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Co-designing teacher support technology for problem-based learning in middle school science

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Abstract

This paper provides an experience report on a co-design approach with teachers to co-create learning analytics-based technology to support problem-based learning in middle school science classrooms. We have mapped out a workflow for such applications and developed design narratives to investigate the implementation, modifications and temporal roles of the participants in the design process. Our results provide precedent knowledge on co-designing with experienced and novice teachers and co-constructing actionable insight that can help teachers engage more effectively with their students' learning and problem-solving processes during classroom PBL implementations.

KEYWORDS

co-design, HLCA, problem-based learning

INTRODUCTION

Technology and social advances are increasingly influencing teaching in modern classrooms, following the increased calls for designing inclusive educational opportunities that engage students in real-world, student-centered, inquiry-based science, technology, engineering and mathematics (STEM) learning (NGSS, 2013). Many advancements have been made for supporting students in open-ended, technology-enhanced problem-based learning (PBL) opportunities (Hmelo-Silver, 2004; Saleh et al., 2022), but there is a dearth of research in teacher support technology that helps them develop and deliver such curricula in their K-12 classrooms in an effective manner without the help of researchers (Chen et al., 2021). In addition, teachers want to ensure that the technology-enhanced curricula align with specified standards, their classroom goals and their teaching strategies (Penuel et al., 2007). However, many teachers have little to no experience in using technology-enhanced PBL

Practitioner notes

What is already known about this topic

- Success of educational technology depends in large part on the technology's alignment with teachers' goals for their students, teaching strategies and classroom context.
- Teacher and researcher co-design of educational technology and supporting curricula has proven to be an effective way for integrating teacher insight and supporting their implementation needs.
- Co-designing learning analytics and support technologies with teachers is difficult due to differences in design and development goals, workplace norms, and AI-literacy and learning analytics background of teachers.

What this paper adds

- We provide a co-design workflow for middle school teachers that centres on co-designing and developing actionable insights to support problem-based learning (PBL) by systematic development of responsive teaching practices using AI-generated learning analytics.
- We adapt established human-computer interaction (HCI) methods to tackle the complex task of classroom PBL implementation, working with experienced and novice teachers to create a learning analytics dashboard for a PBL curriculum.
- We demonstrate researcher and teacher roles and needs in ensuring co-design collaboration and the co-construction of actionable insight to support middle school PBL.

Implications for practice and/or policy

- Learning analytics researchers will be able to use the workflow as a tool to support their PBL co-design processes.
- Learning analytics researchers will be able to apply adapted HCI methods for effective co-design processes.
- Co-design teams will be able to pre-emptively prepare for the difficulties and needs of teachers when integrating middle school teacher feedback during the co-design process in support of PBL technologies.

curricular applications (Bocconi et al., 2016). This poses a big challenge that drives our primary question "*how do we design K-12 teacher support technology that helps teachers leverage technology-enhanced PBL curricula for classroom instruction*?"

Research in the learning sciences emphasizes the importance of integrating teacher insight into the design and development of curriculum materials, assessments and instructional strategies (Könings et al., 2014; Reiser et al., 2000). Our research focuses on *co-design*, coined by Penuel et al. (2007) to describe the collaboration between researchers and teachers for the systematic design and construction of technology-enhanced educational innovations. Given that teachers' perception of the technology strongly impacts their likelihood of adoption, co-design offers a targeted approach where teachers' pedagogical practices and their classroom contexts are given careful consideration by their active involvement in and contributions to the design and development process (Sanders & Stappers, 2008).

However, co-design approaches for developing teacher support technology can be complex. For example, teachers and researchers may have different criteria for establishing student success (eg, Blomberg & Henderson, 1990), which may hinder their decision making on the choice of technology features they consider to be effective in the PBL curriculum. Differences in workplace norms may impact teachers' comfort and willingness to participate in open dialogue about their concerns and needs (Penuel et al., 2007). Moreover, time and productivity constraints may make it difficult to tailor the co-design process for individual teacher's needs (Martinez-Maldonado et al., 2016; Penuel et al., 2007).

While progress has been made towards the creation of co-design workflows to address these issues (cf, Holstein et al., 2019; Martinez-Maldonado et al., 2016), adjustments and additional considerations may need to be made to account for the unique complexities of open-ended, PBL approaches. For example, teachers often have limited experience with the curricular approach, which typically occurs over multiple class days and leverages multiple representations of knowledge (eg, Hutchins et al., 2021). In addition, given that students have agency in their knowledge construction and problem solving, they may produce a multitude of solution construction pathways. As such, teachers must weigh various pedagogical approaches (eg, pair students with contrasting problem-solving approaches, link class discussions relating components of the problem to a real, school-related issue) based on their understanding of how to accommodate individual student, group and classroom pathways. In other words, they must consider taking actions that still maintain overall learning objectives while creating engagement in students to strive creating their own "optimal solutions." This is in contrast to providing direct feedback just to improve students' immediate performance similar to that targeted by current workflows (eg, solve the next step in the problem-solving process as envisioned by the teacher or tutoring system, eg, Holstein et al., 2019). Our approach targets the co-construction of actionable insight with experienced (teachers who may also know the underlying AI inherent in the system) and novice teachers to more deeply understand how feedback is leveraged by all teachers.

In addition to their lack of experience in technology-enhanced PBL curricula, teachers may not have a sufficient understanding of the artificial intelligence and machine learning (AI and ML) approaches that may be used to generate and interpret the learning analytics measures (Ahn et al., 2021; Chen et al., 2021). While these approaches have advanced our understanding of students' learning and problem-solving processes, more research is needed to target the complex task of translating what we know as scientists and researchers into a language that classroom teachers can interpret and convert to *actionable insight* (Wiley et al., 2020). Whereas it is important to generate analytics that highlight the different approaches students take in problem solving (eg using clustering algorithms), it is equally important to help teachers customize these characterizations in ways that they can convert them into actionable information to aid classroom instruction in open-ended PBL contexts, and also to support students who have difficulties individually and in small groups.

It is also important to understand how teachers use interpretations of the learning analytics to adapt their pedagogical approaches (Campos et al., 2021). We hypothesize that this requires earlier engagement in responsive practices with teachers and coming to a shared understanding about the data they need to understand students open-ended PBL strategies. This understanding then has to be translated into the teachers' preferences, concerns and needs in ways that they are comfortable acting on, especially since PBL curricula are often implemented over several class days. Teachers inexperienced in PBL curricula may find it particularly difficult to express their needs and contribute to the co-design, therefore, significant efforts have to be made to support effective contributions by all teachers. Finally, typical co-design workflows provide templates for what questions to ask at each stage (ie, Martinez-Maldonado et al., 2016); however, we hypothesize that additional efforts need to be made to better understand what teachers need from designers and researchers to optimize their contributions to the technology design.

