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Exploring Shifts in Middle School Learners' Modeling Activity While Generating Drawings, Animations, and Computational Simulations of Molecular Diffusion

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Abstract Modeling and using technology are two practices of particular interest to K-12 science educators. These practices are inextricably linked among professionals, who engage in modeling activity with and across a variety of representational technologies. In this paper, we explore the practices of five sixth-grade girls as they generated models of smell diffusion using drawing, stop-motion animation, and computational simulation during a multi-day workshop. We analyze video, student discourse, and artifacts to address the questions: In what ways did learners' modeling practices, reasoning about mechanism, and ideas about smell shift as they worked across this variety of representational technologies? And, what supports enabled them to persist and progress in the modeling activity? We found that the girls engaged in two distinct modeling cycles that reflected persistence and deepening engagement in the task. In the first, *messing about*, they focused on describing and representing many ideas related to the spread of smell at once. In the second, *digging in*, they focused on testing and revising specific mechanisms that underlie smell diffusion. Upon deeper analysis, we found these cycles were linked to the girls' invention of "oogtom," a representational object that encapsulated many ideas from the first cycle and allowed the girls to restart modeling with the mechanistic focus required to construct simulations. We analyze the role of activity design, facilitation, and technological infrastructure in this pattern of engagement over the course of the workshop and discuss implications for future research, curriculum design, and classroom practice.

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Introduction

Science education reform efforts seek to engage learners in authentic scientific practices such as modeling and using technology to make sense of natural phenomena (NRC 2012; NGSS 2013). Among scientists, these practices are becoming increasingly linked as computational representations (such as visualization or simulation) are used to conceptualize and express scientific models. These models are then used to communicate and generate predictions about scientific phenomena (Chandrasekharan et al. 2012).

This linkage between computation and modeling also holds potential for the K-12 classroom. As computational media become more pervasive, it is important for learners to understand programming and simulation as a way to express and test scientific ideas (Papert 1980; Wilensky and Reisman 2006; Wing 2006). Also, different representational forms including computational languages can emphasize different aspects of scientific phenomena (Chapman 2000; Frederiksen and White 1998; Kaput 1991; Kaput et al. 2002; Kozma and Russell 1997; Ochs et al. 1994), allowing learners to explore ideas in ways that may be difficult using just speech or drawing. For example, creating an animation requires one to specify how something changes across time and space (Chang et al. 2010; Gravel et al. 2013); programming a simulation requires one to consider the rules that underlie a system (Blikstein and Wilensky 2009; Papert 1980; Sherin 2001; Wilensky 2003).

In this paper, we explore the ways that learners engage in scientific modeling when working across multiple representational media using coding and conversation analysis. Our data are drawn from a multi-day workshop where five sixth-grade girls created drawings, animations, and computational simulations of a popular smell diffusion modeling problem (Shwartz et al. 2008). Our research questions are as follows: (1) In what ways did learners' modeling practices, reasoning about mechanism, and ideas about smell shift as they transitioned across representational technologies? And (2) What supports enabled them to persist and progress in the modeling activity? Though gender was not an explicit focus of our analysis, we explore these questions specifically in the context of these girls' sustained participation in scientific knowledge construction at a time when females are underrepresented in many science and technology fields (NSF 2013).

With this account, we speak to two questions put forth for this special issue. First, we address *How can technology transform teaching and learning as students develop and use models?* by explicitly exploring the relationship between particular representational technologies, curricular and facilitator supports, and students' modeling practices. A better understanding of these relationships can help address the second question, *What key facets of modeling instruction and or design features of modeling curriculum are most essential in promoting student science learning?* We conclude with a discussion of implications for future research, classroom instruction, and the design of modeling tools and curricula.

Background

Our work is informed by theories of learning that emphasize building from learners' existing knowledge and experiences of the world (Papert 1980; Piaget 1952; Smith et al. 1994). We seek to do this by combining two approaches: having learners discuss their own explanatory and predictive models of scientific and mathematical phenomena (Lehrer and Schauble 2000; Schwarz and White 2005; Engle and Conant 2002), and construct and critique public artifacts (Brizuela 2004; Kolodner et al. 2003; Nemirovsky 1994; Papert 1993).

Toward this goal, we are exploring what happens when students engage in extended scientific modeling activities that involve constructing and reconstructing models across a variety of representational media. By modeling, we mean that students iteratively select the constituent elements of a problem or situation, represent those elements and the relationships among them, evaluate the model with respect to real-world data and experiences, revise the model in light of new evidence, and use the model to predict or explain new or unknown phenomena. This definition is aligned with descriptions in current policy documents (NGSS 2013; NRC 2012) and the STEM education research community (Lehrer and Schauble 2006; Lesh and Doerr 2003). Importantly, this definition of modeling extends beyond simply generating a representation or explanation of a phenomenon of interest. It also requires that students persist in articulating, revising, and testing their model multiple times in order to make progress toward a more explanatory and predictive model.

Despite advances in model-based approaches to science education, research suggests it is still difficult for learners to fully engage in the modeling process; for example, they may not envision how the models they develop can be used to generate new knowledge (Schwarz et al. 2009). The conjecture driving this study is that working across drawing, animation, and simulation can address this by foregrounding complementary aspects of the same scientific phenomenon and encouraging complementary aspects of modeling practice. Here, we review research that highlights (1) the complementary roles that drawing, animation, and simulation can play in learning and discourse, (2) the ways in which working across multiple representations can affect learning and discourse, and (3) the active, social, and longitudinal nature of representational practice as it unfolds across time and context.

The Complementarity of Drawing, Animation, and Simulation

It is well known that different external representations emphasize different aspects of a phenomenon: influencing how people think, learn, communicate about, and interact with the ideas that are represented (Brizuela and Earnest 2008; Kaput 1994; Pérez Echeverría and Scheuer 2009; Prain and Tytler 2012; Zhang 1997). We focus on three genres of representation and the content and practices they emphasize: diagrams, animation, and computational simulation.

Diagrams (which for us, include drawing) are used to emphasize the main *components and relationships* that make up a system. Depending on the type used, diagrams can illustrate the physical or conceptual layout of a problem space (Larkin and Simon 1987) and illustrate how key components of a system are related spatially, ontologically, or causally (Collins and Ferguson 1993). When learners create their own diagrams, they engage firsthand in these practices of identifying key components, laying out a problem space, and organizing components relationally (Ainsworth et al. 2011; Kahn 2013; Wright 2013). Having students generate drawings can improve their understanding of conventional science content (Tytler et al. 2007), make students' ideas evident to instructors, and help them learn about the role of representation in scientific inquiry and modeling (diSessa et al. 1991). Generating particular types of domain-specific or technical diagrams can also help learners integrate existing knowledge with disciplinary conventions (Nemirovsky 1994), for example, by illustrating chemical processes using ball and stick models (Chang et al. 2010).

Animation and dynamic visualization[1] emphasize *process*: the ways that the system and its constituent parts change across space and time. This is especially true for phenomena that are too large, small, fast, or slow to see firsthand (Johnstone 1991; Wieman et al. 2008; Trey and Khan 2008). For example, animations and dynamic visualizations have been shown to improve learners' understanding of the role of molecular motion and intermolecular forces in physical and chemical processes (Kozma and Russell 1997; Levy 2013; Stieff 2005, 2011), and students who interacted with animations outperformed those who interacted with illustrations specifically on items involving dynamic processes (Marbach-Ad et al. 2008). As with drawing, generating animations can further engage learners in thinking about and expressing the temporal dimensions of phenomena (Church et al. 2007), including invisible phenomena (Chang et al. 2013; Gravel et al. 2013).

Finally, computational simulations encode the specific *rules and causal interactions* that drive a system and allow users to *execute and test* those rules in new contexts. This enables learners to interact with the simulation as an experimental tool or site for inquiry (de Jong and van Joolingen 1998; Edelson et al. 1999; Xie and Tinker 2006). Simulations often provide learners direct access to the rules that generate a given behavior, which can further encourage students to explore causal relationships (Gobert et al. 2011; Louca and Zacharia 2008). Modifying or constructing simulations can help learners understand of the role of models and modeling in scientific practice (Stratford et al. 1998; Schwarz and White 2005) and explore the causal aspects of the phenomena under study (Blikstein and Wilensky 2009; Papert 1996; Sherin 2001; Sherin et al. 1993). And, constructing their own simulations also allows learners to make and evaluate predictions about how their models might behave in new or unknown contexts, and revise it accordingly (Jackson et al. 1994; Stieff 2005; Wilensky 2003).

