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Challenges in Interpreting Student Responses for Three-Dimensional Classroom Assessment

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Abstract: Recent reforms in science education have emphasized the importance of students engaging in three-dimensional learning consisting of science practices, disciplinary core ideas, and crosscutting concepts. However, this kind of learning is challenging to assess, and necessitates multicomponent tasks that allow multiple opportunities for students to share their developing understandings. This paper explores the complexities that arise in interpreting student responses and planning for next instructional steps through the analysis of a three-dimensional, phenomenon-based task for high school students' modeling of cellular respiration. We describe two approaches for looking at student responses, and analyze the affordances and constraints of each method. We conclude by discussing practical considerations for classroom teachers and implications for developing three-dimensional classroom assessments.

Introduction

Science education has been undergoing a major wave of reform in the past decade. Building on shifts in situated and sociocultural theory that frame learning as changes in participation in disciplinary practices over time (e.g. Wenger, 1998), these reforms prioritize students' engagement in what has been called three-dimensional science learning (National Research Council [NRC], 2012). This kind of learning involves students participating in science and engineering practices to learn disciplinary core ideas and apply crosscutting concepts as they seek to explain everyday, observable phenomena around them (National Academies of Science, Engineering and Medicine [NASEM], 2019).

This new vision of science learning has placed great demands on classroom assessments that can capture the complexity of student engagement in disciplinary practice. While the field is developing new approaches to designs for assessment tasks, teachers, assessment and curriculum developers are still determining the kinds of tasks that can truly draw out all three dimensions of students' experiences. At the same time, once students have responded to these tasks, teachers are left to interpret student responses to determine next steps for instruction. This presents a heavy lift for teachers still working to understand the three-dimensional vision themselves.

In this paper, we take the example of a co-designed, three-dimensional formative assessment task for high school biology to examine the complexities revealed when interpreting student responses that combine science practices, disciplinary core ideas, and crosscutting concepts. We examine student responses by disaggregating the three dimensions, as well as holistically, determining similarities and differences that could be consequential to teachers' interpretations and determinations of next steps for instruction. We conclude by identifying design considerations for developing three-dimensional science assessments.

Formative assessment tasks as mediating artifacts

We view learning as changes in participation in disciplinary practices over time (Wenger, 1998). From this perspective, classroom assessment can be viewed as an activity in which teachers and students reflect upon how participation in practice is changing (e.g. Greeno & Gresalfi, 2009). This perspective on learning and assessment is starkly different from prior views of assessment as an activity that seeks to understand the 'knowledge in a learner's head,' framed from behaviorist and cognitive views of learning (Shepard, 2000). Further, we view assessment tasks as mediating artifacts that organize classroom activity (Wertsch, 1998). In the context of three-dimensional learning, where students' participation in disciplinary practice is being assessed, along with their understandings of disciplinary core ideas and application of crosscutting concepts, the tasks serve as material representations of student thinking (e.g. Cowie, Jones & Otrell-Cass, 2011) that teachers and students together reflect upon and respond to as they determine subsequent directions for learning.

Three-dimensional science learning

The new vision of science learning consists of three elements - science and engineering practices, disciplinary core ideas, and crosscutting concepts - in which students participate over time (NRC, 2012). This reconceptualization of science learning is built on the 'practice turn' in situated learning theory (Ford & Forman, 2006). Science and engineering practices are ways that scientists and engineers understand the world around them and design solutions to address problems (Schwarz, Passmore & Reiser, 2017). These practices include modeling, or creating simplified representations of phenomena that make its different elements explicit (e.g. Harrison & Treagust, 2000; Schwarz et al., 2009). Modeling has been called the central practice of three-dimensional learning, as it can be placed at the center of other practices such as asking questions, designing investigations, analyzing data, and developing explanations (Passmore, Schwarz, & Mankowski, 2017). Disciplinary core ideas are the second dimension of three-dimensional learning, and constitute the big ideas in life, physical, earth and space science. The third dimension, crosscutting concepts, are sometimes framed as the questions scientists ask themselves when they don't immediately know the explanation for an observable event (Furtak et al., 2021). Crosscutting concepts include systems and systems models, patterns, scale, and matter and energy cycling (NRC, 2012). The latter of these crosscutting concepts - energy and matter cycling - is unique as it is also a disciplinary core idea. For example, students may learn about the role of energy in force and motion in physics, and then relate energy to endo- and exothermic processes in chemical reactions before learning about energy transfer and transformations in photosynthesis and respiration in a biology course.

