Journal of Science Education and Technology
https://doi.org/10.1007/s10956-021-09930-3

Affordances of Computational Models for English Learners in Science Instruction: Conceptual Foundation and Initial Inquiry

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Accepted: 29 July 2021

Abstract

Computational models are increasingly being used in K-12 science classrooms to engage students in developing and testing explanations of phenomena. However, research has only begun to consider whether integrating computational models into science instruction could be particularly beneficial to students from diverse backgrounds, including a fast-growing population of English learners (ELs) in the U.S. context. As this research begins to take shape, we argue for moving beyond the traditional discourse focused on "accommodating" ELs, which de-emphasizes the assets these students bring, and shifting our attention to the distinct *affordances* that computational models offer for harnessing ELs' rich meaning-making potential. In this article, we conceptualize the affordances of computational models for ELs in science instruction. Specifically, we highlight evolving theories in the field of language education that undergird the shift from accommodations to affordances with ELs in the science classroom. We then propose affordances of computational models for ELs in relation to three framework components: *modalities*, *registers*, and *interactions*. Finally, we report on an initial inquiry into these affordances using student interview data from a linguistically diverse elementary science classroom. Ultimately, we argue that an affordances perspective could inform research and the design of learning environments that contribute to broadening participation in science learning and refuting deficit-based views of students traditionally underserved in STEM subjects.

Keywords Computational models · English learners · Science education · Affordances · Equity

Computational models, or representations of phenomena that can be simulated by a computer (Weintrop et al., 2016), have assumed an increasingly prominent role in K-12 science instruction. This prominence can be attributed to both the rapidly changing nature of STEM disciplines (e.g., Foster, 2006) and science education reform movements that seek to authentically reflect disciplinary work (e.g., National Research Council, 2012). In the U.S. context, for example, the Next Generation Science Standards (NGSS) identify "using mathematics and computational thinking" and "developing and using models" as two key science and engineering practices. To support K-12 students' participation in these practices, researchers have designed innovative curricula and interventions that integrate computational models into science instruction (e.g., Basu et al., 2016; Campbell & Oh, 2015; Haas et al., 2020; Lee et al., 2020; Sengupta et al., 2013; Yoon et al., 2018). However, relatively less is known about whether computational models could create more equitable and inclusive science learning environments for students from diverse backgrounds (National Academies of Sciences, Engineering, and Medicine [NASEM], 2018, 2021).

At the same time that science classrooms are becoming more computational in nature, they are also becoming more linguistically diverse. In the U.S. context, students classified as English learners (ELs) comprise more than 10% of the student population (National Center for Education Statistics, 2021) and are expected to meet grade-level science standards through a language they are still developing. Traditionally, the discourse around ELs in science instruction has emphasized *accommodations* as a way to compensate for these students' developing English and facilitate their inclusion in the classroom. However, this perspective fails to recognize the rich repertoire of meaning-making resources—both linguistic and multimodal—that ELs bring to science classrooms and that can support their engagement in rigorous

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Published online: 06 August 2021

disciplinary practices (Canagarajah, 2018; Grapin, 2019). Thus, rather than view the increasing prevalence of computational models as yet another challenge for ELs to overcome, we propose foregrounding the distinct *affordances* these models offer for harnessing ELs' meaning-making potential. To realize this shift from accommodations to affordances with ELs, the fields of science and STEM education could benefit from engaging more substantively with theoretical insights from the field of language education related to what it means to know and use a language.

In this article, we conceptualize the affordances of computational models for ELs to communicate and construct their science understanding. We begin by providing contextual background on computational models in science instruction with ELs. Next, we describe our conceptual foundation. Specifically, we highlight the evolution from structural to ecological theories in the field of language education that undergirds the shift from accommodations (rooted in structural theories) to affordances (rooted in ecological theories) with ELs. Based on this affordances perspective, we propose affordances of computational models for ELs in science instruction in relation to three framework components (Lee et al., 2019): *modalities*, *registers*, and *interactions*. Finally, we report on an initial inquiry into these affordances using student interview data from a linguistically diverse elementary science classroom. Ultimately, we argue that, as computational models occupy an increasing presence in K-12 science instruction, an affordances perspective could inform research and the design of learning environments that contribute to broadening participation in science learning and refuting deficit-based views of students traditionally underserved in STEM subjects (NASEM, 2018).

While acknowledging that a variety of learning goals are possible when integrating computational models into science instruction (Bortz et al., 2020), including students' understanding of computational thinking concepts (e.g., Grover, 2017) and the nature and purpose of models (e.g., Schwarz et al., 2009), in this article, we use the term "science understanding" to refer to students' conceptual understanding of science ideas relevant to explaining phenomena in the natural world. Additionally, we use the term "computational models" in reference to both the models themselves and the practice of developing, revising, and/or using them (i.e., computational model*ing*).

Computational Models Integrated into Science Instruction with English Learners

Whereas computer-based simulations have a long history in science education (e.g., Quellmalz et al., 2012), computational models are a more recent arrival. This is, in part, due to the advent of blocks-based visual programming environments (e.g., Scratch, StarLogo Nova) that alleviate the demands of text-based programming syntax and, in so doing, render computational modeling more accessible to novices, including elementary students. Blocks-based programming environments allow users to write computer programs by snapping together blocks that provide visual cues (e.g., color, shape) regarding their functions (Weintrop & Wilensky, 2015). Blocks-based programming environments such as StarLogo Nova are agent-based, meaning students write computer programs for agents in a system (e.g., interactions between organisms in an ecosystem) and then run their programs to observe aggregate system-level behavior (e.g., how the composition of the ecosystem changes over time). By making visible these agent-aggregate relations in systems, agent-based programming environments are powerful tools for developing and testing mechanistic explanations of phenomena (Hsiao et al., 2019). Because blocks-based, agent-based programming environments are accessible to a wide range of students *and* powerful for explaining phenomena, these environments have been described as "low threshold, high ceiling" (Weintrop & Wilensky, 2015) for engaging K-12 students in computational modeling.

Over the last decade, researchers have ramped up their efforts to investigate empirically the benefits of integrating computational models into science instruction. This surge in research interest is evidenced by two special issues of the *Journal of Science Education and Technology*—one focusing on science modeling with technology (Campbell & Oh, 2015) and another focusing on computational thinking from a disciplinary perspective (Lee et al., 2020). Studies in these two special issues provide evidence that, across contexts and grade levels, computational models afford opportunities for students to engage in authentic versions of the science modeling practice (e.g., Xiang & Passmore, 2015), explore dynamic systems that exhibit emergent behavior (Brady et al., 2015), and deepen their conceptual understanding (e.g., Aksit & Wiebe, 2020). As one example, in their recent intervention study that integrated computational modeling into physical science instruction with middle-school students, Aksit and Wiebe (2020) found that the "dynamic nature of computational models let students both observe and interact with the target phenomenon in real time" (p. 65) and, as a result, develop their understanding of complex force and motion concepts. Moreover, studies have demonstrated that computational models can be particularly powerful tools when introduced in concert with complementary forms of representation (e.g., drawings, physical objects) and when facilitated by well-designed teacher and curricular supports (e.g., Wilkerson-Jerde et al., 2015).