[1] We make a distinction between dynamic visualizations and simulations based on how they are used. If an artifact is used to demonstrate some process to students, we call it dynamic visualization. If students themselves use the artifact to conduct experiments or explore underlying rules, we call this computational simulation.

Working Across Representational Forms

While individual representational paradigms can emphasize certain aspects of a phenomenon and scientific modeling practices, working across multiple representations can provide learners more ways to interact with and communicate about phenomena. In the domain of molecular theory specifically, Kozma (2003) found that expert chemists worked across representations both to aid their own thinking and to support particular forms of discourse with colleagues. For example, they would use structural diagrams to reason about the geometry of compounds, or data from laboratory instruments to test their theories and argue for their findings. Indeed, working across representations is known to be characteristic of expert practice in mathematics, science, and engineering (Ochs et al. 1994; Vergnaud 1998).

Ainsworth (1999) highlighted three potential functions for multiple representations in education: to emphasize complementary processes and information, constrain a learners' interpretation of the phenomena that are represented, or encourage learners to construct a deeper (for example, more generalized or abstract) understanding of the phenomenon under study. She notes that different technological supports can be used to highlight these different functions. For example, dynamically linking representations of physical events and their mathematical representations can provide learners a context to ground their understanding of mathematical concepts such as rate of change and accumulation (Kaput 1994).

When students generate multiple representations across different media for well-specified and well-supported purposes, their engagement with disciplinary content deepens. Zhang and Linn (2011) found that students who first drew diagrams of their ideas about atomic interactions were then able to more productively and precisely interpret a dynamic visualization of hydrogen combustion than students who only interacted with the visualization. Exploring a single idea across different representational forms, while comparing across representations in different media, can lead to more coherent and sophisticated reasoning about mechanism (Gravel et al. 2013). This goes beyond only content: for example, Prain and Tytler (2012) argue that engaging students in constructing their own representations of various forms can emphasize the semiotic, epistemic, and epistemological dimensions of scientific inquiry as students negotiate and build connections across representations (in their case, drawing, acting, beads, and video).

Representational Practice as Intentional, Social and Longitudinal

One cannot simply learn from viewing or even creating representations without actively making sense of them

(Ainsworth 2006; Goldman 2003; Tversky et al. 2002). Research has documented the important roles of metacognitive and meaning-making activities such as self-monitoring (Chiu and Linn 2012) and engaging in disciplinary reflection and inquiry (White and Frederiksen 1998) when working with complex representational technologies such as animation or simulation. Explicitly engaging students in meaning-making practices is important even when students are constructing such representations themselves. For example, Chang et al. (2010) found that while students who designed and critiqued one another's animations improved in describing the particulate nature of matter, those who only constructed animations without receiving peer evaluation did no better than those who only viewed animations.

One way to encourage learners to engage substantively with the representations they and their peers create is by emphasizing representational practice as situated within specific problem-solving and communicative goals (Greeno and Hall 1997), through careful facilitation practices and meaningful, relevant activity contexts. For example, diSessa and colleagues documented a group of middle school students who spontaneously reinvented graphing by inventing, critiquing, and questioning one another's representations of a specific problem involving motion (diSessa et al. 1991). Enyedy (2005) showed how the invention and refinement of representational forms are dependent on what learners agree are the primary goals and shared understandings surrounding a given phenomenon. All of these negotiations unfold over extended periods of time, as facilitators came to understand the needs and interests of students and supported their development toward specific shared goals. In this way, understanding a group's representational decisions also requires understanding its historical trajectory, often across multiple episodes and modes of engagement (Medina and Suthers 2013).

Working across different representational forms is in itself noted as an important representational practice. White et al. (2011) argue that a core component of understanding the nature of science is to understand how different models and model types contribute to scientific theorizing. They note that scientific theories are formed through the process of developing and linking together multiple models that serve complementary purposes (Frederiksen and White 2002). As such, learning about representational practice in science is learning about how complementary representations—and the models they represent—can be linked together and built upon one another over time to make progress toward a coherent, robust theory of some phenomenon.

Research Questions and Contributions of the Current Study

The literature reviewed above supports our conjecture that generating drawings, animations, and simulations of a particular scientific phenomenon can engage learners with complementary aspects of scientific modeling (such as model development, refinement, testing, and use) and disciplinary content. It also suggests that supports beyond the technology or activity itself—such as the technological supports used to create and bridge across representational forms, the facilitation practices of teachers and peers, and design of modeling activities—play an important role in whether and how learners engage with different representations. Understanding these supports can also shed light on how such engagement can be sustained in classroom settings (Roschelle et al. 2010).

However, still little is known about whether or how learners might recognize and integrate these complementary aspects when generating their own models across multiple media, or how to support them in doing so. Not all ideas are equally accommodated by different representational infrastructures, and working across media can introduce tensions or confusion for learners (Goldman 2003; Tversky et al. 2002). For example, transitioning to a different medium might prompt students to abandon a given model and start over, rather than to persist in iteratively revising and building on existing models. Even if students do create connected representations across media, they may not recognize or engage with the conceptual similarities or differences that are foregrounded by the representations they construct in each form. Or, they may not progress from developing and refining models (which is well supported by drawing and animation) to testing them or making predictions (which is well supported by simulation).

Our goal is to explore the potential of engaging learners in modeling across complementary representational forms, and to identify what supports can encourage them to persist and make progress in such modeling activity. Specifically, we ask:

(1) In what ways do learners' *modeling practices, reasoning about mechanism*, and *ideas about smell diffusion* shift as they worked across drawing, animation, and simulation?
(2) What supports enable learners to persist and make progress in the modeling activity as they transitioned across these technologies?

Data Collection

We draw our data from an NSF-sponsored design-based research (Collins 1992; Brown 1992; Cobb et al. 2003)

Fig. 1 Our workshop participants. *Left* to *right* (pseudonyms): Eileen, Arianna, Nicole, Nell, Aisha

project to develop SiMSAM: an integrated animation, simulation, and data analysis toolkit for middle school science classrooms (Wilkerson-Jerde et al. 2013). In fall 2012, we held an extended workshop with five sixth-grade girls (Fig. 1) who served as research participants and design informants (Druin, 2002) using existing stop-motion animation and simulation tools SAM Animation (Searl et al. 2010) and StageCast Creator (Smith et al. 2000). The girls were friends who attended the same school, were comfortable working together, and had prior experience with SAM Animation.

Over four sessions, we asked the girls to use these tools to theorize, model, and test their own and one another's ideas about how an orange can be smelled at a distance (adapted from IQWST; Merritt et al. 2008; Schwarz et al. 2009). The girls chose to explore smell from a set of three problem scenarios we introduced at the beginning of the first session (the other two options were evaporation and sound). Table 1 presents a breakdown of the activities and media used in each session. We intentionally planned for students to begin with drawing because it is familiar and open ended, and move to simulation as a specific rules-driven form, in order to foreground the expressive and inventive nature of modeling activity.

As facilitators, we positioned the girls as the authorities and constructors of knowledge in the modeling activity. We made it clear that we expected them to propose, explore, represent, and evaluate their own models of the phenomenon, and avoided proposing our own ideas. Instead, we worked to encourage mutual understanding and critique among the girls themselves, asking questions such as "What do you think?", "Throw some ideas out there.", or asking for elaboration and clarification of ideas. A detailed analysis of these facilitator–participant interactions can be found in (Macrander et al., in preparation).

All workshop sessions were recorded using multiple video cameras positioned to capture all whole-group and small-group interactions, as well as their gestures toward and interactions with computers (Derry et al. 2010; Fig. 2). We collected all participant-generated artifacts, and on-screen activities were recorded using Camtasia screen capture software (TechSmith 2010; Fig. 3). We analyzed both talk and participant artifacts, since verbal explanations and productions might reveal complementary understandings (Kelly and Jones 2007).

