Designing the Idea Manager to Integrate STEM Content and Practices During a Technology-Based Inquiry Investigation

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Abstract: This design study investigates the role of the Idea Manager, a formative technology-based learning tool, in student learning that integrates STEM practices and disciplinary content. We coordinated curriculum and assessment frameworks to design instructional features of a STEMGenetics unit that engages middle school students in a set of interrelated STEM practices: use a model to construct an explanation of the trait expression mechanism in rice plants. Our analysis of 99 student team responses to three embedded assessments generated formative evidence that delineated three tiers of explainers (non-mechanistic, partial mechanistic, and mechanistic). These students differed in their knowledge and abilities to perform these interrelated STEM practices. We discuss implications of the findings for how (a) teachers can differentiate instruction for students of all levels and across a range of STEM disciplines and interrelated sets of practices and (b) technology tools can be designed to support teachers.

Keywords: science practices, technology, design, student learning, life science

Introduction

A growing emphasis on STEM (science, technology, engineering, and mathematics) requires researchers and practitioners to design learning activities that promote an integrated understanding of STEM topics, applications, and approaches (NRC, 2012). In the past, student learning in STEM has been limited to (a) remembering a set of isolated scientific and mathematical facts often perceived as irrelevant and (b) applying this nominal understanding to prescribed calculations and procedures with limited opportunity for reflection and revision of thinking. New standards for STEM teaching, learning, and assessment call for students to engage in a variety of STEM practices (e.g., use a model, such as a scientific visualization) in order to understand content comprised of disciplinary core ideas (e.g., heredity) and crosscutting concepts (e.g., cause and effect) that bridge STEM fields. These standards also require students to draw upon this more robust understanding of STEM to design and test solutions to existing or potential real-world challenges (NRC, 2012; NGSS, 2013).

These shifts in policy and practice have created a great demand for the learning sciences community to transform STEM teaching and learning. Researchers have problematized what it means to teach and learn STEM practices, asserting that these practices are valuable dimensions of disciplinary work that are learnable, interrelated, and benefit from ongoing evaluation and critique. This requires researchers and practitioners to reframe STEM teaching and learning and generate evidence for how teachers, curricula, and technology can shape STEM participation across different learning settings (e.g., Erduran & Dagher, 2014; Ford, 2015; Stroupe, 2015). This need presents opportunities to bridge curriculum and assessment frameworks that inform the principled design of STEM learning environments intended to engage students in STEM practices and deepen their STEM disciplinary content knowledge (Debarger et al., 2014).

In this study, we focus on a Grade 7 STEMGenetics curriculum unit developed at Michigan State University and SRI International that builds on students' understandings of key genetics concepts. The development of the unit was informed by knowledge integration (KI) and evidence-centered design (ECD) perspectives (Debarger et al., 2014). We investigate the role of Idea Manager (McElhaney, Matuk, Miller, & Linn, 2012), a formative technology-based learning tool embedded in the unit, to answer the following research questions: (1) How does the Idea Manager scaffold middle school students to integrate STEM practices and disciplinary content during a technology-based inquiry investigation? (2) How does the formative evidence generated with the Idea Manager differentiate students' ability to engage in interrelated STEM practices: use a model and construct an explanation?

This study contributes to the growing body of research that seeks to (a) identify the knowledge and abilities needed to perform STEM practices and (b) develop a more nuanced understanding of the types of design features that can support learning of STEM content and practices (NRC, 2012; McElhaney, 2012; Debarger, 2014; Stroupe, 2015; Erduran & Dagher, 2014). The remainder of this paper (1) describes our coordinated theoretical approach, (2) details the methodology, and (3) presents findings about how the Idea Manager scaffolds student learning and provides formative evidence that distinguishes proficiencies in STEM practices and content knowledge. We conclude with a set of implications for STEM classroom learning and future research.