While the benefits of computational models in science instruction have been documented, research has only begun to address considerations for diverse student groups, such as ELs (Jacob et al., 2018; NASEM, 2021; Pierson et al., 2020, 2021; Vogel et al., 2019). As one illustration of this point, Aksit and Wiebe (2020) reported that, while their intervention resulted in conceptual learning gains for student participants, on average, ELs "might not have benefited from the learning activities as much as other students whose native language was English" (p. 79). This finding coheres with a broader trend indicating "only nascent research... on computing learning for English language learners" (NASEM, 2021, p. 114) and suggests the need for further conceptual and empirical work aimed at fostering more equitable learning opportunities for ELs in science instruction that integrates computational models. This work must begin with a theoretically grounded understanding of what it means to know and use a language, which is a question we take up in the next section.

Conceptual Foundation

In this section, we lay the foundation for conceptualizing the affordances of computational models for ELs in science instruction. We begin by describing evolving theories of what it means to know and use a language in the field of language education. Next, we describe how these evolving theories undergird the shift from accommodations to affordances with ELs in the science classroom. Finally, we propose affordances of computational models for ELs in relation to three framework components.

Knowing and Using a Language

The field of language education attempts to answer the question, "What does it mean to know and use a language?" Traditionally, answers to this question have been informed by *structural* theories (see Larsen-Freeman, 2007 for a historical review and critique). Structural theories conceive of language in terms of its formal elements, specifically its lexical (i.e., vocabulary) and syntactic (i.e., grammar) structures. According to structural theories, language exists as an abstract store of knowledge in the minds of its users independent of its contexts of use. Thus, developing language competence is a matter of increasing the inventory of lexical and syntactic structures that an individual has internalized, for example, acquiring more specialized vocabulary (e.g., "photosynthesis") and more complex grammatical forms (e.g., compound sentences with multiple embedded clauses). Because structural theories view context as the backdrop for displaying one's individual competence rather than a veritable source of meaning potential (Canagarajah, 2018), these theories have traditionally paid minimal attention to nonlinguistic aspects of communication (e.g., gesture). Instead, structural theories focus on language as an abstract entity residing in the individual learner (Larsen-Freeman, 2007).

More recently, the structuralism that dominated theoretical understandings of language for decades has given way to more socially oriented theories (Zuengler & Miller, 2006). As one branch of the sociocultural tradition, *ecological* theories turn attention to the relation between learners and their environment (van Lier, 2003, 2004). According to ecological theories, what makes a language user competent is not the set of language structures they have internalized but how they marshal communicative resources made available in their environment to create situated meanings. These meanings are situated because they emerge from and depend on the environment to do their semiotic work (Moschkovich, 2002). For example, whereas structural theories view lexical terms as preordained with readymade meanings (i.e., "yellow" as referring to a color in the visible spectrum), ecological theories attend to the meanings that language users assemble in context in response to affordances in their environment (e.g., yellow, when uttered by a customer pointing to a shirt in a department store, could express to the clerk which shirt the customer intends to purchase). As this example makes evident, ecological theories conceive of nonlinguistic aspects of communication (e.g., gesture) not as "paralinguistic resources that help when language is not adequate for the purpose" (Canagarajah, 2018, p. 39) but as legitimate meaning-making resources that are indispensable to engagement in goal-directed activity. In this way, ecological theories "step out of the individualism that treats each speaker/writer as the locus of competence and focus on the whole activity to address how diverse participants and semiotic resources work as an assemblage to shape meanings" (Sharma & Canagarajah, 2020, p. 5).

In sum, structural and ecological theories differ in how they conceive of context and multimodality, thus resulting in divergent conceptions of the locus of language competence. With regard to context, structural theories posit language as a decontextualized set of structures, whereas ecological theories posit language as inseparable from its contexts of use. With regard to multimodality, structural theories focus narrowly on language, whereas ecological theories focus on how language is entangled with meaning potential in the environment. These differential conceptions of context and multimodality shift the locus of language competence from the individual learner (i.e., what the individual can do with language in the abstract) to the individual-in-environment (i.e., what the individual can do with language and nonlinguistic meaning-making resources in a particular context).

Whether one adopts structural or ecological theories as a conceptual foundation has significant implications for their perspective on how to include ELs in science instruction that integrates computational models. As Valdés et al. (2014) have cautioned, when answers to the question of "What does it mean to know and use a language?" are tacitly assumed rather than explicitly articulated, efforts to promote inclusion of ELs in disciplinary learning risk being incoherent, at best, and further marginalizing this vulnerable student population, at worst. We argue that explicitly articulating a conceptual foundation is particularly crucial in a nascent area of inquiry, such as computational modeling with ELs in science instruction.

From Accommodations to Affordances with English Learners

Consistent with structural theories, the inclusion of ELs in science classrooms has traditionally been addressed from an accommodations perspective (e.g., Echevarría et al., 2011). Accommodations are changes to disciplinary tasks that make the tasks more accessible (Thurlow & Kopriva, 2015), including visual accommodations (e.g., pictures to support comprehension of a reading passage) and linguistic accommodations (e.g., sentence frames to support writing of an explanation). Such accommodations were commonly recommended in early research focused on ELs in science classrooms (see Fathman & Crowther, 2006 for a review). The premise of accommodations is that since ELs have not yet internalized the language structures considered prerequisite to participating in science learning (e.g., technical science terms and complex grammatical structures), these students require accommodations to repair their perceived deficiencies. While accommodations can, in some instances, be useful for facilitating ELs' access to science instruction, accommodations, by their very nature, emphasize the *distance* between ELs' abilities and the demands of science tasks. In other words, accommodations emphasize what ELs cannot do but fail to recognize the rich repertoire of meaning-making resources they bring to science classrooms. In this way, an accommodations perspective can inadvertently position ELs as disciplinary outsiders who require remediation to be considered legitimate participants in their classroom communities.