Analysis

We will report on two complementary analyses of our workshop data, conducted to address each research question we posed above. First, we paint a broad sketch of how the girls' modeling practices, reasoning about mechanism, and ideas about smell diffusion shifted over time across phases of the workshop. This reveals two distinct cycles of modeling activity: the first exploratory and descriptive and the second focused and explanatory. We refer to these two cycles as *messing about* and *digging in*, drawing from Hawkins' (1962) notion of "messing about" as an exploratory, question-provoking activity in science. Second, we present a deeper analysis of these two cycles, and the key events and supports likely to have played a contributing role in their emergence and progression.

Overall Workshop Coding

To explore shifts in learners' modeling practices, reasoning about mechanism, and engagement with disciplinary ideas as students worked across representational forms, we first

Table 1 Summary of activities during each of the four sessions of the workshop

	Day 1	Day 2	Day 3	Day 4
Activities	Experiment with the phenomenon; discuss intuitions about smell; participant drawings; group construction of stop-motion animations	Review of animations; further discuss experiences of smell; introduce simulation (using StageCast Creator)	Explore StageCast system without modeling; re-orient toward modeling activity using StageCast Creator	Revise simulations; discuss model relative to experiences, begin quantifying simulation results
Media	Drawing and stop-motion animation	Animation and Simulation	Simulation	Simulation

Fig. 2 Video data include whole-group and small-group interactions, and gestures toward the computer screen

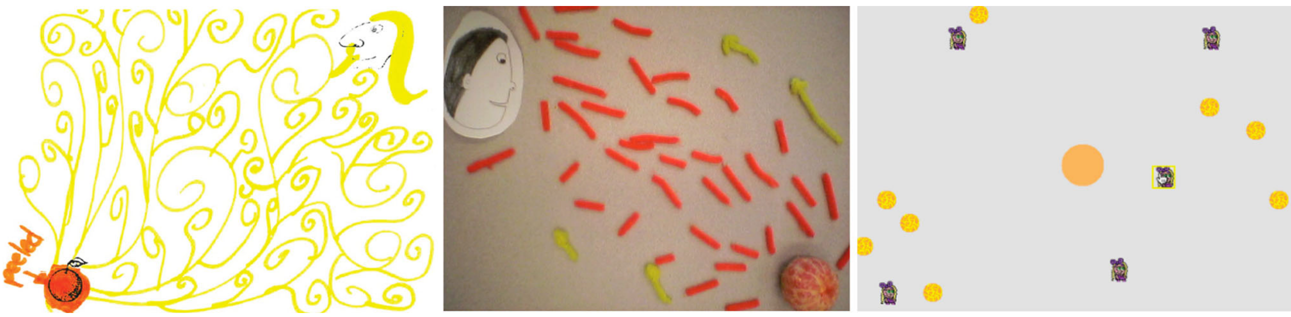

Fig. 3 Participant artifacts included drawings, stop-motion animations, and simulations

sought to document the co-occurrence of these themes over the course of the workshop. Using codes derived from contemporary model-based reasoning research literature (namely Manz 2012 and Schwarz et al. 2009), we looked for evidence of different *modeling practices*—such as referencing past experience, representing the phenomenon, or empirically testing a model—in our data. Similarly, to explore engagement in *disciplinary content*, we used bottom-up verbal analysis (Chi 1997) to identify and mark the presence of a number of ideas about smell diffusion—such as that smell can vary in strength, that smell is comprised of particles, or that smell travels directly to a smeller—that the girls contributed during the workshop.

Additionally, we identified what aspects of *reasoning about mechanism* the girls were engaged in (Russ et al. 2008; a similar technique is pursued in Louca et al. 2011). This includes things such as identifying setup conditions under which smell diffusion occurs, defining what entities are involved in smell diffusion and their properties, or describing the interactions among particles that cause smell to diffuse. Identifying and modeling the causal mechanisms that underlie a given phenomenon represent a key point of connection between modeling practices and conceptual understandings, and contribute to a model's explanatory and generative power.

We generated a list of codes for each of these three foci (modeling practices, disciplinary content, and reasoning about mechanism) prior to the first analysis. All four days of video data were split into 5-min segments using video timestamp information, and we coded each segment for the

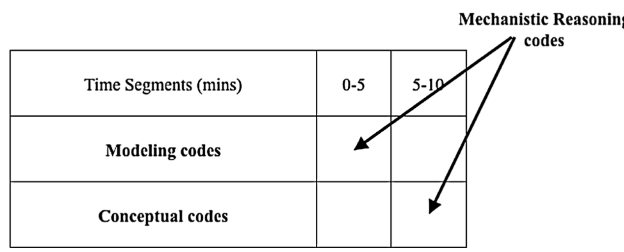

Fig. 4 Illustration of how the analytical codes—*modeling, reasoning,* and *conceptual*—were applied to video data

presence of each code for each of the three foci. Discussion of this first analysis led us to refine the coding scheme such that causal mechanism categories formed an independent axis. This allowed us to identify types of reasoning about causal mechanism *within* modeling practice codes and conceptual codes for each 5-min segment (see Fig. 4). For example, if a cell that represents "wind spreads smell" for a given 5-min period is also coded with the mechanism code "Describing Phenomenon", that means that the group referenced the idea that wind spreads smell as a general description of their experience with smell diffusion. If the same cell is coded with "Interaction," the group might be describing how wind agitates and separates smell particles from their source.

By splitting video data into 5-min units for coding, we are over representing the duration of each code. For example, if we identify one second-long statement within a

5-min period as a prediction, the entire 5-min period would be coded as involving prediction. This approach allowed us to identify intervals of video during which productive shifts in student activity first emerged, which we could then analyze in more detail. It also allowed us to construct a larger-scale representation of emergence and shifts in participant behavior during the workshop, which persisted over the course of hours rather than minutes. A table relating all finalized codes, descriptions, and relationships to existing literature is included in "Appendix 1". Examples of how and why transcript data were coded for each dimension are included as part of the Results section.

All three authors independently coded 20 % of video data drawn from multiple workshop sessions. Raw agreement on modeling and conceptual codes was 90 %; total agreement on presence was 85 %. Raw agreement on causal reasoning codes was 90 %, and agreement on presence was 70 %. We illustrate these codes with transcript excerpts in our Results section; additionally, "Appendix 2" includes three examples of disagreement among coders, to provide more insight into the nature of our process and the meaning of coding disagreement (Hammer and Berland 2013).

Deeper Analysis of Cycles and Supports

The degree to which different modeling practices, disciplinary ideas, and causal mechanisms were represented over the course of the workshop suggests that the girls persisted in and deepened their exploration of the smell diffusion system. To better understand how this productive pattern emerged, we present deeper analyses of the (1) designed activities, (2) facilitation practices, and (3) technological supports present during each cycle, and during the transitional period during which the girls moved from the first cycle to the second.

To do this, we present and analyze short excerpts representative of Cycles 1, 2, and the transition between them, drawing connections to broader themes across the workshop when appropriate. As designers, we are interested in how teacher supports and curricular materials can best align with technological innovations to generate curricular activity systems (Roschelle et al. 2010) that translate well to classroom use. Instead of isolating and making causal claims about the effect of technology on learning, our intention is to explore the workshop as an in-depth case study (Yin 2009) and identify contextual factors that warrant further attention in research and design.

Results

To address Research Question 1, we present results from our overall coding analysis, which revealed that the girls engaged in two cycles of modeling practice over the course of the workshop. The nature of these cycles were quite different from one another in terms of the modeling practices, reasoning about causal mechanism, and ideas pursued in each, with the second involving more sophisticated aspects of modeling and reasoning about mechanism. To address Research Question 2, we present deeper analyses of the designed activities, facilitation practices, and technological infrastructure at play during each modeling cycle we identified, as well as the transitional period between them, to better understand how and why they emerged.

Part 1: Shifts During the Workshop

Figure 5 presents the results of our overall coding analysis. Each column in the table represents a 5-min segment of workshop video data. Along the top, we indicate the primary activity for each segment. When *Drawing*, *Animating*, or *Simulating*, participants were actively constructing models. When *Discussing*, participants shared, critiqued, and otherwise engaged with the models they had just constructed. During *Analog Simulation*, workshop facilitators asked the girls to "program" physical objects using plain language as preparation for building simulations.

Each row in the figure represents the modeling practices and ideas about diffusion that might be present in each 5-min segment. If a cell is shaded, then that 5-min segment was coded for the presence of a particular modeling practice or idea about smell.[2] The darkness of the cell indicates the type of reasoning about mechanism that participants were engaged in (from describing phenomenon, lightest, through identifying setup conditions, defining entities and properties, defining behaviors, and describing interactions, darkest). If more than one form of causal reasoning was identified for a given cell, the cell is colored according to the darkest available shade.

