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Computational models as tools for supporting for responsive teaching

Hillary Swanson [a], LuEttaMae Lawrence[a], Jared Arnell[a], Bonni Jones[a], Bruce Sherin[b] and Uri Wilensky[b]

[a]Instructional Technology and Learning Sciences, Emma Eccles Jones College of Education and Human Services, Utah State University, Logan, UT, USA; [b]School of Education and Social Policy, Northwestern University, Evanston, IL, USA

ABSTRACT

It is widely agreed that science instruction should help students build new knowledge on the foundation of their prior knowledge. *Responsive teaching* refers to a family of teaching strategies that pursue and build on student ideas. We introduce a particular approach to responsive teaching and examine how it can be supported by the use of computational models. We analyse an 8th grade science teacher's facilitation of a class discussion near the end of a lesson on sound. We present a moment-by-moment characterisation of her responsive teaching moves, highlighting the ways she used a computational model to help students articulate and examine their thinking. Our findings make empirical contributions to literature concerned with responsive teaching and literature concerned with the role of computational models in constructivist approaches to instruction.

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Responsive teaching; computational modelling; science education

1. Introduction

It is widely agreed that science instruction should help students construct new knowledge on the foundation of their prior knowledge (Hammer, Goldberg, and Fargason 2012; Jaber, Herbster, and Truett 2019; Richards 2023; Smith, diSessa, and Roschelle 1994). *Responsive teaching* refers to a family of teaching strategies that pursue student thinking to support learning and increase engagement (Levin et al. 2013; Robertson, Atkins, and Levin 2016). Responsive teaching 'begins with watching and listening to' students (Robertson, Scherr, and Hammer 2016, xiii) and then finds ways to build on students' ideas to help them arrive at formal understanding. On the whole, it seeks to develop students' domain knowledge by leveraging the intellectual resources they bring to their classroom learning (Hammer 2000). Because it treats students' prior knowledge as an asset for the construction of new knowledge, responsive teaching is an anti-deficit pedagogical approach (Adiredja 2019).

Responsive teaching can benefit both students and teachers alike. For students, it signals that their thinking is important and relevant (Hammer, Goldberg, and Fargason 2012). Such affirmation can increase the likelihood that they will continue to engage their ideas as they build conceptual models (Gray, Rogan-Klyve, and Canipe 2022). Responsive teaching empowers students to generate and pursue their own ideas (Watkins et al. 2018). This can help them understand the nature of science as a creative endeavour and support their engagement in authentic scientific practices in the classroom (Gray, Rogan-Klyve, and Canipe 2022; Levin et al. 2013). Responsive practices also teach students that causal reasoning and mechanistic thinking are more important than parroting correct answers without deeper understanding (Russ et al. 2009). Responsive classrooms have been found to outperform their district on standardised tests (Radoff et al. 2018), promote higher levels of intellectual work (Bishop 2021), and elicit more rigorous responses during discussions (Barnes, Gray, and Grinath 2022; Grinath and Southerland 2019).

For teachers, responsive instructional strategies can be powerful tools for navigating whole-class problem-solving (Ball and Forzani 2009; Windschitl et al. 2012). In particular, it creates opportunities for formative assessment. In-the-moment assessments go beyond ascertaining whether students have attained a content goal and instead explore the many different axes of learning on which the students can progress (Coffey et al. 2011). Armed with a vision of their students' conceptual needs, teachers can better predict how various instructional adaptations might be used to enhance their students' understanding (Choppin 2011). By granting flexibility to teachers and engagement to students, responsive teaching can reshape the dynamics of classrooms, curricula, and educational experiences.

CONTACT Hillary Swanson hillary.swanson@usu.edu Instructional Technology and Learning Sciences, Emma Eccles Jones College of Education and Human Services, Utah State University, Emma Eccles Jones Education Building, Room 216, 953 E 700 N, Logan, UT 84322, USA

Despite these benefits, enacting responsive teaching can be challenging for instructors. It upturns traditional student-teacher relationships, which may cause issues as students either adapt to or push back against unfamiliar classroom norms (Chazan and Schnepp 2002; Hutchison and Hammer 2010). Students often frame their participation in science class through the lens of producing the 'right answer', which can make it difficult to share their thinking in the context of sense-making discourse (Berland and Reiser 2009). For teachers, it can be difficult to avoid reflexively correcting students' statements, as many teachers are trained to do (Jaber, Davidson, and Metcalf 2023; Levin et al. 2013).

In seeking to respond to students' informal sense-making in ways that connect with and build toward formal knowledge, teachers are faced with the 'constructivist's dilemma' (Prawat and Floden 1994) of determining how to respond to student ideas, especially those that are non-normative (Heaton 2000). Indeed, some educators worry that pursuing students' ideas may not reliably lead students to a correct understanding of the topic (Robertson and Richards 2017). Student-driven tangents are often time-consuming and require on-the-fly decision making, which may cause teachers to minimise or neglect curricular content (Chazan and Schnepp 2002; Felton et al. 2022; Jaber, Davidson, and Metcalf 2023).

We address the challenges associated with responding to student ideas with a particular approach to responsive teaching, which guides students to examine and refine their own ideas. This approach requires a mechanism for providing students feedback on their thinking. There are a number of means for producing such feedback, including the construction and exploration of computational models. For example, Molecular Workbench was developed to allow students to conduct virtual chemistry and materials science experiments, allowing them to test their hypotheses against visualisations of molecular-level interactions underlying outcomes at the macroscopic level (Tinker and Xie 2008). Importantly, these simulations allow students to test hypotheses related to phenomena that would otherwise be impossible to study in the classroom (Xie et al. 2011) and to observe interactions that are invisible to the unaided eye (Urban-Woldron 2009).

Computational modelling environments have also been designed to allow students to build, test, and debug their own models of scientific phenomena. The Boxer modelling environment was developed to lower the threshold to the construction of computational models of Newtonian phenomena, allowing students to articulate, evaluate, and refine their physical intuitions (diSessa 1995, 2000). A number of studies have found that engaging students in building and debugging computational models supports their refinement of intuitions, nudging their thinking toward canonical scientific concepts (Aksit and Wiebe 2020; Aslan et al. 2020; Bielik et al. 2021).

Many computational modelling microworlds and associated activities have been designed to foster understanding of complex systems phenomena through engagement in agent-based computational modelling (Blikstein 2012; Fuhrmann et al. 2022a, 2022b; Horn et al. 2014; Wagh, Cook-Whitt, and Wilensky 2017; Wilkerson-Jerde, Gravel, and Macrander 2015). These guide students to explore, build, test, and debug models of complex systems phenomena, from thermal equilibration to predator-prey dynamics (Wilensky 2003; Wilensky and Reisman 2006). Through model construction and exploration, students build understanding of connections between agent-level interactions and emergent phenomena at the aggregate level (Samon and Levy 2020; Swanson, Sherin, and Wilensky 2021; Wilensky and Resnick 1999). These environments have the added advantage of fostering students' development of conceptual understanding of phenomena, without having to understand the mathematical equations used by scientists to model their dynamics (Pallant and Tinker 2004; Wilensky and Reisman 2006).