These three dimensions are designed to span grade bands and build in complexity as laid out in the Next Generation Science Standards (NGSS; NGSS Lead States, 2013). Accordingly, students' explanations of phenomena will deepen given these multiple opportunities to bridge everyday understandings with scientific principles and develop into describing causal relationships (Braaten & Windschitl, 2011).

Challenges in designing formative assessment tasks for three-dimensional learning

A central element to realizing the new vision of science learning is designing classroom assessment tasks that reinforce, rather than work at cross-purposes with, three-dimensional learning (NRC, 2012; 2014). Formative assessment tasks serve to surface what students know and can do so that teachers and students alike have information about the current learning goals. With this information, teachers can respond accordingly to leverage students' understandings towards meeting the objective. Three-dimensional formative assessment tasks use multiple components to elicit students' three-dimensional learning, and mediate classroom conversations that create space for students to share and respond to each other's developing ideas. In this way, three-dimensional formative assessment consists both of the tasks that teachers can use to draw out student thinking, and the practices that organize classroom activity around the sharing and working out of student ideas (Bennett, 2011).

Not all formative assessment tasks, however, draw out student ideas equally. Kang and colleagues (2014) found that some scaffolds can be more supportive of engaging students in developing an explanation for an observed phenomenon than others. In particular, contextualizing an assessment task with a phenomenon along with another scaffold supports student learning. For example, asking about forces in the context of a skateboarder rolling down a specific hill near the students' school provides an opportunity to apply developing ideas in an everyday and observable context. Then, scaffolding students' responses with sentence starters that help them identify causal relationships, or providing checklists that encourage them to provide specific elements in a model (e.g. to include both visible and invisible components), are more likely to help them share their thinking.

Formative assessment tasks can serve as the 'observation' of what students currently know and are able to do, and then teachers make inferences about the status of student learning to inform subsequent instructional experiences (e.g. NRC, 2001; 2014). The tasks can also serve as mediating artifacts around which other processes - such as whole-class discussions, or small-group conversations - allow students to share their ideas, and get feedback from their teacher and peers. Multicomponent tasks can be designed with this kind of feedback in mind so that students make initial and revised models and explanations, for example, with small-group and whole-class discussions in between. Then, through participating in these discussions, trying out ideas, and listening to their peers, students can integrate new ideas and representations into their models and explanations.

However, these kinds of task formats are still new, and the degree to which those tasks provide interpretable information for teachers is not entirely clear. The methods that teachers currently use for combing through student work to assess and/or identify next steps in instruction may no longer work for such complex three-dimensional tasks. For instance, sorting work into low, medium, and high categories will no longer be straightforward when a task is designed to capture multiple dimensions of learning, and if it contains initial and revised elements. If we are really trying to reconceptualize science learning, the NGSS forces us to rethink not just assessments, but also how to meaningfully interpret the learning demonstrated in such assessments.

In this paper, we seek to determine how we can score and evaluate student responses on these kinds of formative assessment tasks, and identify design considerations to facilitate more effective teacher use of formative assessment to support students' three-dimensional science learning.

Method

This paper analyzes data collected in a multi-year, research-practice partnership with high school science teachers in a large socioeconomically, linguistically, and ethnically diverse school district in the Western U.S. One of the goals of the partnership was to co-design formative assessment tasks around a modeling energy learning progression. In this paper, we focus on two biology teachers who co-designed a task around cellular respiration.