This analysis revealed two distinct cycles of modeling practice that emerged over the course of the workshop: (1) from Session 1 through the first 35 min of Session 2 when drawing and animating and (2) from about 40 min into Session 2 until the end of the workshop when simulating. We identify these as cycles because during both intervals the girls began by *Referencing Past Experience* and *Representing* and moved (though not linearly) toward *Evaluating*, *Revising*, and *Making Predictions* with their model. While both cycles progress in this way, there are dramatic differences in which modeling practices, ideas about smell diffusion, and aspects of reasoning about mechanism were

[2] In Session 3 there is a period of time where no codes are identified. During this time the girls learned how to use StageCast, without focusing on the smell diffusion task. Toward the end of that session and beginning of the next, we moved back to the modeling activity without apparent interruption in the overarching patterns of investigation.

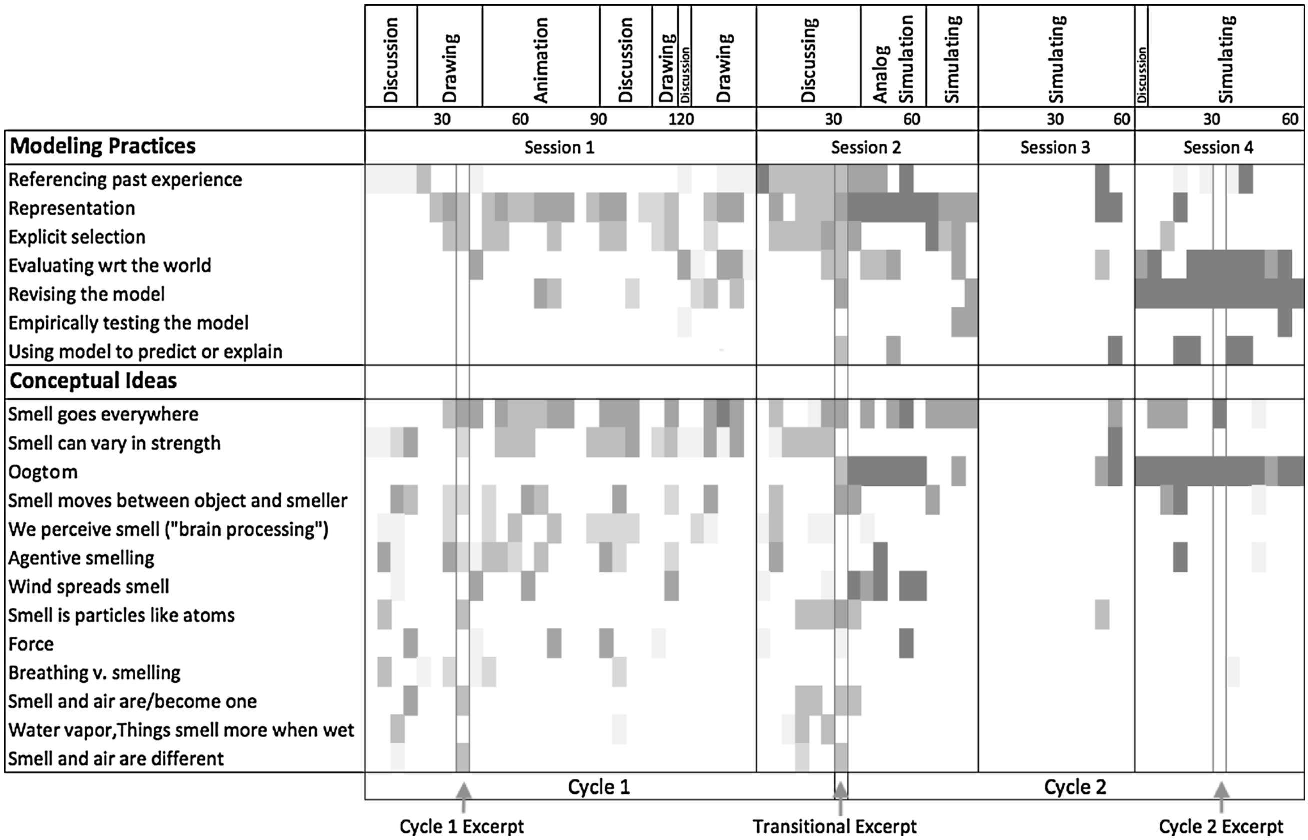

Fig. 5 Results of overall workshop coding. Cell shading corresponds to type of reasoning about mechanism, where the *lightest shade* corresponds to describing phenomenon and darkens for each of identifying setup conditions (*lightest shade*), identifying entities and properties, defining behaviors, and defining interactions (*darkest shade*)

highly represented in each. We as facilitators did not explicitly plan for this pattern to emerge and were not aware of it while conducting the workshop (although, as we report below, we likely contributed to its emergence).

We argue that the nature of these modeling cycles provide evidence that the girls engaged in sustained and deepening modeling practice over the course of the workshop. In the first cycle, which we call *messing about*, the girls spent relatively more time selecting and representing parts of their model than making predictions with, evaluating, or revising it. In the second cycle, which we call *digging in*, they spent more time evaluating, revising, and using their model to generate predictions and explanations. The girls also referenced more ideas about smell diffusion simultaneously during the first modeling cycle, whereas they focused in and elaborated a more specific subset of ideas in the second. While they focused on identifying the setup conditions and components involved in smell diffusion during the first cycle, they shifted to modeling the specific physical behaviors and interactions involved in smell diffusion during the second.

At the same time, though the two cycles were different in many respects, the activity was sustained in that nearly all of the ideas the girls proposed re-emerged, even if briefly, across both cycles. For example, the idea that *Wind Spreads Smell* came up weakly during the first session, but played a larger role toward the middle of the workshop. Other ideas that faded from the group's conversations early, such as *We Perceive Smell* and *Breathing vs Smelling*, still re-emerged briefly during the last day of modeling activity. We see this as evidence that although the girls' modeling activity and focus seemed to shift dramatically, they still perceived both cycles as fundamentally part of the same activity, and all times the girls were working toward the same goal.

Part 2: Cycles and Supports

Given the differences revealed above, here we present and more deeply analyze representative excerpts from the workshop. In particular, we seek to describe the (1) designed activities, (2) facilitation practices, and (3) technological supports involved during the first and second modeling cycle, as well as during the period of transition between them. Figure 5 indicates the position of each excerpt and provides evidence for how representative each excerpt was of the more general patterns we identified during coding analysis.

Fig. 6 Drawings discussed in Excerpt 1: Arianna's drawing (*left*), Nicole's drawing (*center*), and Eileen's drawing (*right*)

Cycle 1: Messing About with Drawing and Animation

Our first analysis revealed that during Cycle 1, the girls engaged with more ideas about smell, focused most of their time on selecting, representing, and connecting those ideas to past experience, and emphasized the setup conditions and entities that they wished to represent with their model. The excerpt below exemplifies what this looked like in practice. During the first day of the workshop, we asked the girls to describe how they thought smell travels and provided them with real oranges and clementines that they could peel and examine. After some discussion, we asked each of the girls to generate a drawing to show how smell moves from an orange to a person some unspecified distance away. We provided a schematic template with an orange in one corner and a person with an exaggerated nose in the other to complete (see Fig. 6). In the following excerpt, B*[3] is encouraging the girls to describe and explain what they had drawn, making comparisons with other drawings when appropriate.

Arianna	So when I used the full *[unpeeled]* orange, and the full orange…you could still smell it…. but it wasn't as strong as once it was peeled. And once it was peeled you could keep it far away and still get it to your nose pretty fast. And I also wrote that the guy, he's breathing and smelling, and so, but more importantly smelling… and, like if the breathing is part of the smelling, he's smelling it.
B*	So these wavy lines, this is, you said the scent?
Arianna	Yeah.
B*	Coming out of the peeled orange. And it's not as strong on the full *[unpeeled]* orange, that's why the lines are shorter?
Arianna	Yeah.
B*	Ok. Nicole?