Whether structuring students' exploration or construction of computational models, the tools and activities discussed above support students in testing their ideas and refining them in response to model feedback. This makes computational models and their associated activities rich contexts for eliciting and responding to students' thinking in ways that nudge them towards canonical scientific understanding. Despite this potential, empirical work is yet needed to illustrate it. In this paper, we investigate one teacher's efforts to engage in responsive teaching, with a focus on understanding how she used a computational model to support her students' articulation and examination of ideas. We analyse a whole-class discussion that took place near the end of a lesson, to address two research questions:

1. What responsive teaching moves did the teacher enact during her implementation of the whole-class discussion?
2. What role did the computational model play in supporting the teacher's efforts to help students articulate and examine their ideas during the whole class discussion?

2. Conceptual foundations

Responsive teaching is a philosophy of instructional practice where classroom activities are adapted to foreground and respond to the students' emerging ideas. It is a style of teaching that directly challenges classical ideas of teaching as presenting information for students to absorb and comparing student thinking against canonical knowledge for evaluation (Levin et al. 2013; Robertson, Atkins, and Levin 2016; Russ et al. 2009). Responsive teaching builds on an anti-deficit epistemological perspective, advocating for the utility of students' intellectual *resources* in sense-making and learning (Hammer 2000). It opposes the 'misconceptions' view, which considers students' naive ideas as obstacles to overcome during instruction (Hammer, Goldberg, and Fargason 2012; Larkin 2012; Richards 2023). In addition to supporting student learning of particular subject matter, responsive teaching aims to help students establish reliable patterns of interaction for continued learning (Empson and Jacobs 2008). Centreing students' thinking as a primary driver of instructional decisions is a challenging and radical practice that can transform classroom environments.

Responsive teaching is often operationalised into three components: (1) recognising and understanding students' ideas, (2) connecting those ideas to the content or discipline, and (3) redirecting instruction to pursue those connections (Robertson, Atkins, and Levin 2016). It begins by resisting surface-level evaluations of students' thinking as simply right or wrong, which may disincentivize students to engage in the deeper process of inquiry (Chazan and Schnepp 2002; Empson and Jacobs 2008; Robertson, Atkins, and Levin 2016). Instead, teachers pay attention to the content of students' contributions and how the students engage with the classroom context. This includes how students frame learning activities – their answer to the question 'what is going on here?' (Coffey et al. 2011; Hutchison and Hammer 2010).

Once teachers have elicited and understood students' ideas, they can look for ways to connect those to each other, the subject matter, or the discipline at large (Dyer and Sherin 2016; Lam and Chan 2020; Robertson, Atkins, and Levin 2016). This is especially important for student contributions, which, at first, may appear to diverge from the desired learning trajectory. With discretion, teachers may find these have creative, alternative connections to the topic at hand (Jaber, Herbster, and Truett 2019). Finding such connections requires that teachers have rich content knowledge and a deep understanding of the purpose and direction of instructional materials (Larkin 2012; Namakshi et al. 2022; Robertson et al. 2021). As connections are found, responsive teachers redirect their instruction to actively pursue and make use of the productive elements of student thinking.

Responding to student ideas is, in some ways, the crux of responsive teaching. It can be common for educators to advocate for the elicitation of student ideas without incorporating them into the discussion or using them to influence the course of instruction (Larkin 2012). Some educators may elicit student ideas but then only selectively respond to them in a way that allows them to pursue a predetermined learning goal, rather than allowing the ideas to guide their instruction (Gruver and Hawthorne 2022). In contrast, responsive teaching avoids funneling or closing down the sense-making process by providing students with opportunities to continue their intellectual exploration through argumentation or experimentation (Hammer, Goldberg, and Fargason 2012; Lineback 2015; Schwarz et al. 2021). The pursuit of students' ideas may take place moment to moment or over larger timescales (Hammer, Goldberg, and Fargason 2012; Robertson, Atkins, and Levin 2016; Robertson, Scherr, and Hammer 2016). In either case, these responsive adjustments let students investigate the ways in which their everyday thinking can form a foundation for complex scientific understanding.

The present research is based on a particular approach to responsive teaching, which grew out of the *knowledge in pieces* epistemological perspective (KiP; diSessa 1993). KiP views the knowledge of an individual as a complex system of discrete knowledge elements, which are activated in networks depending on the sense-making demands of a given context. For novices, these networks are less rigid and knowledge elements may be activated in contexts where they are unproductive. For experts, knowledge networks are more rigid, and knowledge is reliably activated in contexts where it plays a productive role in sense-making. Expert knowledge is developed through a gradual process of reorganising and refining the knowledge system. For this reason, novice knowledge is viewed as a resource rich with raw materials for the construction of expert knowledge.

The KiP epistemology suggests pedagogy that elicits and responds to student thinking and therefore falls into the family of responsive teaching approaches. We propose a particular approach, where the teacher guides students in a process of *reflective refinement* that

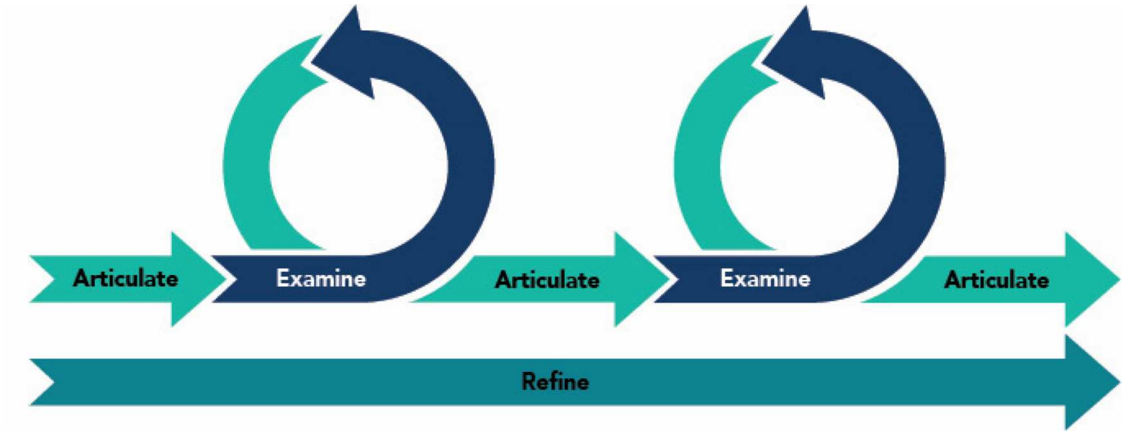

Figure 1. Iterative cycles of articulation and examination of ideas help students refine their thinking.

involves an iterative cycle of articulation and examination of ideas (Figure 1).

In reflective refinement, what is meant by *articulating thinking* is relatively straightforward. It refers to using words, drawings, gestures, and other semiotic means to move an individual's thoughts out of their head and into a form that makes them an object for consideration by the individual and their peers. What is meant by *examining thinking* is more nuanced. It includes processes through which an individual's thoughts are considered, unpacked, and otherwise made sense of. Through articulating and examining their ideas, learners may reinforce or revise their thinking, gradually reorganising and refining their knowledge system.

Reflective refinement supports the gradual shifts in thinking characteristic of learning, from the KiP perspective. Guiding students through this process can be accomplished through both pedagogical moves and the design of instructional activities. To help students articulate their thinking, a teacher might present them with a puzzling phenomenon and ask them to explain it. To help students examine their thinking, a teacher might ask them to consider an explanation that has been shared and agree or disagree with it, explain why it does or does not make sense, or find evidence that supports or refutes it.