A learning progression for modeling energy

We founded our process of task design on a learning progression as a representation of the ways in which students might progress in their development of a disciplinary core idea or science practice (Corcoran, Mosher & Rogat, 2009). Learning progressions generally start with representing the experiences and preconceptions that students bring with them to school and progress with increasing sophistication of representing and interweaving ideas until reaching a level of mastery appropriate with grade level. We developed a three-dimensional learning progression for modeling energy transfers and transformations within the process of cellular respiration, including specific indicators or "look-fors" (Table 1). As this learning progression has served as a grounding framework for developing tools and routines in our work with supporting teachers to co-design 3-dimensional classroom assessments, it also serves as an analytical lens for evaluating what students know and can do from such tasks.

Table 1: Learning progression and sample DCI-specific look-fors (Buell et al., 2019)

Level	Description	Sample Look-Fors
5	• Students generalize their model to unknown or multiple phenomena and explain limitations of applying the model to a new phenomenon.	• [Task not designed for this level]
4	• Models illustrate a mechanism that can explain or predict the phenomenon, and make predictions about how changing one part of the model would influence energy flows elsewhere. • Students explain how the total energy of the system constrains the magnitude of change possible. • Students describe limitations of the model.	• Relationship between amount of inputs rate of cellular respiration; indicators of conservation and dissipation through different parts of the body; food molecules sustaining life processes
3	• Students' models relate changes in the phenomenon directly to changes in energy through transfers/ transformations by identifying specific, observable indicators. • Students begin to show evidence that their model is accounting for conservation and dissipation. • Model includes energy flows into, within, and out of the system.	• Relationship between amount of inputs and outputs in cellular respiration • Indicators of conservation and dissipation; eg. sweat, heat
2	• Students' models illustrate a relationship or pattern between the increase in one form of energy and the decrease in another form, or transferred from one location or object to another. • Students identify the most relevant components and relationships in the model and distinguish between the system and surroundings. • Model focuses on energy flows within the system only.	• Key inputs and outputs of cellular respiration (including oxygen, carbon dioxide); shows a flow of inputs in and outputs of cellular respiration
1	• Students use or develop a model that shows, through drawings or labels, the components involved in a phenomenon, some (but not necessarily all relevant) energy forms, transfers, or transformations.	• Components include food molecules or oxygen, but not a focus on how energy flows in cellular respiration

Data sources

We analyzed student responses to the respiration task co-designed with high school biology teachers and linked to the learning progression in Table 1. The task presents students with the phenomenon of how visiting athletes who play at elevation experience more fatigue than their 'home-team' counterparts, and was designed for use early in the unit about cellular respiration. The design of the task included multiple activity settings - individual work, as well as small group and whole-class discussions - intended to perform a learning function in which students surface their individual ideas, discuss them in multiple settings, and then create revised models. We analyzed 134 samples of student work collected from two biology teachers across six sections of their classes.

Each piece of student work consists of three subtasks: an initial model, three open-ended written-response questions, and a revised model.

Analytic approach

We developed a multifaceted coding system in order to capture the complexity of responses in students' initial and revised models, and in the explanations they provided on the basis of those models. The coding system allowed us to code each part separately (disaggregated approach, Table 2), and apply codes that looked at the whole task relative to the learning progression as an interpretive framework (holistic approach, Table 1). First, we segmented the student work into three subtasks (the initial model, the explanation, and the revised model). The disaggregated approach treated the initial model, explanation, and revised model as distinct entities. There are three codes for this approach: Phenomenon, Disciplinary Core Idea (DCI), and Type of Explanation. The Phenomenon code captured if students are writing or modeling their explanations in the context of the 'playing football at high elevation' phenomenon (Odden & Russ, 2019; Kang et al., 2014). The DCI code identified scientific content as related to the appropriate NGSS performance expectation (PE). Here, the PE (HS LS1-7) is centered around modeling matter and energy flows in the context of cellular respiration. The Type of Explanation code is meant to capture and identify the different approaches that can be taken in conceptualizing explanations of a phenomenon which might follow a "trajectory from describing 'what' happened to explaining 'how' and 'why' events happen" (Braaten & Windschitl, 2011, p. 663). We then interpreted the codes – which are organized hierarchically - as scores and created sum scores that aggregated student performance on the different categories.

