	
→ 4	Aria	[No, it makes more]	
5	Arjun	Ye::ah, more dissolved oxygen.	

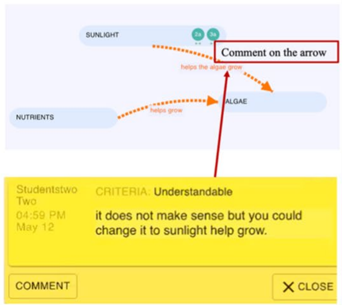


In Excerpt 1, Priya read aloud the model and questioned the oxygen-algae relationship (line 1). Arjun responded with direct negation on the bubbler-oxygen relationship, with an emphasis on "decreases" (line 2). Priya and Aria immediately and simultaneously corrected Arjun's misconception and rephrased "increases" as "makes more" to clarify the bubbler's effect (lines 3 & 4). The direct negation prompted Arjun to acknowledge the correction and modify his initial idea (line 5), thus building a shared understanding of the bubbler-oxygen relationship. Note there seemed to be a misunderstanding concerning the term "increase." Priya read "gives" as "increases," which went uncorrected by other members. This might suggest a potential lack of clarity around the words "increase" and "decrease."

Direct negation also occurred when students defended their own model against critiques from their invisible peers. For instance, in response to a comment that Group A received, Arjun immediately reacted: "It says we were copying them? We were <u>**not**</u> copying them, we were learning from them." This example shows that students disagreed not only about content, but also about metacognitive aspects of their learning behaviors.

Challenging rhetorical wh-questions Another direct form of disagreements was the use of *challenging rhetorical wh-questions*. These questions, while using interrogative language like *what, why, how*, are not meant to seek information when they appear within an "already-established environment of disagreement, accusation, complaint and the like, where challenging is a sequentially appropriate next response" (Koshik, 2003, p. 52). They convey the speaker's strong negative assertions and are used to reveal that what the interlocutor is arguing for is impossible (Georgakopoulou, 2001). For example, "why should we" indicates "we should not." They may convey some aspect of metacognitive monitoring or evaluation. In these 10 instances, students predominantly directed their disagreements towards invisible peers to challenge the models or comments they made (8 instances), with only 2 instances aimed at groupmates, followed by explanations to soften their tone. The following example in Excerpt 2 demonstrates this form in response to a peer comment that Group A received. The comment made on the arrow suggested changing the label "helps the algae grow" to "help grow," viewing the original as problematic.

Excerpt 2

#	S	Utterance	MEME Model
1	Priya	(*Reading aloud the comment*) "Understandable [*"Understandable" doesn't mean that Priya thinks that it is understandable, but that Priya is repeating the category of criticism, that reviewers choose "understandable" to indicate that they think that the model is not understandable.*] It does not make sense you could change it to sunlight helps grow." That's what we did, sunlight helps the algae grow. Um, okay. Maybe we can just add the word sunlight.	
→ 2	Arjun	Wait, it is understandable though. **<u>How</u>** is that not understandable?↑ "It does not make sense, you could change it to sunlight helps grow." That's what we did, sunlight helps the algae gr::ow=	
3	Priya	=Let's just put sunlight. Sunlight helps the algae grow. Let's just put the word sunlight.	
4	Arjun	=Wait, what?!	

Priya read aloud the comment for the group. Arjun used the direct negation "it is understandable" to express his disagreement with the critique, followed by the rhetorical question "how" to further assert a strong negative stance, indicating "it should be understandable," as their model included "sunlight (entity) → helps the algae grow (process)→ algae (entity)" (line 2). Priya proposed a compromise by suggesting they add the word "sunlight" to the label on the process (line 3), but Arjun rejected this suggestion (line 4), perhaps because it was redundant to the sunlight entity. While this did not substantively change the students' resulting model, it did provide them with experience exploring the need to have their models be clear to peers, an important aspect of meta-modeling expertise (Pierson et al., 2017).

Occasionally, students used rhetorical questions to challenge their group members' viewpoints, as illustrated in Excerpt 3. This disagreement occurred among students within Group B regarding how to respond to a peer comment using the MEME commenting feature, which allowed them to reply to comments, potentially leading to more feedback.

Excerpt 3

	#	S	Utterance
	1	Zoe	Comment on the comment? So they realize that we counted on them and they can comment on us.=
⟶	2	Rohan	=Well, **<u>why</u>**↑would they want to do that? They're **<u>never</u>** going to see this model again. That was the last time they're ever going to see it.=
	3	Zoe	=I mean, they might see it by the time we fix everything. Let's start fixing stuff because we've been here for like four minutes.

In this excerpt, Zoe proposed "comment on the comment" to foster reciprocal engagement with other groups (line 1). However, Rohan responded with a rhetorical why-question to express his disagreement, emphasizing "never" and "last time" to argue against implementing Zoe's suggestion (line 2). This rhetorical why-question, along with the explanation that their model would not be reviewed again, clearly conveyed Rohan's negative stance on the need for reciprocal commenting, implying the impracticality of Zoe's suggestion. Zoe, using hedges "I mean," "they might" (discussed below) to explain her rationale, indicated an indirect disagreement with Rohan, serving as a defense of her own position. Her immediate shift to focus on revising their model suggests an attempt to redirect the conversation towards the productive aspect, avoiding direct confrontation and maintaining a positive climate (line 3).

Sensemaking challenges Students also used *sensemaking challenges*, including expressions like "it doesn't make sense," "I don't get what they don't understand," or "I don't understand why they said that" to challenge the sensemaking or reasoning behind specific elements of models or comments made by their invisible peers. These expressions were often used when students identified logical flaws in the mechanisms presented in peer models they reviewed, or when they believed their model was well-supported but received critiques suggesting otherwise. Notably, these expressions may signal authentic confusion, but they also provided framing for disagreements. For example, Group C also reviewed Group B's model (see Fig. 4) and challenged the model's mechanism (see Excerpt 4).

Excerpt 4

	#	S	Utterance
→	1	Sophia	Wait what? That doesn't make sense. Bubbler gives oxygen needed algae.
	2	Lucas	No, algae's taking the oxygen.
	3	Sophia	Wait, but what is, wouldn't it go in the other direction there?
	4	Lucas	Yeah, because algae's taking the oxygen. So I think you should write a comment for that.
	5	Sophia	*(select criterion "understandable," add a comment on the arrow between oxygen and algae)*

After Lucas reading aloud the model, Sophia used a sensemaking challenge to critique the model by asserting that "That doesn't make sense," indicating her direct disagreement with the model's mechanism: "bubbler (entity) →gives (process) → oxygen (entity) →needed (process) →algae (entity)" (line 1). Lucas supported Sophia's critique by clarifying that algae took up the oxygen (line 2). Sophia further claimed that the direction of the arrow should be reversed, i.e., algae→needed→oxygen, to accurately depict the relationship (line 3). Following Lucas' immediate agreement and proposal to add a comment (line 4), Sophia proceeded to comment on the model: "Algae is the one that is taking the oxygen from the fish and we don't think that the oxygen needs the algae and we think its the other way around."