Coordinated theoretical approach to designing for integrated STEM learning

We draw upon knowledge integration (KI) and evidence-centered design (ECD) to (a) articulate integrated learning goals and outcomes, (b) define learning engagement and evidence, and (c) organize learning task features in the STEMGenetics learning environment. KI characterizes learning in everyday life and designed learning environments as the opportunity to (a) add ideas about STEM topics, practices, and disciplines to learners' existing repertoire of ideas and (b) revise the connection learners make between existing and new ideas into an increasingly integrated understanding of science. The KI design framework guides the design of coherent STEM instruction (Kali, Linn, & Roseman, 2008; Linn & Eylon, 2006; Lee et al., 2010). The *metaprinciples* (make science accessible, make thinking visible, help students learn from each other, and promote autonomous and lifelong learning) communicate the nature and quality of learning experiences that promote knowledge integration. The *instructional patterns* (e.g., develop a model, engage in argument with evidence) help designers coordinate learning activities that (a) engage students in the knowledge integration *process* (elicit ideas - add ideas - distinguish ideas - reflect on/explain ideas) and (b) scaffold students' participation in STEM practices (Bransford, Brown, & Cocking, 2000; Linn, Davis, & Bell, 2004).

While KI emphasizes deepening students' understanding in a discipline through practice, evidence-centered design (Mislevy & Haertel, 2006) can heighten instructional designers' awareness of how assessments provide evidence for learning as it occurs during instruction. ECD provides a principled framework to analyze the target learning domain and structure the articulation of (1) integrated learning goals that specify the knowledge and abilities of interest, (2) evidence that will be produced in the form of student work products, and (3) design features of learning environments and tasks that elicit this evidence from students (Mislevy & Haertel, 2006; Debarger, 2014). The coordination of KI and ECD frameworks results in the principled design of instruction and assessment that guide students toward an integrated understanding of STEM content and practices. The instruction includes deliberate learning activities that explicitly engage students in knowledge integration and offer multiple opportunities for teachers to formatively evaluate student progress. With careful design, the coordinated framework allows these learning and assessment opportunities to distinguish separable proficiencies within the domain so that teachers can focus their subsequent instruction where it is most needed.

Design features that scaffold students to integrate STEM content and practices

This research utilizes the Web-based Inquiry in Science Environment (WISE), an online platform aligned with the KI design framework. WISE features a suite of learning tools to support STEM teaching and learning, such as writing prompts (e.g., critique and feedback), activity templates (e.g., inquiry and role play, brainstorm), interactive simulations (e.g., dynamic scientific models), and explanation generation tools (e.g., Idea Manager) (Slotta & Linn, 2009). The Idea Manager includes the (1) Idea Basket, a persistent space where students add and sort information ideas as they learn and (2) Explanation Builder, an organizing space where students (a) consider all the ideas in their idea basket and (b) distinguish and sort relevant ideas into the desired scientific explanation (McElhaney, 2012). We designed instruction using the Idea Manager to (a) guide student engagement in the knowledge integration process, (b) scaffold student learning of the disciplinary core ideas (e.g., trait expression mechanism) and the STEM practices (e.g., use a model and construct an explanation), and (c) offer opportunities to formatively evaluate progress toward integrated STEM understanding. Table 1 organizes the contributions of the KI and ECD design frameworks across three design dimensions and exemplifies resulting design features of the Idea Manger in the Grade 7 STEMGenetics unit.

Learning context

Our collaborative design team of education researchers, curriculum and assessment designers, biologists, technology developers, and teachers designed the Grade 7 STEMGenetics unit to promote students' understanding of inheritance through STEM practices of using models and constructing explanations (NRC, 2012). The unit introduces a situation where the world will be running short of food and fossil fuels in 2052 and students inquire about how to selectively breed for more nutritious rice in order to propose a genetics-driven solution to end world hunger. As students answer the driving question, "How can you use genetics to feed the world in 2052?", they engage in a variety of WISE learning activities, hands-on laboratories, and whole class discussions facilitated by the teacher. This study was based on the second design iteration of the STEMGenetics Grade 7 unit, which has been informed by evidence from the pilot study (Debarger, 2014) and teacher feedback during a co-design professional learning session.

