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ORIGINAL RESEARCH

Designing educative curriculum materials in interdisciplinary teams: designer processes and contributions

Anushree Bopardikar[1,2] · Debra Bernstein[1] · Brian Drayton[1] · Susan McKenney[2]

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Abstract

Educative curricula support teacher learning as well as the learning of students. High quality educative curricula contain features that help teachers customize learning opportunities and environments in ways that meet the needs of their learners. Designing these features requires expertise related to subject matter content, pedagogy, teacher and student learning, and instructional design. In other words, it requires interdisciplinary team work – which is notoriously challenging. To understand and support collaborative interdisciplinary design processes, a retrospective case study was conducted on interdisciplinary design team work that yielded a high quality educative curriculum for inquiry-based science learning. Design documents and transcripts of interviews with six designers (a cognitive psychologist, a practising physicist, and four science educators) were analyzed to identify their contributions during the phases of analysis, development, and evaluation to create educative features for developing pedagogical content knowledge (PCK). Findings articulate specific educative features that can contribute to supporting PCK and thereby supporting instructional performance. Findings also reveal the proactive and reactive nature of designer contributions, describing different ways in which designers provide specialized inputs from a disciplinary perspective. Further, this study shows how designer contributions intermeshed, with contributions from one discipline shaping the work of colleagues, and thereby coordinating varied inputs to yield coherent educative materials. In addition, theoretical insights and recommendations for research on the nature of collaborative interdisciplinary design processes and implications for practice are given for supporting designers working in interdisciplinary teams to create educative curriculum materials for teacher (and student) learning.

Keywords Pedagogical content knowledge · Science curriculum · Educative curriculum · Design process · Interdisciplinary design

✉ Anushree Bopardikar
anushree_bopardikar@terc.edu

[1] TERC, 2067 Massachusetts Ave, Cambridge, MA 02140, USA

[2] ELAN, Department of Teacher Professional Development, University of Twente, Postbox 217, 7500AE Enschede, The Netherlands

Introduction

Teachers' knowledge of a subject for teaching and the nature of supportive materials for enactment influence the quality of classroom instruction (Hill and Charalambos 2012). Materials designed to support both teachers' and students' learning simultaneously are referred to as educative (Davis et al. 2014). This study focuses on educative features for developing teachers' pedagogical content knowledge (PCK). PCK is knowledge relevant to teaching specific topics (Grossman 1990) and comprises components such as knowledge of instructional strategies and student thinking (see Theoretical Framework for more details on PCK components). Teachers rely on their PCK to (re)design, customize or curate the learning opportunities in their classrooms (McKenney 2017). Indeed, recent research shows that teachers' PCK affects their instructional skills in the act of teaching, such as explaining scientific phenomena to students (Kulgemeyer et al. 2020).

The importance of educative materials has been widely recognized in science education research (Krajcik and Delen 2017). This is largely because they have been shown to positively influence both teaching and learning in science (Pareja Roblin et al. 2018; Bismack et al. 2015). For example, educative materials highlighting specific teaching moves and language about scientific practices help teachers engage students in key scientific practices, such as making observations and predictions (Arias et al. 2016). Similarly, supports foregrounding specific strategies and representations help teachers facilitate students' understanding of science content (Schneider and Krajcik 2002). Furthermore, instructional supports that help teachers understand student thinking enable them to customize classroom environments to provide timely, targeted guidance to foster student learning (Matuk et al. 2015).

Studies on educative materials have focused on heuristics and principles for designing such materials (Davis and Krajcik 2005; Davis et al. 2017); specific educative features (e.g. Rosemann et al. 2017; Schneider and Krajcik 2002) teachers' use of educative materials during classroom enactment (e.g. Arias et al. 2016) and the impact of the materials on PCK (e.g. Marco-Bujosa et al. 2017; Schneider 2013). Furthermore, the frequency and quality of supports in existing educative materials have been evaluated, yielding specific recommendations for facilitating teacher learning (Beyer et al. 2009). However, what is less understood are the systematic processes for creating educative materials that can inform instructional design in different contexts (Davis et al. 2014).