With the shift from structural to ecological theories of language, we propose the need to shift from an accommodations to an affordances perspective on ELs in science classrooms. In contrast to accommodations, affordances emphasize the *match* (rather than the distance) between learners and their environment. Specifically, affordances are "what [the environment] *offers* the animal" (Gibson, 1979, p. 127). For a squirrel, an affordance of a tree is shelter; for a group of picnickers, it is shade on a hot day. Thus, affordances are best understood as "relations of possibility that yield further opportunities for engagement and participation" (van Lier, 2004, p. 81). In the department store example above, the interactional context between the customer and clerk, combined with the presence of the yellow shirt in that context, provided affordances for the customer to indicate the item they intended to purchase simply by pointing and saying "yellow." Importantly, from an affordances perspective, the customer's lack of elaboration would not be seen as a deficiency in their language competence but a product of the situated communicative activity in which they were taking part.

In science classrooms, ELs also act on affordances made available in their environment through engagement in goal-directed disciplinary activity (Walqui & Bunch, 2019). These affordances can be physical, as in a measurement scale that allows an EL to express an observation indexically by pointing at the scale (Moschkovich, 2015), or symbolic, as in a dialogue with peers or a teacher to grapple with an idea (Kibler et al., 2020). In science instruction that integrates computational models, affordances are made available not only by the physical and symbolic environment surrounding the learner but also the *computational* environment that facilitates the model's creation. This computationally enriched science learning environment affords a "rich semiotic budget of resources" (van Lier, 2004, p. 81) for ELs to perceive and act upon as they make meaning of science. Unlike accommodations, which are typically add-ons or afterthoughts to science learning, affordances emerge in the context of authentic engagement in science disciplinary practices (e.g., modeling).

Overall, a shift from an accommodations to an affordances perspective reorients our focus from remediating what ELs lack in terms of the structural elements of language (i.e., locus of competence as individual) to designing learning environments that harness ELs' rich meaning-making potential (i.e., locus of competence as individual-in-environment). From an affordances perspective, ELs bring a wealth of meaning-making resources to their science learning that is optimized by semiotically rich learning environments and, as we will argue, computationally enriched science learning environments. By positioning the meaning-making potential of ELs as matched to (rather than distant from) science learning environments, an affordances perspective could "flip the script" on deficit-based views of ELs and create more equitable opportunities for these students to participate—and be *seen* as participating—meaningfully in science learning.

Affordances of Computational Models for English Learners in Science Instruction

We propose affordances of computational models for ELs in science instruction in relation to three components: (a) modalities, (b) registers, and (c) interactions. These three components build on our existing framework for language use in the science classroom (Lee et al., 2019), which was featured prominently in a recent consensus report on ELs in STEM subjects (NASEM, 2018). Whereas the existing framework describes affordances made available in the science classroom in relation to each component (summarized briefly below), we extend the framework by conjecturing how these affordances are likely to be enhanced by computational models. Consistent with a sociocultural perspective that views communication and sense-making not as separate but as intertwined (Howe, 1996; Vygotsky, 1986), we highlight the potential affordances of computational models for both *communicating* science understanding (i.e., communication) and *constructing* science understanding (i.e., sense-making). Although some affordances could apply to computational models broadly, we focus specifically on computational models that employ blocks-based programming given the increasing prevalence of these programming environments in science classrooms (e.g., Lee et al., 2020).

Modalities

Modalities refer to sets of semiotic resources for making meaning (Bezemer & Kress, 2008), including visual, linguistic, and actional modalities. Whereas science instruction (and schooling generally) has traditionally privileged linguistic modalities, especially written language (see Kress, 2000 for a critique), visual (e.g., drawing) and actional (e.g., gesture) modalities offer distinct affordances for all students, including ELs, to engage in science disciplinary practices (Grapin, 2019; Jewitt et al., 2001; Kress et al., 2014).

We conjectured that computational models would enhance these affordances by introducing another powerful modality for ELs to communicate and construct their science understanding—*the blocks-based visual code modality*. This modality provides a rich budget of semiotic resources (e.g., arrangement of code blocks, color trait of agents), with each resource offering distinct meaning-making potentials (e.g., color to distinguish between agents with different rules of behavior). The decisions students make in configuring and combining these resources provide a window into their thinking. For example, by configuring code blocks in hierarchical relations (e.g., a block is executed only if the condition specified by its superordinate block is met), students are able to represent conditional relationships and causal chains of events underlying phenomena. When students run their code and make sense of the outcome, they engage with additional semiotic resources, including dynamic visualization, data boxes, and graphs, which students interpret in relation to their agent-level code to uncover the (often surprising) agent-aggregate relations in the system being modeled (Wilensky & Reisman, 2006). Beyond the modalities within the computational model itself, the presence of the model in an interactional context (e.g., multiple participants interacting around the same model) is likely to increase the salience of other modalities, such as gaze and gesture, to facilitate joint attention (discussed further as part of "Interactions" below).

Registers

Registers refer to ways of using language in different contexts. Registers exist on a continuum from more everyday (i.e., the language used in daily life) to more specialized (i.e., the language used among members of a particular community to carry out their collective work). Whereas science instruction has traditionally privileged the specialized science register, especially technical science terms (e.g., August et al., 2016), the use of multiple registers in combination offers distinct affordances for ELs to make meaning of science (Brown & Ryoo, 2008; Grapin et al., 2019; Ryoo, 2015; Warren et al., 2001).

We conjectured that computational models would enhance these affordances by adding another register—*the specialized programming register*. Blocks-based programming environments have their own ways of using language that borrow terms and phrases from other registers (e.g., "collide" as an everyday term) but give those terms/phrases specialized meanings that provide the tools to model complex systems (e.g., "on collision with" as a way of specifying an interaction of agents). For example, to describe the interdependent relationships among organisms in an ecosystem, students may draw from the everyday register (e.g., "shark eats fish") and the specialized science register (e.g., "predator eats prey") but also the specialized programming register from the code underlying their computational model (e.g., "shark, on collision with fish, delete collidee"). Given that complex systems are notoriously difficult to describe in language (e.g., Chi, 2005), this specialized programming register could provide affordances for ELs to communicate and construct their science understanding while they are still developing the specialized science register frequently expected in science classrooms.

Interactions

Interactions refer to the settings and participants involved in communication, including one-to-one interactions (e.g., one student talking/writing to a partner) and one-to-many interactions (e.g., one student talking/writing to an audience not immediately present). Whereas science instruction often prizes explicit language use associated with one-to-many interactions (e.g., avoiding deictic expressions, such as "this one here"; Avenia-Tapper & Isacoff, 2016), one-to-one interactions offer distinct affordances for ELs by providing a shared frame of reference and opportunities to clarify, elaborate, and negotiate meaning in real time (e.g., one participant asking another, "What do you mean?"; Bailey & Heritage, 2014; Grapin, 2020; Ruiz-Primo, 2011).