While direct disagreements were legitimized in this activity of peer critique, students predominantly embraced soft forms (64%). They employed various forms to downgrade disagreements, avoiding direct confrontation and conflicts, and seeking to maintain a friendly climate. For space considerations, we focus on hedging and partial agreement that feature more explicit linguistic markers in this dataset.

Hedging The most frequent form used by students to express disagreement was *hedging* (*n* = 56). Hedging serves as a *positive politeness strategy* by mitigating disagreement and striving to reach agreement with the receiver (Brown & Levinson, 1987). Our analysis reveals several types of hedges, including modal expressions such as "might," "would," and probability adverbs like "maybe," "probably," which conveyed a sense of uncertainty; propositional hedges like "I think," "I mean," "I feel like," serving the purpose of "self-effacement" and creating distance from the disagreement, allowing students to avoid imposing on their peers' autonomy (Rees-Miller, 2000). Excerpt 5 illustrates the use of hedging in negotiating a task within Group B.

Excerpt 5

#	S	Utterance
1	Ethan	Can we quickly look at the pond simulation cause I didn't (see it).=
2	Rohan	=Um, maybe we can try for a second.=
→ 3	Zoe	=I think we should do that after? Can I control the screen?=
→ 4	Rohan	=I feel like we should let Ethan control it, because he is kind of hasn't. But remember we're kind of like in a hurry, we only have five minutes.=
5	Zoe	=Yeah. So let's only, we're aware only get to do this for 30 seconds.
6	Ethan	*(Play with the simulation)*

Ethan expressed a desire to view the pond simulation before transitioning to the next task (line 1). Rohan tentatively agreed (line 2). Zoe *posed an alternative idea* (a soft form), suggesting an alternative timing for the simulation (line 3). This neither directly contradicted Rohan's position nor challenged Ethan's request, allowing for further negotiation (Muntigl & Turnbull, 1998). Zoe also employed the hedge "I think" to mitigate the potential of face threat of her disagreement. Rohan responded with "I feel like," followed by an account to advocate for Ethan's request (line 4). His response recognized Ethan's lack of knowledge about simulation while acknowledging Zoe's concern about time constraints ("but"). This approach softened the assertion of disagreement and fostered group consensus. Zoe then agreed and reinforced the time constraints (line 5). The group hence collectively decided to let Ethan control the screen and engage with the simulation.

Yes, but partial agreement In this pattern of *agreement-plus-disagreement*, speakers begin with an affirmative token "yes" or "yeah," signifying partial agreement through validating the prior turn, to foster solidarity; and then use "but" to introduce a contrasting or alternative viewpoint to show weak disagreement (Pomerantz, 1984). For example, in Excerpt 6, Group A had divergent interpretations of a peer comment concerning a piece of evidence.

Excerpt 6

#	S	Utterance
1	Priya	So let's give the evidence a skim again. Can we give the evidence a skim?=
2	Arjun	=But it literally says dissolved oxygen in tanks.↑= *(Facilitator opens the evidence "dissolved oxygen in tanks")*
→ 3	Priya	=Yeah, but we have to hear them out. Let's hear them out. Let's just, let's just see what they're talking about. If we don't agree with it, then we don't take their suggestion. This is easy as that. *(The students skim the evidence)*

Priya proposed skimming the evidence before responding to the comment (line 1), but Arjun resisted the proposal, stating that the title clearly addressed the topic, requiring no need to revisit it (line 2). To seek agreement, Priya acknowledged Arjun's thought with a brief "yeah" and then immediately used "but" to indicate disagreement, emphasizing the necessity of considering the reviewers' perspective and the straightforward nature of the solution, while maintaining a cooperative and respectful tone. The group then accessed MEME evidence library to review the evidence and continue their discussion.

Students also used "yes, but" to offer polite and constructive critique in their written comments. For instance, Group C wrote this comment: "**we understand** what you are saying and it might or might not be true **but** we think that what you are saying is only part of the situation. We think that the algae is taking the most the air and not leaving enough for the fish" (bold added by researchers to help highlight the intended emphasis). The comment acknowledged the invisible peers' perspective, "but" also introduced an alternative explanation about how algae might be depleting oxygen, which was valuable for consideration and well-grounded in the evidence. This comment also reflected students' adherence to the social norm–showing appreciation of others' work and being critical, which was likely to support reviewees' uptake of the critique.

In summary, the answer to RQ1 helps identify the ways that students engaged in disagreement, but it is also important to understand how these disagreements were resolved, as RQ2 addresses.

RQ2: The resolution of disagreements

To address the second question, we first categorized the 48 episodes based on disagreement forms they encompassed (see Table 4). Among these, 10 episodes exclusively featured direct forms of disagreements, 20 exclusively featured soft forms, and 18 featured mixed disagreements, incorporating both direct and soft forms. We counted the average number of turns and perspectives that students expressed in each episode. Episodes of mixed disagreements and exclusive soft disagreements tended to have more extended turns and slightly more perspectives than episodes of exclusive direct disagreements. We then examined how disagreements were resolved within each episode and identified similarities and potential differences across these different types of disagreements.

Resolution patterns Out of the 48 episodes of disagreements, 4 involved disagreements with invisible out-of-group peer, requiring no agreement. Most disagreements were successfully resolved, namely, group members explicitly agreed on a consensus understanding or

Table 4 Comparison of episode characteristics across disagreement forms

	Direct	Soft	Mixed
No. of episodes	10	20	18
Avg. turns per episode	3.8	7.3	12.9
Avg. perspectives per episode	1.8	2.4	3.2

decision in 39 out of the 44 episodes (88.6%) requiring resolution (see Fig. 5). This consensus was evident in group members stating explicit agreements, using expressions such as "Yeah," "I agree," or "OK, let's…" and in their subsequent actions. Among the 5 instances without an explicit consensus, 3 ended with shifting topics after an initial disagreement, where the proponent defended their position, as exemplified in Excerpt 3. This behavior distinguished itself from merely ignoring others' ideas, as it entailed defending one's stance while avoiding further discussion and agreement seeking. Only 2 instances remained unresolved: one disagreement went unheard thereby being ignored; while the other led to a prolonged discussion that abruptly ended with the class concluding.

Within the 39 resolved episodes, we observed nuanced differences in how disagreements were resolved. Specifically, 25 involved concessions, where students accepted an idea from a single side, either genuinely embracing corrections of misconceptions, or as a gesture of surrendering to their peers. In the remaining 14 instances, resolution occurred through co-construction, where students integrated ideas from both sides. Notably, co-construction was exclusively found in soft and mixed disagreements. Among the 10 episodes of exclusive direct disagreements, with 3 episodes requiring no agreement with invisible peers, 6 were resolved through concession, while the other one ended with topic shifting.