Problem statement

The literature on curriculum and instructional design points to general processes and models (e.g., Gustafson and Branch 2002; Thijs and van den Akker 2009), and offers generic guidance through case examples for teaching instructional design (Ertmer and Quinn 2007). A few studies also document design processes for developing educative science materials, describing measures taken to yield specific educative features (Davis et al. 2014; Kruse et al. 2013; Roseman et al. 2017). Furthermore, collaborative design processes have been investigated in the contexts of curriculum (Barber 2015), technology-enabled immersive learning systems (Flood et al. 2015), and informal science learning spaces (Wang, 2014). Whereas this line of work offers valuable insights into how designers from different backgrounds make specific contributions and tackle shared problems through dialogue and co-constructed artifacts, it does not elucidate their processes for producing *educative materials*. Specifically, what is missing is fine-grained information about processes and inputs of designers with different disciplinary backgrounds, clarifying how they contribute based on relevant expertise and synthesize their perspectives to create educative science materials.

This is an important gap to address because designing educative science materials requires simultaneous attention to subject matter, student understandings, and instructional approaches. To do so, design teams may require the expertise of scientists, educational psychologists, and those with teaching experience at target grade levels. But how can a disparate team of designers coordinate their inputs to create educative science materials that support the development of multiple PCK components, such as teacher knowledge of student thinking, instructional strategies, and assessments? PCK components are interconnected (Magnusson et al. 1999; Park and Chen 2012; see Theoretical Framework for details); hence, educative materials must support them together. Research is needed to ascertain, for example: How do designers with different expertise contribute to supporting specific PCK components? Do all designers attend to the same concerns about PCK across phases of the design process? How do designers negotiate differing perspectives, and how are designer tasks integrated to yield coherent educative features that can support the development of PCK?

Detailed knowledge about interdisciplinary collaboration is important because designers tend to approach shared problems and goals with varied knowledge bases (Fischer and Ostwald 2005). They may also initially value different and possibly conflicting strategies for teaching and learning (Barber 2015). Further, designers often have limited understanding of how other designers' work is pertinent to their own (Arias et al. 2000). Whereas each designer domain may offer unique and valuable input, innovative solutions stem from integration, which is notoriously difficult. Therefore, detailed insights into collaborative interdisciplinary processes for designing educative curricula can shed light on how to optimize and coordinate varied designer expertise to help teachers support custom learning opportunities for their students.

Goal of the study

The goal of this study was to yield a detailed understanding of collaborative interdisciplinary processes of designers geared towards supporting teachers' PCK. Specifically, the study aimed to generate insights on how designers make discipline-based contributions and coordinate their contributions to systematically create coherent educative materials. Further, based on these theoretical insights, the study also sought to provide practical recommendations for designers engaging in interdisciplinary curriculum design. In so doing, the study aimed to contribute to the knowledge base on designer expertise and processes, especially in the context of educative science materials. To that end, the retrospective analysis focused on producing a worked example of the interdisciplinary design process behind a robust primary school science curriculum* containing many educative supports for teachers. Comparable to process-oriented worked examples (see Van Gog et al. 2004), this example delineates key activities and specialized inputs of designers with different disciplinary backgrounds to produce educative features of a high-quality science curriculum. The study was guided by the following research question: *Throughout the design process (analysis, development and evaluation), how do designers create educative materials that* *support development of PCK, and in so doing, what is the contribution of designers with different disciplinary backgrounds?*

*NB: In this study, we use Taba's (1962) classic definition of curriculum as meaning "a plan for learning." This includes broader processes and goals that span larger chunks of time (e.g. unit objectives addressed over weeks or months), specific plans for learning and instruction that are enacted within smaller chunks of time (e.g. activities lasting several minutes to an hour), and information about bringing them into alignment (e.g. instructional sequences or lesson structures).