Table 2: Codes for disaggregated approach to analyzing student work

Category	Code	Description
Phenomenon Student response links back to the phenomenon (Odden & Russ, 2019; Kang et al., 2014)	0	Does not refer to original phenomenon posed in task
	1	Refers to phenomenon
DCI (Disciplinary Core Idea) Identifies relevant macro and/or micro-level elements **of cellular respiration** (see Jin, Choi & Anderson, 2009)	0	DCI-related content not present
	1	Observable inputs and outputs, and ideas from everyday experiences
	2	Observable/experiential indicators with *some* identification of molecular inputs and outputs; Begins to connect macro and micro.
	3	Explanation describes *all* inputs and outputs including observable/experiential indicators
Types of Explanation This code indicates the kind of explanation students are using in order to explain the phenomenon (Braaten & Windschitl, 2011)	0	Explanation of phenomenon not present
	1	Everyday explanation
	2	Covering law - phenomena are the result of specific laws or law-like statements
	3	Emerging Causal - explicitly seeking underlying causes for events/phenomena
	4	Emerging Manipulationist - identifying mechanisms that answer how outcomes would change if the mechanism was manipulated or if there is a different desired outcome

Lastly, we used the modeling energy learning progression to holistically code the task as a whole. We drew upon the teacher-designed, performance expectation-specific "look fors" as indicators for holistically assigning the student work to a learning progression level. Although there are five levels to the learning progression, this classroom assessment task was situated at the beginning of an instructional unit and therefore not designed to attain a level 5. Three raters independently coded 20% samples of the student work, improving in Cohen's Kappa as an indicater of interrater agreement each round. Ultimately, given the high-inference nature of the coding approach, researchers adjudicated every piece of student work to reach 100% agreement.

Findings

Our analysis reveals differences, but also key overlaps, in the disaggregated and holistic coding approaches. We first present our findings from the disaggregated coding, and then look at broader themes from the holistic coding relative to the learning progression. Finally, we analyze the association between the two approaches.

Disaggregated approach

Table 3: Summary of Disaggregated and Holistic Coding Approaches

Code		Disaggregated Approach		
		Initial Model	Explanation	Revised Model
Phenomenon *Min=0, Max=1*	Mean	0.95	0.99	0.99
	SD	0.21	0.09	0.09
DCI *Min=0, Max=3*	Mean	1.19	1.31	1.40
	SD	0.80	0.55	0.84
Explanation Type *Min=0, Max=4*	Mean	1.18	2.00	1.37
	SD	0.81	1.02	0.81
		Holistic Approach		
Learning Progression *Min=1, Max=5*	Mean	1.52		
	SD	0.70		

Overall, the disaggregated approach revealed shifts between students' initial and revised models, as well as qualitative differences between student models and explanations (Table 3). The results of the Phenomenon code showed that in almost all instances (not including a small number of blank responses) students were modeling and explaining about the phenomenon. Across the initial model, explanation, and revised model, students referred to the phenomenon an average of 97.7% of the time. There were very few instances in which students provided an explanation devoid of context, which is in line with what we hope to see given the design of the task around a phenomenon.

The DCI and Explanation Type codes reveal differences across the subtasks. Across all student responses, we observed a shift towards more DCI understanding as students progress from the initial model (m = 1.19), to the written explanation (m = 1.31), to the revised model (m = 1.40). These shifts are visible in Figure 1, particularly in how more students reach a level 2 by the time they revise their model.