Additionally, students' management of disagreements through polite and respectful communication, positively influenced the socioemotional climate and collaboration. Chiu (2008a) highlighted that "rude disagreements can kill the collaboration" and even surviving collaboration after rude disagreements may suppress ideas sharing among group members (p. 420). Our analysis of each disagreement episode and their subsequent turns revealed that collaboration consistently sustained following both direct and soft disagreements across all episodes. Having explored how disagreements were resolved in RQ2,

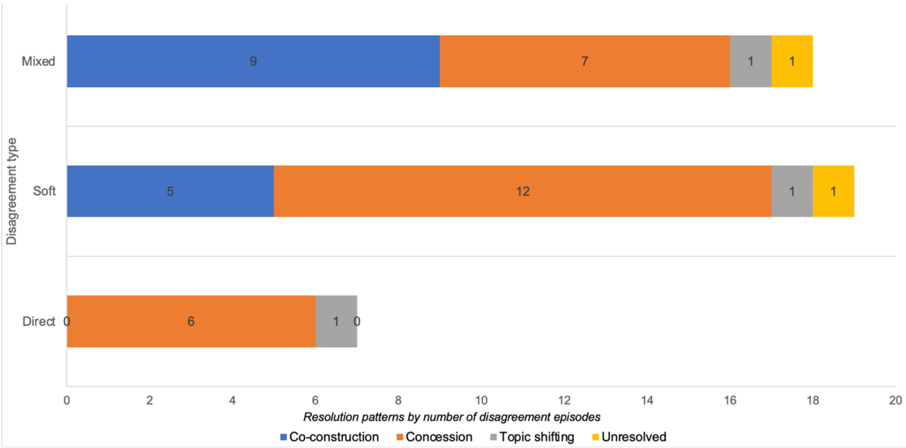


Fig. 5 Resolution patterns in different types of disagreement episodes requiring resolution

R3 addresses how students' management of disagreements advanced their collective knowledge.

RQ3: The impact of managing disagreements on collective knowledge advancement

Influence of direct disagreements A salient pattern observed in episodes of exclusive direct disagreements was that direct disagreements drove students to build shared and accurate understandings rapidly and resolve the disagreements effectively, thereby advancing collective knowledge. In those episodes, students immediately identified and corrected group members' emerging misinterpretations about scientific concepts or peer comments, leading to swift concession, with initial misunderstandings being refined. For example, in Excerpt 1, direct negation from Priya and Ariya enabled Arjun to change his misconception about the bubbler-oxygen relationship, facilitating the group building a shared understanding and subsequently composing a comment addressing the model's issue. When identifying discrepancies or errors in peers' models, students were compelled to challenge them and leave constructive comments. For instance, in Excerpt 4, Sophia and Lucas directly disagreed with the invisible peers regarding the algae-oxygen relationship and immediately left a helpful comment with a specific suggestion.

Moreover, students demonstrated a readiness to express direct disagreements without the need to soften them once errors were identified. Likewise, those who were challenged displayed a willingness to accept corrections and alternative ideas, without concerning about losing face. This was evident in all groups' smooth transitions from discussion to action, such as adding comments or revising models. We present another example to further illustrate this (see Excerpt 7). Priya read aloud the comment with selected model criterion, suggesting the inclusion of nutrients. Arjun disagreed with the invisible peers' comment, whereas Priya disagreed with Arjun's interpretation. The students successfully resolved their disagreements in 4 turns (lines 2 to 5), resulting in a shared understanding and revision of their model.

Excerpt 7

#	S	Utterance	Disagreement form	Student progress
1	Lucas	I don't think they made too much. Like I don't think they made that many changes because we made like a lot of changes. But I feel like the only, I feel like (3.0)		
2	Sophia	But you don't have to change it if the change isn't necessary.	***Posing an alternative idea***	Sophia initiated the disagreement.
3	Lucas	You know they didn't=		
4	Neil	=Honestly we did is that we ruled out that one (pointing to the trash corner), the viruses and added the water helps the algae bloom. That's what we did.	***Indirect challenge***	Neil participated in the disagreement.
5	Sophia	Yeah.		
6	Neil	That's not a lot.		
7	Sophia	That's the rain thing. And then we changed a couple names on the thing. Oh wait, how about we read it loud like we did to ours and see if their thing makes sense.=		Sophia ended the disagreement and proposed to read the model. Lucas agreed and started reading it.
8	Lucas	=Okay. Sunlight helps the algae grow… (*reading the model*)		

Arjun initially negated the peer comment, assuming that the reviewers wanted the evidence #4a linked to their model, which had already been done (line 2). His direct negation made his misinterpretation visible to the group, triggering Priya's direct disagreement. Priya clarified that the reviewers actually referred to the absent element "nutrients" (line 3). Her clarification was instrumental in fostering a shared understanding of the reviewers' intention, otherwise they might have overlooked an opportunity to refine and improve their model. Priya's clear explanation helped mitigate the directness, making it easier for the group members, including Arjun, to accept her correction. Arjun's immediate concession ("Okay"), accepting Priya's correction and aligning with the group's decision-making process, was interpreted as genuine, given the group's subsequent move–a smooth transition to revise the model. After reaching a consensus, the discussion sustained. Priya proposed adding "nutrients" to their model (line 8). The group incorporated it, connected it to "algae," and labeled the process "helps grow" to highlight their relationship, thus making their model more complete (see Fig. 6).

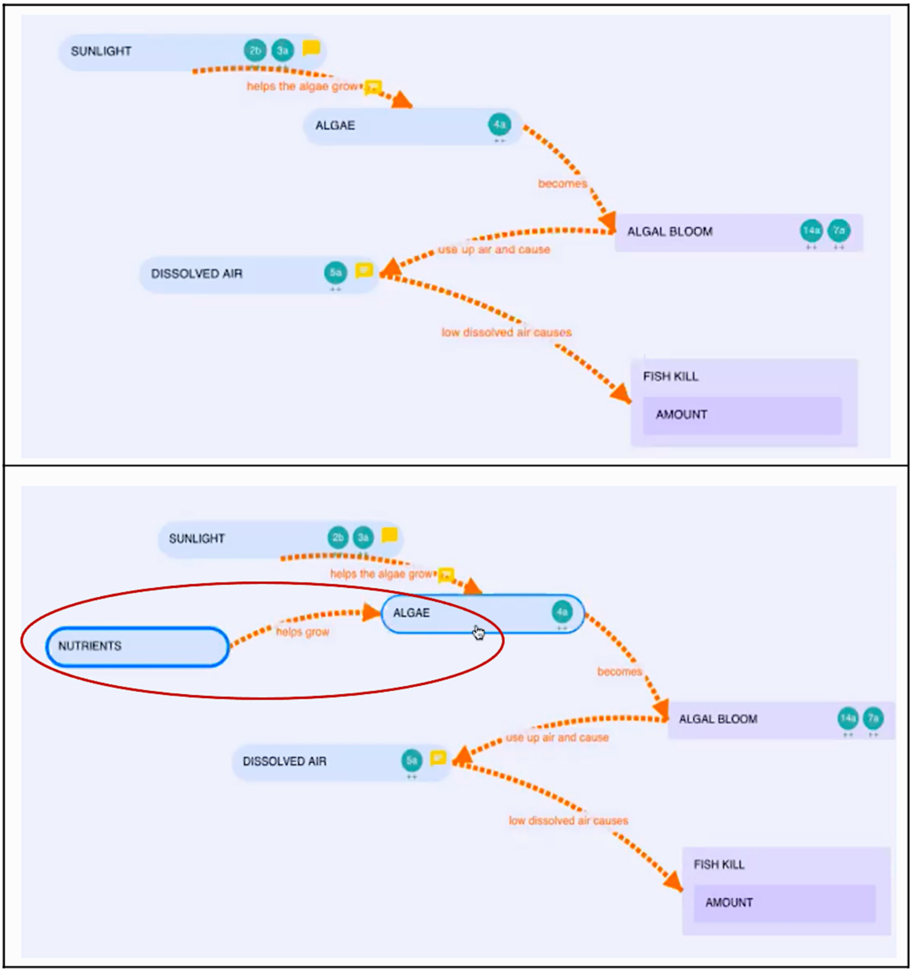


Fig. 6 Group A's model before disagreement (top) and after disagreement (bottom)