Computational models and associated activities provide a natural structure for engaging students in reflective refinement. Computational models can support students' articulation of ideas by broadening the range of information available to them and by giving them a stable point of access to that information. It can help students examine their thinking by allowing them to test their hypotheses and providing them with feedback on their thinking in real time.

In this paper, we analyse one teacher's efforts to engage her students in a process of reflective refinement. We identify her pedagogical moves and investigate how she leveraged a computational model to support her students' articulation and examination of thinking.

3. Method

3.1. Research design

Our paper presents a case study taken from a larger design-based research project (Collins, Joseph, and Bielaczyc 2004) aimed at the development and investigation of middle school computational modelling instruction. The focal case is *instrumental*, as it serves the purpose of illuminating *how* computational models can be used to support responsive teaching (Stake 1995). The case was selected because it features a teacher making an extended attempt to enact responsive teaching and utilising a computational model to support her efforts to help students articulate and examine their ideas. As such, studying the moves made by the teacher and the supporting role of the computational model can shed light on how computational models can be used to support responsive teaching more generally.

The focal case is an 18-min class discussion, which took place at the end of a lesson on sound near the end of a 9-day unit on sound energy. The students had already been introduced to sound production, wave propagation, and concepts such as kinetic and potential energy. The lesson (which had originally been designed to take two days but was extended to four) had been designed to help the students understand how sound energy moved through a medium as a wave, and more specifically the relationship between a sound wave's volume and energy. The lesson engaged students in building a block-based model of a sound wave propagating through a medium. They then explored the model to infer the relationship between volume and

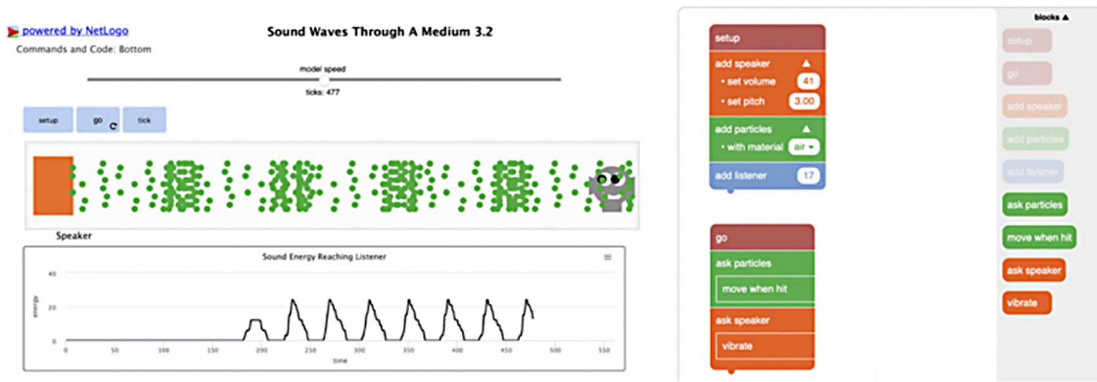

Figure 2. The *Sound* modelling microworld, featuring the model used by Ms. K during the discussion.

energy. The teacher had co-designed the *Sound* model (Figure 2) with our research team over the preceding summers to meet school and state expectations related to standards for 8th grade science content and practices.

3.2. Research context and participants

The discussion took place in the classroom of a teacher we call Ms. K, who taught 8th grade science at a public middle school in the rural Mountain West of the United States. Ms. K was a National Board Certified teacher with over 20 years of teaching experience and a master's degree in Science Education. The focal class had 32 8th grade students, ages 13–14. The class was mixed gender, and representative of the ethnic and racial make-up of the county (83% White, 11% Hispanic/Latinx, 6% Asian, Black/Multi-Racial/Indigenous). The teacher and students included in the analysis were invited to participate in the study and provided informed consent through a formal process approved by Northwestern University's Institutional Review Board (STU00208135). Students included in the case study were given pseudonyms. The school was a small public middle school, serving about 700 7th and 8th grade students from the surrounding small towns, which featured mostly agricultural economies.

3.3. Modelling microworld

The *Sound* modelling microworld was co-designed by Ms. K and the research team using the NetTango web interface (Horn, Baker, and Wilensky 2020). NetTango uses a block-based modelling language to make the computational power of NetLogo (Wilensky 1999) accessible for science classrooms. NetTango blocks are not a full programming language, but rather, blocks relevant to a domain that is modelled. The *domain blocks* (Wagh, Cook-Whitt, and Wilensky 2017) are primitive elements of code that can be combined to model a specific phenomenon.

The *Sound* modelling microworld (Martin et al. 2020) is shown in Figure 2. The image on the left shows the *world* that depicts the activity of the agents that are programmed to behave according to the rules specified by the model, which the student builds using available domain blocks. The *setup* and *go* buttons are controlled by *setup* and *go* procedures. These procedures must be programmed in the modelling field using blocks from the block library (right).

3.4. Data collection

Data were collected for the duration of the lesson, which was originally scheduled to run Tuesday and Wednesday, but was extended by Ms. K to include Thursday and Friday. Data were collected during Ms. K's second period class each day. Each class period lasted one hour. Data were collected in the form of video footage and researcher field notes. Two video cameras were used to capture the lesson's implementation. One was positioned at the back of the classroom to catch the activity of the class and the teacher at the front board. The second camera was positioned beside a small group, to capture their activity and discussions.

3.5. Data analysis

Our analysis focuses on a whole-class discussion that took place at the end of the second day of the computational modelling lesson. The particular discussion we selected had been intended by Ms. K to be a wrap-up discussion at the end of the lesson. We selected this class discussion as it allowed us to investigate Ms. K's responsive teaching and the supporting role of the computational model. We analysed video and transcript for the whole-class discussion, creating a fine-grained picture of how the computational model supported Ms. K's efforts to help students articulate and examine their thinking. High-resolution descriptions of the moment-by-moment dynamics of classroom interactions and the learning they afford are relatively rare in educational research, though they stand to give researchers insight into details that are critical to understanding the mechanisms underlying processes of teaching and learning (diSessa 2014). To produce a high-resolution description of the moment-by-moment dynamics of our focal case, we conducted a microanalytic (diSessa, Sherin, and Levin 2016) grounded (Glaser and Strauss 2017) qualitative analysis, characterising each of the moves we found through our line-by-line analysis of the transcript. We then created a temporal decomposition (Collins and Ferguson 1993), dividing the class discussion into a sequence of eight moves. We characterised each move through the lens of responsive teaching, as either a move to help students articulate or examine their ideas. We then analysed the transcript to understand when and how the computational microworld was leveraged to support the teacher's enactment of each move.

4. Findings

Below, we present Ms. K's facilitation of the whole-class discussion, illuminating how she engaged in responsive teaching and how the computational model supported her efforts to help students articulate and examine their ideas.

The discussion took place at the end of the last hour-long class period planned for the *Sound* unit. Earlier that period, the students had finished constructing their *Sound* models and responded to questions meant to help them explore relationships between system elements and behaviour. This included the relationship between a sound wave's amplitude and its energy, the relationship between its frequency and pitch, and the relationship between its speed and the medium through which it travelled. We present a narrative account of the last 18 min of class, dividing the narrative into a sequence of eight moves made by Ms. K to help her students articulate and examine their ideas.