Nicole	So, um, mine, I un-peeled the whole orange so all the smells went everywhere. And I was trying to show that once you opened it, it sort of goes into one specific pathway. And when you open the whole thing, then it sort of spreads out along the whole thing, and
B*	Along the whole thing, meaning, like, inside the box there? Inside the room?
Nicole	Yeah. And this one's *[lines representing smell near the person's nose]* a little thicker because when you breathe it in, you sort of create force to bring the scent toward your nose.
B*	But that's only happening near the nose, you drew? Not everywhere?
Nicole	Yeah?
B*	So, sort of similar to Eileen's but a little different?
Nicole	Yeah.
B*	Can you describe how they're different?
Nicole	Hers… like, all the way to the orange… all the way from his nose. No, all the way from the orange to his nose is like really dark *[Eileen's smell lines]* showing that it's […] dense
B*	[to Eileen] That was the word that you used, right? *[Eileen nods]*

Table 2 describes in detail how the excerpt above corresponds to the codes featured in Fig. 5. The excerpt illustrates many of the patterns that emerged in Cycle 1. The girls volunteered many, often disparate ideas about smell at once: peeled versus unpeeled (lines 1–5 and 16–17), smell goes everywhere (line 17), the smeller creates a force that brings scent to the nose (lines 24–27), etc. They focused on identifying and representing the key components that play a role in smell diffusion, but less on the particular ways in which components behaved and interacted with one another to generate it. Like in this excerpt, many of the conversations during the first modeling cycle exhibited this

[3] On all of the transcript excerpts presented, we identify workshop facilitators by one initial followed by an asterisk. All workshop facilitators are also authors of this manuscript.

pattern of "messing about" (Hawkins 1974) with ways of describing and representing aspects of smell.

Designed Activities During this excerpt and throughout the majority of the first cycle, we engaged the girls in individual or multi-group activities where they were expected to externalize, share, and learn about one another's ideas. For the drawing activity, each participant worked independently to generate a drawing (although we made no attempt to prevent them from sharing their work or talking while they drew) and shared them afterward. Similarly, during the animation activity, the girls worked in one group of two and one group of three to generate their stop-motion animations of smell diffusion, and they shared these afterward. The space for variability between students and groups likely contributed to the emergence of a large variety of ideas during the first modeling cycle. It also likely contributed to the proportion of discussion focused on selecting and describing the constituent elements of each student's model of smell.

Facilitation As facilitators, we worked to create a culture within which students' ideas were valued, seriously considered, and shared. During the early stages of the workshop, this took the form of inviting students' ideas, identifying commonalities and differences between them, and asking the girls to elaborate or comment on their own and one another's artifacts (as B does throughout the featured excerpt). We encouraged them to use what they knew about smell from their everyday experiences and to experiment with the oranges and clementines we had provided. This approach also likely contributed to the variety of ideas generated by students, as well as their emphasis on identifying and representing setup conditions.

Technological Infrastructure As suggested by the literature, drawing allowed the girls to elaborate their problem space and to identify and organize what they believed were important aspects of smell to represent in some way (such as the substance of smell, its patterns of movement and that humans perceive it). Creating animations required the girls to make more specific commitments to what smell is made of and what behaviors and processes it exhibits across time and space. However, the specific type of animation tool we used—a stop-motion animation platform—allowed them to select materials from a large collection. This likely encouraged students to continue to explore the space of representational possibility, rather than focusing their attention. Their animations still included a number of at times disconnected ideas (for example, one animation showed smell particles that move from the orange to the nose directly, but also featured arrows to indicate that the smell goes everywhere; Fig. 3b).

Table 2 Detailed explanation of coding for Excerpt 1

Modeling codes	Mechanism codes	Justification
Explicit selection	Setup conditions: Lines 1–5 and 16–21 Entities & Properties: Lines 16–21	Arianna & Nicole are discussing the states of the smell emitter (the orange being "full" or "peeled"), and how a "peeled" orange emits a stronger smell
Representation	Setup conditions: Lines 34–37 Entities & Properties: Lines 24–25 and 34–27	Nicole comments on the use of line darkness by Eileen to show the "dense"-ity of the smell going from the orange to the smeller, suggesting that the intensity of the line ("it's really dark") indicates the intensity of the smell ("it's … dense.") along a particular path between the orange and smeller
Conceptual codes	**Mechanism codes**	**Justification**
Smell goes everywhere	Setup Conditions: Lines 16–21 Entities & Properties: Lines 16–21	Opening the "whole thing" means peeling the orange, and it "spreads out along the whole thing" refers to the scent spreading throughout the room. In this utterance, Nicole identifies a condition of the orange, the scent as an entity represented by lines on paper
Agentive smelling	Setup conditions: Lines 24–27	Nicole identifies a condition of the model as the smeller breathing in the scent, "when you breathe it in", you sort of create force," which suggests an agentive smelling condition for the model
Smell moves between object and smeller	Setup conditions: Lines 5–7 and 16–21	Arianna and Nicole include as setup conditions that the model is to describe how smell moves between the object and smeller
Smell can vary in strength	Setup conditions: Lines 1–5	Arianna and others considered the state of the orange as a way of indicating the intensity (or perhaps the amount) of scent being released as a result of how "peeled" or "whole" the orange was
Breathing vs. Smelling	Setup conditions: Lines 5–7	Arianna is navigating the differences between breathing and smelling to determine which components need to be accounted for in her model

Transition: The Creation of "Oogtom"

About 35 min into the second workshop session, the patterns representative of Cycle 1 shifted dramatically. Before then, the group had been discussing their ideas about smell, revisiting the animations they had constructed during the last workshop session and bringing up specific situations in which smell is made stronger (such as during cooking or when water is added to some substance). Figure 5 shows that the girls quickly moved from sharing a wide variety of ideas about smell to focusing on only a few ideas, describing in more depth the particular behaviors and interactions involved in smell diffusion, and exploring the validity and predictive power of the models they generated. Below, we feature a short excerpt from the transitional period between Cycle 1 and Cycle 2. Arianna had just posed a specific goal for the group, which was "[We] have to find out what smell is made of." During the excerpt, the girls invent a representational object they eventually named an "oogtom" (a combination of the words "oogie" and "atom" used below), as part of a proposal to revise the animations they had constructed in the last session.

Eileen	Like, if we redid this *[animation]* project, I would have done an orange, orange and like, I would have done like yellow, like both of them to show that there was atoms and oogies
Nell	Oh, yeah, yeah, you know like intertwine them, like they were paperclips.
Arianna	Yea, so there would be like a yellow one and a red one together.
B*	Ok, so you'd make these little atom oogie… *[yea]* intertwined twirlies.
Nell	I wouldn't make them, I guess for that *[indicates animation]* one it works because it's like you're like trying to show how it hits your nose because it's like pointy, but if it was an actual atom and oogie, I think I'd make it circular, I think like round.
B*	Okay, so like if we zoomed in on an atom and an oogie?
Nell	It would be round, it would be like—because you know how those are like so, so say this *[lifts index card; Fig. 7a]* is like an atom and an oogie, well *[pulls on edges of card; we suspect to indicate a bias in direction]*, like…
Eileen	Oh, I like
B*	Do you want to draw one?
Nell	Yea, thanks. So here is what like that one would be, an atom and an oogie, because you want the smell to be like everywhere, but this I feellike it would come off maybe… well, I don't know. I feel like if it's circular, then it would come off like, pretend that's a sphere, and so then it comes of everywhere but then if it's a line, then there's gonna be somewhere, like some place on it that it's gonna be more thick then it is like right here or right here, and maybe it's like really thick like right there.

In this excerpt and over the course of the transitional period, the girls converged upon a description of smell as a composite of atoms ("because everything is made of atoms") which dictate how smell moves and spreads, and "oogies," which became a stand-in for whatever smell "is made of," as Arianna said. This object represented smell as a substance, but also encapsulated ideas such as that smell goes everywhere (which Nell suggested in Lines 11–34 should mean the object is round rather than linear), that smell is related to both air (atoms) and the smell's source (oogies; which lead the girls in Lines 1–8 to suggest intertwining two colors), and that smell is made of particles like atoms (so that each microscopic object is only visible because it is understood to be "zoomed in"; revoiced by B* in Line 16–17). Table 3 provides a detailed description of how this excerpt was analyzed in terms of our coding scheme.