While direct disagreements effectively prompted rapid decision-making and problem-solving, they may limit the exploration of alternative ideas or solutions due to the quick closure of disagreements, as opposed to soft disagreements, which invite joint exploration of different ideas and reasoning avenues during the argumentative process (Georgakopoulou, 2001). However, among all 9 episodes of direct disagreement, we found no instances where better ideas or solutions were overlooked. This suggests that students' constant joint attention to the screen, shared understanding, and commitment to shared goals enabled them to make quick and appropriate decisions without dismissing valuable contributions.

Influence of soft disagreements In the 20 episodes of soft disagreements, students engaged in extended collaborative argumentation and co-construction that allowed for slightly more perspectives to be shared, helping them make constructive critiques and model revisions while fostering group cohesion. The students tended to disagree softly when they examined peers' models ($n=6$), revised specific components of their models, including revisiting and discussing evidence($n=6$), compared peers' models with their own ($n=3$), and negotiated task priorities ($n=3$). Within those episodes, students dedicated time to consider the nuances of different viewpoints and develop arguments and cultivated their increased appreciation of the legitimacy of diverse positions and explanations (Barzilai et al., 2020). The frequent use of hedges, *yes-but* partial agreement, or posing alternative ideas signified a more open approach to decision making, contributing to an inclusive environment that valued different opinions. For example, in Excerpt 5, students used soft forms to express disagreements, ultimately reaching a compromise that enabled Ethan to engage with the simulation. Their decision highlighted the group's recognition of Ethan's lack of knowledge about simulation and privilege of developing the understanding shared by other group members. This inclusivity could also foster group cohesion, ensuring Ethan did not feel excluded.

Interestingly, across all three groups, students employed soft disagreements during comparisons of peers' models. Typically, one student might observe similarities, such as "I feel like this looks like our model," while other group members indirectly disagreed by noting differences, such as "They forgot the rain thingy," or "Just one big difference, we mentioned that blue pond shouldn't have had any fish death." These discussions, involving self-reflection, often led to consensuses and concluded with written comments, which could benefit their learning process through constructing critique and revising their models (Tsivitanidou et al., 2018). When reviewing a peer model, Group C made comparisons, but their group discussion also unpacked their understanding about the nature of how much change was needed to make a model better, in response to critiques on their models (Excerpt 8).

Excerpt 8

#	S	Utterance	Disagreement form	Student progress
1	Priya	(*Reading aloud a comment received*) The criterion "shows all steps in process", "sunlight is not the only thing that algae needs to grow. It also needs the nutrients that the rain helps with. look on evidence 4." =		Arjun initiated the disagreement; Priya corrected Arjun's idea.
2	Arjun	=Well, we **did** put that. We put 4a on algae↑ =	***Direct negation***	
3	Priya	=**No.** No. What we're thinking, but remember, you're just thinking to add nutrients. We didn't add that. That's why they commented to add it.=	***Direct negation***	Disagreement was resolved. Arjun accepted the correction.
4	Aria	=Yeah, we (inaudible).		
5	Arjun	Okay.		
6	Priya	And they also want to have help algae grow.		Discussion sustained. Priya further elucidated the comment.
7	Arjun	Ye::ah. *(Facilitator inquired about potential changes following the comment.)*		
8	Priya	Yeah. Let's add the nutrients to help the um, algae grow. *(The group added the entity "nutrients" and connected it to "algae")*		The students integrated the feedback into their model revision.

Lucas asserted that the group under review made minimal changes to the model, which sparked a disagreement (line 1). Sophia posed an alternative perspective, stating that changes should only be made if necessary, implying her disagreement while leaving room for further discussion (line 2). Lucas tried to defend his position (line 3), but Neil's indirect challenge, detailing their group model's changes, which were "not a lot," and delaying negation until later (lines 4 & 6), countered Lucas's stance and echoed Sophia's view. Sophia provided additional evidence to support Neil's point (line 7). Thus, Neil and Sophia co-constructed the evidence to support their shared perspective that their own group made only a few changes to their model. Although the disagreement did not reach a clear resolution, as Lucas did not explicitly ascertain his agreement, it engaged students in the reflective process through comparing peer work. Importantly, Sophia's soft disagreement made her perspective visible and available for discussion, emphasizing the focus on making the right changes over the quantity. Sophia then redirected the discussion to reading the model aloud to examine it as a collaborative effort, indicating a proactive approach to move forward. Lucas promptly agreed and took the lead to read it (line 8).

Influence of mixed disagreements In the 18 episodes of mixed disagreements, where students used both direct and soft forms, they engaged in the most prolonged discussions and explored a wider range of perspectives, contributing to their knowledge advancement. This is demonstrated by students' collective changes in evidence interpretation ($n=5$), improved understanding of peer comment ($n=3$), and constructive critiques ($n=3$). Notably, there was a trend in these episodes–a transition from direct to softer forms towards finding resolutions. Among the 18 episodes of mixed disagreements, 11 started with a direct form; interestingly, in the majority of these episodes (14/18), the disagreements gradually transitioned to soft forms as the discussion proceeded. The transition may imply a deliberate effort by students to reconcile differences and foster consensus, and potentially mitigate socioemotional tensions that might be associated with directness of disagreements. To illustrate this, we draw an example from Group A, where students discussed a peer comment (as referenced in Excerpt 2), which sparked strong disagreements within the group (Excerpt 9).