4.1. Move 1: helping students articulate their ideas by asking each table to share an idea

With about 18 min left in class, Ms. K initiated a discussion meant to help her students publicly articulate and examine their thinking. She first asked them to work with the other students at their table to compile lists of the main points they had gleaned from their exploration of the sound model. She asked each student to contribute one main point, which resulted in lists of about 4 main points per group. She then called on one representative from each of the eight groups to share a unique main point, which she recorded on the whiteboard at the front of the classroom. The activity took about 10 min. The list written by Ms. K on the front board is captured below, in Figure 3.

4.2. Move 2: helping students examine one idea

With approximately 8 min remaining, Ms. K turned to engage her students in a whole-class discussion with the intention of helping them make sense of the ideas they had just shared. She stood in front of the whiteboard at the front of the classroom. Written on the board to her

Summary Notes

- If you change the pitch, the particles move faster
- Closer the person is, the sound is more bigger
- The louder the volume, the greater the sound waves
- When it's quieter or louder, the speed changes
- The medium can change how fast the speed in a certain direction
- The closer the listener gets to the speaker, the further the energy moves
- A lower volume has a lower wave
- Amplitude affects volume

Figure 3. The list of main points offered by each of eight table groups, written on the front board by Ms. K.

left was the list of the eight main points. To the right of the list was a projection of her computer screen, featuring a correctly coded *Sound* model, which had yet to be initialised and run. Ms. K waited until the room was quiet and then addressed the students.

> Ms. K: OK, here's what I wanna do. There are a lot of ideas on the board. I'm gonna pick a couple of these statements to focus on for a few minutes just as we wrap up.

Here, Ms. K began to chart the course of the discussion, letting the students know she would focus on addressing a narrow sample of the ideas they had shared. The remark that she 'couldn't possibly address them all' was perhaps meant to promote a feeling of fairness. The students had shared eight main points and due to time constraints (8 min of class time remained), she would not be able to address them all. It may be that she hoped to reassure students that their ideas were all valuable, that it was not due to any deficiencies in their thinking that any particular idea would not be addressed during the discussion.

> Ms. K: We have people saying things like 'faster,' 'greater,' 'louder,' and I'm not sure we're all talking about the same thing. So, I'm gonna put it up here like you tell it to me and let's see if we're talking about the same thing, OK?

Ms. K continued to set up the whole-class discussion, referencing several of the ideas written on the board. She problematised the language the students used and set as an initial goal for the discussion sorting out whether the students were talking about the same thing, or if they understood the sound phenomena differently from one another.

> Ms. K: So let's do … I wanna do like this one right here [points at third statement on the list as shown in Figure 4] … 'The louder the volume, the greater the sound waves.' That's … 'The greater the sound waves' … What does 'greater the sound waves' mean and look like? Could we write that, so that we know what is greater about the sound waves?

Ms. K selected the third statement on the list and read it aloud. She problematised the specific clause 'greater the sound waves', asking students to clarify what that meant to them. In doing this she prompted them to examine one of their initial articulations and arrive at a more precise description of 'what is greater about the sound waves'.

4.3. Move 3: helping students articulate their ideas by running the simulation with low and high volume and asking them to identify what is greater about the high-volume sound waves

Ms. K turned to the projection of the *Sound* model and addressed the class.

> Ms. K: So, I'm gonna go down here, I'm gonna change the volume, first low, you're gonna watch, everybody's gonna watch, you tell me what is becoming greater about the sound waves. So, here's a low volume [uses smartboard pen to set the speaker to low volume as shown in Figure 5], low volume.

Ms. K used her smartboard pen to open the volume parameter and lower the volume of the speaker. She started the simulation, waiting for about a minute while a train of longitudinal wave fronts propagated through the air particles between the speaker and listener.

She then paused the simulation and raised the volume of the speaker.

> Ms. K: Now here's a high volume [uses smartboard pen to set the speaker to high volume], high volume.

She waited while a new train of wave fronts propagated from speaker to listener.

In using the technology in this way, Ms. K gave the students concrete images to compare to consider what

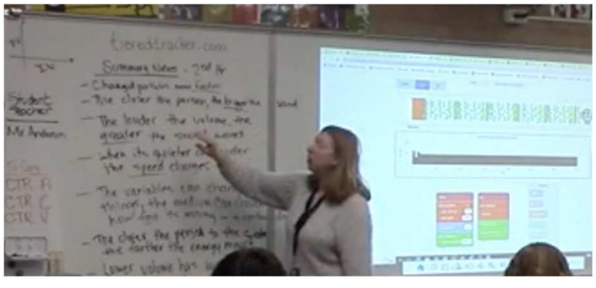

Figure 4. Ms. K selected the third statement on the list as the focus of the discussion.

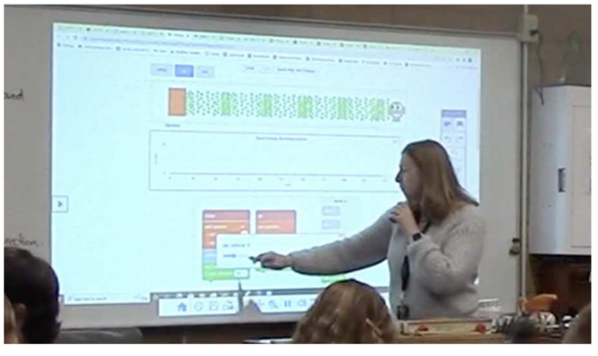

Figure 5. Ms. K uses the smartboard pen to lower the speaker volume.

Figure 6. Ms. K points to the main point as she reads it aloud.

quality of the sound wave might be greater for the high-volume wave. The simulation allowed her to present them with real-time experimental results, or data from which they could infer what was greater about the sound waves when the volume was increased. This is important, as the students who did not suggest the main point may not have previously noticed the 'greater sound waves' phenomenon and the students who did write the statement may not remember what they had meant by it or they may not have thought about it enough to articulate what precisely was 'greater about the sound waves'. With this move, Ms. K set the students on equal footing with regards to addressing the question 'what is greater about the sound waves?'

Ms. K walked back over to the list of student ideas and read the focal statement aloud again.

Ms. K: This person said, 'The greater the sound waves' [points to the main point as shown in Figure 6] … What is 'greater' about this wave? Can somebody address that for me?

She looked out at the students and asked for a volunteer to tell her what 'greater sound waves' might mean. In doing this, she asked the students to connect what they saw in the simulation with the relationship one group of students had described. She asked them to use evidence from the simulation to elaborate and make more precise the original main point.

A student raised their hand and Ms. K called on them.

Ms. K: [Points to Austin] Thank you.
Austin: It's a lot faster.

4.4. Move 4: helping a student examine their idea by prompting them to unpack their thinking

Ms. K responds to the student's answer with another question, probing for greater specificity.

Ms. K: What's faster?
Austin: The molecules.
Ms. K: The molecules are moving faster? [Points at the simulation particles as shown in Figure 7]

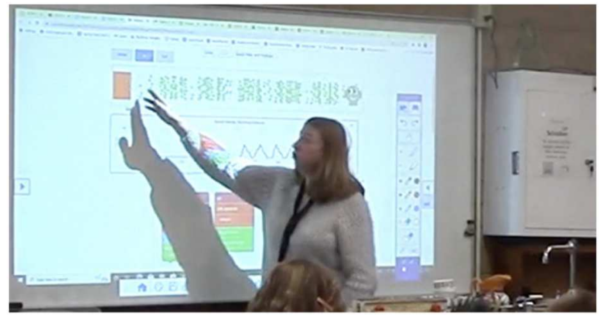

Figure 7. Ms. K points at the simulation particles as she revoices the student's assertion.