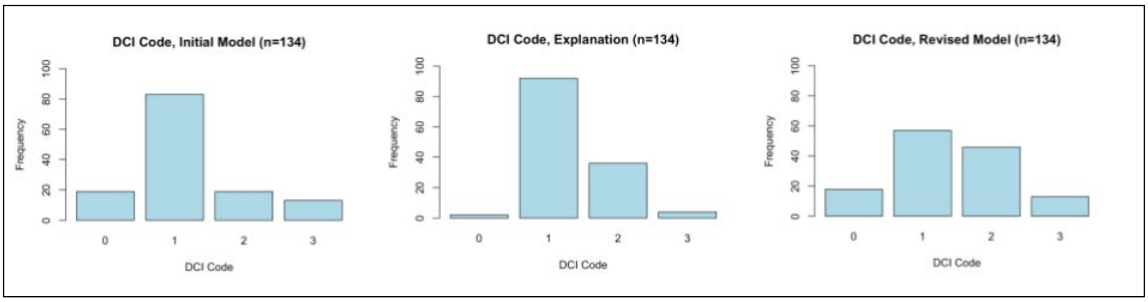

Figure 1. DCI code distribution across the three subtasks

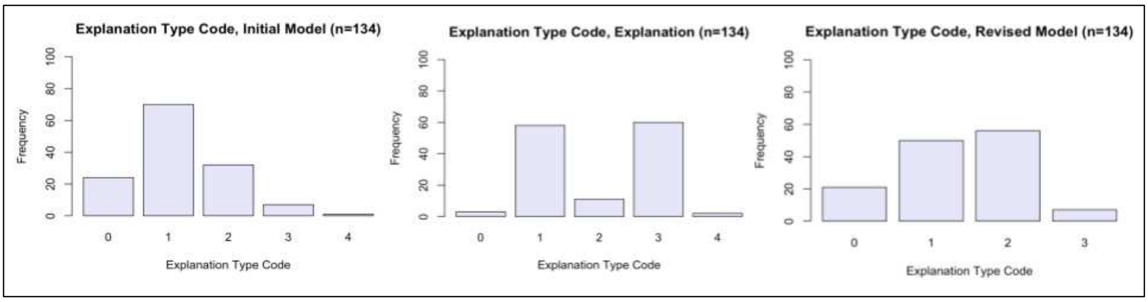

Figure 2. Explanation type code distribution across the three subtasks.

When we considered the explanatory approach of the responses, students shifted from using more everyday explanations towards integrating scientific principles by the revised model. The distribution of Explanation Type for Initial Model is skewed right (see Figure 2), indicating a tendency towards Everyday-type responses. There is a bimodal distribution in the Explanation part of the task, showing high frequencies of Everyday-type and Causal-type responses. This could again be explained by the design of the task as students were asked to explain differences experienced by “home” and “away” players, which might lend itself towards more Causal-type explanations. The distribution in the revised model shows a shift towards more Covering Law-type responses. Overall, this indicates a shift from Everyday-type to more Covering Law- and Causal-type explanations. In Figure 3, we see an illustrative example of a student who begins by drawing upon more everyday language, and by the revised model, has shifted towards including more content knowledge to more fully explain how cellular respiration fuels the football player. Next, we describe how this same example may be interpreted differently using the holistic approach.