Excerpt 9

#	S	Utterance	Disagreement form	Student progress
1	Priya	(*Reading aloud the comment*) "Understandable. It does not make sense you could change it to sunlight helps grow." That's what we did, sunlight helps the algae grow. Um, okay. Maybe we can just add the word sunlight.	***Direct negation***	Priya initiated the disagreement.
2	Arjun	Wait, it is understandable though. **How** is that not understandable?↑ "It does not make sense, you could change it to sunlight helps grow." That's what we did, sunlight helps the algae gr::ow=	***Direct negation*** ***Challenging wh-question (how)***	↓ Arjun expressed direct disagreement; discussion continued.
3	Priya	=Let's just put sunlight. Sunlight helps the algae grow. Let's just put the word sunlight. =		
4	Arjun	=Wait, what?!		↓
5	Priya	We know sunlight helps the algae grow right, let's put sunlight helps the algae grow.=		Disagreement was not resolved.
6	Arjun	=I don't get it. It just doesn't make sense.=	***Sensemaking challenge***	

As noted in Excerpt 2, the reviewers recommended changing the label on the arrow from "helps the algae grow" to "helps grow." This comment immediately prompted two disagreements (see Excerpt 9). Both Arjun and Priya disagreed with the comment and each other's approaches to addressing it. Priya seemed to be willing to make a minor change, whereas Arjun strongly disagreed with any change. Arjun employed a direct negation and rhetorical *wh*-question (*how*) to challenge the comment's validity (line 2). While Priya used "just" to downplay the revision effort required, likely to ease the acceptance of her suggestion (line 3), Arjun resisted accepting it. This exchange reveals a clear conflict between Arjun's resistance to revision and Priya's persistence in advocating for it. At this point, Arjun and Priya seemed to struggle to reach a consensus, leading to a point where Arjun continued to express strong disagreement not only with the reviewers but also with Priya (line 6). Additionally, the frequent successive turns without pause (=), Arjun's heightened pitch (↑), stretched sound (gr::ow), and questioning intonation (?) throughout the exchange revealed underlying tensions. These tensions indicated students' eagerness to defend their positions and reluctance to consider alternative perspectives, thus challenging the collaborative climate.

Given the impasse (see Excerpt 10), the facilitator stepped in to guide how to react to peer critique and granted the agency to the students (line 7). Subsequently, Priya acknowledged the model's clarity (line 8), yet Arjun continued to express his strong disagreement with the comment and adding an additional reason, "wasting our time" (line 9). Priya initially implied her disagreement with that reason using hedges and emphasizing the "quick" nature of the change, but then quickly conceded, downplaying the need for others' understanding to align her viewpoint with Arjun's and prevent further disagreement (line 10). This move led Arjun to soften his disagreement and emphasize his disagreement with the invisible reviewers ("they") (line 11). Priya immediately agreed with Arjun and sought other members' agreement (line 12), before proposing to move on (line 14). Thus, the group reached an agreement to disregard the comment and proceeded to review another comment (line 16), sustaining collaboration after resolving the disagreement.

Excerpt 10 Discussion continued

#	S	Utterance	Disagreement form	Student progress
7	Fa	Remember it's up to you to decide if you agree with the comment. So you could say we think it's clear.=		
8	Priya	=[I mean to me it looks clear]		Facilitator provided guidance; Priya made a concession.
9	Arjun	=[I really] I really don't agree with the comments. Cause I feel like it's gonna be wasting our time if we just put sunlight there.=	***Direct negation***	↓
10	Priya	=I mean it's like a quick change, but like, it doesn't need to be they understand them, pretty sure.=	***Hedging***	Disagreement continued.
11	Arjun	=I mean, I don't get what they don't understand on that comment.=	***Hedging***	
12	Priya	=Me neither. Do you guys get it?		↓
13	Arjun	I don't get what they don't understand. Oh, this was from group C! Okay.		The group reached a consensus.
14	Priya	So let's check um dissolved air then if we choose not to put [any feedback].=		↓
15	Arjun	[Yeah, we should] close it.		The students sustained their collaboration.
16	Priya	Ok. *(Students moved on to view another comment they received.)*		

While no changes were made to the model in the end, their engagement in the argumentation was still productive. They navigated disagreements, attempted to reconcile, and ultimately agreed not to make a change. Meanwhile, the facilitator's permission to ignore the comment helped shift group dynamics. The permission enabled Priya to make a concession and revise her initial idea, followed by Arjun transitioning from a strong to a softer tone in expressing his thoughts. Ultimately, this facilitated consensus and diffused tension within the group. Note that Priya also misunderstood the reviewers' intention regarding deleting "the algae" instead of adding "sunlight" on the label. Although from the communication perspective, taking out of "the algae" could enhance the model clarity, the group's decision to disregard this seemingly trivial issue was appropriate, as it allowed them to move on and maintain a positive group climate.

Discussion

This study aimed to understand the ways students managed disagreements during peer critique within small groups and how these ways affected their collective knowledge advancement, ultimately to inform the design of CSCL environments. Previous research has indicated that elementary school students may have few opportunities for peer critique, which limits their chances to engage in scientific reasoning, resulting in less science learning (Henderson et al., 2015). Our study contributes to the exploration of effective CSCL interventions for enhancing engagement in disagreements and peer critique among students. The prevalence of disagreements generated by 5th-grade students highlights how group peer critique motivated students' engagement in disagreements, or more broadly, collaborative argumentation. Moreover, our findings demonstrate that students were able to express disagreements and effectively resolve them while maintaining a positive and collaborative socio-emotional space.

Disagreeing softly

Our analysis shows that elementary students used both direct and soft forms of disagreements during the scientific practice of peer critique. These forms reflect the categories identified in prior research using CA to examine disagreements in various contexts (e.g., Muntigl & Turnbull, 1998; Netz, 2014). Interestingly, we noticed a tendency among students to use soft forms of disagreements, such as partial agreement or hedging, rather than direct forms, to engage in peer critique. This tendency aligns with the prevailing notion that people prioritize "sociability, support, and solidarity," leading them to mitigate direct disagreements (Pomerantz, 1984). Moreover, our study found a considerably higher frequency of direct disagreements, compared to a previous study involving medical school students, who tended to avoid direct disagreements (Hmelo-Silver & Barrows, 2008).

Another interesting finding is that students showed their awareness of presence and collaborators when disagreeing. Specifically, students were more inclined to disagree softly with their in-group peers to minimize conflict and seek consensus, thereby accomplishing their tasks and maintaining a positive group climate. Even when they directly disagreed with in-group peers, they frequently provided reasons and effectively resolved their disagreements. Students also adapted their approach to express disagreements based on their peers' behaviors. For instance, in Excerpts 9 and 10, both Arjun and Priya transitioned from using direct disagreements to using a softer tone. In contrast, students were more likely to directly disagree with the invisible peers, through rhetorical wh-questions or sensemaking challenges. The directness in disagreements might be motivated by the peers' lack of presence, thus that in-group students need not be concerned about disrupting the socio-emotional climate; or by the peers being from another group. This is a particularly striking finding given the affordances of CSCL environments for asynchronous interaction, which may promote different group dynamics with invisible others.

Advancing collective knowledge

Our analysis provides evidence that students' effective management of both direct and soft disagreements during peer critique supported their collective knowledge advancement, including building shared understanding about what a model communicated and the underlying science concepts, and improving model accuracy. The high rate of resolving disagreements consensually (88.6%) suggests a potential facilitation of students' collaborative knowledge construction, as prior research highlights that resolving disagreements is important for knowledge construction to take place (Sandoval et al., 2019). Furthermore, our observations indicate that students may have learned through engaging in disagreements, as seen in changing understandings and ideas, and expressing arguments supported by reasons and evidence, which consistent across all groups. Students' corrections of misconceptions from groupmates and peer critiques helped refine their ideas and models, contributing to knowledge building at the group level (Hmelo-Silver & Barrows, 2008; Scardamalia & Bereiter, 2006). In expressing their arguments, students made their ideas visible to each other and could possibly find a better solution through sustained discussion (Baker, 2009). Additionally, following resolving disagreements, students provided constructive comments and refined models based on comments, which can improve learning outcomes (Gerard et al., 2019). However, disagreements may not always lead to collective knowledge advancement, particularly when students opted to shift topics before reaching a consensus. For instance, the discussion in Excerpt 3 did not demonstrate changes in understanding, yet their discussion was valuable in that "comment on the comment" might lead to more feedback if they had more sessions.