We conjectured that computational models would enhance these affordances by adding another type of interaction—*one-to-one-to-model interaction*. This triadic communication (van Lier, 2004) involving two human participants interacting around one computational model could allow ELs to leverage resources in the immediate context to communicate their science understanding (e.g., deictic gestures and expressions to indicate agents in their models). However, beyond being objects of joint attention, computational models could themselves become veritable participants in interaction (Pierson et al., 2020). Computational models are executable, that is, they "run semi-independently of their human authors" (Brady et al., 2015, p. 278). Therefore, students could run their models and receive real-time feedback (in the form of data produced by the model) that helps them construct their science understanding and the language to communicate that understanding in real time. Even when students do not actually run their computational models, the models could serve as artifacts for participants to collectively think with (Papert, 1980).

Overlap and Synergy of Affordances

Although the affordances related to each component of our framework have been presented separately for conceptual clarity, they are best understood as overlapping and synergistic. For example, the specialized programming register (i.e., the natural language appearing on the code blocks and simulation interface) is embedded within the blocks-based code modality. Likewise, the physical context of a one-to-one-to-model interaction makes salient the use of certain modalities (e.g., gesturing at the model to facilitate joint attention with another human participant). Given these overlaps, we conjectured that the affordances related to the three components would work synergistically. For example, to explain a phenomenon, a student might run their model with a human participant (*interactions*) and then use the data and visualization produced by the model (*modalities*), in combination with specialized programming language (*register*), to construct their science understanding and communicate their explanation.

Initial Inquiry

We conducted an initial inquiry into the affordances of computational models for ELs in an elementary science classroom. Given the early stages of this work and the limited research literature on computational models with ELs in science instruction (e.g., NASEM, 2018, 2021), the analyses reported here focused on exploring the theoretical cogency and practical plausibility (Berland et al., 2020) of our argument that computational models offer distinct affordances for ELs to communicate and construct their science understanding. This initial inquiry into "what is *possible*" (Berland et al., 2020, p. 278) is meant to lay the groundwork for further conceptual refinement and empirical inquiry in future research efforts.

Curriculum

The data come from a larger design-based research project focused on developing and implementing a yearlong fifth-grade NGSS-aligned curriculum that integrates computational models into science instruction (nyusail.org). During the 2019–2020 school year, five teachers implemented the curriculum in their urban science classrooms. In the teacher's classroom with the largest number of ELs, eight students formally classified as ELs agreed to participate in artifact-based interviews (i.e., the focus of the analyses reported here). All eight were at an intermediate level of English proficiency (Level 3 of 6), as determined by an English proficiency assessment administered annually by the school (as per federal and state law). Five participants identified as male and three as female, and all were Spanish speakers.

In each of the four instructional units that comprise the yearlong curriculum, students developed a computational model using StarLogo Nova in order to explain a science phenomenon. We focused on the first instructional unit in which students were explaining the phenomenon of what happens to garbage in their local community while developing their understanding of physical and life science ideas in the NGSS for fifth grade (e.g., conservation of weight, decomposition). Prior to developing their computational models, students created physical landfill bottles of open and closed systems (Fig. 1) and observed changes in the properties and weight of food materials over time. Upon observing that the weight of the closed system did not change, even as the food materials appeared to vanish, students developed computational models to explain how microbes decompose food materials from a solid to a gas while conserving weight in the closed system. Decomposition and its relation to conservation of weight are challenging science topics for young students (Cetin, 2007; Ero-Tolliver et al., 2013; Smith & Anderson, 1986).

Artifact-Based Interviews

At the end of the instructional unit, students participated in artifact-based interviews (Brennan & Resnick, 2012), which are commonly used to elicit what science ideas students have learned in studies that integrate computational models into science instruction (e.g., Aksit & Wiebe, 2020). Given the

Fig. 1 Physical landfill bottle systems (open and closed)

nascent nature of our conjectures, the interview context, as compared to the classroom context, provided a more manageable system to focus our initial inquiry (i.e., two human participants interacting around one computational model). Future studies could build on this initial inquiry to investigate the affordances of computational models for ELs in the more complex system of classroom activity (see "Future Research Directions" section).

The artifact-based interviews focused on eliciting students' understanding of the phenomenon they had modeled, specifically how microbes decompose food materials from a solid to a gas and how this process conserves weight in a closed system. Either the first or third author met individually with each student interview participant. Before each interview, the interviewer uploaded the student's computational model to a laptop computer. Each student participant was asked to sit next to the computer such that they could interact with their model in a way that was clearly visible to the interviewer, thus setting up a one-to-one-to-model interaction among the student, interviewer, and computational model. This "ecological huddle" (Canagarajah, 2021, p. 9), or configuration of bodies and objects with a shared focus of attention, is pictured from the interviewer's vantage point on the right side of Fig. 2.

At the beginning of the interviews, students were asked broadly to describe their computational model ("What does this model show?"). Contingent on students' responses, the interviewer drew from a menu of questions aimed at further eliciting students' science ideas (see Haas et al., 2020 for more details). The interviews lasted, on average, 12 min, and the complete corpus comprised approximately 100 minutes of video/audio data. Interviews were transcribed using multimodal conventions (Flewitt et al., 2017) to capture students'

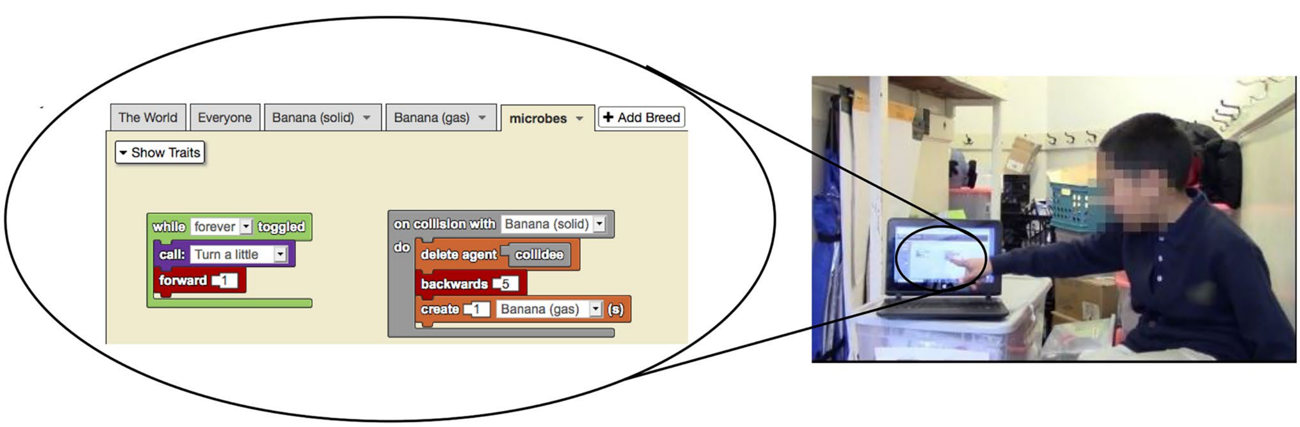

Fig. 2 Ricardo's computational model (code blocks)

gestures as well as their on-screen interactions with their computational models.