We argue that the invention of "oogtom" represents a key event in the progression and sustainment of the girls' modeling practice across media and over the course of the workshop. By creating this object, the girls consolidated some ideas that were proposed during Cycle 1, and retired others. The object and its development also represented a consensus description of smell that the girls negotiated during this transitional period (which can be seen in Nell, Arianna, and Eileen's agreement and encouragement of one another on Lines 5–6, 7–8, and 23). The result was a simpler, more consistent system that freed them to focus on the physical mechanisms that underlie smell diffusion. The emergence of "oogtom" also provided an object that could "carry" ideas and conjectures from the drawings and animations into the simulation environment while adhering to that environment's representational constraints.

Designed Activities We did not explicitly design for this event. In the moments leading up to the girls' proposal of "oogtom", we led an open-ended conversation where we asked the girls to elaborate on the ideas they proposed

Table 3 Detailed explanation of coding for Excerpt 2

Modeling codes	Mechanism codes	Justification
Explicit Selection	Entities & properties: Lines 11–15	Nell explicitly discussed two kinds of shapes smell particles can have: "pointy" and "round"
Representation	Entities & properties: Lines 1–6	Several participants contributed ideas about how smell particles should be represented in a model
	Behavior: Lines 28–34	Nell described how the shape of a smell particle has implications for how it moves. Specifically, a spherically symmetric particle would have no directional preference and, on average, move in all directions
Revising the model	Entities & properties: Lines 1–4 Behavior: Lines 11–14	Participants explicitly revised their animation models, focusing both on the representation of smell particles and the implications for particle movement
Conceptual codes	**Mechanism codes**	**Justification**
Smell goes everywhere	Behavior: Lines 25–29	Smell should move in all directions equally, on average
Smell moves between source and smeller	Behavior: Lines 11–15	Smell has a specific directionality (it's "pointy") toward the smeller
Smell is particles like atoms	Entities & properties: Lines 1–34	This is implicit in the whole discussion; smell is being discussed as and represented by discrete objects
"Oogtom"	Entities & properties: Line 5–6	Although the participants had not coined the word "oogtom" yet, this is the first time they represented atoms and oogies as a unified ("intertwined") object
Smell and air become one	Entities & properties: Lines 3–4	The girls suggest using two colors to indicate that the new particle they are constructing possesses qualities of air (it moves and is particulate like air), and of smell (it carries some part of its source)

during the first session and consider how they might refine their animations accordingly. We provided the girls with the animations they constructed the week before, and brought many of the same craft materials that were available for generating animations to this second session. Making these materials and artifacts available to the girls may have provided a sense of continuity, and made available tools to articulate representational decisions that would be difficult if only done verbally (such as Nell's gestural rationale for making "oogtom" round to indicate they travel in all directions; Lines 18–22). We recalled statements from the prior workshop session and invited the girls to respond to and question one another's ideas directly, which likely paved the way for the consensus building that emerged during this period.

Facilitation Though we did not deliberately plan for the girls to invent a specific object to represent "what is smell made of", we quickly recognized its potential for use in our next planned activity, building computational simulations. The StageCast simulation tool we intended to use requires discrete graphical objects, which are programmed using spatial rules. Therefore, soon after the girls proposed "oogtom" as physical objects, we prompted them to create those objects (Fig. 7b) and used them as what the girls "programmed" in plain language during Analog Simulation. Thus, while the nature and meaning of oogtom were primarily developed by the girls, our encouragement and continued use of these objects moving forward reified their value and emphases within the larger pattern of activity during the workshop.

Technological Infrastructure Reviewing the animations, the girls constructed reminded them of the problem space they had defined during the prior workshop session, including questions about what smell is and how they might represent its behavior across time and space. It also re-emphasized the problem space that students had mapped out during the last session, making available for reflection the many ideas that they had proposed. At the same time, an awareness that we would transition to constructing simulations that require rules and interactions to be defined for discrete objects attuned facilitators to the appropriateness of "oogtom" for the representational medium. During this transitional event, the technological infrastructures involved in what came before (mapping the problem space and defining important behaviors across time and space), and what would come next (using a multi-agent-based simulation tool to simulate specific objects and interactions) shaped how the girls and we as facilitators contributed to modeling decisions.

Cycle 2: Digging In with Simulation

During the second modeling cycle, the types of modeling activity and ideas that the girls were focused on were dramatically different. Rather than contributing a number of simultaneous and loosely related ideas about smell, the girls focused on articulating a model in terms of "oogtom",

Fig. 7 Nell showing that oogies and atoms should be intertwined (*left*); the girls constructing "oogtom" using pipe cleaners (*right*)

"princesses" (as smellers), and a source orange. They spent a great deal of time critically evaluating how well that model represented their own expectations for how smell should behave, and proposing revisions to modeled behaviors and interactions in order to better accommodate those expectations. In the excerpt below, the girls are revising a computational simulation that featured an orange object that released digital "oogtom" (represented as round orange and yellow objects) that they moved randomly around the available space. The simulation featured a princess "smeller" that the girls had just decided to remove from their simulation.

1	M*	So can I ask about deleting the princess? If we're talking
2		about smell, and there's no one smelling here, then why
3		is it a good –
4	Nell	Oh yea we should put–
5	M*	–well I'm not saying it's wrong, I'm just wondering why
6		you guys are comfortable without having someone
7		smelling
8	Nell	Because in like in real life I don't think this would happen,
9		but in this they have to go, well I guess in real life would
10		have to go around. But like with this it has like a circuit
11		so if it gets moved, it goes back and you like miss a
12		whole spot, but with the princess you block like stuff and
13		the circuit will keep going around but will miss

For a few turns of talk, we questioned the girls to try and understand whether they deleted the princess to indicate that smell diffusion is not dependent on the presence of a "smeller" (perhaps an indication that they were considering the generality of the model), or because the princesses' presence in the simulation changed the simulated behavior of nearby oogtom particles (as Nell suggests in Lines 8–10). Then, B* asks:

14	B*	Imagine I'm sitting here, I'm a princess, what's
15		gonna happen to the oogtom?

16	Arianna	I have an idea, you know how we got the orange to
17		produce oogtoms? So if we added a princess in the
18		room right there, and any oogtoms hit her while it's
19		in the circuit, wouldn't it like go away because
20		you're taking them in your body because you're
21		smelling them? So like, maybe if we got the
22		opposite of producing oogtoms to get them to go
23		inside of her to like eat them or something?
24	Nicole	Oh yea. I don't know if they go like through your
25		body, or around yourbody. Cuz like, if we open an
26		orange I don't think it's gonna go like down the
27		hallway and the third classroom over they can smell
28		the orange. But I'm not sure if it dies down or we've
29		like, used the smell
30	Nell	That's a good point to make, if it's dying down or
31		we're consuming

The excerpt is representative of the sustained and specific strands of inquiry the girls engaged with throughout what we identify as Cycle 2 of the workshop. Table 4 provides a detailed analysis of how it was coded as part of our overall analysis. Rather than briefly sharing several ideas and experiences with smell briefly, during this period of the workshop, the girls evaluated the particular ways in which their modeled smell particles behaved, and whether they did or did not represent what they expect (Lines 8–10 and 25–29). They also focused their evaluations and revisions on the objects that already exist within the model (Lines 16–23), rather than adding new ideas as often happened when drawing or animating in Cycle 1.

Designed Activities Throughout the periods of the workshop corresponding to Cycle 2, we worked to support continuity in the ideas, objects, and models the girls worked with from session to session and as they transitioned to computational media. To prepare for simulation, we planned to conduct an activity during Session 2 where the girls would practice giving verbal instructions to index cards that we would move by hand. When the girls created "oogtom", we used these instead. Next, we worked with them to create a

Table 4 Detailed explanation of coding for Excerpt 3

Modeling codes	Mechanism codes	Justification
Evaluating w/r/t the world	Behavior: Lines 8–10 Interaction: Lines 18–21	Participants compare the behavior (movement) and interaction (potential consumption) of oogtom with how they might expect the smell of an orange to "die down" at far distances
Revising the model	Setup conditions: Lines 17–18 Interaction: Lines 18–21	Participants are revising the setup conditions (re-introduction of the princess) and interaction (princesses "smelling" or "eating" and thus consuming the oogtom)
Modeling codes	Mechanism codes	Justification
Smell goes everywhere	Behavior: Lines 8–12 Interaction: Lines 12–13	Nell discussed the idea of smell going everywhere, and the behaviors and interactions responsible for its diffusion—through moving and being "blocked" by smellers in the system
"Oogtom"	Behavior: Lines 8–12 and 28–31 Interaction: Lines 12–13 and 16–17	"Oogtom" was referenced as the primary smell object, and its behaviors (moving and possibly losing intensity over time) and interactions (being produced by the orange and blocked or consumed by smellers)

version of "oogtom" within StageCast for them to program (Fig. 8a). During Sessions 2 and 3, the girls worked in small groups to construct simulations, and we took note of the behaviors they tried to include, even when they were not successful enacting them in their simulations. At the beginning of Session 4, we provided sample simulations that illustrated some of the behaviors they had suggested or tried to include in prior sessions. Though we planned for them to continue to work in small groups (see the extra laptop in Fig. 8b), in Session 4, the girls took over and modified a simulation from the prior session as a large group.