We found nuanced differences in how different forms impacted collective knowledge advancement. Specifically, episodes of direct disagreements were typically resolved through concession, which means that one position was accepted, and the other was refuted or abandoned. Direct disagreements appeared to be effective in promptly addressing errors or misconceptions, facilitating immediate corrections and progress. Conversely, episodes involving soft and mixed forms of disagreements were frequently resolved through collaborative efforts, i.e., co-construction, or compromise. This approach could enable students to better recall arguments from both positions, facilitating a more comprehensive understanding of the problem (Andriessen & Schwarz, 2009). Additionally, in those episodes, students tended to articulate and defend their positions more extensively, leading to richer discussions. Furthermore, the tendency of students to shift from direct to softer forms in reaching a consensus suggests that soft disagreements may mitigate the tension associated with direct disagreements. The deliberate shift indicates that students actively sought to mitigate potential conflicts while working towards agreement, to maintain a collaborative and less confrontational atmosphere.

Implications for the design of peer critique activity

In this study, peer critique served dual purposes: promoting disagreements and serving as a scientific practice. Engaging in peer critique within group settings not only provided rich opportunities for students to generate and resolve disagreements, but also supported the production of constructive critiques and the improvement of models. This underscores the value of fostering peer critique at a group level. Given the limited research on group critique, our study identified four key design features crucial for its effective implementation in CSCL environments.

(1) Using a mix of in-group and across-group negotiation: In our study, we provided students with opportunities to engage in both face-to-face in-group discussions and asynchronous across-group interactions through sending comments. The in-group discussion enabled students to jointly critique and learn from other groups' models (Jeong & Hmelo-Silver, 2016), while the asynchronous negotiation through MEME commenting feature allowed students to pinpoint flaws on specific model elements, ensuring prompt identification and addressing of problematic areas.

(2) Facilitating joint attention: We achieved this in two ways. First, locating comments on specific elements of the models allowed for focused discussions on particular features. Second, the strategies of sharing screen and reading aloud helped students orient to the same part of the shared representation simultaneously. In this way, models and comments formed boundary objects for group discussions (Akkerman & Bakker, 2011), facilitating successful collaboration among students (Barron, 2003).

(3) Providing rich evidence and easy access: Accessible evidence played a crucial role in resolving disagreements in a manner similar to the kinds of professional practices that we aim to develop. As shown in the examples, students frequently referred to specific pieces of evidence (e.g., "look at evidence 4") and constructed evidence-based explanations following both direct and soft disagreements. This demonstrates that their grasp of evidence aided resolving disagreements and revising models (Duncan et al., 2018).

Students also proactively verified evidence in the MEME library to address peers' questions, ensuring discussions progressed smoothly.

(4) Fostering social norms for engaging in peer critique: Attending to others' thinking and pursuing consensus are essential norms (Kuhn, 2015; Sandoval et al., 2019). Our study cultivated these norms through whole-class instruction and facilitator modeling in small groups. By adhering to these norms, students expressed different perspectives and considered others' ideas, recognizing that managing disagreements was a foundational step towards reaching consensus.

Additionally, we identified an emerging norm across groups. Despite our encouragement towards pursuing epistemic goals, students occasionally tended to end or downplay disagreements to maintain group harmony. For instance, Zoe shifted the topic in Excerpt 3, and Priya opted to overlook a peer critique in Excerpt 10 to foster a more positive group climate, potentially at the expense of making more critiques and revisions. Students' deliberate effort on balancing harmony with epistemic pursuits was critical; otherwise, socioemotional problems may interfere with their cognitive processes and become a barrier to productive practice (Borge & Xia, 2023). This underscores the need for additional facilitation to guide students on when and how to effectively manage these dual priorities.

Finally, the study also highlights challenges that need to be addressed in future design. For instance, some disagreement stemmed from ambiguities in comments made by their invisible peers, suggesting a need for clearer and more detailed critiques. Enhancing comment clarity, particularly by specifying suggestions with explicit descriptions, could mitigate such misunderstandings and support knowledge improvement (Tan et al., 2023).

Limitations

This study has provided valuable insights, yet we acknowledge several limitations. The data for this study were collected from an online afterschool science club during the COVID-19 pandemic in Summer 2021, so that our participants may have had a high motivation or interest in science learning that impacted their willingness to engage in science practice. Meanwhile, the study had to be conducted with a small class size due to pandemic-related constraints. However, the study showed promising results, prompting us to expand this research since then. Furthermore, it is essential to consider that how disagreement is perceived, conveyed, and accepted can be influenced by cultural context and social norms within the context (Angouri & Locher, 2012). As this study focused on students in a specific context, i.e., a science club in the U.S. context, the findings may not fully capture how disagreement is approached in other cultural settings. Additionally, while our findings highlight the impact of disagreement forms on knowledge construction, it is important to note that the potential influence of other factors were not measured in this study, such as discussion topics, prior knowledge and beliefs, and gender dynamics. These factors are known to play a role in shaping how disagreements are expressed and resolved (Barzilai et al., 2020; Noroozi et al., 2012; Nussbaum & Bendixen, 2003).

Conclusion

Engaging in disagreement is challenging yet beneficial for science learning. This study deepens our understanding of how disagreement, often perceived negatively in social contexts, can be positive during peer critique in science learning. Grounded in a sociocultural perspective (Danish & Ma, 2022), our study highlights how interaction through disagreement and peer critique enables students to challenge peers' positions, provide supporting reasons and evidence, reconcile different ideas, and refine their own understanding, thereby advancing collective knowledge, as evidence of learning. Notably, our study reveals how students' reactions to peer critique were related to the critic's position with respect to the small group and presence status. Students varied their disagreement strategies, using softer forms with in-group peers and more direct forms with out-group and invisible peers. These findings can prompt teachers to consider how to help students navigate different contexts for disagreements and critique and apply appropriate disagreement strategies in various settings.

Our study advances the literature on peer critique and feedback by conducting in-depth moment-to-moment analysis of the critique process. Unlike existing research focusing on students' beliefs and perceptions towards peer feedback (Alqassab et al., 2023), behavioral dimensions of peer feedback quality (Zhang et al., 2024), or artifacts like concept maps and written feedback (Tan et al., 2023), our study emphasizes the importance of making reviewers' and reviewees' reasoning visible. This visibility is central to driving the development of students' models in different ways. Additionally, the analysis of small group work offers valuable insights into student-driven group critique and the role of language in managing disagreements, both effectively and sometimes ineffectively. These insights can inform future design of effective group critique activities, including scaffolding and task design (Zhou et al., 2024). Suggestions include leveraging joint representations, encouraging screen sharing and reading aloud, ensuring easy access to evidence, and promoting social norms. Future research especially needs to pay attention to scaffolding language use in articulating constructive critiques and fostering norms that promote productive disagreements while maintaining a positive socioemotional climate.