Would you say they have more energy than before?
Austin: [inaudible]
Rebecca: Yeah? All right, let's keep going.

The student offered an imprecise response to Ms. K's question, saying 'it's a lot faster'. Pushing for greater precision, Ms. K asked the student to specify what in particular was 'faster'. The student responded with 'the molecules', which Ms. K revoiced in the form of a question. She then attempted to connect the student's idea with the scientific concept of energy, which the class has been studying for the last 10 weeks. Perhaps Ms. K knew that molecule speed (or at least the wave speed) should not change based on the sound's volume, or perhaps she knew it would be difficult to ascertain the truth of the student's statement using evidence from the simulation. For whatever reason, she appears to have determined that this particular idea may not be fruitful and she moved on to ask other students to share their thoughts.

4.5. Move 5: helping students articulate their ideas by asking them to identify what is greater about the high-volume sound waves

Ms. K pointed to another student and asked them to share their thoughts on 'what is greater about this wave'.

Ms. K: What is greater about it to you? [Points to Penny]
Penny: The more, the more the waves are moving through.

4.6. Move 6: helping one student examine their idea by testing it against simulation output

Ms. K responds to the student's idea that 'more waves are moving through' for a higher volume sound wave.

Ms. K: You think that there are more waves moving through? [Moves her hand along the wave, as

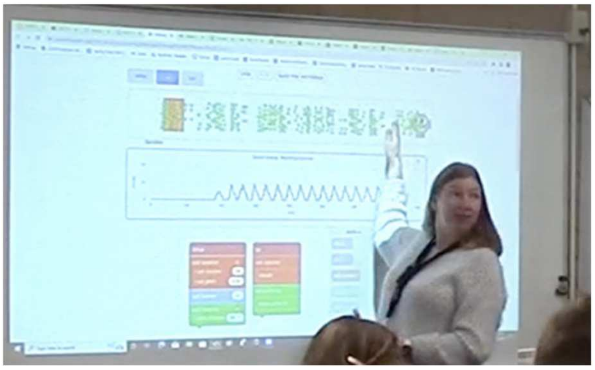

Figure 8. Ms. K moves her hand along the wave as she revoices the student's idea that more waves are moving through the medium.

shown in Figure 8]. Did you count them?

Penny: No.

Ms. K: Can I count them? Is that OK? OK, so from 200 to … well, we'll do from 300 to 400, I'm gonna count them. Let's see. We've got one wave, two wave, three wave, four wave [counts the number of waves, as shown in Figure 9] … Technically three because this is a half and this is a half. But …

The student responded to Ms. K's question with a specific, testable hypothesis. Ms. K asked whether the student had counted the waves. The student had not, and Ms. K asked if she could count the number of waves. She counted four waves over a period of 100 ticks (from $t = 300–400$) and then explained that the wave number was actually three because two of the four waves were half waves. It is likely that Ms. K knows that changing the volume should not change the number of waves, and she is using the simulation to gather data with which to refute the student's hypothesis and determine that it is not the number of waves that is greater about the sound wave, when the volume is increased.

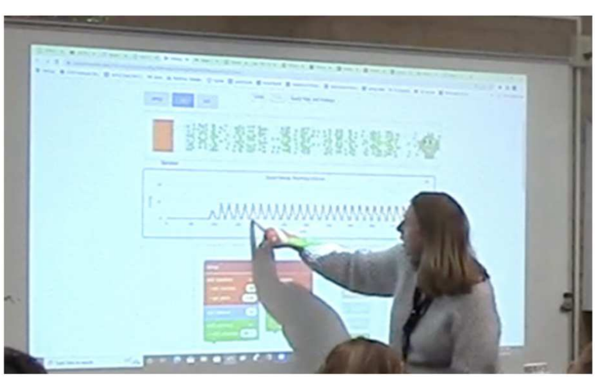

Figure 9. Ms. K counts the number of waves for the higher volume sound wave.

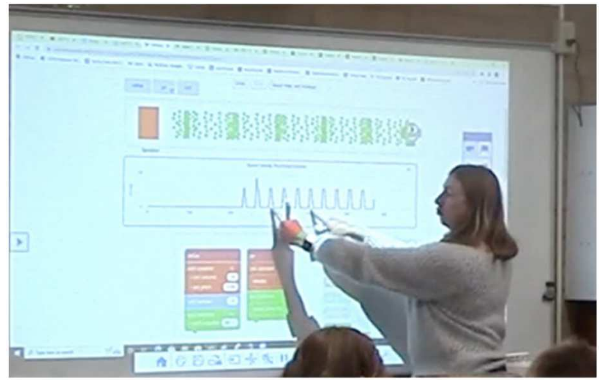

Figure 10. Ms. K counts the number of waves for the lower volume sound wave.

Ms. K: Now let's change it and I'm gonna count 'em again and see if that is true. So, I'm gonna take the volume back down. And let's let it run for a minute. Let's see if there are more waves or less waves in 100 ticks. K, we're starting to get some data here … So, I'm gonna stop it for just a second … So, here are our 100 ticks, one wave, two wave, three wave, four wave [counts the number of waves, as shown in Figure 10]. Are we getting more waves when we change the volume? Or less waves? You with me? Do you know what I'm saying? Are there more waves happening or less waves happening when we change the volume? Does our data show that?

Ms. K lowered the volume and counted the number of waves over the same interval (100 ticks). She counted four, which was the same number of waves she had counted for the high-volume sound wave. She asked the students to compare the number of waves for the low volume vs. high-volume wave, hoping to refute Penny's hypothesis. No students responded to her request, so she turned to Penny.

Ms. K: Can I ask you? 'Cause we were the ones that were talking about it. Does the data show that?

Penny: Yeah.

Ms. K: So, look we've got from 300 to 400, it's the same [points to 100-tick interval, as shown in Figure 11].

Ms. K: So, when you tell me 'the louder the volume the greater the sound waves' are we talking about a greater number of waves? When we say 'greater the sound waves' what is greater? I'm not sure we've got to the bottom of this yet [looks out at class]. Somebody suggested that maybe greater means we have more waves when we take the volume up. But we just counted them, and there's four waves in

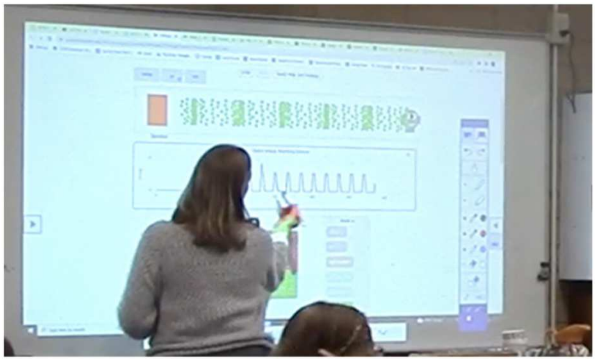

Figure 11. Ms. K asserts that the number of waves is the same for the 100-tick interval for both volumes.

between the same number of ticks. We're not getting more waves that way.