In this paper, we adopt human-computer interaction (HCI) approaches to investigate participants' experiences and roles in co-designing the Responsive Instruction for STEM Education (RISE) dashboard, a teacher support technology to aid in the implementation of a PBL curriculum in middle school science. We explore the mechanisms that enabled stakeholder engagement through the various phases of the design process and we elaborate more on the differences of our approach in Section "Methods". Our approach adopts *design narratives* to describe the co-design methods and their progression. This includes *analysing partner needs* to ensure decision-making contributions and to consider *role transitions* that are linked to the type of co-design activity. Establishing a meaningful contribution from teachers to shape learning analytics technologies that emphasize instructor support is a central open challenge in HCI research (Baumer, 2017). Appreciating the *dynamic evolution* of these processes can help researchers and teachers create collaborative engagement that makes the technology developed directly applicable to their classroom contexts. Furthermore, it helps all participants recognize and document potential difficulties in the collaboration process so that they may be mitigated through future interactions.

The rest of this paper is organized as follows. Section "Co-Designing Instructional-Support Tools" defines the co-design process, the key design perspectives and the workflows that impacted our implementation. Section "Methods" presents our co-design workflow and our data collection and analysis methods. Section "Design Narratives in Co-Designing a Teacher Tool" details our co-design stages and activities and provides design narratives that are discussed in two phases: (1) defining actionable insights and (2) enacting responsive pedagogy. Section "Insights, Conclusions and Future Implications" then summarizes our insights and novel takeaways from co-designing the teacher support technology for PBL instruction and discusses the limitations of the work and directions for future research.

CO-DESIGNING INSTRUCTIONAL-SUPPORT TOOLS

Co-design shares assumptions and philosophies with other design paradigms. For example, consider participatory design, where stakeholders are actively involved in the design process from the start to the end (Cober et al., 2015; Muller et al., 1992). Two important considerations are *value-sensitive design*, where the adoption of the technology depends on the degree that the design reflects the users' values and needs (Friedman et al., 2002), and *scenario-based design*, where the focus is on the context of the technology implementation (Carrol, 1999). Co-design distinguishes itself because it needs the active *contributions* of all participants (eg, teachers, students, researchers) through the design and development process (Martinez-Maldonado et al., 2016), and emphasizes adaptability that supports stakeholder (eg, teachers, students) engagement, ownership and value in the design and outcomes (Penuel et al., 2007).

Key co-design recommendations have been identified in the literature to leverage the benefits discussed above. For instance, the co-design approach must target the creation of a tangible end product for a technology-enhanced curriculum that allows for flexibility and adaptability in its application that meets the needs of the different teachers and adapts to their teaching strategies (eg, Martinez-Maldonado et al., 2016; Sanders & Stappers, 2008). In this process, it allows for more direct contributions from a diverse group of teachers (Penuel et al., 2007). To ensure alignment with co-design perspectives, which are separate from common participatory or cooperative design approaches, all stakeholders must have active engagement and contributions from the beginning of the design process (Martinez-Maldonado et al., 2016).

In school, teachers work with a diverse set of students and may have insights into how chosen pedagogical approaches may impact the current student class. To ensure mutually beneficial learning and communication, the co-design process must include activities that bring co-design partners together to discuss and come to a shared understanding of the technological needs (Penuel et al., 2007). As the co-design process evolves, roles can be customized to adapt to the progressive needs of all stakeholders. This must also consider that teachers' knowledge may grow through active participation. For example, a teacher's AI literacy may increase over time as they visualize and interpret the generated learning analytics (Roschelle & Penuel, 2006).

Finally, we believe all partners need to benefit from the co-design process. This could include payments, learning and donations for their contributions to the design of the tangible artefact (cf, Dollinger & Lodge, 2018; McKercher, 2020). Co-design processes for educational technology should be timed to fit into the school cycle to support deeper insights into the impact of teacher strategies on student learning (Penuel et al., 2007). The latter has the additional benefit of supporting timeliness in the application as the design cycle can be scheduled with the teacher's curriculum schedules.

These approaches have demonstrated significant benefits (Ahn et al., 2019; Sarmiento & Wise, 2022). These include: (1) supporting teacher and student learning (Penuel et al., 2007), (2) aligning educational goals and instructional strategies across multiple stakeholder perspectives (Barab & Luehmann, 2003), (3) creating unexpected innovations (Holstein et al., 2019), (4) empowering participants by giving them a voice in shaping the technology that impacts their practice (DiSalvo et al., 2017) and (5) helping ensure sustainability by keeping materials relevant and usable (Barab & Squire, 2004; Blumenfeld et al., 2000). Moreover, researchers are provided enriched opportunities to learn from teacher experience to more clearly understand teaching activities, processes and goals that can serve as the basis for defining technology requirements (Matuk et al., 2016), which is important as we develop technologies to facilitate the complex task of engaging in students' problem-based learning (Chen et al., 2021).

However, as discussed above, a number of challenges have limited the application of this approach. With a few exceptions (ie, Holstein et al., 2019; Prieto et al., 2019), little guidance is provided for end-to-end co-design. Neither Holstein nor Prieto cover student-centred approaches, such as open-ended PBL curricular implementations, and limited co-design research exists that supports responsive teaching in science (Matuk et al., 2016). Our research targets this deficiency in the literature by providing details on a multi-step co-design process that culminated in the creation of the RISE teacher dashboard for PBL. By presenting the details of the design and development process, our research aims to contribute precedent knowledge (Oxman, 1994) of useful co-design and development approaches for instructor-support technology for PBL curricula in K-12 classrooms.