Table 1: Contributions of KI and ECD design frameworks across design dimensions for instructions

Design Dimensions	**Contributions of KI and ECD Design Frameworks**	**Resulting Design Features of Instruction using the Idea Manager**
Learning Goals and Outcomes	KI: Connections between key disciplinary ideas that promote lifelong learning	Learning Performance: Students can use a model showing the mechanistic processes of trait expression to construct an explanation about why an organism has a particular trait
	ECD: Combination of content knowledge and practices as the target of instruction and embedded assessments	
Learning Engagement and Evidence	KI: Learning as engagement through eliciting, adding, distinguishing, and sorting ideas	Learning Engagement: Students (1) observe model to add ideas about trait expression and (2) construct an explanation to distinguish and sort ideas about trait expression Learning Evidence: Students (1) use a model of trait expression to document mechanistic elements of the phenomenon of trait expression and (2) construct a scientific explanation integrating observable and non-observable aspects about why an organism has a particular trait
	ECD: Clear articulation of evidence produced by students to indicate progress toward and attainment of learning goals	
Learning Task Features and Flow	KI: Application of design patterns and tools to promote knowledge integration within and across tasks	Prompts for students to (1) focus students' use of the model on mechanistic aspects of the phenomenon and document them in the idea basket and (2) use idea basket entries to construct an explanation about the phenomenon
	ECD: Specification of instructional and assessment design features to elicit desired evidence	

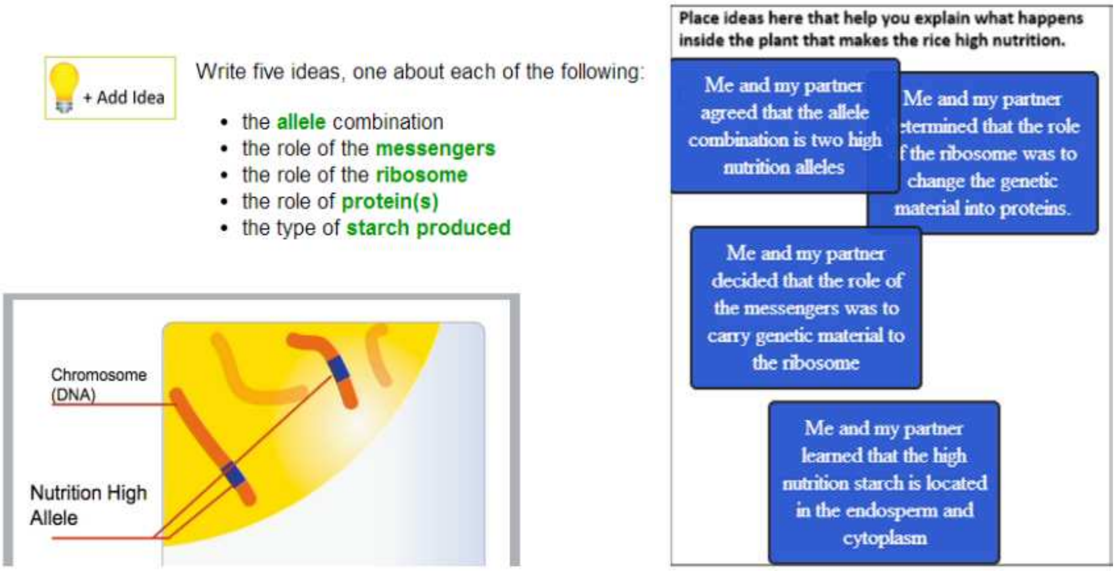
Learning goals and outcomes

Based on our analysis of the Framework for K-12 Science Education (NRC, 2012), the design team initially developed twelve learning goals for the unit that centered on the disciplinary core ideas that comprise a deep understanding of inheritance for 7th grade students (e.g., trait expression and sexual reproduction) and two STEM practices: developing and using models and constructing explanations. Findings from our pilot study prompted us to recast the twelve learning goals into five learning performances that explicitly consider the application of the STEM practices within genetics (Debarger, 2014). This study focuses on the learning performance: *Students can use a model showing the mechanistic processes of trait expression to construct an explanation about why an organism has a particular trait.*

Learning engagement and evidence

For each learning performance, we articulated statements that clarify the evidence students would need to indicate progress toward the learning goal. The evidence for the focal learning performance included: s*tudents (1) use a model of trait expression to document mechanistic elements of the phenomenon of trait expression and (2) construct a scientific explanation integrating observable and non-observable aspects about why an organism has a particular trait.* To generate this evidence, students were requested to (a) first observe a dynamic scientific model that visibly explained how the structures, functions, and interactions of alleles, messengers, ribosomes, proteins, and starch yield the high-, medium-, or low-nutrition traits observed in rice plants, (b) add their observations as ideas in their idea basket that described how the model elements represented the trait expression mechanism, and (c) use the Explanation Builder to distinguish and sort these model observations into an organizing space, and use selected observations as evidence to build an explanation of the trait expression mechanism in high-nutrition rice plants.