Theoretical framework

Three generic phases of design

Across disciplinary conventions, three phases of (science) curriculum design can be distinguished. The design process generally commences with an *analysis* phase in which designers work towards defining the problem and range for improvement (Thijs and van den Akker 2009). They analyze the contexts where the curriculum will be used and the needs of the target teacher and student audience (McKenney and Reeves 2012; Edelson 2002). Typical activities include reviewing literature to understand how other designers have formulated and tackled similar problems (McKenney and Reeves 2012). The review may include: learning theories and prior research on curriculum materials to support teachers' knowledge (Kruse et al. 2013; Roseman et al. 2017); science standards frameworks to identify what scientific concepts and practices need to be taught (Krajcik et al. 2008; Songer 2006); and policy documents providing evaluation criteria for curriculum materials (Roseman et al. 2017). Designers may also analyze the content of existing science materials to identify instructional requirements and opportunities related to science concepts, practices, and assessment of student learning (Davis et al. 2014). Additionally, designers collect data to conduct a needs and context analysis (Edelson 2002). Examples of data sources include: surveys given to school personnel (McKenney and Reeves 2012); lesson observation protocols; teachers' instructional logs and interviews; and students' pre-post test data to understand teachers' instructional decisions and challenges in using existing curriculum materials (Davis et al. 2014). The analytic activities help designers define the problem, derive overall goals, and generate initial design principles and requirements. The preliminary design specifications guide designer work: the intended outcomes (the target learning objectives to be achieved); their envisioned enactment (what instructional activities to help achieve the those outcomes look like); and the written curriculum (including supports for teachers and students) (McKenney and Reeves 2012; Roseman et al. 2017).

Following analysis, a *development* phase involves exploring ideas for potential solutions, mapping details and constructing prototype solutions (McKenney and Reeves 2012). In this phase, designers take concrete steps to respond to the goals and contextual needs identified previously (Edelson 2002). For example, based on content analyses and data from teachers' enactment of existing materials from the preceding phase, designers may prepare supports such as content storylines and concept maps (Davis et al. 2014). Notable development activities include review of policy documents and prior research to specify science learning goals and sequences of instructional activities (Krajcik et al. 2008; Songer 2006). In so doing, designers may choose a limited set of scientific ideas to create coherent content storylines and other supports to depict the storylines (Roseman et al. 2017). The literature review may also focus on students' difficulties, recommended approaches in the field, and strategies for engaging students in scientific practices to create appropriate educative supports (Davis et al. 2014). Additionally, designers may utilize frameworks-based rubrics specifying criteria for designing educative supports to help teachers understand students' conceptions and to assess students' learning (Roseman et al. 2017). Other activities include seeking insights from scientists serving as subject matter experts to identify which scientific facts to address (Songer 2006). Based on the activities in this phase, designers plan measurable intended outcomes (Gustafson and Branch 2002), identify target content (Smith and Ragan 1999), prepare instructional tasks and sequences aligned with those outcomes (Krajcik et al. 2008; Songer 2006), and generate written materials according to design specifications (McKenney and Reeves 2012).

Finally, designers conduct both formative and summative *evaluations* – collecting data to guide revisions and to determine the impact of the curriculum (Gustafson and Branch 2002). Key activities include: using criteria in frameworks-based rubrics to assess quality and coherence of educative supports (Kruse et al. 2013; Roseman et al. 2017); gathering external expert appraisal on matters such as accuracy of scientific ideas presented in the materials (Davis et al. 2014; Thijs and van den Akker 2009) and conducting pilots of preliminary prototypes and field tests of more mature versions of the curriculum in classrooms (McKenney and Reeves 2012). Designers collect data from varied sources such as observations of classroom enactments, teachers' interviews and instructional logs, written tests of teachers' knowledge of science subject matter, curriculum and students' thinking, and students' work and written tests of students' learning outcomes (Davis et al. 2014; Kruse et al. 2013; Roseman et al. 2017). Based on evaluation data, designers make required revisions to the key curriculum features (redesign).

Pedagogical content knowledge and educative curriculum materials

When designers perform the above-mentioned systematic, iterative processes to create materials that support teacher learning, they typically generate features that support the development of teacher PCK, which is broadly conceptualized as "teachers' understanding of how to help students understand specific subject matter" (Magnusson et al. 1999). This knowledge is specific to subjects (e.g., science) and topics within those, and teachers draw on this knowledge both in the act of teaching and in reasoning about and planning for teaching (Kirschner et al. 2016). The present study examines interdisciplinary designer work in supporting *personal PCK*, which is knowledge held by individual teachers, and *enacted PCK*, which is knowledge utilized in the act of teaching (Kulgemeyer et al. 2020). The study focuses on the following five components of PCK: knowledge of student thinking, instructional strategies, curriculum, assessment, and subject matter. This section defines each component, describes its importance, and provides examples of relevant educative materials. The framework on PCK components served as an analytical lens in the present study to interpret designer inputs and activities in the context of educative curriculum materials.