METHODS

Curriculum application

This research centres on supporting teachers in the application of the Spice Project Integrating Computing and Engineering (SPICE) PBL curriculum, co-designed and developed through an iterative, design-based process, where each component of the SPICE curriculum was systematically refined based on multiple research studies conducted across the United States. SPICE supports teachers in the implementation of a curriculum that introduces students to why flooding and runoff may occur after heavy rainfall (Hutchins et al., 2021). The PBL curriculum (illustrated in Figure 1) consists of five core units (1) physical experiments; (2) conceptual modelling; (3) paper-based computational thinking tasks; (4) computational modelling of the water runoff phenomenon; and (5) the engineering design

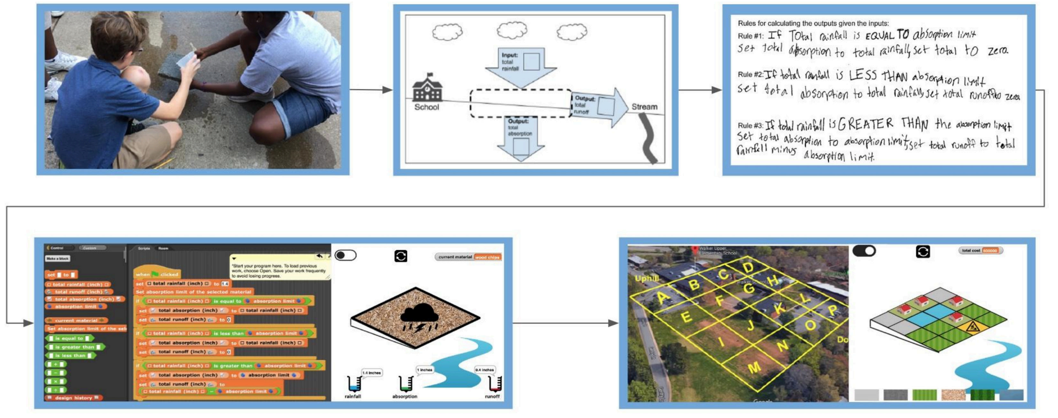

FIGURE 1 SPICE curriculum progression.

problem, where students use their computational models to redesign their schoolyard. The three-week curriculum unit challenges students to redesign their schoolyard using appropriate surface materials (from a given set) to minimize the amount of water runoff after heavy rainfall while adhering to a series of design constraints. These include the overall cost and accessibility while providing for different functionalities for the schoolyard. The learning context is authentic and relevant to students who may face similar problems in their day-to-day lives, for example water runoff causing flooding and pollution in their own schoolyards. The curriculum is aligned with key science, computing and engineering standards at the national and state level in the United States.

Participants

Nine middle school STEM teachers (6 female, 3 male) participated in three design sessions. Due to varying availability, three teachers participated in all three sessions, one participated in two sessions, and the remaining five participated in one session. Each teacher consented to take part in the Vanderbilt University IRB-approved research. The teachers were from different urban and rural locations in Tennessee, Illinois, Virginia, New York, Wyoming and the US Virgin Islands. They were recruited based on their prior collaborations with the research team, and to ensure we had a variety of locations and experience with the PBL curriculum. However, our low participant numbers were due to difficulties we had in scheduling given the other time commitments of the teachers. Because COVID-19 was still prevalent in the United States and other countries, all co-design sessions took place virtually to ensure physical distancing requirements were not violated, to ease the scheduling requirements of all stakeholders and to allow for increased diversity in teachers' school demographics. Three teachers had prior ABC implementation experience, one teacher had prior experience with the core learning environment (Hutchins et al., 2019), and five teachers had no prior experience with our environments.

Overview of co-design process and methods

Our technology development particularly focuses on facilitating responsive teaching of PBL by co-designing the learning analytics and visualizations to make them interpretable and actionable to teachers. As such, we aim to provide teachers with insight into students'

STEM-related problem-solving processes during PBL, which then helps them to support students in self-directed construction of their knowledge (as opposed to teacher-directed knowledge construction in which teachers disseminate the needed knowledge). This requires additional considerations on what makes problem-solving analytics actionable and the types of actions teachers can take by interpreting those analytics. Overall, the goal is to promote responsive teaching practices that lead them from interpreting information provided on the dashboard to enacting PBL responses.

Our workflow was initiated based on the LATUX (learning awareness tools—User eXperience) workflow (Martinez-Maldonado et al., 2016). Given the concerns regarding teacher feedback for open-ended PBL curriculum, discussed previously, we identified four key limitations in prior co-design workflows. First, there is limited opportunity for the development of a shared understanding of what constitutes an actionable insight. This issue is identified in two parts: stakeholder contributions focused on usage feedback instead of direct contribution to the technology design (eg, the providing of multiple options for visualizations and stakeholders picking their favourite, as opposed to understanding data available and discussing pipelines that go from data to visualization outputs) and the enacting of possible pedagogical responses takes place later in the co-design process. This may limit opportunities for designers to advance their knowledge on various pedagogical approaches to support open-ended PBL. We hypothesize adjustments here can support a better co-design partnership as it requires a deeper understanding of what stakeholders need from designers and developers (and vice versa) to adequately contribute to the software development instead of simply acquiring feedback from stakeholders.

Second, prior workflows also demonstrated minimal consideration for inexperienced stakeholder contributions, which may bias teacher feedback towards designer preferences. For instance, with minimal knowledge of available data, AI/ML literacy and experience with prior curriculum applications, teachers may feel designers are more knowledgeable of the curriculum implementation and all potential feedback possible, which may limit their willingness to contribute new ideas (Penuel et al., 2007). We hypothesize that integrating experiential sessions (ie, exploring student journeys through the curriculum using past data) can not only support unique insights to educational feedback technology development but also provide inexperienced teachers with additional experience needed with the open-ended PBL curriculum.

Third, workflows developed for such technologies have focused on single representations for learning (eg, completion of a sequence of math tasks in an intelligent tutoring system or a group project). Open-ended PBL curriculum often are significant in length and involve learning through multiple, linked representations (Hutchins et al., 2021). Co-design methods should support teachers in the linking analysis and feedback of these multiple representations to support students in leveraging these links. Taking these identified concerns into consideration, we have developed our co-design workflow that is illustrated in Figure 2.

The first phase of our co-design process addresses the need to define actionable insight. This can be linked to problem identification and low-fidelity prototyping events in LATUX, where teachers, researchers and designers have to come to a shared understanding of the available data (including its ethical, privacy and inclusivity aspects), what information can be gleaned by analysing that data, what actions may result from these insights, and how those responsive actions impact the student-centred learning approach. This approach addresses some of the key limitations in the literature. For example, researchers can go beyond an understanding of teachers' goals, preferences and concerns, and focus on the strategies the teachers develop to facilitate students' learning by studying different visualizations of the students' results. Moreover, developing such a shared understanding may limit issues of ability bias by researchers and designers as they more holistically look at the curriculum and classroom context from the perspective of the teachers.

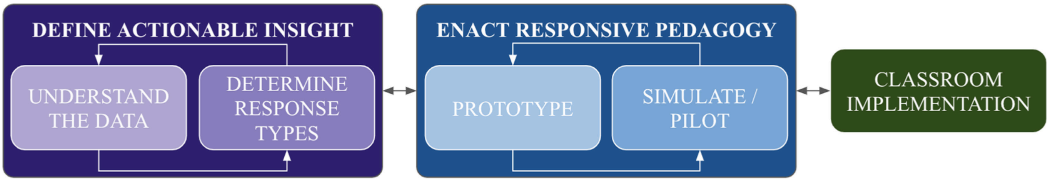

FIGURE 2 RISE co-design process.