Specific prompts were designed to guide students' observation of the models; students were asked to add at least one idea for each mechanistic element during or after their model observations (Figure 1a). The ideas added at the model steps provide formative evidence for how well students understood the model. Later in the Explanation Builder, students were instructed to (a) consider all the observations in their idea basket and (b) distinguish which ideas were relevant to their scientific explanation of the trait expression mechanism in high-nutrition rice plants (Figure 1b). As students constructed their explanations, they sorted these ideas into an evidence-based characterization of trait expression mechanism in rice plants.



Write five ideas, one about each of the following:

- the **allele** combination
- the role of the **messengers**
- the role of the **ribosome**
- the role of **protein(s)**
- the type of **starch produced**

Place ideas here that help you explain what happens inside the plant that makes the rice high nutrition.

Me and my partner agreed that the allele combination is two high nutrition alleles

Me and my partner termined that the role f the ribosome was to change the genetic material into proteins.

Me and my partner decided that the role of the messengers was to carry genetic material to the ribosome

Me and my partner learned that the high nutrition starch is located in the endosperm and cytoplasm

(a) (b)

Figure 1. Screenshots of (a) model observation step with specific prompts and (b) examples of students' ideas placed in the organizing space.

Methodology

Research setting and participants

Two 7th grade science teachers who taught 50 and 49 teams of 2-3 students at two middle schools within the same district in the southwestern USA used the STEMGenetics unit in their classrooms during the 2013-14 school year. The district is comprised of 64% African American, 28% Hispanic, and 8% Caucasian students; sixty-one percent of the district's students receive free or reduced price lunch.

Data sources and scoring

The data of this study come from a set of embedded assessments in the unit: (a) the idea basket in the two activities, (b) the organizing space at the end of the two activities, and (c) students' responses to the prompt of the Explanation Builder at the end of activity four, "*Explain what happens inside a rice plant that makes it high nutrition*."

Idea basket and organizing space

To investigate how the Idea Manager tool scaffolded students' use of a model to construct coherent scientific explanations of the trait expression mechanism, we designed a conceptual inventory (CI) rubric to score ideas in the idea basket and organizing space (Table 2). The CI rubric identified ideas for five non-observable cellular structures that comprise the trait expression mechanism: genetic information, messengers, ribosomes, proteins, and starch. For each of these mechanistic elements, a set of possible normative ideas were listed to guide scoring of each idea in the idea basket and organizing space. If an idea was present and accurate about a mechanistic element, it received a score of 1. If absent or non-normative, it received a score of 0. Two researchers (the first and second authors) established inter-rater reliability of 95%, then coded separate sets of student responses. We then computed composite scores for the idea basket and organizing space for each student group by adding their scores on all ideas together (e.g., *normative model score*: number of normative ideas added during a model observation step).

Scientific explanation

We constructed and applied a 5-score KI rubric to students' explanations of the trait expression mechanism at the end of the activity. The rubric was iteratively revised based on several rounds of team feedback and review of samples of student work with consideration of boundaries between scores and distribution of scores (Table 3).

Two researchers established inter-rater reliability of 90%, then coded separate sets of student group responses. Each team's explanation was assigned a KI score of 1-5.