Ms. K asked Penny, who had originally offered the 'more waves' hypothesis, 'does the data show that?' It appears she is asking if the data show whether there are 'more waves happening or less waves happening when we change the volume'. Penny responded with a short 'yeah', which Ms. K did not pursue further. It may be that she senses hesitation in Penny's voice and is worried about putting her on the spot. It may be that she is worried Penny will not give the correct response, and she wants to make sure the students understand that the hypothesis was refuted by the data produced by the simulation. At this point, there were about 3.5 min remaining in class. It is possible Ms. K had not realised how much time it might take to unpack her students' thinking and connect their ideas with normative scientific concepts. She may therefore be feeling pushed to make connections for her students, rather than letting them take the time to arrive at the connections on their own.

4.7. Move 7: helping students articulate their ideas by running the simulation with low and high volume and asking them to identify what is greater about the high-volume sound waves

Having refuted the possibility that 'greater means more waves', Ms. K turned back to the students to solicit more possible meanings for 'greater waves'.

Ms. K: So, I'm gonna play this one more time. You help me figure out what is greater. I don't think there's anything we could do that could be more important today, so here we go. Turned up the volume – I'm looking for everybody's good focus here. What is greater? So, we already, so Austin already said that he feels like the particles are moving more. How, what is greater about this? [calls on student in front row] Thank you.
Henry: The waves look bigger.

4.8 Move 8: helping students examine their ideas by using the model to identify a causal relationship

Ms. K responded to the student's idea by pressing for greater specificity.

Ms. K: The waves look bigger [uses hands to indicate a bigger wave, as shown in Figure 12] … What is causing that? What piece of this model is causing the wave to be bigger?
Henry: The particles.
Ms. K: The particles are causing themselves to be bigger? What's causing the particle wave to wave bigger?
Henry: I dunno.
Ms. K: He's not sure …

Henry suggested that 'the waves look bigger'. While somewhat vague, Ms. K may have recognised that the idea was heading in the right direction. She asked Henry what was causing the waves to be bigger. This move may have been to help the students make logical connections between cause and effect in the model, which would ultimately allow her to connect the idea with the concept of energy, her lesson's learning objective. Henry wasn't able to answer her question, so Ms. K tossed the question back to the group.

Ms. K: Does anyone know what I'm asking here? What piece of the model is causing the wave to be 'bigger?' [looks out at the group]
Roy: [Speaks out of turn] The volume.
Ms. K: [Points at Javier] Can you help me?
Javier: The speaker.
Ms. K: The speaker! [nods and points to the speaker in the microworld] Isn't it true that the volume affects the speaker? Do the particles

Figure 12. Ms. K uses her hands to show a big compression wave.

affect the speaker or does the speaker affect the particles? Which one? Do the particles tell the speaker what to do or does the speaker tell the particles? The speaker! So, you set the volume, right? That tells the speaker what to do and the speaker controls what the particles do. Is that the correct statement? So, can I go back and [starts the simulation] - who just told me this - that it was moving …

Henry: It looked bigger

Ms. K: It is a bigger wave! So, bigger in what way? Look, watch my hand here, whoops! Too far [traces front end of speaker back and forth with a white board marker to capture its displacement as it vibrates, as shown in Figure 13]. See what the speaker is doing?

Ms. K: If I turn the volume down, watch what the speaker does. Doo-Doo-Doo-Doo [does not lower the volume, moves her hand back and forth covering a smaller horizontal distance singing ‘doo-doo-doo-doo’ in a high-pitched note to demonstrate that the speaker would cover a smaller distance]. Right?

Javier: The movement of the speaker …

Ms. K: The movement of the speaker is [points at Javier as if to affirm his contribution] – watch! I’ll turn it down [adjusts speaker parameter to lower the volume; looks at students and waits, as shown in Figure 14].

Ms. K: How could you describe the energy of this speaker? Does it have a lot of energy? Does it have a little bit of energy? How do you know? We’ve studied energy since the beginning … How do you know that this speaker has a lot or a little?

Eric: [inaudible]

Ms. K: Right? It’s moving a lot or moving a little … So, let’s think about this … when it’s moving a little it only has a little bit of movement, a little bit of energy, where is it giving that energy? [Nods head as though to affirm something said by Eric, whose voice is inaudible] It’s giving it to the wave, right, to the particles, and the particles - little bit of movement here, right - a little bit of squish, vs. let’s look at this - a lot a bit of squish right? - pushing those particles way far.

Ms. K ignored the first student (Roy) who responded to her question about what caused the wave to be bigger. This may be because he spoke out of turn, without raising his hand. It may also be because he voiced his idea rather softly, and while it was caught by the audio recording device on the camera, Ms. K may have missed it. It is also possible that the student’s response was not what she was looking for, so she pressed forward, looking for a student who could answer her question. The student she called on next (Javier) gave her what she was looking for, asserting that the speaker caused the wave to be big. A third student (Henry) joined in, seconding this point.

Ms. K used the simulation to demonstrate the speaker’s movement, showing how it moved back and forth with a greater displacement for the high-volume sound, as compared to the low volume sound. She then connected the speaker’s movement with its energy, asserting that when the speaker moves a little, it has a little energy. She asked the students what the speaker gives its energy to, but didn’t wait for students to respond, asserting that it gives its energy to the wave, or more specifically to the particles whose movement comprises the wave. She then compared the amount of speaker movement with the amount of wave ‘squish’, asserting that a little bit of speaker movement results in a little bit of squish, while a lot of speaker movement results in a ‘lot a bit of squish’. It is reasonable that Ms. K made these connections for the students, as she was attempting to tie everything together and leave the students with a clear takeaway in the final seconds of class.

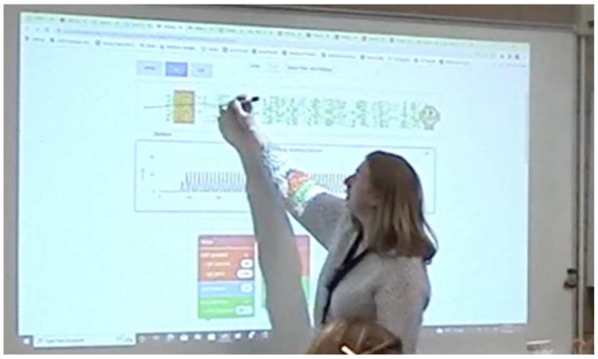

Figure 13. Ms. K uses the white board marker to trace out the displacement of the high-volume speaker as it moves back and forth.

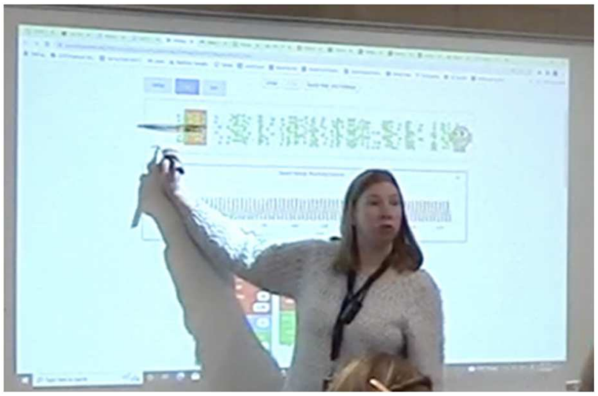

Figure 14. Ms. K asks students what is different about the movement of the speaker for the high-volume sound, vs. the low volume sound.