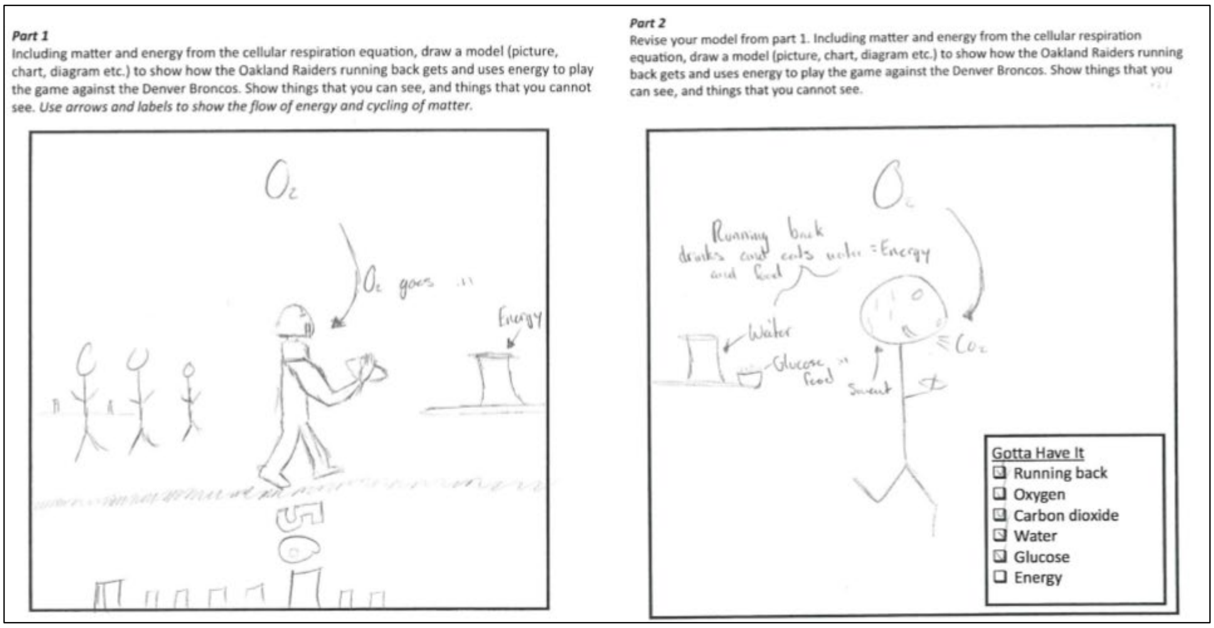

Figure 3. Student work example illustrating shift from initial to revised model.

Holistic approach

To apply the learning progression (LP) code, we looked at all three subtasks holistically and used the context-specific indicators, or “look-fors,” to determine an assigned level. The average learning progression level across all 134 samples of student work was about 1.5 (see Table 3). We can see in Figure 4 that the majority of students were placed at level 1 (n=78), while some students were placed at level 2 (n=41), and a fewer number of students were placed at level 3 (n=15). The high number of students placed at level 1 is not surprising given that this was the first task in the instructional unit. Returning to the student work in Figure 3, this example also highlights the student attending to dissipation of energy through an observable indicator, sweat. Including this element in the model corresponds to a level 3 element on the LP and may otherwise be overlooked by the disaggregated coding scheme.

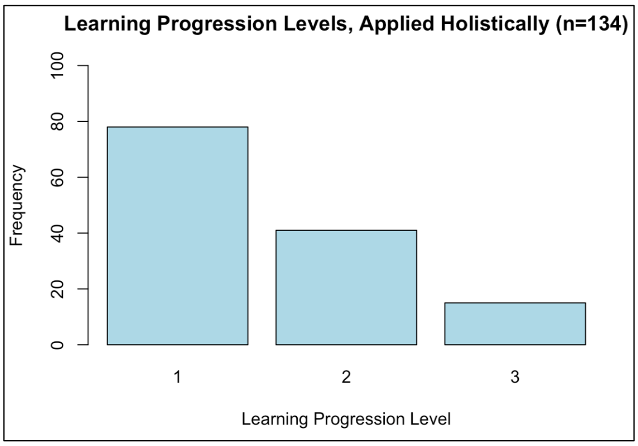

Figure 4. Distribution of holistic approach.

Comparison

When we directly compared each individual student’s disaggregated and holistic score, we found the Pearson correlation coefficient to be 0.78 indicating that the disaggregated and holistic approach are fairly comparable to each other. This indicates that if students are referencing the phenomenon, increasing their DCI understanding, and producing more sophisticated types of explanations, this will likely result in a higher learning progression level. Though, as we can see this relationship illustrated in Figure 5, the variance may be an important consideration for pracitioners. There is more variance with the disaggregated totals and level 1 of the LP, though we see much less variance as we approach level 3. We also see overlap in the disaggregated score between the upper and lower quartiles of adjacent LP levels, so the holistic approach potentially runs the risk of creating distinctions between students whose responses were similar relative to the specified codes. This might indicate a need for a more nuanced approach if analyzing student work falling mostly into level 1. This variance could be explained by students who drew detailed models with multiple elements represented but who may not have been including elements of the LP and might have missed key indicators of energy flow or dissipation, for example. This range may also reflect the difficulty of taking up modeling as a relatively new science practice for teachers and students alike.