The transcripts were analyzed in two phases. In the first phase, we looked across the transcripts to identify instances in which students leveraged affordances related to each component of our framework (modalities, registers, interactions). This phase began with the first and third author co-viewing the videos and co-reading the transcripts for two student interviews to develop the initial coding scheme (Powell et al., 2003). The unit of analysis was an utterance; however, given the nested nature of interactional discourse (i.e., utterances nested within turns of talk), this unit was expanded, as needed, to capture sequential interactions among participants (e.g., student produces an utterance, interviewer requests clarification, student responds with another utterance; Furtak et al., 2017). Consistent with our conjecture that the three components would work synergistically, utterances were frequently assigned multiple codes (e.g., after running the model [*interaction* with model], a student says, "These two right here [actional *modality*] collide together [specialized programming *register*]."). This deductive coding, based on our framework, was followed by a round of inductive analysis to identify more nuanced distinctions within each component (e.g., within modalities, "agent color" and "deictic gestures"). The first and third authors coded the remaining transcripts independently and then met to resolve discrepancies, refine the scheme, and come to consensus through discussion.

In the second phase, and consistent with a theory of affordances as emergent and situated in relations between learners and their environment (Walqui & Bunch, 2019), we looked within each interview at how affordances emerged in moment-to-moment interaction and were acted upon in ways useful to each student. Following guidance from multimodal interaction analysis (Norris, 2004), we focused specifically on excerpts exhibiting high modal density in each interview, defined as excerpts in which students leveraged multiple affordances related to our framework toward performing a higher-level action (in our case, constructing an explanation of the phenomenon they were modeling). Within these excerpts of high modal intensity, we analyzed how students deployed different modalities (e.g., visual, linguistic, actional) and shifted between registers (e.g., everyday, specialized programming, specialized science) in response to interactions with their computational models and the interviewer. In keeping with our conceptual foundation that considers "all resources working together as an assemblage in shaping meaning"(Canagarajah, 2018, p. 31), the three components of our framework were analyzed collectively in this phase (rather than in a multipass serial process).

Excerpts from Two Student Interviews

We present excerpts from two student interviews to illustrate patterns that emerged from our initial inquiry. By focusing on these two interviews, we are able to illustrate, with sufficient depth and turn-by-turn detail, the practical plausibility of the affordances we have proposed. While both interviews speak to affordances related to all three components of our framework (modalities, registers, interactions), each interview foregrounds particular affordances. The first interview highlights how ELs drew flexibly from multiple *modalities* and *registers* within and around their computational models to communicate their science understanding. The second interview highlights how *interactions* with their computational models and a human participant (i.e., the interviewer) invited ELs to construct their science understanding and the language to communicate that understanding in real time. While our primary interest in presenting the excerpts is to illustrate the framework's practical plausibility (rather than bolster claims about typicality or generalizability that should be the focus of future empirical inquiry), at the end of each excerpt, we comment on its representativeness in the context of the interview data.

Ricardo: Focus on Modalities and Registers

Figure 2 shows the code blocks that Ricardo assembled in the blocks-based visual code modality to communicate his understanding of how microbes decompose a banana from a solid to a gas. Ricardo included multiple agents in his model, including "banana (solid)," "banana (gas)," and "microbes." By programming the bulk of his code in the microbes' tab (pictured in Fig. 2), Ricardo established microbes as the central agent responsible for decomposing the banana. Within this tab, Ricardo programmed an interaction in which each microbe agent, upon colliding with a solid banana agent (in other words, feeding on it), deleted the solid banana agent and created a gaseous banana agent. By embedding the "delete" and "create" blocks inside of the "on collision" block, Ricardo represented his idea that the interaction between microbes and solid banana is what causes the solid banana to vanish and a gaseous banana to be produced. While some of Ricardo's classmates developed similar representations of decomposition, others programmed their code such that microbes deleted the solid banana *without* creating a gas, resulting in a decrease in weight of the closed landfill bottle system. Thus, Ricardo's representation in the blocks-based visual code modality operationalized a sophisticated understanding of decomposition that became the basis for his explanation in the interview.

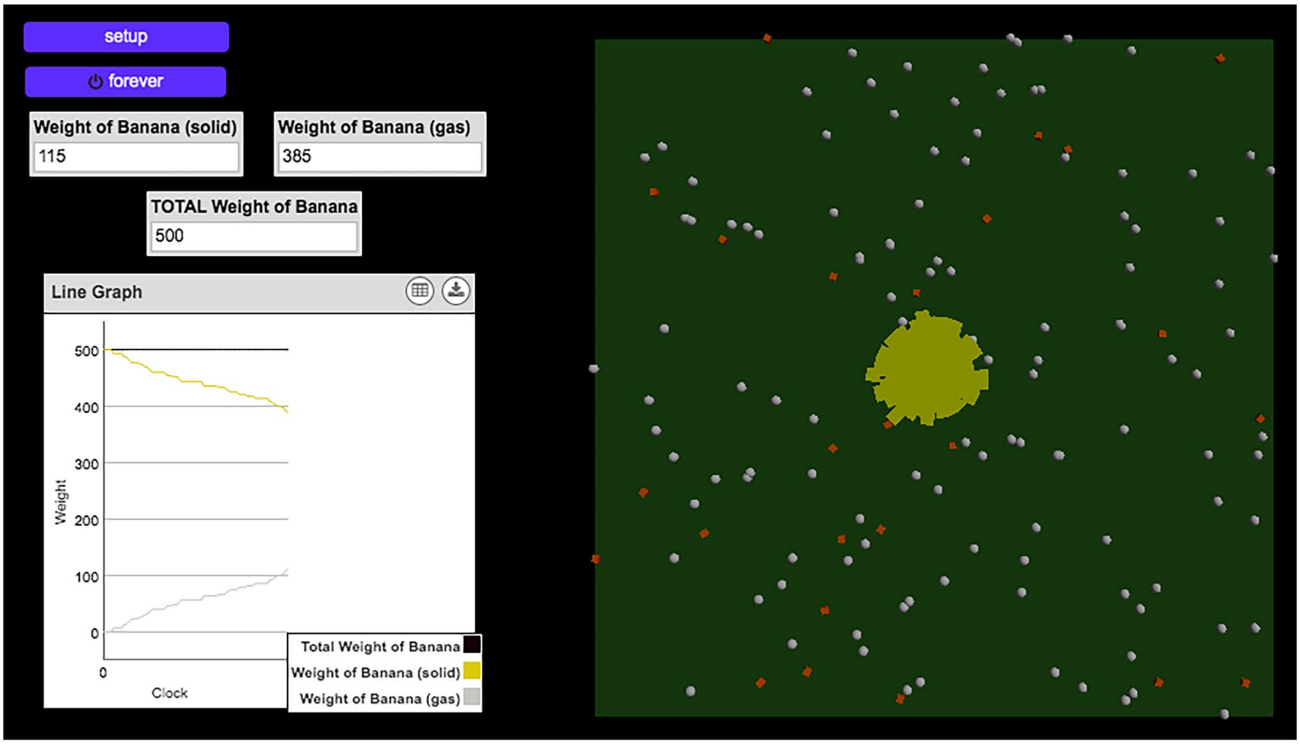

Fig. 3 Ricardo's computational model (simulation interface)