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References

Akkerman, S. F., & Bakker, A. (2011). Boundary crossing and boundary objects. *Review of Educational Research, 81*, 132–169.

Alqassab, M., Strijbos, J. W., Panadero, E., Ruiz, J. F., Warrens, M., & To, J. (2023). A systematic review of peer assessment design elements. *Educational Psychology Review, 35*(1), 1–36.

Andriessen, J. E., & Schwarz, B. B. (2009). Argumentative design. In N. Muller Mirza & A.-N. Perret-Clermont (Eds.), *Argumentation and education: Theoretical foundations and practices* (pp. 145–174). Springer-Verlag.

Angouri, J., & Locher, M. A. (2012). Theorising disagreement. *Journal of Pragmatics, 44*(12), 1549–1553.

Asterhan, C. S., & Schwarz, B. B. (2016). Argumentation for learning: Well-trodden paths and unexplored territories. *Educational Psychologist, 51*(2), 164–187.

Baker, M. (2009). Argumentative interactions and the social construction of knowledge. In N. Muller Mirza & A.-N. Perret-Clermont (Eds.), *Argumentation and education: Theoretical foundations and practices* (pp. 127–144). Springer-Verlag.

Barron, B. (2003). When smart groups fail. *Journal of the Learning Sciences, 12*(3), 307–359.

Barzilai, S., Thomm, E., & Shlomi-Elooz, T. (2020). Dealing with disagreement: The roles of topic familiarity and disagreement explanation in evaluation of conflicting expert claims and sources. *Learning and Instruction, 69*, 101367.

Bathgate, M., Crowell, A., Schunn, C., Cannady, M., & Dorph, R. (2015). The learning benefits of being willing and able to engage in scientific argumentation. *International Journal of Science Education, 37*(10), 1590–1612.

Berland, L. K., & Lee, V. R. (2012). In pursuit of consensus: Disagreement and legitimization during small-group argumentation. *International Journal of Science Education, 34*(12), 1857–1882.

Borge, M., & Xia, Y. (2023). Beyond the individual: The regulation and negotiation of socioemotional practices across a learning ecosystem. *Journal of the Learning Sciences, 32*(3), 325–375.

Brown, P., & Levinson, S. (1987). *Politeness: Some universals in language usage*. Cambridge: Cambridge University Press.

Chen, J., Wang, M., Kirschner, P. A., & Tsai, C.-C. (2018). The role of collaboration, computer use, learning environments, and supporting strategies in CSCL: A meta-analysis. *Review of Educational Research, 88*(6), 799–843.

Chinn, C. A. (2006). Learning to argue. In A.M. O'Donnell, C.E. Hmelo-Silver, & G. Erkens (Eds.). *Collaborative learning, reasoning, and technology*, 355–383.

Chin, C., & Osborne, J. (2010). Students' questions and discursive interaction: Their impact on argumentation during collaborative group discussions in science. *Journal of Research in Science Teaching, 47*(7), 883–908.

Chinn, C. A., Rinehart, R. W., & Buckland, L. A. (2014). Epistemic cognition and evaluating information: Applying the AIR model of epistemic cognition. In D. N. Rapp & J. L. G. Braasch (Eds.), *Processing inaccurate information: Theoretical and applied perspectives from cognitive science and the educational sciences* (pp. 425–453). MIT Press.

Chinn, C. A., & Clark, D. B. (2013). Learning through collaborative argumentation. In C. E. Hmelo-Silver, C. A. Chinn, C. K. K. Chan, & A. M. O'Donnell (Eds.), *International handbook of collaborative learning* (pp. 314–332). Routledge.

Chiu, M. M. (2008a). Flowing toward correct contributions during group problem solving: A statistical discourse analysis. *Journal of the Learning Sciences, 17*(3), 415–463.

Chiu, M. M. (2008b). Effects of argumentation on group micro-creativity: Statistical discourse analyses of algebra students' collaborative problem solving. *Contemporary Educational Psychology, 33*(3), 382–402.

Danish, J. A., & Ma, J. Y. (2022). What is learning, for whom, and to what end? An overview. In R. J. Tierney, F. Rizvi, & K. Ercikan (Eds.), *International encyclopedia of education* (Fourth Edition, pp. 1–11). Elsevier.

Danish, J., Vickery, M., Duncan, R., Ryan, Z., Stiso, C., Zhou, J., Murphy, D., Hmelo-Silver, C., Chinn, C. (2021). Scientific model evaluation during a gallery walk. In de Vries, E., Hod, Y., & Ahn J. (Eds.). (2021). *Proceedings of the 15th International Conference of the Learning Sciences - ICLS 2021*. Bochum, Germany: International Society of the Learning Sciences.

Duncan, R. G., Chinn, C. A., & Barzilai, S. (2018). Grasp of evidence: Problematizing and expanding the next generation science standards' conceptualization of evidence. *Journal of Research in Science Teaching, 55*(7), 907–937.

Engeström, Y. (1987). Learning by expanding: An activity-theoretical approach to developmental research. Helsinki, Finland: Orienta-Konsultit Oy.

Fischer, F., Kollar, I., Ufer, S., Sodian, B., Hussmann, H., Pekrun, R., ... & Eberle, J. (2014). Scientific reasoning and argumentation: advancing an interdisciplinary research agenda in education. *Frontline Learning Research*, *2*(3), 28–45.

Ford, M. (2008). 'Grasp of practice' as a reasoning resource for inquiry and nature of science understanding. *Science & Education, 17*(2), 147–177.

Gao, X., Noroozi, O., Gulikers, J. T. M., Biemans, H. J., & Banihashem, S. K. (2023). A systematic review of the key components of online peer feedback practices in higher education. *Educational Research Review*, 100588.