Facilitation Throughout Cycle 2, as in the excerpt presented above (Lines 1–7, 14–15), we asked mainly probing or clarifying questions about what the girls were doing with their models. We also helped the girls to enact specific rules within the simulation environment when needed. However, by this period of the workshop, the girls were comfortable contributing ideas and often engaged with one another's ideas directly and in depth. For example, B*'s question on Line 14–15 led Arianna, Nicole, and Nell to discuss ideas with one another and eventually introduce new revisions to their model, without ever directly responding back to B*. This is dramatically different from the interactions representative of Cycle 1. Toward the end the workshop, the girls became so focused and self-directed that we as facilitators stood back and watched as the group independently worked on and tested their simulation for more than 15 min (Fig. 8b).

Technological Infrastructure In the StageCast Creator environment, behaviors of objects (like the smell particle, or "oogtom," and the smeller, "princesses") and interactions between those objects are highlighted. In order to construct a working simulation, the girls had to explicitly define how these objects move—in particular, how they move when they are alone in space, and when they are positioned near other objects. These considerations, and the girls' ability to run and observe the entailments of these decisions, offered specific ways the girls could evaluate and refine their model. For example, in the excerpt presented above, the conceptual question of whether smell dissipates or disappears over time (Lines 28–31) emerged from the girls' reconsideration of whether smellers are a necessary (Lines 1–13), and what function they serve within the smell diffusion system (Lines 16–25). Simulation also allowed the girls to quantify their model, providing new ways to test it. In one instance, they spontaneously began to count the number of smell particles that reached smellers at different distances from the source orange, noting that the model should predict a stronger scent closer to the orange.

Discussion

Our research questions were: (1) In what ways did learners' *modeling practices, reasoning about mechanism*, and *ideas about smell diffusion* shift as they worked across drawing,

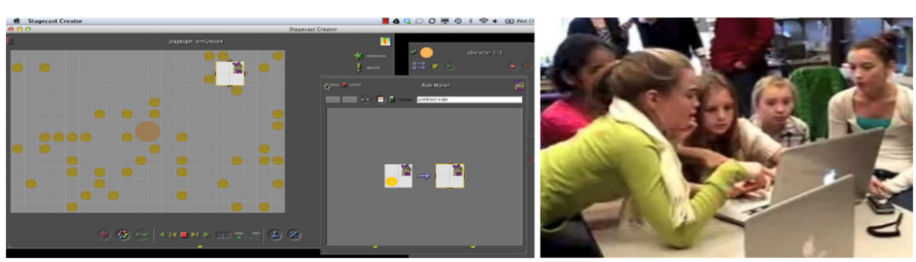

Fig. 8 The girls work together to revise their simulation by defining a new rule to make oogtom objects disappear when "smelled" (*simulation screenshot left, video right*)

animation, and simulation? And (2) What supports enabled the girls to persist and progress in the modeling activity as they transitioned across these technologies?

We found that the girls engaged in two distinct cycles of modeling practice. The first emerged as they created drawings and animations, and the second as they created computational simulations. Across the two cycles, the girls' engagement in the modeling activity persisted and deepened. In the first, referencing past experience, selecting what about smell should be included in the model, and representing smell diffusion were more highly represented than evaluating, revising, testing, or making predictions. The girls' reasoning about mechanism focused on identifying the setup conditions, entities, and properties involved in smell diffusion, and they referenced many different ideas about smell at once. During the second, the girls' engagement shifted dramatically: they more frequently evaluated, revised, and used their model to make predictions. In many ways, the girls' engagement with the phenomenon of smell reflected learning progressions documented in the literature (Merritt et al. 2008; Schwarz et al. 2009). But, they emerged over a short period of time and extended beyond kinetic molecular theory into the quantitative patterns the model predicts. While the workshop was notably different from typical classroom engagement in a number of ways, we do find this evidence to be promising.

Upon further analysis of each cycle and the transition between them, we worked to identify what aspects of the representational technologies used in the workshop might have supported these shifts. During the first cycle, drawing allowed the girls to express, organize, and problematize a variety of different ideas about smell they wished to include in their model. Animation added to this a requirement that those ideas be illustrated consistently across space and time, but the girls still included a number of at times conflicting representations. Across both drawing and animation, the girls focused on showing ideas, rather than working to explain or predict smell diffusion. As such, Cycle 1 was reflective of other studies that suggest that students have difficulty understanding how scientific models can help make predictions on generate new knowledge (Schwarz et al. 2009).

Prompted by a question about what smell was made of and how they would indicate this consistently in their animations, the girls invented a new representational object they called "oogtom" that represented smell particles (a combination of "oogies", or smell, and "atoms"). "Oogtom" encapsulated many of the ideas the girls had included in their drawings and animations about smell: for example, that it goes everywhere and is related to both air and to the source of the smell. This relieved the girls of the need to describe particular characteristics of the entities or situation. Instead, they could focus on how smell particles behave and interact. It also fit a necessary requirement for the simulation environment, which was that discrete physical objects be programmed visually to move through a space.

To generate simulations, the girls had to attend to the behaviors and interactions of these "oogtom" particles, their source, and smellers. Once the simulations were created, they could be run to determine what patterns of smell diffusion the rules produced. This focused the girls' attention on the predictive and generative power of their models, as has been found in the simulation literature (Jackson et al. 1994; Stieff 2005; Wilensky 2003). At the same time, some of the ideas and experiments from earlier sessions re-emerged as ways to explore the validity of the models they were creating. We argue that one reason for this is that "oogtom" served as a representational bridge that packaged ideas from those early sessions, where the media used and the nature of discussion were more expository, and brought them into the later sessions where they could serve as fodder for the girls to test, evaluate, and extend their models further.

Of course, the shifts we observed were not a result of media alone, and we also sought to identify how designed activities and our moves as facilitators influenced the girls' patterns of engagement. As facilitators and designers, we encouraged many of these patterns (both intentionally and unintentionally) through activity design and facilitation practices. By asking each participant to generate a drawing independently and then share what they produced during Cycle 1, we contributed to the workshop's early focus on selection and representation and made space for many ideas to be discussed at once. We intentionally did this position the girls as generators and evaluators of knowledge, and to help them realize the wealth of knowledge they already had about smell diffusion—both ideas that served them well in evaluating and refining models later.

During the transitional period between Cycles 1 and 2, we modified our original plans in response to students' behavior. By noticing and encouraging the invention of "oogtom", we found a way to establish representational continuity across the girls' early exploratory discussions and observations, and their later mechanistically focused computational explorations. We argue this continuity provided a context for the girls to evaluate and revise their computational models so that the rules and interactions they defined would generate the patterns they had identified as important early on: that smell travels everywhere, should be stronger next to the source, that smell is related to air, and so on. Our role as facilitators became backgrounded as the girls recognized these preexisting ideas and experiences (rather than our suggestions or questions) as a way to evaluate their model's validity and interpret its predictions.

Conclusion and Implications

This study was motivated by existing literature that suggests moving across drawing, animation, and simulation can engage learners with complementary elements of scientific reasoning and content. It contributes to that literature a detailed case study in which learners' engagement sustains and deepens across these media over many days and documents the technological, curricular, and social supports that played a role in that sustained engagement.