At the beginning of the interview, Ricardo scrolled to the simulation interface (Fig. 3) and described his model as follows:

> Ricardo: When they [the microbes] touched the banana solid, it turned into gas. The banana. We put to the banana solid that it couldn't move, and it would only be a blob that's . . . that's yellow. And the microbes would be the orange one. Every time they touched the . . . (*points to solid banana*), there would . . . it would . . . it would multiply the banana gas that would be white. And any time they touched it, the white would gain, and this would lose (*points to solid banana data box*).

In this excerpt, Ricardo deployed resources from multiple registers and modalities. First, he paraphrased the specialized programming register from his computational model ("microbe, on collision with Banana [solid]...") in a more everyday register ("when [microbes] touched the banana solid, it turned into gas"). Then, he established the different agents—still using the agent names as they appeared in their respective tabs (e.g., "banana gas" instead of gaseous banana)—and identified the color trait associated with each agent (e.g., white for banana gas). While, at first, the colors appeared superfluous to his explanation, for Ricardo, they created a shorthand that would allow him to reference these agents and make connections between the visual simulation and the data boxes in his model. Ricardo explained that, when microbes touched the solid banana, "the white would gain," in other words, the weight of the gaseous banana would increase. He also used deictic gestures and expressions to communicate that the weight of the solid banana would simultaneously decrease ("*this* would lose" while pointing at the solid banana data box). Later in the interview, Ricardo would build on this initial explanation by reformulating it in a way that more closely approximated the specialized science register: "The weight of the banana gas will gain weight, but the total weight of the banana would stay the same."

Summary of Ricardo's Excerpt Ricardo drew flexibly from multiple modalities and registers within and around his computational model to communicate a sophisticated understanding of decomposition and its relation to conservation of weight. Although the linguistic modality has typically been considered "the standard precision of meaning" (Lemke, 2002, p. 31), Ricardo's use of the blocks-based visual code modality demanded as much, if not greater, precision as the linguistic modality in representing the process of decomposition. For example, the code modality required Ricardo to make a commitment (Bezemer & Kress, 2008) to the ratio of solid banana deleted and gaseous banana created (1:1) that would conserve weight in the closed system—an aspect of the science idea that might otherwise have been glossed over by a linguistic explanation alone (e.g., a student simply parroting that microbes decompose the banana and produce gas). Importantly, the opportunity to use multiple modalities was not a compensatory modification to bridge the *distance* between Ricardo and the computational modeling task (i.e., accommodations perspective) but a result of the *match* between the task expected of all students and Ricardo's meaning-making potential (i.e., affordances perspective).

Ricardo also benefited from using multiple registers to communicate his explanation, including everyday, specialized programming, and specialized science. While research has underscored the benefits of multiple registers for communicating and constructing science understanding (e.g., Ryoo, 2015), Buxton et al. (2019) caution that the everyday register can "run out of explanatory power for the desired science meaning-making" as students are expected to develop increasingly sophisticated explanations of phenomena (p. 979). The consequence is that ELs could be prevented from demonstrating their thinking while they are still developing English proficiency. However, Ricardo's example shows how the specialized programming register could mediate between ELs' everyday ways of describing phenomena and the more canonical expression of those ideas. Ricardo was able to piggyback (van Lier, 2003) on his use of everyday and specialized programming registers (e.g., "banana gas that would be white would gain") to produce a more specialized science register (e.g., "the weight of the banana gas will gain weight").

Overall, by leveraging affordances made available in his environment—both the computational environment of his model and the physical and symbolic environment surrounding it—Ricardo was able to communicate his science understanding even as he was still developing the specialized science register that is traditionally privileged in science classrooms (e.g., "decompose" and "conservation") but that may have been difficult for Ricardo due to his emerging English. In our interviews, five of eight students (including Ricardo) communicated their explanations by deploying a range of modalities and registers but *without* explicitly naming the process they were modeling (i.e., decomposition). In contrast, the remaining three students used the specialized science register (e.g., "decompose" paired with accurate representations of decomposition in the code modality) even as they were still developing their science understanding and the language to communicate that understanding. This was the case with Martín, whose interview we turn to next.

Martín: Focus on Interactions

As the previous excerpt from Ricardo illustrates, ELs' use of multiple modalities and registers was facilitated by the one-to-one-to-model interaction in which they were co-participating. For example, due to the shared frame of reference afforded by his computational model, Ricardo was able to use deictic gestures (e.g., pointing at the data boxes) and everyday expressions (e.g., "this would lose") to communicate about changes in the weight of the banana. Beyond providing affordances for ELs to communicate science ideas they had already developed, one-to-one-to-model interactions also afforded ELs the opportunity to construct their science understanding in real time along with the language to communicate that understanding. This affordance emerged from ELs' interactions with both their models, which produced data that helped them revise and refine their science ideas, and the interviewer, who prompted them to clarify and elaborate on the science ideas they were developing.

Martín's initial explanation demonstrated an emerging understanding of decomposition and the language to communicate about this science idea:

> Martín: [My model] shows me how, um, the banana decomposes while the microbes, um, decompose the banana. And, um, it showed me when . . . when other fruits were when the, uh, microbes were decomposing it how the gas started keeps around the whole entire model and the world (*moves hands randomly in different directions*).

In this initial explanation, Martín posited two processes: one in which the banana decomposed on its own ("the banana decomposes...") and another in which microbes acted as a mechanism of decomposition ("... while the microbes, um, decompose the banana"). He also described the free movement of the gaseous banana using gesture (moving his hands randomly in different directions) paired with the everyday register ("the gas started keeps...") and the specialized programming register ("... around... the World"; in StarLogo, "World" refers to the area where agents are displayed). However, Martín did not explicitly connect the production of this gas with the decomposition of the solid banana.