Table 2: Sample CI rubric for scoring of students' ideas about trait expression mechanism in rice plants

Mechanistic Elements	**Possible Normative Idea**	**Student Examples**
(G) Genetic Information	G3. The allele combination is two high nutrition alleles	*The allele combination was high nutrition.* -- WISE ID 137243
(M) Messenger	M2. The messenger is/has/carries genetic information or instructions from the allele/chromosome	*The messengers are genes that are sent out to the ribosomes to make proteins.* -- WISE ID 136931
(R) Ribosome	R2. The ribosomes use instructions from the messenger or genetic information to create a protein	*The ribosomes make proteins and use the genetic info from the messenger to make up the body in a certain way.* -- WISE ID 13589
(P) Protein	P2. The glucose/reactants interacts with or passes through proteins	*The role of the proteins is to come together and transform glucose into starch.* -- WISE ID 137040
(S) Starch	S1. The rice plant has/produces high-nutrition starch	*The starch inside of the Endosperm cell inside has high nutrition.* -- WISE ID 136929

Table 3: KI rubric for explanations of the trait expression mechanism in rice plants

	KI Score	**Characteristics of Model-based Explanations**	**Student Examples**
Mechanistic Explainers	5 | Complex Integration	DESCRIBE KEY INTERACTIONS of NON-OBSERVABLE cellular structures and functions that comprise the trait expression MECHANISM .	*The way the rice plant is high nutrition is when the high nutrition allele sends messengers to the ribosomes and the ribosomes makes protein and the protein makes starch and forms in a granule. -- WISE ID 136899*
	4 | Full Integration	DESCRIBE the one (1) KEY INTERACTION of NON-OBSERVABLE cellular structures and functions that comprise the trait expression MECHANISM	*Inside the nucleus, the high nutrition alleles are located in the chromosome. From there, the messengers transport genetic material to the ribosomes. Then the ribosome turns the genetic material into proteins. -- WISE ID 137402*
Partial Mechanistic Explainers	3 | Partial Integration	DESCRIBE the RELATIONSHIP between the FUNCTION of NON-OBSERVABLE cellular STRUCTURES of the trait expression mechanism --OR-- Partially DESCRIBE the KEY INTERACTIONS of NON-OBSERVABLE cellular structures and functions that comprise the trait expression MECHANISM	*The alleles tell the ribosomes to make protein and starch to make the high nutrition cells. -- WISE ID 136847* *The first thing that will happen is the messenger will help the ribosome produce proteins. Then the protein will produce starch. -- WISE ID 137263*
Non-Mechanistic Explainers	2 | Isolated, Non-observable	IDENTIFY NON-OBSERVABLE cellular structures of the trait expression mechanism	*Inside of a rice plant the allele combination, proteins, messengers, and ribosomes all work together and produce High Nutrition. -- WISE ID 136825*
	1 | Isolated, Observable	IDENTIFY OBSERVABLE characteristics or traits	*The farmer can use IKI to indicate whether or not it's high or low in nutrition.* -- WISE ID 137265
	0 | Incorrect or Irrelevant	Only incorrectly IDENTIFY, DESCRIBE RELATIONSHIPS, or INTERACTIONS of model elements	*In a rice plant there is starch, and starch is a complex carbohydrate and it turns to sugar in the body, which acts as an energy boost. -- WISE ID 136930*

Analysis

The KI analysis provided evidence about the range of model-based explanations among students. Given the formative design of the Idea Manager, we compared composite scores for idea basket and organizing space to differentiate how students engaged in the interrelated STEM practices: use a model and construct an explanation to deepen their disciplinary content -- trait expression mechanism in rice plants.

Findings

The two teachers in this study implemented the Grade 7 STEMGenetics unit with fidelity. Students completed the designed learning activities; they added a mean of 18.71 ideas to their idea baskets during the two activities (SD=6.41). No statistically significant differences in total ideas added were detected between higher and lower performing students as measured by their KI score. However, we did notice a significant difference in the quality of the ideas as explained further below.

Knowledge integration of the trait expression mechanism

Across both classrooms, 99 student teams scored a mean of 2.21 for their explanation of trait expression (SD =1.52). We grouped student teams into three significantly different categories: non-mechanistic explainers (KI score 0-2), partial mechanistic explainers (KI score 3), and mechanistic explainers (KI score 4-5), [$t(53)=-14.354$, $p<.001$; $t(16)=-11.785$, $p<.001$].