Knowledge of student thinking

Knowledge of student thinking is considered to be a central component of teachers' PCK (Van Driel et al. 1998). This component includes knowledge of students' typical understandings, preconceptions and misconceptions of specific science topics, the reasons behind their thinking, and knowledge of what makes specific topics easy or difficult for students to learn (Cochran 1991; Kirschner et al. 2016; Magnusson et al. 1999; Shulman 1986; Tamir 1988; Veal and MaKinster 1999). This study defines knowledge of student thinking in science as the *knowledge of students' typical conceptions (including preconceptions and misconceptions), the reasoning behind their thinking, and their learning needs and difficulties in relation to specific science topics.*

Knowledge of student thinking is important to understand their students (Magnusson et al. 1999) and to select appropriate instructional strategies to support students' learning of specific topics (Gess-Newsome et al. 2017; Park and Chen 2012). To this end, educative features include overviews of typical student misconceptions and their instantiations in student work (Roseman et al. 2017). Additionally, lesson-embedded notes point to students' preliminary understandings and possible reasons behind their difficulties (Schneider 2013; Schneider and Krajcik 2002).

Knowledge of instructional strategies

Knowledge of instructional strategies is also considered to be a central component of teachers' PCK (Van Driel et al. 1998). This component consists of teachers' knowledge of strategies to represent topics in a subject and to make them comprehensible to students (Shulman 1986). It includes knowing about representations (i.e., models, analogies, explanations and examples) and activities (i.e., investigations, experiments and simulations) (Magnusson et al. 1999; Park and Oliver 2008; Veal and MaKinster 1999) in relation to specific topics. Some conceptualizations of this component also include strategies that are applicable to science as a subject compared to other subjects, for example, instructional sequences like the learning cycle (e.g. Park and Oliver 2008; Veal and MaKinster 1999), and phases of particular kinds of science lessons (Tamir 1988). This study defines knowledge of instructional strategies as the *knowledge of subject-specific (general) instructional strategies in science like phases of inquiry-based lessons as well as knowledge of topic-specific strategies like investigations, questions, and explanations to help students understand scientific concepts and practices.*

To help teachers understand and enact appropriate instructional strategies, scientific practices like argumentation are defined (Marco-Bujosa et al. 2017) and specific strategies like modeling are provided to help them engage students in the practices (McNeill 2009). Educative features also include rationales of representations and activities (Roseman et al. 2017); boxed notes indicating key concepts to highlight to students (Arias et al. 2016); and short scenarios and questions to model teacher language (Schneider 2013; Schneider and Krajcik 2002).

Knowledge of curriculum

Knowledge of curriculum refers to teachers' knowledge of the learning goals, activities and materials of different curricular programs available to teach particular subject matter and topics, and knowledge of horizontal and vertical curricula in the subject area (Grossman 1990; Magnusson et al. 1999; Park and Oliver, 2008; Shulman 1986). Additionally, this component can include knowledge of mandated goals at particular grade levels (Magnusson et al. 1999); how topics are organized (Marks 1990); pre-requisite concepts to learn particular topics (Tamir 1988); and core concepts of the topic and central and peripheral ideas and activities in relation to the overall curriculum (Park and Chen 2012). The present study operationalizes this component as the *knowledge of topic organization and core concepts to teach, of overall learning goals and activities, and of concepts addressed vertically during prior and successive units of the curriculum.*

Knowledge of curriculum guides teachers in adapting activities and eliminating peripheral activities or ideas in science instruction (Park and Chen 2012). To develop this component, unit overviews clarify topic organization, describing relationships between scientific concepts and their development through lessons (Schneider and Krajcik, 2002). Overviews prior to sections of lessons also explain how the lessons contribute to the unit (Roseman et al. 2017). Finally, lesson-embedded content storylines describe how a lesson relates to the overall unit, the intended scientific concepts, and their relevance to subsequent lessons (Arias et al. 2016).

Knowledge of assessment

Fourth, *knowledge of assessment* consists of knowledge of the aspects of science learning that are critical to assess in a unit of study (Park and Oliver 2008). It extends beyond conceptual understanding to include dimensions of scientific literacy (Magnusson et al. 1999) and particular skills (Tamir 1988). This component further includes knowledge of different methods of assessment, including particular activities, procedures or approaches applicable to a given unit of study (Magnusson et al. 1999; Park and Oliver, 2008); particular instruments (Tamir, 1988); and knowledge of the strengths and limitations of the different methods (Magnusson et al. 1999). Topic-specific pre-tests, different lines of questioning, and student-generated products such as journal records, drawings and models are examples of assessment methods. The present study operationalizes knowledge of assessment as the *topic-specific knowledge of key conceptual understandings and scientific disciplinary practices to assess, and of various methods (activities or instruments including student-generated products) for assessment relevant to the unit of study.*