Georgakopoulou, A. (2001). Arguing about the future: On indirect disagreements in conversations. *Journal of Pragmatics, 33*(12), 1881–1900.
Gerard, L., Kidron, A., & Linn, M. C. (2019). Guiding collaborative revision of science explanations. *International Journal of Computer-Supported Collaborative Learning, 14*(3), 291–324.
González-Howard, M., & McNeill, K. L. (2020). Acting with epistemic agency: Characterizing student critique during argumentation discussions. *Science Education, 104*(6), 953–982.
Henderson, J. B., MacPherson, A., Osborne, J., & Wild, A. (2015). Beyond Construction: Five arguments for the role and value of critique in learning science. *International Journal of Science Education, 37*(10), 1668–1697.
Herrenkohl, L. R., & Guerra, M. R. (1998). Participant structures, scientific discourse, and student engagement in fourth grade. *Cognition and Instruction, 16*(4), 431–473.
Hmelo-Silver, C. E., & Barrows, H. S. (2008). Facilitating collaborative knowledge building. *Cognition and Instruction, 26*(1), 48–94.
Hmelo-Silver, C. E., & Jeong, H. (2022). Synergies among the pillars: Designing for computer-supported collaborative learning. In O. Zawacki-Richter & I. Jung (Eds.), *Handbook of open, distance and digital education* (pp. 1–16). Springer.
Hmelo-Silver, C. E., Liu, L., Gray, S., & Jordan, R. (2015). Using representational tools to learn about complex systems: A tale of two classrooms. *Journal of Research in Science Teaching, 52*(6), 1–35.
Hüttner, J. (2014). Agreeing to disagree: 'Doing disagreement' in assessed oral L2 interactions. *Classroom Discourse, 5*(2), 194–215.
Jefferson, G. (2004). Glossary of transcript symbols with an introduction. In G. H. Lerner (Ed.), *Conversation analysis: Studies from the first generation* (pp. 13–23). John Benjamins.
Jeong, H., & Hmelo-Silver, C. E. (2016). Seven affordances of computer-supported collaborative learning: How to support collaborative learning? How can technologies help? *Educational Psychologist, 51*(2), 247–265.
Koshik, I. (2003). Wh-questions used as challenges. *Discourse Studies, 5*(1), 51–77.
Kotthoff, H. (1993). Disagreement and concession in disputes: On the context sensitivity of preference structures. *Language in Society, 22*(2), 193–216.
Kuhn, D. (2015). Thinking together and alone. *Educational Researcher, 44*(1), 46–53.
Lester, J. N., & O'Reilly, M. (2019). *Applied conversation analysis: Social interaction in institutional settings*. SAGE Publications.
Longino, H. E. (2002). *The fate of knowledge*. Princeton University Press.
Lopez-Ozieblo, R. (2018). Disagreeing without a 'no': How teachers indicate disagreement in a Hong Kong classroom. *Journal of Pragmatics, 137*, 1–18.
Muntigl, P., & Turnbull, W. (1998). Conversational structure and facework in arguing. *Journal of Pragmatics, 29*(3), 225–256.
Myers, G. (1998). Displaying opinions: Topics and disagreement in focus groups. *Language in Society, 27*(1), 85–111.
Netz, H. (2014). Disagreement patterns in gifted classes. *Journal of Pragmatics, 61*, 142–160.
Noroozi, O., & De Wever, B. (Eds.). (2023). *The power of peer learning: Fostering students' learning processes and outcomes*. Springer International Publishing.
Noroozi, O., Weinberger, A., Biemans, H. J., Mulder, M., & Chizari, M. (2012). Argumentation-based computer supported collaborative learning (ABCSCL): A synthesis of 15 years of research. *Educational Research Review, 7*(2), 79–106.
Nussbaum, E. M. (2008). Collaborative discourse, argumentation, and learning: Preface and literature review. *Contemporary Educational Psychology, 33*(3), 345–359.
Nussbaum, E. M., & Bendixen, L. D. (2003). Approaching and avoiding arguments: The role of epistemological beliefs, need for cognition, and extraverted personality traits. *Contemporary Educational Psychology, 28*(4), 573–595.
Paulus, T., Warren, A., & Lester, J. (2018). Using conversation analysis to understand how agreements, personal experiences, and cognition verbs function in online discussions. *Language@ Internet*, *15*(1).
Pierson, A. E., Clark, D. B., & Sherard, M. K. (2017). Learning progressions in context: Tensions and insights from a semester-long middle school modeling curriculum. *Science Education, 101*(6), 1061–1088.
Pomerantz, A. (1984). Agreeing and disagreeing with assessments: Some features of preferred/dispreferred turn shapes. In J. M. Atkinson & J. Heritage (Eds.), *Structures of social action: Studies in conversation analysis* (pp. 57–101). Cambridge University Press.
Pomerantz, A., & Heritage, J. (2013). Preference. In *The handbook of conversation analysis*. Wiley-Blackwell.
Rees-Miller, J. (2000). Power, severity, and context in disagreement. *Journal of Pragmatics, 32*(8), 1087–1111.

Ryan, Z., Danish, J., Zhou, J., Stiso, C., Murphy, D., Duncan, R., Chinn, C., & Hmelo-Silver, C. E. (2023). Investigating students' development of mechanistic reasoning in modeling complex aquatic ecosystems. *Frontiers Education, 8*, 1159558.

Sacks, H. (1992). *Lectures on conversation* (Vol. I). Blackwell.

Sampson, V., & Clark, D. B. (2011). A comparison of the collaborative scientific argumentation practices of two high and two low performing groups. *Research in Science Education, 41*, 63–97.

Sandoval, W. A., Enyedy, N., Redman, E. H., & Xiao, S. (2019). Organising a culture of argumentation in elementary science. *International Journal of Science Education, 41*(13), 1848–1869.

Scardamalia, M., & Bereiter, C. (2006). Knowledge building: Theory, pedagogy, and technology. In K. Sawyer (Ed.), *Cambridge handbook of the learning sciences* (pp. 97–118). Cambridge University Press.

Tan, J. S. H., Chen, W., Su, J., & Su, G. (2023). The mechanism and effect of class-wide peer feedback on conceptual knowledge improvement: Does different feedback type matter? *International Journal of Computer-Supported Collaborative Learning, 18*(3), 393–424.

Tasker, T. Q., & Herrenkohl, L. R. (2016). Using peer feedback to improve students' scientific inquiry. *Journal of Science Teacher Education, 27*(1), 35–59.

Tsivitanidou, O. E., Constantinou, C. P., Labudde, P., Rönnebeck, S., & Ropohl, M. (2018). Reciprocal peer assessment as a learning tool for secondary school students in modeling-based learning. *European Journal of Psychology of Education, 33*(1), 51–73.

Villarroel, C., Garcia-Mila, M., Felton, M., & Miralda-Banda, A. (2019). Effect of argumentative goals in the quality of argumentative dialogue and written argumentation. *Journal for the Study of Education and Development, 42*(1), 37–86.

Zhang, J., Hong, H. Y., Scardamalia, M., Teo, C. L., & Morley, E. A. (2011). Sustaining knowledge building as a principle-based innovation at an elementary school. *Journal of the Learning Sciences, 20*(2), 262–307.

Zhang, J., Scardamalia, M., Lamon, M., Messina, R., & Reeve, R. (2007). Socio-cognitive dynamics of knowledge building in the work of 9-and 10-year-olds. *Educational Technology Research and Development, 55*, 117–145.

Zhang, Y., Schunn, C. D., & Wu, Y. (2024). What does it mean to be good at peer reviewing? A multidimensional scaling and cluster analysis study of behavioral indicators of peer feedback literacy. *International Journal of Educational Technology in Higher Education, 21*(1), 26.

Zheng, L., Chen, N. S., Cui, P., & Zhang, X. (2019). A systematic review of technology-supported peer assessment research: An activity theory approach. *International Review of Research in Open and Distributed Learning, 20*(5), 168–191.

Zhou, J., Albert, L., Hmelo-Silver, C. E., Danish, J., Ryan, Z., Stiso, C., Murphy, D., Duncan, R. G., Chinn, C.A., & Lin, Q. (2024). Scaffolding students' adoption of norms for peer critique. In Clarke-Midura, J., Kollar, I., Gu, X., & D'Angelo, C. (Eds.). (2024). *Proceedings of 17th International Conference on Computer-Supported Collaborative Learning – CSCL 2024.* Buffalo, USA: International Society of the Learning Sciences.