4.9. High-level sketch of Ms. K's responsive teaching moves

The analysis presented above walks through a whole-class discussion that took place in the last 18 min of class, during which Ms. K elicited students' ideas and then focused their attention on making sense of an idea offered by one group. Her goal had been to use the discussion to move from the students' own words to the scientific relationship between a speaker's volume and the energy of the wave it produces. The analysis divided the discussion into eight responsive teaching moves, named according to whether the move was aimed at helping students articulate or examine their thinking. With the first move, Ms. K helped students articulate what they had observed about sound waves in the model. She recorded one idea from each table on the front board. With the second move, she set up the discussion, announcing the focus of the activity as making sense of a few of the ideas shared by students. She seeded the discussion with a single idea for students to examine: 'The louder the volume, the greater the sound waves'. With the third move, she projected the model, running it with the volume set first high and then low, asking the students to identify what was greater about the sound waves with the louder volume. This helped one student articulate the idea: *greater means faster molecules*. With the fourth move, she responded to the student's idea, asking them to unpack what it meant and then moving on, perhaps recognising that the idea would not be fruitful in moving the students towards her learning objective.

With her fifth move, Ms. K turned to the students and elicited another idea: *greater means more waves*. With her sixth move, she responded to the idea, helping the student to examine their idea by running the simulation with the speaker set to high and then low volume, counting the number of waves on a 100-tick interval for each. She compared the number of waves for each volume setting and announced that they were the same, thus providing the student with data to refute their hypothesis. With her seventh move, Ms. K again ran the model and asked students what might be meant by 'the louder the volume, the greater the sound waves'. This prompted a student to articulate a new idea: *greater means bigger waves*. She responded with an eighth move, engaging the students in probing the model for a possible cause of bigger waves, and one student identified the speaker. She then used the simulation output for different volumes to illustrate causal connections between the volume, the movement of the speaker, the energy of the speaker, and the energy transferred into the particles/wave. Her logic was something along the lines of: the louder the volume, the more the speaker moves and the more energy it has to transfer to the air particles between the speaker and the listener, resulting in a wave with more 'squish'. The class period then ended with the bell.

In leading the class discussion, Ms. K enacted moves meant to guide students through a process of reflective refinement by helping them articulate and examine their thinking. Some of her moves depended directly on the computational model she had co-designed. She pushed for precision, asking the students what they meant by 'greater sound waves'. She chose particular ideas to pursue, acknowledging but not following others. She gathered data by running the simulation at different volumes to directly test the meanings for 'greater' that the students provided. She guided students to see important relationships in the simulation. She connected their ideas to science terms like energy, in order to build on their ideas and approach her learning objective in just 8 min.

4.10. How Ms. K leveraged the computational model in her responsive teaching

Figure 15 shows the sequence of the eight moves made by Ms. K to help students articulate and examine their ideas during the 18-min discussion. The diagram highlights five moves, which were directly supported by the computational model. These moves and the role of the technology in their enactment are elaborated below.

4.10.1. Helping students articulate ideas through open exploration of the model

Ms. K opened the discussion by asking each small group to share one of the observations they had made about sound waves while exploring the model earlier in the period. Here, the computational model played a foundational role in creating patterns for students to observe and then articulate during the class discussion. In making this move, Ms. K demonstrated an aspect of responsive teaching which is particular to an approach that guides students through reflective refinement. This move initiates the process by prompting students' initial articulation of ideas, thus setting the stage for their subsequent examination. Ms. K used the computational model to facilitate this move by inviting the students to explore the model and then asking them what patterns they observed. Their responses became the raw material from which Ms. K selected one idea, 'the louder the volume, the greater the sound waves', for students to make sense of.

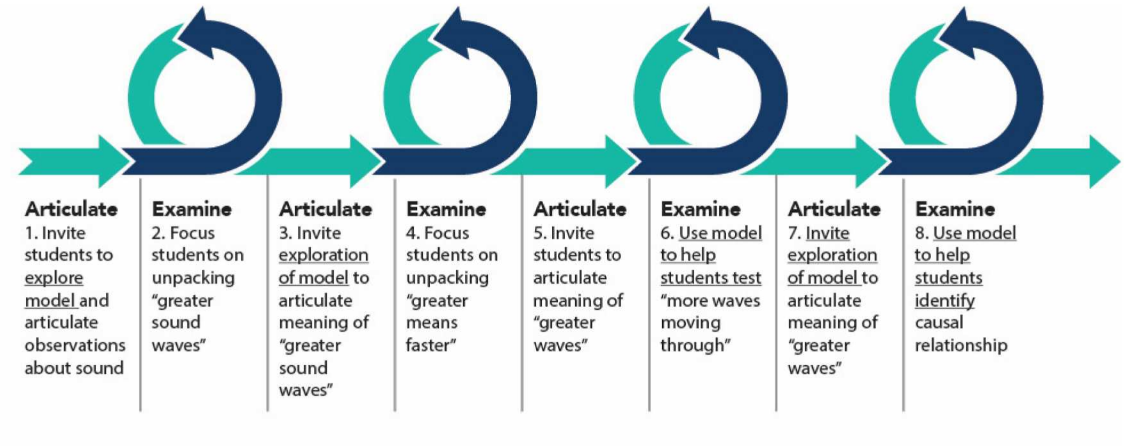

Figure 15. Temporal decomposition of moves made by Ms. K to help her students articulate and examine their thinking.

4.10.2. Helping students articulate ideas through focused exploration of the model

Ms. K revoiced the focal idea and then asked students what it might mean, more precisely. She used the model for focused exploration, running the simulation with both high and low volume, and asking students what was 'greater' about the sound waves when the volume was higher. She used the model in this way twice (moves three and seven), both times running the model with high and low volumes and asking students what was visibly different about the waves, which might make them 'greater' when the volume was higher. In these moves, Ms. K demonstrated general principles of responsive teaching, which are to recognise and understand student ideas, and redirect instruction to pursue particular ideas. She chose a particular idea to recognise publicly and redirected the remainder of class time to focus students on unpacking the idea and articulating its connection to scientific concepts. She used the computational model to systematically engage them in pursuing this goal.

4.10.3. Helping students examine ideas by using the model to test a proposed hypothesis

One student suggested that 'the louder the volume, the greater the sound waves' might mean 'the more the waves are moving through'. Ms. K used the computational model to test the student's hypothesis, setting the volume to high and then low, and counting the number of waves for each volume setting. She determined that the number of waves were the same, thus providing feedback to the student that an increase in volume does not correspond with a greater number of waves moving through. In this move, Ms. K demonstrated a defining feature of reflective refinement, which is helping students examine their own ideas, so that they might decide whether or not to continue to use them in their reasoning. Ms. K used the computational model to systematically test the student's idea, producing feedback with which they could examine their own thinking.

4.10.4. Helping students examine ideas by investigating a hypothesis through focused exploration of the model

Ms. K elicited another idea from a student, who suggested that the louder the volume, the 'bigger the wave'. She ran the simulation at high volume and guided the students through identifying a cause for the 'bigger wave', locating it in the movement of the speaker. She then lowered the volume and ran the simulation, directing students' attention to the smaller displacement of the speaker. She connected the movement of the speaker with its energy and explained that the energy from the speaker would be transferred into the particles and therefore the resulting wave. In this episode, Ms. K used the simulation to help students identify and understand causal relationships in the speaker-medium-listener system, ultimately pointing to a causal mechanism underlying the pattern 'the louder the volume, the bigger the wave' and connecting this pattern with the scientific concepts related to energy transfer. In this move, Ms. K demonstrated another approach to helping students examine their ideas, by guiding them to search for what might be causing a pattern they had articulated. She also demonstrated a general principle of responsive teaching – connecting student ideas to scientific content – by using the computational model to systematically explore the student's idea in the context of the model and connect it to scientific concepts such as energy and energy transfer.