The second phase involves the enacting of responsive pedagogical approaches using the co-designed feedback. In this phase, we offer multiple opportunities for teachers to reflect and plan evidence-based pedagogical responses using high-fidelity prototyping and simulations. As designers and researchers, this phase allows us to compare teachers' responsive teaching practices against our assumptions of what could be possible with the designed technology. This phase was inspired by previous work, where teachers gain experience with real student data from prior implementations (eg, Holstein et al., 2019). However, in our work and akin to PBL approaches, the curriculum is flexible, and teachers' responses are not limited to individual student support or feedback but can result in class and group-level discussion and curriculum changes. The goal of this phase is to give teachers ample opportunities to experience the feedback and practice pedagogical responses that best emulate what they may do in their classrooms. Finally, we believe it is important for this technology to be systematically piloted in teachers' classrooms as this can highlight engagement and inclusivity concerns that are hard to enact outside of the classroom, and gradually ease teachers into using such technology without researcher support.

The final step is the classroom implementation without a researcher's presence. It is important to note that this process is not sequential because it may involve the return to previous steps of the process as new knowledge is acquired by all partners.

For the purpose of evaluating the co-design processes, this paper focuses on an analysis of the *define actionable insight* and *enact responsive pedagogy* phases of the design process (Figure 2). The Define Actionable Insight phase is adapted from HCI techniques like card sorting, low-fidelity prototyping and user journey mapping (Martin & Hanington, 2012) to actively support the co-construction of actionable insight by our design partners (the teachers). The enact responsive pedagogy phase adapted high fidelity prototyping discussed in Martinez-Maldonado et al. (2016) to emulate response scenarios and allow design partners to understand the impact of the design technology on pedagogical decision making. Choices of the method used for each phase of the multi-step design process were made adaptively, based on (1) uncertainties present in learning analytics and accompanying visualizations, (2) teacher experience and background and methods needed to support meaningful contributions and (3) logistic concerns (eg, time constraints and COVID protocols). For each of these approaches, we discuss how they were implemented, how different representations were used to open discussions, and how we grounded design decisions in evidence derived from the approach. As discussed earlier, it is important to note that due to COVID-19 limitations, we were unable to implement a classroom study. However, a classroom study was implemented in the spring of 2023 and we discuss anecdotal findings in the conclusions.

Data collection and analysis

To support a thick description (Hoadley, 2002) of our design prototypes, tools, processes and decisions, we used a range of data sources, mostly collected through video recordings as described in Table 1. All sessions were conducted virtually and recorded using a video

TABLE 1 Data collection by design session.

Phase	*n*	Video	Observations	Prototypes	Meetings
Define actionable insight	5	2 4-hour videos, 2 1-hour videos	14 pages of notes	3 journey maps (Miro.com); 30 slides	10 pages of notes; 20 slides
Enact responsive pedagogy, Hi-Fi prototype	4	4 2-hour videos, 1 1-hour video	6 pages of notes	1 interactive proto type	15 slides; 1 affinity diagram; 4 pages of notes
Enact responsive pedagogy, simulations	8	16 1-hour videos	22 pages of notes	1 interactive proto type (XYZ)	10 slides; 14 pages of notes

conferencing platform. In total, we had approximately 35 hours of video data, which we transcribed using an online transcription service. After each design phase, members of the research team met to synthesize insights and make decisions about the next prototype phase.

We used methods of inductive coding and constant comparative analysis (Charmaz, 2006) as opposed to theoretically developed codes, to support the development of the design narratives presented in this paper. To our knowledge, there is very little research examining the dynamic roles and mechanisms needed to support design partner contributions for technology enhanced PBL support tools. As such, this approach better supported the exploratory nature of this research and provides a systematic way to present insights from our novel co-design process.

To accurately balance units of analysis, we first divided the transcripts into smaller excerpts related to *idea units* (Jacobs & Morita, 2002), in which a single topic was discussed, and observation notes were paired based on time and relevance. An example idea unit includes, "*I mean, domain-specific results would be really useful for me, because then I could, because sometimes it's hard to know, for the kids to articulate what's hard for them. They'll just say, this is hard, or I'm confused, or I don't understand*." Researchers met to code idea units for 10-minute segments of each design phase and to come to a consensus about targeted codes. One researcher (the first author) coded the remaining idea units. This process allowed the researchers to leverage developed codes and linked observation notes for memoing (Hatch, 2002), summarizing the main ideas and context of the design sessions, the design partners and their roles, the structuring and timing of the collaborative design activities, and the focus of the design partners during each activity. The next step in our analysis was to use our memos for developing *design narratives* (Hoadley, 2002), a technique used in the learning sciences to illustrate the context, outcome, and contributions of the co-design techniques. We identified key insights from these design narratives to target our goal of providing precedent knowledge for future co-design research with K-12 teachers and support future co-design work for technology enhanced PBL environments and tools. We note that this analysis is subjective and alternate interpretations may be possible. Therefore, our work primarily offers insights into developing and supporting future co-design approaches.

DESIGN NARRATIVES IN CO-DESIGNING A TEACHER TOOL

In this section, we provide design narratives and reflections on these events for each of the two main co-design phases.

Design phase: Define actionable insight

This phase leveraged low-fidelity prototyping and physical artefacts as they have shown to be more conducive to teachers' feedback and critiques as they convey preliminary views of the overall approach (Matuk et al., 2016). This included a series of design activities adapted from established participatory design methods, and this included card sorting, the love letter and the break-up letter, and user journey maps (cf, Martin & Hanington, 2012).

Understanding experienced and novice teachers' needs, values and concerns regarding PBL facilitation prior to prototype development

The first step in this process involved discussing and eliciting teacher insight regarding (1) how they perceive integrating PBL into their classroom teaching, the concerns they have, and their preferences regarding classroom implementation; (2) what they need (eg, educational technology requirements, curriculum and classroom resources, etc) to facilitate the implementation of PBL; and (3) what potential actions they may take to support students if their needs are addressed. The focus was on gaining a better understanding of middle school STEM teacher needs for implementing the PBL curriculum in their classrooms (for both experienced and novice teachers). Example artefacts from each session are provided in Figure 3.

First, in order to support a freer flow discussion of teachers' goals and concerns about teaching PBL, and specifically for integrating computing and engineering into their science classrooms, we conducted an activity that avoided the use of terminology, for example, “learning analytics”, “artificial intelligence” and “technology support.” Instead, we adapted Holstein et al.'s Superpowers activity (Holstein et al., 2019), a card-sorting approach in which teachers described and compared the superpowers they needed to do their jobs well. To do so, we

- prompted teachers by asking, “If you were granted superpowers to better understand student learning and the successes and difficulties they experience during their learning, what superpowers would you like to possess?”,
- provided initial “superpower” cards leveraging results from past work (Holstein et al., 2019) to initiate discussions, and
- conducted the activity via shared Google Slides while using a video conferencing system (because we were restricted by COVID protocols).