The assessment methods may be used formatively to gather and interpret evidence of students' understanding related to the learning goals and to identify next steps in teaching and learning (Harlen 2006). Indeed, formative assessment is critical in supporting scientific inquiry and practices (National Academies of Sciences, Engineering and Medicine 2017), and is emphasized in recent research on fostering science teachers' professional learning (Furtak et al. 2016). This component has implications for the two central components of knowledge of student thinking and of instructional strategies. Knowing different formative assessment methods may help teachers identify their students' thinking and modify instruction to better facilitate students' learning (Park and Chen 2012). Educative materials for assessment include pointers at the beginning and end of lessons on assessing specific conceptual understandings and skills in student-generated artifacts (Schneider and Krajcik 2002), and rubrics and sample student work with recommended teacher feedback on students' understandings (Davis et al. 2014).

Finally, while there is little dispute that *subject matter knowledge* is a crucial component of a teacher's professional knowledge base (Kind 2009; Tobin et al. 1994; Veal and MaKinster 1999), expert opinions differ as to whether or not it should be included as a PCK component (Kind 2009; van Driel et al. 1998). The present study does not tackle this divergence, but it does include explicit attention to subject matter knowledge because educative curricula must support teachers' understanding of (scientific) concepts and practices (e.g., Davis and Krajcik 2005).

Subject matter knowledge

Subject matter knowledge includes understanding not only of the major facts and concepts of a subject, or their interrelationships, but also of the processes by which those ideas are established (Grossman 1990; Shulman 1986; Tamir 1988). It may be topic-specific (Veal and MaKinster 1999) and includes understanding the importance of a topic to the discipline (Shulman 1986). This study operationalizes knowledge of subject matter as the *topic-specific knowledge of the meaning of key scientific facts and principles and theoretical frameworks, and includes knowledge of the importance of the topic and knowledge of disciplinary practices by which the content is established.*

Educative supports for subject matter knowledge include overviews with definitions and rationales of scientific practices (Bismack et al. 2015; Davis et al. 2014), and explanations of scientific concepts at a level beyond the intended student understanding (Schneider and Krajcik 2002). Explanations may also appear in content charts and boxed notes in background material or they may be embedded in the directions for specific lessons (Arias et al. 2016; Schneider 2013).

Designing in interdisciplinary teams

Curriculum design often involves collaboration among designers of different disciplinary backgrounds. Interdisciplinary collaboration is an interpersonal process for efficient attainment of goals that cannot be attained when individual professionals act independently (Bronstein 2003; Bruner 1991). It is important because all of the relevant and requisite knowledge to yield solutions for long-term, complex design endeavors is not contained within a single designer's contributions but is distributed among designers (Arias et al. 2000). Through dialogue and establishment of shared vision and goals, the resultant design reflects synergies among designer work, taking advantage of varied expertise to craft solutions that are greater than any individual designer contributions (Barber 2015).

Models of interdisciplinary collaboration highlight specific components of desirable interactions (Bronstein 2003). For example, a core component is interdependence among professionals to achieve their tasks, in which they communicate formally or informally via oral or written means and show respect for colleagues' contributions. And another core component is collective ownership of goals, in which professionals take shared responsibility throughout the process for collectively formulating and reaching those goals.

The literature also shows how designers make unique contributions based on their expertise and how they interact with one another to generate new insights. For example, in designing engineering challenges for tinkering in informal learning spaces, science educators contribute methods of accessible learning, while practising engineers offer inputs to make content relevant and authentic (Wang 2014). And in designing virtual tutors, computer scientists and learning scientists engage in analysis, communication, and reflection to understand shared design issues with embodied interactions (Flood et al. 2015). In so doing, studies have shown the importance of designer interactions around *boundary objects*—shared artifacts to establish common ground (Barber 2015; Fischer and Ostwald 2005). This is because collaboratively created artifacts, such as documents of plans or prototypes, externalize designer thinking and provide a basis to communicate and develop new understandings (Fischer and Ostwald 2005; Flood et al. 2015). The use of boundary objects is especially important in interdisciplinary design teams because these function as *communities of interest,* where members from different fields of practice come together to tackle problems of shared interest (Fischer and Ostwald 2005). Whereas multiple backgrounds offer potential for creative solutions, doing so requires designers to establish shared understanding of design tasks, for which boundary objects play a crucial role.