Our findings have implications both for classroom instruction and for the design and study of modeling tools and curricula for middle school science classrooms. In particular, this study suggests ways that representational technologies, curricula, and facilitation can be aligned to leverage students' knowledge of experientially rich contexts such as smell, sound, air, and evaporation toward extended modeling activity. For example, as predicted by prior work, generating drawings and animations of smell diffusion allowed our participants to organize a variety of knowledge and experiences they had about smell. Our findings suggest that complementing these representational emphases with curricular and social supports that highlight this diversity of ideas and common experiences the girls had set the stage for deeper engagement later on.

Sharing, comparing, and synthesizing their ideas about what is important to know about smell diffusion set the stage for the girls to create "oogtom". This representational object encapsulated and reified their ideas experiences of smell (such as that it is related to both air and its source, that it goes everywhere, and that it behaves like particles) into a single physical instantiation on which they could focus their attentions. Our findings suggest that having students explicitly negotiate representational objects as part of moving across representational media might serve as an important transition point from "messing about" (Hawkins 1976) to specifying particular behaviors and interactions in a system. It can also preserve students' initial knowledge, intuitions, and questions to be examined in light of a more well-specified, mechanistic model.

Our study also contributes new methods for exploring students' sustained, in situ modeling activity as they work with representational media. The coding scheme developed for this study juxtaposes modeling practices, mechanistic reasoning, and conceptual aspects of the phenomenon being explored. While in this study we report on a single-group intervention, this method will allow us to identify how the coevolution of student learning and practices emerges across groups within the context of a dynamic activity. It can also be used to compare modeling engagement across student groups, or as a means to link different patterns of student engagement with outcomes such as model sophistication or performance on future tasks.

Finally, these findings speak to two of the broad questions driving this special issue, *How can technology transform teaching and learning as students develop and use models?* And *What key facets of modeling instruction and or design features of modeling curriculum are most essential in promoting student science learning?* Our case study highlights the complementary roles that working across different representational technologies can play in helping learners engage in scientific modeling. It also illustrates that iterative modeling activity across multiple representational technologies can sustain and deepen student learning and engagement. Rather than seeming repetitive or less interesting to the participants, we found that re-presenting models of smell diffusion in new ways led the girls in the workshop to create increasingly causal, sophisticated, and generative models of smell diffusion, while still remaining fundamentally tied to (and hence beholden to) their own experiences and ideas of smell. These patterns became more evident when explored as part of a system involving modeling practice, conceptual engagement, causal reasoning, and representation as interrelated components of scientific inquiry.

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Appendix 1

See Table 5.

Table 5 The table presents the coding scheme used in study, including the categories, descriptions of the categories, and citations of literature that supported the a priori establishment of reasoning and practices codes

Category	Description	Related literature
Reasoning about mechanism		
Describing Phenomenon	Wondering, providing examples of the phenomenon without linking them together or with a model; brainstorming ideas, relationships between ideas, and experiences with the target phenomenon	Russ et al. (2008); Hawkins (1974); Hammer (2004)
Determining setup conditions	Attending to the conditions and components of the target phenomenon; considering spatial and temporal arrangements; and considering states of entities in the target phenomenon	Russ et al. (2008); Schwarz et al. (2009)
Entities and their properties	Consideration and identification of the objects/things relevant to the target phenomenon; consideration of their properties and representations. Describing the state of the entity, without describing the "space between"	Russ et al. (2008)

Table 5 continued

Category	Description	Related literature
Entity behaviors	Explicit consideration of the behaviors of the entities—e.g., how they move, why they move—with a level of entity by entity description and detail. Describing the "space between" states of the entity	Russ et al. (2008); Schauble (1996)
Entity interactions	Explicit consideration of the interactions between entities, the range of possible results of those interactions, and connections between individual entity behaviors and multi-entity interactions and/or observable effects	Russ et al. (2008); Schauble (1996)
Modeling practices		
Referencing past experience	Conversation referencing some experience with the target phenomenon used to either propose, call into question, confirm, or refine some aspect of the model	Schwarz et al. (2009)
Representation	Symbolizing entities, behaviors, interactions, and other aspects of the model (e.g., drawing a pink curly line for scent, making an oogtom out of pixels in StageCast, and creating a specific term/name for something in discussion)	Lehrer and Schauble (2000); Manz (2012)
Explicit selection	Explicit decisions about what to include as elements/components of the model; evidence of a field of elements/components from which they chose	Manz (2012); Schwarz et al. (2009)
Evaluating w/r/t the world	Considering the model from the standpoint of personal experiences and perceptions of smell in the known (to the participant) world (e.g., "That's not right because so-and-so is SUPPOSED to smell the same amount"). Evaluation is directed to the model, specifically, as opposed to discussion of the target phenomenon, generally	Schwarz et al. (2009)
Revising the model	Refinement, addition, pruning, or reorganization of aspects of the model (e.g., setup conditions, entities, behaviors, and interactions)	Schwarz et al. (2009)
Empirically testing the model	Within the model, enacting of an empirical test to explore a dimension of the model; extending the model to a new context or new conditions (e.g., placement of new smellers within the mapped smelling space)	Schwarz et al. (2009); Manz (2012)
Using model to predict or explain	With a version of the model, a prediction of another context or an explanation of a context related to the model, using the model and described behaviors and interactions	Schwarz et al. (2009)

Ideas about smell diffusion	
Smell goes everywhere	Smell, or scent, goes everywhere within a space (e.g., a room and box)
Smell can vary in strength	Smell has differing strengths and can be time dependent
"Oogtom"	An invented symbol/concept encapsulating the variety of ideas that were discussed, negotiated, and agreed upon for inclusion in a single object to use in the model
Smell moves between object and smeller	Smell, or scent, moves directly from the object to the smeller; with some intended directionality
We perceive smell ("brain processing")	Smell involves a process in our brains/minds
Agentive smelling	The smeller breathing into generate the required action to bring smell from the object to the smeller
Wind spreads smell	Smell, or "scent", however identified, is moved by wind at meso and macroscales
Smell is particles like atoms	Smell is comprised of small particles, called "scent" earlier on and "oogtom" as ideas about smell were developed
Force	Either internal or external, there are forces that influence how smell moves from object to smeller
Breathing v. smelling	Discussion of a difference between breathing and smelling; at times they are considered the same, at other times they are considered different
Smell and air are/become one	Smell, or scent, and air are the same thing
Water vapor; things smell when wet	Water and water vapor influence how smell is formed, its intensity, and its transmission
Smell and air are different	Smell, or scent, is distinctly different from air

Appendix 2

Examples of coding disagreement (Hammer and Berland 2013).

Here, we describe three main types of systematic disagreement that emerged during analysis.

Type 1) Describing Phenomenon vs Setup Conditions. One frequent disagreement was between identifying reasoning about mechanism as *Describing Phenomenon* or *Defining Setup Conditions*. For example, the quote "We were deciding whether the skin of the orange smelled more pungent than the actual fruit part." was coded by one author as *Describing Phenomenon*, since Eileen was recalling a general exploration, but coded by another author as *Setup Conditions*, since Eileen highlights the skin and flesh of the orange as different potential setups of the model. We preserved these disagreements because it might be unclear even to learners whether a particular noticing about the phenomenon will yield explicit selection of model components.

Type 2) Entailments of Setup Conditions. If a coder identified an exchange as involving *Setup Conditions* rather than *Describing Phenomenon*, they were also more likely to subsequently identify *Entities & Properties, Behaviors* or *Interactions* for the same code. For example, if a coder identified Eileen's quote above about skin and fruit as *Setup Conditions*, they may subsequently code references to skin and fruit as *Entities & Properties* (the orange as peeled or unpeeled) of the model. We preserved these disagreements as evidence of the messiness of elaborating, articulating, and problematizing aspects of the phenomenon to be modeled.

Type 3) Representations as Evidence. There was some disagreement over whether participants did or did not reason about *Behaviors* or *Interactions* during a given video segment. Often, these disagreements had to do with whether the coder considered evidence from participants' representational artifacts. For example, one group of girls placed a series of pipe cleaners emitting from an orange and pointing toward a nose in their animation. The group never verbally articulated why they did this, but the animation showed smell particles traveling in the direction they were pointing. One author used the animation as evidence for the codes *Representation* of *Entities* and *Behavior*—of the smell particles and their movement. Another who relied on the transcript only coded for *Representation* of *Entities*, but not their behavior. We preserved these disagreements because coders did not always have access to what participants did physically, and because coding participants' representations without evidence from participant talk is necessarily interpretive.

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