An example of a teacher's superpowers card sorting activity is shown in Figure 3a. This approach allows us to view the problem at a high level and determine examples of teacher priorities that we need to target in a teacher dashboard as well as any feedback adaptivity or personalization that we need if teachers demonstrate significantly different priorities. In addition, this allowed us to learn more about a teachers' perspective on what kind of feedback better supports their pedagogical strategies and prior experience, as teachers needed to rank what superpowers they felt best aligned with their needs and preferences in the classroom.

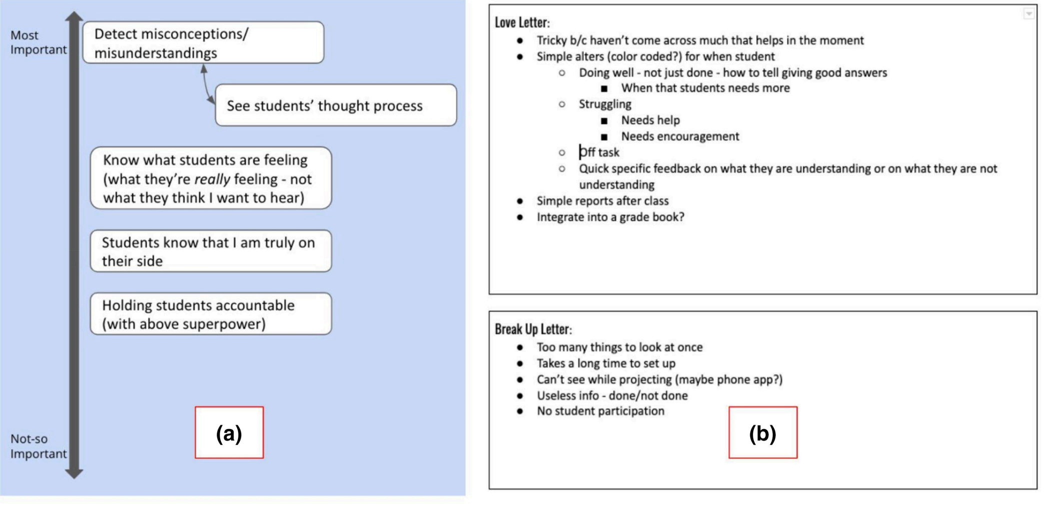

FIGURE 3 Example artefacts from the superpowers (a) and love/break-up letter activities (b).

For instance, in the example in Figure 3a, the teacher focused on (1) identifying students' misunderstandings and the thought processes that may have led to these misunderstandings; (2) knowing what students were really feeling in the PBL curriculum (eg, frustration and anxiety); for example, a teacher noted "*it's tied to a lot of anxiety with kids and depression, which we're seeing in kids so much now more and especially since pandemic more than ever before, where they can't, they're so overwhelmed, they can't articulate what they don't understand*"; and (3) holding students accountable, which is a difficulty identified in the PBL literature (eg, Hmelo-Silver & Barrows, 2015). We also utilized results from this session as a key resource for our user interface (UI) visualization requirements. For example, if it became necessary to determine what to eliminate from the UI to prevent displaying too much data, this resource reminded us to keep our attention on the key priorities of the teachers.

As a next step, following an initial presentation on SPICE (over video conferencing), teachers completed a written prompt, which they wrote as a love letter and a break-up letter (Martin & Hanington, 2012) about their use of technology to evaluate students. In these letters, teachers described "*what excites you and what you like about the availability of feedback on student learning processes and behaviours, including what it may help you to do* (love letter)" and "*what concerns you and would cause you to 'break up with' this technology along with what would prevent you from using this type of analysis in your classes*." An example love letter and breakup letter for a participating teacher are shown in Figure 3b. This activity extended our focus on teachers' needs, values and concerns regarding technology enhanced PBL curriculum implementation by diving deeper into what would engage them in using educational technology, especially teacher support technology, to support PBL in their classroom and what may cause them to stop using it (and potentially stop adopting PBL curricula in general). To our knowledge, this is one of the first attempts at acquiring such details on teacher insights for technology enhanced PBL curricula.

Low-fidelity prototyping for teacher data visualization insights

The next step started off with low-fidelity prototyping. We were faced with unique issues in this process:

- problem-based, technology-enhanced learning approaches such as computational modelling can include a variety of data types and possible analyses that target student learning across multiple domains. Further, how do we identify the many different learning pathways students can employ in their computational modelling tasks that combine science and computing knowledge? The literature is scarce on what teachers need to know from student activity data to support evidence-based responses, and
- in our PBL curriculum, learning occurs through multiple, linked representations over 15 lessons. Developing an understanding of how students learn, what teachers need to understand of students learning processes, and how they may respond will be impacted by student work that occurs at different time-points in the curriculum.

In order to address these concerns, we adapted the concept of user journey maps to create a curriculum journey map (see partial depiction in Figure 4). Instead of visualizing the experiences students had at each step when using a specific environment, these journey maps visualized the SPICE learning progression and were supported by three student examples developed for each "moment" (or lesson). In addition, the teachers were also presented with the overall class-level data visualizations.

To begin, all teachers received a brief presentation over video conferencing (due to COVID protocols) about the SPICE curriculum. This included a review of the research team's prior