Methods

Case study

To gain insight into how designers with different disciplinary backgrounds contribute to creating educative materials that support development of PCK, a qualitative interpretive case study (Merriam 1988) was undertaken. This method was deemed suitable because the intended outputs were a detailed worked example of a finished curriculum product and its design process (Howard et al. 2012). The curriculum was designed at an independent STEM educational research and development organization in the USA. First, curriculum projects were sought using the following criteria: (i) target audience of K-12 teachers and learners; (ii) stand-alone school curriculum (as contrasted with supplementary or out-of-school curriculum); (iii) intention to support students' understanding in science; and (iv) evidence of positive learning outcomes. This yielded six potential cases. The present case was selected for this analysis because it focused on educative supports. The researchers did not contribute to developing the written curriculum materials, but for this study they were granted access to documentation about the development of the curriculum and opportunities for in-depth conversations with the designers. This access was critical to gather detailed data for the qualitative case study.

This case constituted a stand-alone, inquiry-based longitudinal curriculum for grades 3–5. As stated in the project's grant proposal, the curriculum was inspired by research on learning progressions on the nature of matter that "is organized around big ideas in science and inquiry practices," "inquiry-based learning and (formative) assessment" (Harlen 2006), and an established model of teacher professional learning (Harlen and Altobello 2003). A nine-week unit was developed for each of the three grades, involving a coherent sequence of investigations with hands-on explorations and discussions to help students gather data and to make meaning of the data and scientific principles. The units for Grades 3 and 4 had 17 investigations each and the Grade 5 unit had 18 investigations. The curriculum materials consisted of a teacher guide, student notebooks, and a hands-on kit.

This curriculum was chosen for its high quality and potential insights into educative supports and the collaborative interdisciplinary nature of its design process. Field tests of the curriculum revealed positive shifts in teacher understanding of the major concepts or topics in the curriculum after teaching it. For example, an external evaluation report for the Grade 3 unit stated that "all teachers reported a better understanding [of the content] in at least one [section of the curriculum] (materials, weight, standard measure, volume). Where

Table 1 Data sources and their corresponding information

Data sources	Designers' disciplinary contributions	Design process phases	PCK components	Educative features
Project documents (grant proposal, prototypes of educative materials, memos, classroom testing notes, progress reports to funding agency, external evaluation reports)	X	X	X	X
Finished educative materials	Not applicable	Not applicable	X	X
Interview transcripts	X	X	X	X

change occurred, all changes were positive, teachers came to a clearer understanding of the topic." Furthermore, observations of their teaching practice during curriculum enactment indicated a greater familiarity with, and ability to implement, inquiry-based instruction. For example, an external evaluation report for the Grade 4 unit stated that all five field test teachers were scored higher on the RTOP[1] for the [curriculum] lesson than the baseline lesson enacted before the curriculum field test. The ratings increased to 57, 56, 64, 55 and 56 from 40, 25, 35, 42, and 49 respectively for the five field test teachers. There was an increase in teachers' attempts to engage students in making predictions/estimations and/or hypotheses and devising means to test them, and in thought-provoking activity that frequently involved the critical assessment of procedures. Furthermore, teachers' questioning strategies changed from the baseline lesson prior to the field test to the curriculum lesson. For example, an external evaluation report for the Grade 3 unit mentioned that teacher questions changed from eliciting recall and comprehension to probing and guiding students' conceptual understanding. The percentage of questions higher than recall questions (e.g., asking students to provide evidence for their answers; helping students build on/refine one another's responses and understanding) on a sub-section of the INCRE observation protocol increased to 86%, 29% and 55% from 0%, 0%, and 35% respectively for the three field test teachers.

Additionally, as stated in an annual report to the funding agency, field tests tracking progress of treatment and control group students over three years showed that the curriculum helped students make progress in understanding ideas related to a network of concepts, including weight, volume, and material things. For instance, statistically significant differences were found on assessment tasks about properties of tiny things, with the treatment group outperforming the control group at all three grade levels. The treatment group also made statistically significant progress compared to the control group in understanding that tiny invisible things have weight. And on a water displacement task assessing students' understanding of volume, too, the treatment group statistically outperformed the control group. Finally, personal communication with the curriculum project's principal investigator revealed that the curriculum continues to be in use.