Because Martín did not mention the weight data in his initial explanation, the interviewer directed Martín's attention to the data boxes in his model:

> Interviewer: Did you use the data boxes at all? Can you scroll up?
> Martín: (*scrolls up and points to data boxes*)
> Interviewer: Yeah, the data boxes. Did you use those at all?
> Martín: Yeah, and it started to grow a little (*makes rising movement with hand*).
> Interviewer: What do you mean?
> Martín: It started to, um . . . (*points to data boxes*) I think it just stay the same, because the weight just started to go down because of the microbes decomposing it.
> Interviewer: What weight started to go down?

Martín: The banana . . . the banana gas and the total weight.
Interviewer: Why did it go down?
Martín: Because the . . . the microbes started decomposing the banana and the gas started to spread around, so the gas started to go up, but the total weight started to go down.

As Martín scrolled to locate the data boxes, he recalled an observation from his earlier modeling work ("it started to grow a little"), which he accompanied with a rising hand movement to indicate an increase of some kind. In response to Martín's lack of explicitness ("*it* started to grow a little"), the interviewer made two requests for clarification ("What do you mean?" and "What weight?"). While Martín initially indicated that both the gaseous banana and total weight decreased, he subsequently revised his recollection, indicating that the gaseous banana increased (accurate since a gas was produced) while the total weight decreased (inaccurate since the total weight would be conserved in the closed system). Although Martín's recollection was only partially accurate, his explanation moved a step closer to connecting microbes' decomposition of the solid banana with the production of gaseous banana ("the microbes started decomposing the banana *and* the gas started to spread around").

At this point, the interviewer invited Martín to run his computational model:

Interviewer: You wanna run the model right now? See what happens?
Martín: (*runs the model*)
Interviewer: Is it running?
Martín: (*nods affirmatively*)
Interviewer: So, what's happening to the weight?
Martín: The weight . . . all the weight staying the same, but the banana gas is going up.
Interviewer: So, why is that happening?
Martín: Because the microbes are decomposing the banana. And . . . the . . . the gas is getting more larger, but the weight the banana still there . . . it still hasn't disappear, it's just turning into gas.
Interviewer: What do you mean "the gas is getting larger"?
Martín: Because when the microbes decompose the banana, the gas . . . the gas comes outta the banana, and the weight is still there in the landfill bottle.

When the model "spoke" (i.e., produced data), Martín observed that, while the weight of the gaseous banana increased (as he had recalled), the total weight of the closed system stayed the same (*contrary* to what he had recalled). This feedback from the model set the interaction on a new course, prompting Martín to reformulate his idea. When the interviewer invited Martín to revise his explanation in light of the data produced by his model ("So, why is that happening?"), Martín's subsequent response conveyed a more fully elaborated explanatory mechanism, namely, the "[solid banana] turning into gas" as a way of accounting for the gas getting "more larger" but the total weight being "still there." Given that "more larger" could refer to the physical size and/or the weight of the gaseous banana, the interviewer pushed Martín to clarify his intended meaning ("What do you mean 'the gas is getting larger'?"). Martín's final explanation reached toward causality in a way that his explanation at the beginning of the interview did not, positing a relationship between microbes decomposing the banana from a solid to a gas ("when the microbes decompose the banana, the gas comes outta the banana...") and conservation of weight in the closed landfill bottle system ("... and the weight is still there").

Summary of Martín's Excerpt Based on his initial explanation, Martín was still developing his science ideas and the language to communicate those ideas. As Martín received feedback in this one-to-one-to-model interaction from both his model (in the form of data it produced) and the interviewer (in the form of requests for clarification and elaboration), he was able to iteratively revise his ideas and language to construct an increasingly sophisticated explanation of the phenomenon. As in Martín's example, four of eight students interacted directly with their models by running them (whether at the interviewer's suggestion or on their own accord), which produced feedback in the form of weight data that students subsequently incorporated into their explanations.

Notably, one-to-one-to-model interactions blended the affordances of the physical and symbolic environment surrounding the learner with the computational environment of the model (Brady & Lehrer, 2021; Roth, 1995). It was neither the feedback from the model nor from the interviewer alone that created affordances but the dynamic interaction among the student, the model, and the interviewer. For example, the interviewer initially guided Martín to the data boxes in his model. Then, after the model "spoke" and adjudicated between his competing ideas, Martín needed support from the interviewer to clarify his ideas and reformulate his explanation. Thus, Martín's interaction with his model was mediated by the interviewer as an expert-other (Vygotsky, 1986) who was closely attuned to Martín's developing science understanding and the way Martín communicated that understanding through his emerging English (Grapin, 2020). In this way, one-to-one-to-model interactions created their own complex systems from which students' science understanding and language emerged. Understanding these systems, in their full complexity, may prove crucial with ELs, whose science learning and English proficiency are emerging simultaneously.

Contributions and Future Research Directions

This article represents a first step toward conceptualizing and empirically investigating the distinct affordances of computational models for ELs in science instruction. Below, we discuss contributions of our framework to the literature as well as future research directions that build on this conceptual foundation and initial inquiry.

Contributions to the Literature

Research that is just beginning to emerge suggests the challenges of ensuring ELs' meaningful participation in science instruction that integrates computational models (e.g., Aksit & Wiebe, 2020). These challenges may, in part, stem from a lack of engagement with contemporary theories of what it means to know and use a language. Thus, at the onset of this literature, we underscore the significance of articulating a conceptual foundation that guides research in productive and equitable directions.

The theories that inform this conceptual foundation have significant implications for whether ELs are seen as meaningful participants in science instruction that integrates computational models. Based on structural theories of language that locate competence strictly in the individual, both Ricardo and Martín could be seen as deficient, lacking the language structures considered prerequisite to communicating their science understanding effectively. However, based on ecological theories that locate competence in the individual-in-environment, Ricardo and Martín are reframed as competent participants who leverage affordances in their environment to create situated meanings (e.g., Ricardo's "white would gain" as conveying an increase in weight of the gaseous banana). By "flipping the script" on structural theories of ELs as lacking (which undergird an accommodations perspective), ecological theories (which undergird an affordances perspective) offer the possibility not only of recognizing and harnessing ELs' rich meaning-making potential but also reframing these students as legitimate members of their classroom communities and, by extension, broader STEM communities.

The affordances we have proposed related to modalities, registers, and interactions are not entirely new in the literature on computational models in science instruction. For example, in relation to *modalities*, leveraging multiple forms of representation, including computational models, can deepen students' science understanding (e.g., Wilkerson-Jerde et al., 2015). In relation to *registers*, students draw on various kinds of language as they engage with computational models, even inventing their own terms as they pursue personally meaningful lines of inquiry (e.g., Pierson et al., 2021; Wilkerson-Jerde et al., 2015). In relation to *interactions*, students' interactions with and around their computational models can engage them in the social dimensions of modeling (e.g., Brady et al., 2015). However, while these affordances can be gleaned piecemeal from the literature, they have not formed a coherent framework. Moreover, even as these studies have been richly theoretical, frequently grounded in learning theories, such as constructionism (e.g., Papert, 1980), this research has not made sufficient connections to contemporary theories in language education, such as ecological theories, which are particularly relevant to ELs in science classrooms. Thus, an important contribution of our framework is an analytic lens to guide future research efforts focused on integrating computational models in linguistically diverse science learning environments (for more specific recommendations, see "Future Research Directions" section below).