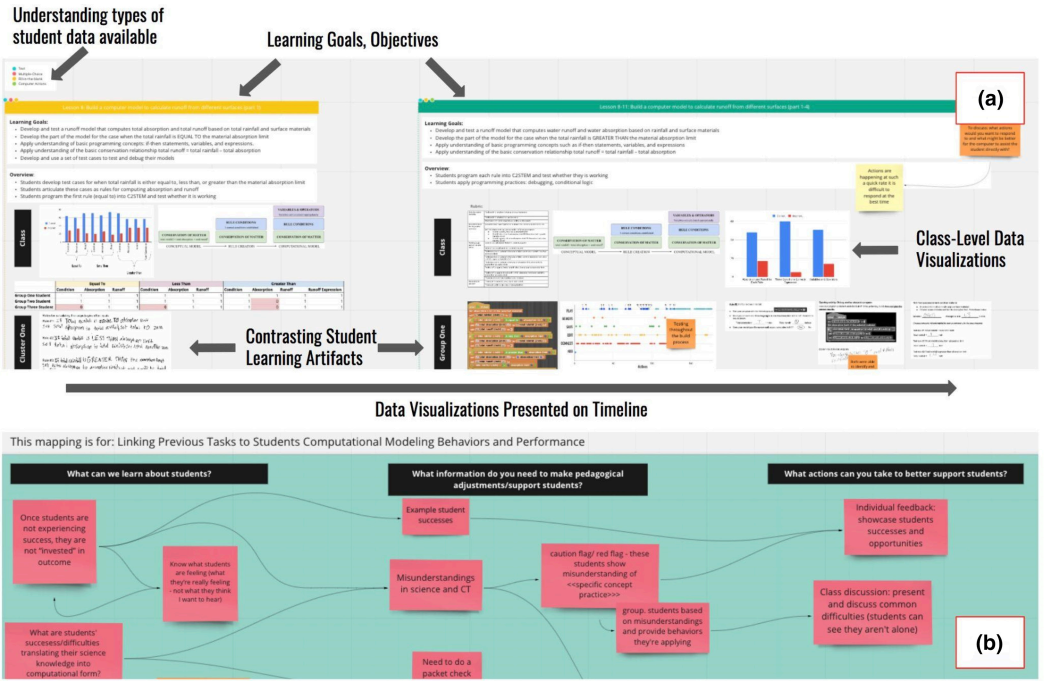

FIGURE 4 Curriculum journey map components.

experience implementing such curricula, such as learning performances in the integrated domains and example student difficulties. Teachers with no SPICE experience were also invited to complete the computational modelling activity and test design prototypes to gain user experience with the technology-enhanced learning environment.

Using the Miro software, we created a timeline of SPICE activities, shown in Figure 4a. Each lesson included:

1. lesson objectives and goals (to orient each teacher),
2. details about the type of student artefacts available (to identify the type of student data available for analysis),
3. initial analysis of student learning (data visualizations to demonstrate initial dashboard feature ideas), and
4. three example artefacts representing contrasting cases (to promote strong reactions by participating teachers, see Matuk et al., 2016).

This visualization of the curriculum timeline allowed researchers and teachers to (1) map lesson objectives to examples of student work for an in-depth discussion on the quality of tasks and analysis, (2) link multiple representations of student learning to discuss the impact of pedagogical approaches on learning over time (in prior research, we identified the importance of students' learning through multiple, linked representations to support integrated science, CT and engineering learning) (Hutchins et al., 2021), for instance a teacher identified that an example student "*seemed to struggle linking conceptual models to this task* [unplugged computational modelling activity] *or they are struggling with the difference between absorption limit and total absorption*" and (3) support reflection on how teachers would enact evidence-based pedagogical responses based on the illustrated student journeys (eg, experienced teachers based on students results and novice teachers based on their experience in completing curriculum tasks). For instance, an experienced teacher recalled key transitional moments in the curriculum, "*Well, remember a lot of them were like me … when I had that a-ha moment—I had never heard of permeable concrete*," to highlight how the results support reflection and action. Moreover, connecting stakeholder understanding of what data were available for analysis, to the learning analytics used, the data visualizations used, and the learning objectives and standards of the curriculum provided an opportunity for the partners to more deeply discuss the analysis techniques used in the context of the curriculum, thereby potentially lessening the impact of teachers' potentially limited data science knowledge on learning analytics selections. These allowances directly targeted the three limitations of prior workflows, discussed previously.

In addition, our key leading discussion questions were displayed on a board that was available throughout each lesson discussion (shown in green in Figure 4b) in order to represent the data analysis and evidence-based feedback pipeline. Some of these questions were:

1. What can we learn about students?
2. What information do you need to support students?
3. What actions can you take to better support students?

This board served as a shared note-taking tool in which teachers and researchers linked answers to the questions (input as post-it notes on the Miro board) to form a journey from what could be learned about student performances and processes used in the curriculum to potential evidence-based responses that might be taken to support their learning. The curriculum journey map (and all its elements) and the shared note-taking board served as boundary objects (Akkerman & Bakker, 2011) to support researcher-teacher partnership discussions about responsive teaching in the curriculum and ways technology could support it.

In this design phase, the activity events provided teachers opportunities to express their needs, preferences and concerns in different formats (eg, sorting superpowers based on their experience, background and pedagogical preferences), reason about the curricular application from both a teacher and a student perspective, and reflect on their own personal experiences with the curriculum as students in ways that allowed them to reason about the learning analytics provided across the multiple-linked curricular representations. Simultaneously, these tangible objects served as boundary objects that allowed researchers and teachers to co-construct an understanding of what makes data visualizations and analysis actionable for the classroom teacher from such perspectives.

Design phase: Enact responsive pedagogy

The goal of the second design session was to support feedback for refining and extending the features of the co designed dashboard in the context of teacher needs through high-fidelity prototyping and planning period simulations.

High-fidelity, prototype supported teacher training

This work was inspired by Replay Enactments (Holstein et al., 2019) and the use of real classroom data from prior SPICE implementations. The purpose was to simulate example situations where teachers could review the information on the dashboard, interpret the findings, and make in-the-moment decisions on the next steps, which could include evidence-based pedagogical responses to individuals or groups of students. We conducted this session as part of a virtual, SPICE teacher training workshop. During these sessions, teachers collaborated with researchers by going over curriculum lessons and discussing modifications to tasks, formative assessments and instructional strategies. It was also recommended that teachers complete the computational modelling and engineering design activities as if they were students. This would help them reflect on problems students may have. We paid careful attention to the literature for the potential misalignment between co-design work and professional development (Boschman et al., 2014) to ensure meaningful contributions by the participating teachers. Our reasoning behind integrating this design session with teacher training was to support contributions by teachers with no prior SPICE experience.

During the session, the lesson plan was introduced along with an overview of the lesson objectives, instructional strategy and tasks. The research team then shared the high-fidelity dashboard prototype (Figure 5) with teachers with the goal of simulating responsive teaching practices for each lesson and targeting key design questions including a better understanding of how much is too much in terms of visualizations presented and how to present information that facilitated PBL instruction and support. A think-aloud protocol (Martin & Hanington, 2012) was implemented, in which teachers were tasked with describing what they notice, and their interpretation of the results based on the lesson objectives. Teachers then discussed what they might do in terms of any potential changes needed prior to that lesson day or adjustments they would want to make in the next lesson. In one example, given the practice of verbally describing next-day responses, a teacher noted that "*So maybe there should be in the reflection* [tool], *a task tweak for something that's ongoing, and then in the drop down a task tweak for next time*", which provided an actionable contribution that the developer could use to refine the reflection and response tools provided to the teachers. Researchers would ask probing questions as needed. In addition, as seen in Figure 5, teachers were shown three post-it notes at all times to help prompt collaborative discussion. Finally, in reflecting on potential pedagogical responses, teachers and researchers reflected on the visualizations present and discussed design recommendations to aid in teachers noticing, interpreting and responding process. Conflicting contributions of teachers were recorded and used as discussion items during the Planning Period Simulations (next).