[1] RTOP stands for Reformed Teaching Observation Protocol, a standardized instrument to determine the degree of reform in K-20 classroom instruction in science and mathematics. It has a maximum possible score of 100. https://eric.ed.gov/?id=ED447205.

Data sources

Consistent with recommendations for case study research (Guba 1981; Yin 2014), this study gathered evidence from multiple data sources, namely project documents, finished curriculum materials, and transcripts of interviews with the designers. Table 1 maps the sources and their corresponding data.

Participants

Following purposeful and referral sampling techniques, the researchers recruited six participants based on their disciplinary backgrounds and stages of work in the curriculum design. The principal investigator of the curriculum project served as informant for further sampling (Yin 2014), presenting a preliminary list of candidate participants who, in turn, provided subsequent referrals. The list below summarizes information about the six participants, stating the alphanumeric codes (used in the results section), their disciplinary backgrounds, and relevant experience.

- P1: Science Educator (primary school teaching, design of science curriculum and teacher PD)
- P2: Science Educator (engineering, design of science curriculum and teacher PD)
- P3: Science Educator (primary school teaching, design of science curriculum and teacher PD)
- P4: Science Educator (engineering, primary school teaching, design of science curriculum and teacher PD)
- P5: Cognitive Psychologist (research on conceptual change and learning progressions in science)
- P6: Practising Physicist (Subject matter knowledge of science)

Owing to commonalities in the backgrounds of P1, P2, P3, and P4, namely their experiences with designing science curriculum and teacher PD, and primary school teaching in the case of three of the designers, these four designers were treated as a single group – "science educators" – for data analysis and presentation of findings. This treatment of the four science educators as a single unit in the data analysis was justified by their overlapping expertise, and by the goal of being able to highlight how the science educators' contributions differed from those of the physicist and the cognitive psychologist, and reveal patterns in disciplinary contributions.

Procedures

Researchers prepared an initial project summary and timeline depicting the curriculum, its design activities and outputs. Next, they conducted prolonged interviews with each participant (Yin 2014); each interview lasted approximately two hours. The project summary and timeline was used to facilitate participants' recall during the interviews. A semi-structured protocol guided the interviews, containing open-ended questions about curriculum materials such as, "How did your curriculum support teachers' and students' understanding of science concepts?", and "How did your curriculum support teachers and students to engage in scientific inquiry?" There were also questions about design process phases. For example, a question for the analysis phase was, "What was your role in the project's activities to learn about the target audience, their needs and abilities, and any barriers to teaching and learning science?" Similarly, sample questions for the development and evaluation phases were, "What was your approach for designing the [specific educative material]?", and "What was your role in testing the curriculum?" All interviews were audiotaped and transcribed.

Data analysis

The data were coded twice, deductively and inductively. The deductive approach was undertaken in four phases, namely to examine: (i) designer work at the curriculum level; (ii) PCK components in designer work; (iii) educative features in relation to the PCK components; and (iv) design process phases related to the PCK components and educative features. Across all deductively coded data, inductive analysis was then undertaken. Each of these processes is elaborated below.

Deductive analysis: designer work at the curriculum level

In the first phase, the interview transcripts were examined to identify key aspects of designer work at the curriculum level (intended outcomes, envisioned enacement, written curriculum, and design processes; see Table 2). The first author and another researcher independently coded one transcript at a time at the sentence-level. They resolved discrepancies through discussion and established final coding decisions through consensus. This process continued until an acceptable level of inter-rater reliability was attained (Cohen's Kappa was 0.79[2]). The first author then coded the remaining dataset.

Deductive analysis: PCK components in designer work

In the second phase, the interview and document data were coded for designer work on the different PCK components as defined in the conceptual framework. Specifically, the data were analyzed for how designers supported teacher knowledge of student thinking, instructional strategies, curriculum, assessment, and subject matter. Table 2 gives an overview of the codes.

Deductive analysis: educative features in relation to the PCK components

Furthermore, the educative features of the written curriculum were mapped to the PCK components. A total of 10 relevant educative features were identified in the teacher guide. They were deemed relevant if they were aligned with one or more of the PCK components as defined in the conceptual framework of this study. There was a total of 52 lessons and 14 sections across the three grade-level units of the curriculum. One feature was designed to be referred to across the whole curriculum; one feature was designed for use at the unit level; two features at the section level; and five features at the lesson levels. Finally, one

[2] The study reported in this paper was part of a larger research project on science curriculum design. The Cohen's Kappa was calculated for a set of 13 codes associated with the larger research project.