The 54 student teams categorized as non-mechanistic explainers identified only (a) observable characteristics or features (e.g., rice plant is high nutrition) or (b) non-observable cellular structures that comprise the trait expression mechanism (e.g., alleles or ribosomes). The explanations of the 28 student teams in the partial mechanistic explainers category either (a) describe the structure-function relationship of at least one non-observable cellular structure of the trait expression mechanism (e.g., ribosomes create proteins) or (b) partially describe the key interactions of non-observable cellular structures and functions that comprise the trait expression mechanism (e.g., messenger helps ribosomes create proteins, which produce starch). In the mechanistic explainers category, 17 student teams fully describe at least one key interaction of non-observable cellular structures and functions that comprise the trait expression mechanism (e.g., messenger carries genetic material from the alleles to ribosomes; ribosomes create proteins, which produce starch).

Using a model to construct an explanation of trait expression

Overall, students added a mean of 3.01 (SD=2.27) normative ideas to their idea baskets when they observed a dynamic scientific model and were prompted to add ideas about specific elements of the trait expression mechanism in three steps of the two learning activities. Despite a small difference in the total number of basket ideas, non-mechanistic explainers differed significantly in the mean number of normative ideas (2.33, SD=2.04) added to their idea baskets compared to the partial mechanistic (3.61, SD=1.77, $t=-2.931$, $p=0.005$) and mechanistic (4.18, SD=2.96, $t=-2.393$ $p=0.026$) explainers (Figure 2). The addition of normative model ideas across all coherence groups suggests the modeling steps scaffold students to (a) attend to the structure, function and interactions of the non-observable cellular structures of the trait expression mechanism and (b) add normative ideas about these mechanistic elements to their idea baskets.

Student teams who constructed a more mechanistic scientific explanation (KI scores 3-5) about the trait expression mechanism added a mean of 1.28 to 1.85 more normative model ideas to their idea baskets than the non-mechanistic explainers. This suggests that non-mechanistic explainers may have struggled more than other students to correctly identify the structure, function, and interactions of the non-observable cellular structures represented in the trait mechanism model.

During the Explanation Builder step, student teams selected relevant ideas from their idea baskets to place in the organizing space. Overall, student teams placed a mean of 1.78 (SD=1.78) normative model ideas in their organizing space. Again, the non-mechanistic explainers differed significantly in the number of normative model ideas (1.28, SD=1.70) placed in the organizing space compared to the partial mechanistic (2.32, SD=1.61, $t=-2.730$, $p=0.008$) and mechanistic (2.47, SD=1.87, $t=-2.339$ $p=0.028$) explainers (Figure 2). Students who constructed a more mechanistic scientific explanation about trait expression (KI scores 3-5) placed 1.04-1.09 more normative ideas in the organizing space. These students had more normative ideas about the mechanistic elements available in their idea baskets during the Explanation Builder step where they distinguished and sorted these relevant ideas into scientific explanations of the trait expression mechanism.

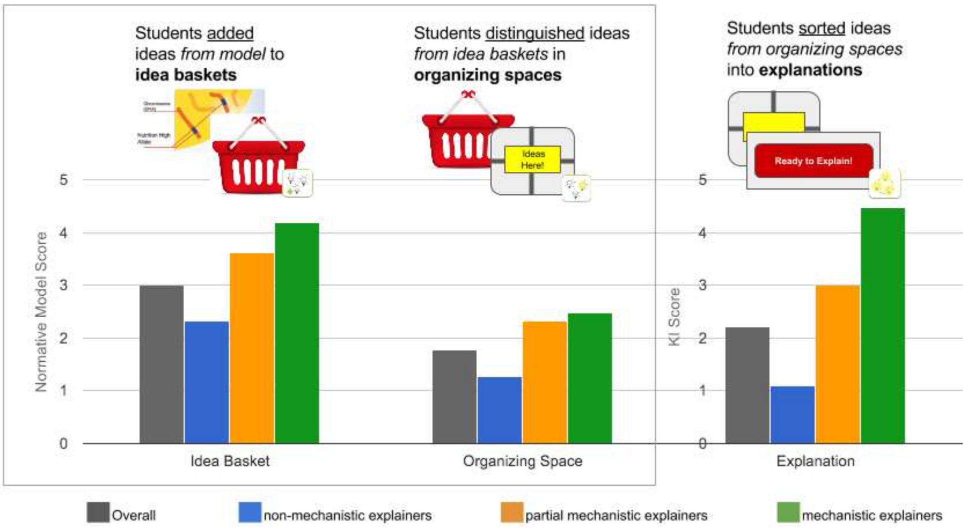


Figure 2. Differences among explainers when engaged in a set of interrelated STEM practices: use a model to construct a scientific explanation.