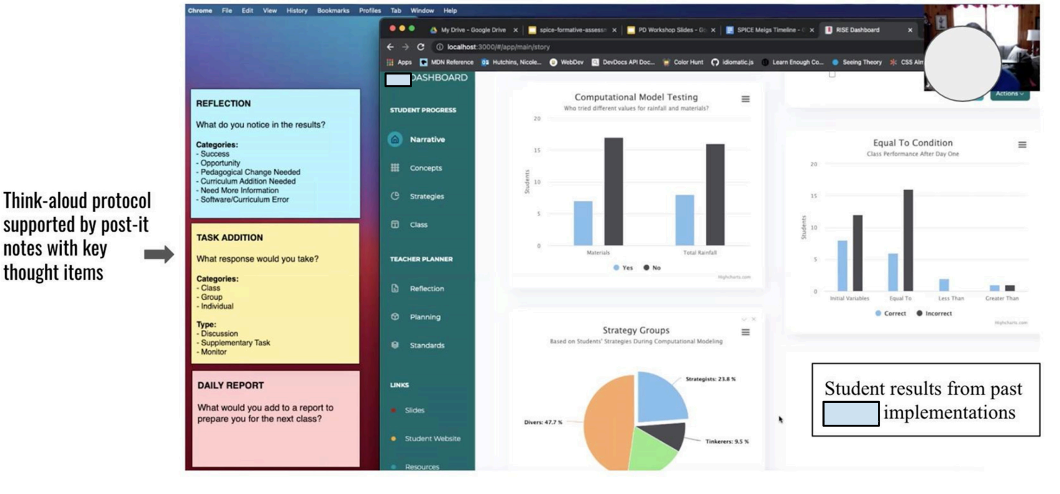

FIGURE 5 Example from the high-fidelity, prototype-supported teacher training.

Planning period simulations

Eight teachers (four experienced and four novice with the PBL curriculum) completed five planning period simulations in which teachers enacted five 15-minute "planning periods" by utilizing the RISE dashboard (see Figure 6) to review and reflect on student, group and class performance and then develop evidence-based lesson plan customizations for the "next" class day. These simulations were inspired by the teacher moments research at MIT (Benoit et al., 2021). Student data used for each simulation was pulled from prior SPICE implementations. Student data from the prior implementations were de-identified and students were given gender-neutral names. The five simulations were selected based on the average summative assessment performances in science and CT (eg, one simulation included a class that had an above-average pre-test performance in science, but a below-average pre-test performance in CT).

Each teacher first completed a 90-minute professional development session on the ABC curriculum led by the research team. For each simulation, a research team member first described the class scenario, including the class performance on the pre-test and other class results prior to the simulation "day" (eg, students' scores on the science conceptual models). Teachers then had 15 minutes to complete the simulation exercise. Fifteen minutes was selected based on an estimated class period time length of 60 minutes and an average estimated class roster of 4 classes per teacher, therefore, 15 minutes were devoted to each class in the planning period.

Using a think-aloud protocol, teachers reviewed student results and feedback provided on the RISE dashboard, interpreted what they saw, and customized class lesson plans for the next day (as they saw fit). Prior research has noted the benefits of think-aloud protocols on tasks involving building interpretations (Charters, 2003), including providing a low-entry barrier (Campos et al., 2021) and tracing users' thinking (Liu & Stasko, 2010). To obtain verbalizations that accurately reflected the cognitive processes teachers implemented during responsive teaching, we refrained from providing detailed instructions or interpretation of results. Instead, we utilized prompts such as "*what possible actions would you take with this group?*" and answered questions about technology that did not impact class evaluations (eg, describing how to use the reflection form). This approach is modelled after Campos et al.'s approach for evaluating teacher sense making (2021) and helped minimize issues concerning bias in the data if researcher support or feedback impacted teachers' responses (Sherin & Russ, 2014).

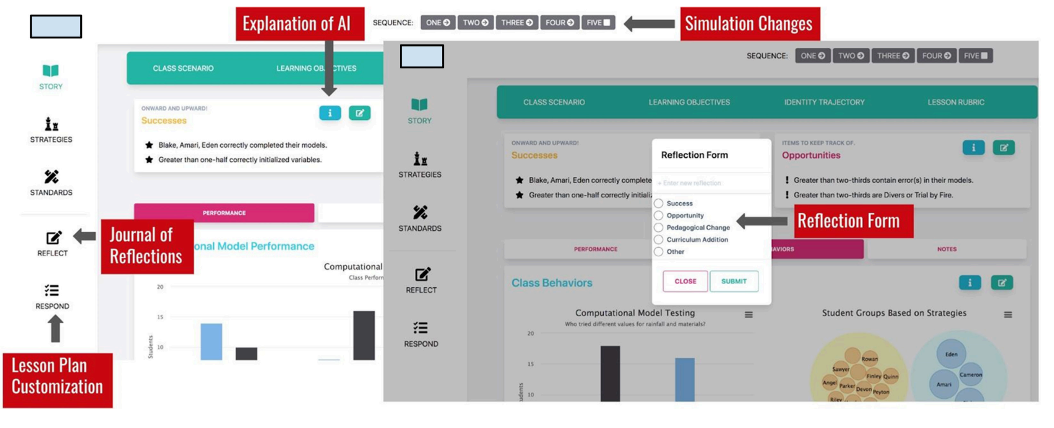

FIGURE 6 RISE dashboard for planning period simulations.

While teachers took on the role of dashboard users, researchers completed an observation sheet during the simulations. The observation sheet consisted of a table for researchers to identify (1) discussed idea (eg, computational model scores), (2) visualization targeted, when applicable (eg, bar graph of class performance) and (3) keywords used or links made (eg, poor initialization of science variables score during computational modelling relating to prior science performance). These observations were used for post-simulation discussions with teachers in which we reviewed the responsive teaching process teachers implemented, discussed teacher feedback on their process and the technology's support of that process and came to a consensus on adjustments or customizations that may be needed for a real classroom implementation. For instance, in our data visualizations of strategy groups, a teacher noted that it would be beneficial to indicate, via a colour scheme, the students that transition to new strategy groups, as it may be beneficial to highlight students that improve on their problem-solving skills. This activity also addresses a key concern in the literature regarding the limitations of high-fidelity prototyping not providing adequate testing of the feedback software (Martinez-Maldonado et al., 2016), as scenarios were designed to best represent traditional teacher planning periods in US K-12 classrooms.