In sum, the analysis suggests that computational models can be used to support responsive teaching by facilitating moves that engage students in a process of reflective refinement. Specifically, computational models can be used to prompt students' articulation of ideas, by running the model and asking students what they see. They can be used to help students examine their ideas, by running the model to produce feedback that either supports or challenges their thinking, and by revealing relationships that are not immediately apparent. These activities, in turn, can help students refine their thinking in the direction of scientific understanding.

5. Discussion

From the analysis of classroom data, it's clear that Ms. K was enacting responsive teaching strategies. On the whole, the discussion was a responsive act – when she noticed the unclear language in her students' statements, she pivoted to circle back and help her students make sense of and refine their conceptual models instead of moving on to new content. Ms. K also demonstrated responsiveness in her moment-to-moment interactions with her students. The 'greater means faster particles' explanation elicited by move three was unclear, yet Ms. K avoided dismissing it on the grounds of brevity or correctness. Instead, she indicated how the reasoning was productive when considered next to the related topic of energy. Later, when the 'greater means more waves' idea was elicited by move five, Ms. K led the class in a real-time experiment to determine the validity of the proposition. Responsive teaching scholars often advocate for experimentation, as it simultaneously foregrounds student contributions while also engaging the students in authentic scientific practice (Hammer, Goldberg, and Fargason 2012). The validation seen in move four and the experimentation seen in move six provide examples for how responsive practices can play out in shorter interactions. Together, these observations showcase how responsive teaching can be a nested and iterative experience, especially when the pursuit of student ideas generates new opportunities for further elicitations and responses.

Technology played a central role in Ms. K's enactment of responsive teaching strategies. Because the simulation was at the heart of the activity, Ms. K was able to leverage its affordances to prompt students' articulation of ideas during the whole-class discussion. By running the *Sound* model at low and high volumes one after the other, she provided the students with ample information for conjecturing what was 'greater' about the high-volume wave. Most notably, she employed the simulation to help students examine the *greater means more waves* idea in move five. The simulation allowed Ms. K to conduct immediate data-collection without any further set-up. Additionally, the simulations' ability to quantify and display the wave characteristics in real time was necessary to answer Penny's inquiry. The visual representation of the speaker also gave Ms. K a salient object to reference when demonstrating the difference in amplitude between low and high volumes and connecting the speaker volume with the wave energy. These examples demonstrate how the properties of the simulation directly shaped the manner in which Ms. K was able to utilise it during her responsive practice.

Findings from the analysis of classroom data suggest that responsive teaching can be supported by the use of computational models. The study also suggests implications for the design of computational microworlds that support reflective refinement. For example, a simulation should be able to test student hypotheses and provide enough visual detail to refute or support their ideas, as demonstrated by the case of Ms. K testing and refuting Penny's idea about a louder volume sound corresponding with more waves. Similarly, simulations should be accessible and quick to operate in order to mitigate the time-based tensions which can arise when pursuing students' ideas. A simulation should also provide enough visual detail that students can observe the relationships between system parameters and behaviour through multiple representations, as demonstrated by the case of Ms. K guiding student attention to the relationship between the speaker's movement and the resulting 'squish', and therefore energy, of the wave.

It is encouraging to see how a computational model supported one teacher's efforts to engage in responsive teaching, however, questions and tensions remain. While Ms. K managed to connect her students' ideas to normative scientific concepts by the end of the period, it is not clear that her students followed her logic and arrived at a scientific understanding. This leaves the question open as to whether or not reflective refinement paired with exploration of a computational model indeed supports student learning, which is a concern commonly associated with responsive teaching (Robertson and Richards 2017).

There is also a tension pervading responsive teaching approaches, between teacher guidance and student agency. While Ms. K actively pursued her students' ideas, she was still keenly invested in moving their thinking towards her learning objectives. With only 8 min dedicated to the activity, she was pressured in negotiating the balance between student ideas and canonical scientific concepts. To reach her instructional target, Ms. K did not have the luxury of allowing any one student to unpack their thinking according to their own pace. This is reflected in the transcript, where we see her engage with student contributions in a manner that is efficient, but which may unintentionally curtail student thinking.

From the perspective of the student, the new activity structure and expectations for participation may have also presented challenges. This was the teacher's first implementation of responsive teaching and based on their patterns in participation, it is likely these students had not had prior experience participating in a process of reflective refinement. The students were hesitant to offer contributions, and when called on, their responses were minimal, even when the teacher pursued their thinking with follow-up questions. These tensions for both teacher and students are consistent with the literature, which suggests such tensions arise due to the inversion of the traditional student-teacher relationship (Chazan and Schnepp 2002; Hutchison and Hammer 2010).

5.1. Contributions

The paper presented a fine-grained analysis of an instrumental case, showing how a teacher leveraged a computational model to help students articulate and examine their ideas and nudge them towards canonical scientific understanding of sound waves.

In doing this, the paper extends the standard conception of responsive teaching with a particular approach based on the *knowledge in pieces* epistemology, which guides students through a process of reflective refinement. While responsive teaching is generally characterised as a process that foregrounds and pursues the substance of students' ideas, (Robertson, Atkins, and Levin 2016), reflective refinement specifically pursues students' thinking by guiding their articulation and examination of ideas. Computational models are uniquely positioned to support this approach, with the capability of simulating focal phenomena that prompt students' articulation of ideas and the capacity to run experiments that provide them with the feedback they need to examine their thinking.

The paper offers a high-resolution description of how one teacher leveraged a computational model to engage her students in reflective refinement, thus contributing empirical insight into how computational models and associated activities can be used to support teachers' enactment of responsive teaching. While several studies have examined the ways in which *responsive teaching supports students' engagement in scientific practices* such as modelling and argumentation (Felton et al. 2022; Gray, Rogan-Klyve, and Canipe 2022), the present work illuminates how *engaging students in modeling practices can support teachers' enactment of responsive teaching*.

The study also adds to literature concerned with computational microworlds as instructional tools (Tinker and Xie 2008; White 1984; Wilensky and Resnick 1999). Specifically, the work shows how microworlds can play a central role in supporting responsive teaching practices and makes recommendations for the design of models that support teachers in engaging students in articulating, examining and refining their knowledge.

5.2. Limitations

While the findings suggest ways teachers might leverage computational models to enact responsive teaching strategies, the specific moves and the role of the technology in supporting those moves were idiosyncratic to the teacher, students, lesson topic and specific computational microworld, which all came together in the focal case. The findings are therefore not meant to be generalised to similar populations, but instead, are meant to help paint a general picture of the ways in which computational microworlds can be leveraged by teachers to productively elicit and respond to student ideas.

6. Conclusion

In this paper, we examined Ms. K's enactment of responsive teaching strategies during a whole-class discussion. The whole-class discussion was her first experience with responsive teaching. Our analysis highlighted the ways she helped her students articulate and examine their ideas, characterising her moves in detail over the discussion, during which she tried to help the students make sense of the student-generated idea 'the louder the volume, the greater the sound waves'. The paper examined how her implementation of responsive teaching was supported by her use of a computational model she had co-designed with our research team. The paper makes empirical contributions to literature concerned with responsive teaching and literature concerned with engaging students in computational modelling in the science classroom.

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ORCID

Hillary Swanson http://orcid.org/0000-0001-5953-6780

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