Despite the significant difference in the KI scores among partial mechanistic and mechanistic explainers, these students did not differ significantly in the number of normative model ideas added to their idea baskets or placed in their organizing space. This finding suggests that these students engaged similarly in the STEM practice, use a model, to identify the mechanistic elements in trait expression. Yet, mechanistic explainers may be better able to (a) understand the relationship between mechanistic elements represented in the trait expression model or (b) sort their distinguished ideas into a coherent mechanistic explanation of trait expression.

Conclusions and implications

Our coordination of the KI and ECD design frameworks afforded the opportunity to design instruction based on the Idea Manager tool for integrated STEM learning of content and practices. Embedded in the Grade 7 STEMGenetics unit, this formative learning tool engaged students in the observation of dynamic scientific models of the trait expression mechanism in rice plants. Students were prompted to document their observations by adding ideas to their idea baskets about the non-observable structures, functions, and interactions that comprise the trait expression mechanism. Later, the organizing space within the Idea Manager tool prompted students to distinguish and sort the ideas in their idea basket, in order to construct a written explanation for how the trait expression mechanism yields the high-nutrition trait in rice plants.

The findings from this study delineated three tiers of students who differed in their abilities to use a model and construct an explanation, and their integrated understanding of the disciplinary content -- trait expression (Figure 2). These documented differences in student learning revealed opportunities for (a) teachers and tools to differentiate scaffolds that engage students in STEM practices and (b) refinement of the Idea Manager's design features to generate more nuanced formative evidence for how students use a model to construct an explanation.

Non-mechanistic explainers demonstrated limited use of the trait expression models. They added an insufficient number of normative model ideas to their idea baskets, indicating a limited understanding of model elements. They articulated isolated ideas about observable traits or non-observable structures in their explanation of the trait expression mechanism, which was likely due to the limited availability of normative model ideas in their idea baskets. These findings suggest that non-mechanistic explainers need differentiated scaffolding to add normative model ideas to their idea baskets so that they are made visible to students when it is time to distinguish and sort relevant ideas into scientific explanations. Also, these students likely need scaffolding beyond the structure-specific prompts during model steps, such as computer-aided or teacher feedback about the contents of their idea baskets.

Both partial mechanistic and mechanistic explainers demonstrated requisite use of the trait expression models, indicating an understanding of model elements. These students differed in their ability to construct an explanation. The mechanistic explainers demonstrated a higher ability to construct an explanation as evidenced by articulation of key interactions of structure and functions that comprise a mechanism, indicating an integrated disciplinary content knowledge of trait expression. Alternately, partial mechanistic explainers articulated non-observable structure-function relationships or partial interactions of structures and functions that comprise the trait expression mechanism. This is likely due to partial understanding of the key interactions in a mechanism. Differences in how students understand the relationship between mechanistic elements might become more evident when students construct an explanation that characterizes the trait expression mechanism. These findings suggest the need for (a) additional scaffolding in the organizing space to help students organize and sort their ideas into a coherent scientific explanation and (b) refinement of the Idea Manager tasks to elicit evidence of students' abilities to describe the relationships between model elements and the correspondence to the trait expression mechanism. For example, we could redesign the organizing space to use a sequential organizing principle and help students organize their normative model ideas into the trait expression mechanism.

The implications of this study extend beyond the disciplinary content in Grade 7 Genetics and the interrelated STEM practices, use a model and construct an explanation. Formative learning tools, like the Idea Manager and Explanation Builder, can provide intermediary artifacts for teachers and researchers to (a) identify which practices challenge students most and (b) analyze formative evidence to determine how to best to provide scaffolds and adjust instruction. In addition, the Idea Manger could be used to distinguish proficiencies between different sets of interrelated STEM practices, such as analyzing and interpreting data and engaging in argument from evidence. Further design and study of formative learning tools will advance more nuanced understanding of learning design that can support learning of STEM content and practices.

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