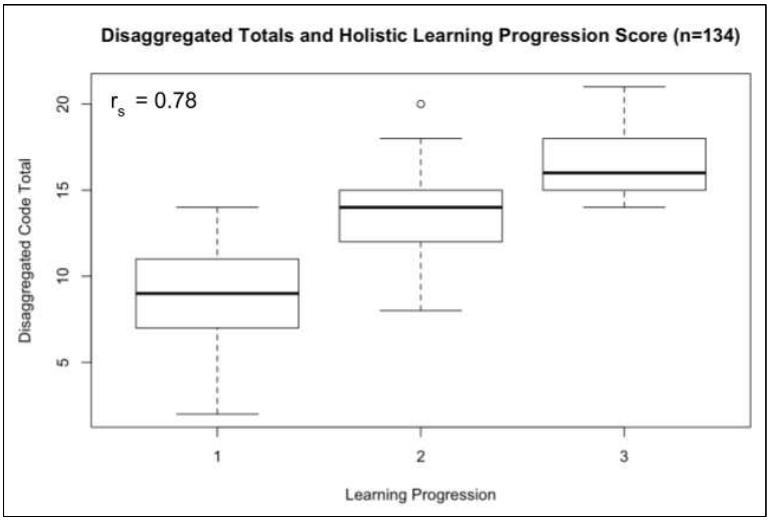

Figure 5. Relationship between disaggregated totals and holistic scores

Overall, our findings suggest that a classroom teacher with upwards of 120 students may find the holistic approach to be the most economical approach to evaluating student work; however, the teacher would want to consider how this approach does not account for changes from the initial to the revised model. Additionally, the holistic approach may be a simpler, mediating artifact for students to reflect on their progress. These results are also consistent with how we might expect the facilitation around a phenomenon to coincide with student gains in modeling energy, where teachers are supporting students in leveraging their everyday understandings towards the goal of modeling energy in the context of cellular respiration.

Discussion

In this paper, we have examined two approaches to scoring multicomponent tasks: a holistic approach, based on an overall appraisal of student engagement in three-dimensional learning, and a disaggregated approach, which provides finer-grained information about student performance. Through our analysis, we found that these two approaches to scoring yielded closely related results; that is, in general, students scoring higher with the holistic approach also had higher overall scores on the disaggregated approach. However, we also found that for students with lower scores in the holistic approach, that were found to be performing at the lowest level of the learning progression, the disaggregated approach revealed more nuances and variations in the nature and quality of their responses. These differences were not as effectively captured when the holistic approach was applied.

These findings have key implications for teacher enactment of three-dimensional formative assessment tasks. Given the complexity of multicomponent tasks and the time-consuming approach of examining individual student responses to different elements of the task, our study suggests that taking a more holistic approach - comparing students' overall responses to a framework that includes disciplinary core ideas, science and engineering practices, and crosscutting concepts together - may be a faster way to determine what students have learned so far, and to identify next instructional steps. However, it also suggests that for students with lower-quality responses, teachers may benefit from spending more time analyzing student responses for additional patterns that could better tailor instruction to meet specific student needs.

At the same time, we note that the benefits of engaging students in complex, multicomponent tasks may far outweigh the challenges of fine-scoring these kinds of tasks. In the context of ongoing efforts to broaden engagement in science learning, particularly for those historically marginalized in classrooms, these kinds of tasks provide important space for students to show what they know and make sense of everyday phenomena. Our disaggregated approach indicated that using these tasks in combination with classroom activities that surfaced and worked with student ideas seemed to support improvement of models and explanations from the first to second part of the task. As such, our analysis indicates that teachers may not even need to closely examine formative assessment tasks such as these, especially since they consume so much time; instead, the teachers may know that the design of the tasks themselves serve a learning function. Future research may more broadly examine this possible finding across a larger range of classrooms and disciplinary contexts.

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