Throughout the enact responsive pedagogy design phase we identified the importance of simulating pedagogical decision making to support a deeper understanding of what makes feedback actionable to classroom teachers. In these activity events, the prototype and simulation served as tools to enact the responsive teaching process in a way that researchers and developers could observe the processes teachers took. Moreover, the process highlighted the importance of new technology innovations (eg, reflection and response enactment support via interactive tools) and future research could leverage this high-fidelity prototyping and simulation approach to increase our understanding of how we can advance from simple displays of student results via dashboards to interactive teaching support technology that better supports implementation and classroom enactment needs.

INSIGHTS, CONCLUSIONS AND FUTURE IMPLICATIONS

This paper demonstrated a novel approach to co-design considering insights from experienced and novice teachers when designing and developing teaching-support technology to improve responsive teaching with PBL curricula. Moreover, we provided precedent knowledge of a new co-design workflow that highlights the importance of co-constructing actionable insight and allows for opportunities to enact classroom pedagogy with the developing technology. Our methods centred on eliciting teacher insight to help them engage when student learning and problem solving took place across multiple domains.

Our findings are similar to prior work that discuss the benefits of beginning with stakeholder needs, prototyping user tasks and usage scenarios early and often, and using real-world data sets to support prototyping (Holstein et al., 2019). However, we had to adapt these processes to support our goals for helping teachers with PBL curricula. The adaptations that we implemented include:

- *Regularly connecting student results across multiple, linked representations*: Problem-based learning often requires the application of knowledge and skills from multiple domains and highlights the importance of NGSS cross-cutting concepts. Teachers should be actively involved in creating these representations so that they better understand the linkages and the data used to evaluate students across the multiple representations. In addition, regularly linking representations allows for critical reflection on the impact of pedagogical responses to student learning over the course of the PBL curriculum.

- *Immersing teachers, especially novice teachers, in the student experience prior to promoting rich insight into visualizing student problem-solving processes*: In this research, we integrated the high-fidelity prototyping session into our SPICE professional development with the goal of receiving feedback from novice teachers (who had not previously implemented SPICE). In doing so, teachers became aware of their own problem-solving difficulties, and therefore, could better connect to real student results.
- *Regularly reflecting on instructional strategies at different social levels and throughout the co-design process*: An important update to our conjecture map was the need for teachers to understand student performance at different social levels (eg, class, group and individual) so that they could systematically weigh potential class adjustments at all three levels. This process not only supported our understanding of considerations teachers make in deciding the type of responses to provide (eg, conducting a class discussion if two-thirds of the class demonstrate an issue), but it also helped us refine data visualizations that allowed teachers to explore student learning from multiple perspectives.

The completion of these design phases has provided us with four important perspectives. First, in recognizing the differences in teachers' prior knowledge and experience, developing research-aligned prompts and questions is critical to eliciting needed information from teachers and for motivating increased conversation. For instance, we often experienced data visualization think-aloud processes in which teachers (experienced and novice) would identify that the results "*make sense*." But because of the prompt to teachers "*what possible actions would you take with this group*?" the discussion went from interpretation of results to co-constructing what made the result actionable for each teacher. Second, the notion of flexibility in both the curriculum *and* the support technology was the key to framing the co-design process. One teacher noted that they often used dashboards but they were still left with hundreds of post-it notes around their computer to capture and remember all of the results that were noteworthy. Based on capturing these experiences, when we think about the tangible objects we are creating, we should not only think about the feedback we provide but we must also think about how stakeholders can enact their preferred pedagogical response by leveraging and integrating the findings that are most actionable to their pedagogical strategies. Third, the teachers often combined their own teaching experiences and perspectives with student perspectives – understanding how the curriculum and external factors (eg, impacts of the pandemic) played a role in the students' learning and how this influenced the way the teachers responded. We believe this coincides with findings that emphasize the increased need of student contributions to these technology development processes (ie, Buckingham Shum et al., 2019). Finally, when discussing the data used and the analytics presented (particularly in the define actionable insight phase), teachers often asked significant questions about the process of taking logged action data and using it to group students based on common problem-solving strategies. While this led to contributions on how to name groups and information needed in the explainable AI feature, we believe that future work in explainable AI should focus on who the AI is being explained to in terms of the output or explanations generated.

Anecdotally, in a Spring 2023 classroom implementation of the curriculum and dashboard with a pair of 6th-grade teachers at the same school, the teachers reviewed the feedback from the classes as a pair after school so that they could work together to plan the next class day. The teachers identified that the majority of students struggled on the unplugged Rule Creation activity and that after the second day of computational modelling, approximately one-third of the students in 6 classes were unable to accurately implement one of the conditional statements. The teachers created a new activity for the students in classes that struggled to construct the conditional statements: students were grouped and were tasked with developing a video to teach a 5th grade student to construct the computational model, referencing their rule creation task and the science experiments they completed previously. The teachers described this as an opportunity to better understand any potential issues groups were having based on how they discussed the video creation as a group and would allow students to learn from each other as they created the video. For the remaining class, the teacher focused on linking the rule creation task to the computational model through a systematic class testing activity. This experience also highlights the planning period simulation as a useful testing opportunity, as these teachers used feedback as a post-class reflection, and preferred not to receive feedback in real time.

We believe that our approach will be applicable to other PBL and open-ended problem-solving curriculum contexts, particularly in aligning stakeholder questions to the research and design goals of each design phase, ensuring flexibility not only in the curriculum but in the learning analytics and support technology approach, and in the importance of negotiating and integrating both teachers and student perspectives into the design of such technology. We are in the process of implementing our workflow for the development of a teacher dashboard for an open-ended curriculum in which students build causal models of science phenomena to teach a teachable agent, examining how the teacher can better engage in students learning in such environments. This process has included engaging teachers in the type of data that we receive about students (including what the AI-based features in the system leverage to determine adaptive responses) to support their understanding of how AI/ML is used and how the pipeline directly targets the learning objectives of the curriculum.

Some limitations of our work include the small participation numbers. As such, this work focuses on depth over breadth in the demonstration of our co-design process using HCI approaches and we aim to continue implementing this approach with more teachers of varying background and locations. In addition, due to the impact of the pandemic, we were unable to conduct a classroom experiment in the past. As mentioned, we have completed such a study, and we are analysing how some of our teachers used the co-designed dashboard for reflection work when teaching the PBL curriculum in middle school classrooms.

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CONFLICT OF INTEREST STATEMENT

The authors have no conflicts to disclose.

DATA AVAILABILITY STATEMENT

De-identified data are available upon request.

ETHICS STATEMENT

This research was approved by Vanderbilt University's IRB.

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