As our framework continues to evolve, it could inform the design of learning environments that serve to broaden participation of ELs in science learning. This design work calls for a fundamental shift from adding accommodations to existing instructional designs as a way of addressing ELs' perceived deficiencies to designing learning experiences that take as their starting point ELs' rich meaning-making potential. Such design work could begin with creating science learning environments that provide a rich budget of modalities for ELs to perceive and act upon as they engage in purposeful, goal-directed interactions with both human and technological participants. This design work could also involve carefully sequencing learning experiences such that ELs have opportunities to construct their science understanding using everyday and specialized programming registers before they are introduced to or expected to produce specialized science registers, thus providing the "infrastructure to grow language" (van Lier, 2003, p. 151) and treating the specialized science register as "a product of doing science, not a precursor or prerequisite" (NASEM, 2018, p. 65). In addition to informing designed-in aspects of science learning environments, an affordances perspective calls for shifts in how teachers interact dynamically with their ELs, including how teachers hone their listening skills to hear the science (Grapin, 2020) in ELs' use of multiple registers and modalities (Even when science learning environments are semiotically rich, ELs may continue to be seen from a deficit perspective if their teachers hold steadfast to traditional notions of what "counts" as effective language use and meaningful participation in science learning.). Given that this work involves integrating diverse theoretical insights in a principled manner (e.g., ecological theories of language with constructionist theories of learning), it will require substantive and sustained collaboration across multiple fields (e.g., language education and STEM education).

One important question is whether the affordances we have conjectured and illustrated are specific to ELs. In other words, would these affordances apply equally to their non-EL peers? While this question merits further empirical inquiry, we suggest two possible responses. First, the affordances could be particularly beneficial to ELs, even if applicable to all students, given that ELs are still in the process of developing English proficiency. For example, the affordances of the code modality and specialized programming register enabled Ricardo to communicate a sophisticated understanding of decomposition and its relation to conservation of weight, even as he was still developing proficiency with technical science terms (e.g., "decompose" and "conservation"). Second, we consider that, if non-ELs also benefit from these affordances, this would support (rather than undercut) our central argument that an affordances perspective has the potential to promote inclusion of ELs in the science classroom. Specifically, this would mean that the affordances we have proposed are not just accommodating ELs based on perceived deficiencies (an approach that could result in their further marginalization), but rather including ELs in the science classroom in ways expected of *all* students. In essence, an affordances perspective extends to ELs what has normatively been assumed of their non-EL peers, namely, that they bring rich meaning-making resources to the classroom that are matched to (rather than distant from) the task of science learning.

Future Research Directions

Building on this conceptual foundation and initial inquiry, future research should investigate the affordances of computational models in the context of classroom activity, where such affordances have the most potential to promote the inclusion of ELs in science learning. This research could refine our understanding of the affordances illustrated by our initial inquiry in the interview context while surfacing new affordances specific to the classroom context. For example, while the interview context focused on one-to-one-to-model interactions involving the student, interviewer, and computational model, the classroom context could involve one-to-one-to-model interactions in which peers mediate *each other's* thinking and communication as they work together on a model. These affordances could also be investigated in relation to different learning goals targeted in science instruction that integrates computational models. For example, Ricardo's description of the agent-aggregate relations in his model showed emerging evidence of "thinking in levels," a key computational thinking practice (Weintrop et al., 2016). Finally, this research could examine the affordances of computational models for ELs beyond blocks-based programming environments (e.g., Weintrop & Wilenksy, 2015) and when used in concert with other forms of representation (e.g., Wilkerson-Jerde et al., 2015).

Another future direction could involve expanding the scope of our framework. In its current formulation, the framework focuses primarily on ways in which computational models harness ELs' meaning-making potential. However, ELs bring to science classrooms not only expansive meaning-making resources but also rich knowledge and experiences from their homes and communities (Bang et al., 2012; González et al., 2005). Tissenbaum and colleagues (2017) have shown how anchoring computational tasks in issues relevant to the lives and communities of marginalized youth (e.g., issues related to disaster relief and mental health) provides affordances for harnessing youth knowledge and experiences and "developing their computational identities toward being digitally empowered" (p. 1707). Likewise, in our own research, the microbe computational model (used to illustrate the framework in this article) is embedded in a broader sequence of instruction that engages ELs in explaining what happens to garbage produced by their community and how they can develop a local solution to the problem of plastic pollution (Lee et al., 2019). Building on these (and other) instructional designs, future research could expand the framework to include the affordances of computational models for empowering ELs—a group traditionally marginalized in schools and in society—to become agents of social change in their local and global communities. Indeed, the meaning-making affordances of computational models (i.e., the *how* of making meaning) may fall short of being fully leveraged if these models are not embedded in instructional tasks that resonate with ELs' lives, experiences, and visions for the future (i.e., the *why* of making meaning).

As science classrooms become both more computational and more linguistically diverse, there is a need to rethink perspectives that have traditionally guided research and design in STEM education with ELs. An accommodations perspective and an affordances perspective both seek equity for diverse student groups but differ in their starting points: Whereas accommodations are premised on the *distance* between students' abilities and the demands of STEM learning, affordances are premised on the *match* between what learners bring to STEM classrooms and what the disciplines afford them. By reorienting our focus from what learners lack to the "relations of possibility" (van Lier, 2004, p. 81) between them and their environment, an affordances perspective promotes an asset-oriented view of ELs (and potentially other marginalized groups) as "able to participate in STEM learning... when they are challenged through instruction that respects them and what they have to offer" (NASEM, 2018, p. 22). With computational models being a relatively new arrival to the science education landscape, the time is ripe to (re)imagine computationally enriched science learning environments from the ground up in ways that leverage the rich assets that diverse student groups bring to science classrooms. We hope this article stimulates further research that seizes this unique and timely opportunity.

Funding This research was supported by a National Science Foundation grant (DRL-1742138).

Declarations

Ethics Approval This research was approved by the University Committee on Activities Involving Human Subjects (IRB-FY2019-1053).

Consent Statement In accordance with requirements established by the University Committee on Activities Involving Human Subjects, consent and assent were obtained from all participants in advance of data collection.

Conflict of Interest The authors declare no competing interests.

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