Table 2 Deductive coding scheme (first and second phases)

Code	Description	Sample quote
Designer work at curriculum level		
Intended Outcomes	The learning objectives for the curriculum that the designers set out to attain	*The goal was to develop [students'] understanding of properties of matter, at least leading up to being ready to learn about the particulate nature of matter*
Envisioned Enactment	The designers' vision for teacher enactment and student experiences	*So the model was that you start with helping the learner to become familiar with his or her ideas, to have first-hand experiences that would provide additional data, and that through discussion, new meaning would develop*
Written Curriculum	Written supports for teachers and students	*The purpose of [child and scientist essays] was to help the teacher understand how a child thinks about these concepts, what the core concepts are, and to help them think about what is the real science behind this?*
Design processes	Designer considerations and measures to generate and refine the curriculum features	*So there was some kind of planning where we were writing sequences of concepts in little boxes, about what would happen in [grades three, four, five]. There was an initial grid, and then after piloting it, P4 would fix it and rearrange it*
PCK components in designer work		
Student thinking	Supporting teacher knowledge of students' typical conceptions and possible difficulties	*Child essays were created to help teachers] think a little bit differently—that here are some rich understandings your [students] have, but are really different from the scientist's, so [teachers] begin to think about, how can you acknowledge where your students are starting*
Instructional strategies	Supporting teacher knowledge of general and specific strategies to teach concepts and practices	*We realized that when we were working in classrooms, that oftentimes, there weren't class discussions, Meaning Making discussions, and so the meaning making discussions were in the curriculum. And so one of the things that came again from that was that every discussion would begin with a question, and that the discussion would have the same components to it, in the same way that the lesson had the same components*

Table 2 (continued)

Code	Description	Sample quote
Curriculum	Supporting teacher knowledge of the organization of the content, and overall learning goals and activities	*They were like grids, where you had to write down. And there'd be two of them, for the third grade, for instance. And one of them would be how the concepts were developing, day by day by day, and how you're sort of building. And the other one would be like the activity that you did day by day by day*
Assessment	Supporting teacher knowledge of the scientific concepts and practices to assess, and of activities and student work to use as assessment methods	*We didn't want [the formative assessments] to be too long or too complicated, so how do you do this in a very concise way? And then I had to go looking for resources, and the idea was that your source of information was either what kids write, or what they say, or what you watch them do*
Subject matter	Supporting teacher knowledge of the target concepts and practices and their importance	*I guess my first task was to try to answer the question for myself. So if P1 would call up and say, we need an essay on why the idea of matter is important. So the first thing I would have to do is, I would have to really think about it, and sort of come up with an answer that satisfied me about, why is it scientifically an important concept. And then I would have to try to think of a way to express that to the intended audience*

feature was designed for use at multiple levels. The subsequent paragraphs describe each feature in more detail.

At the curriculum level, the Curriculum Concepts Chart (C–C) portrayed the three-year progression of student understandings of a network of fundamental concepts, consistent with the learning progression approach undergirding the curriculum. At the unit level, the Curriculum Overviews (C-O) summarized learning activities of the unit. At the section level, the Child Essays (ST-CE) and Scientist Essays (SM-SE) clarified typical student understandings and important scientific concepts and practices respectively to help teachers prepare prior to enactment. At the lesson level, the Consistent Tripartite Structure (IS-CTS) provided a broad lesson structure in-the-moment to help teachers facilitate student engagement in scientific inquiry practices. The Boxed Notes at the lesson level reminded teachers in-the-moment about possible student conceptions (ST-BN), instructional strategies to respond to student ideas (IS-BN), and provided conceptual clarifications respectively (SM-BN). The Formative Assessments (A-OW) at the lesson level pointed teachers to various activities and instruments (including student-generated products) to assess students' understanding of scientific concepts and practices. Finally, the Curriculum Narratives (C-N) highlighted topic organization and learning goals and activities at the unit, section, and lesson levels.

Deductive analysis: design process phases for PCK components and educative features

The design processes behind the PCK components an**d** educative features were also examined at a fine-grained level in terms of the analysis, development, and evaluation phases (see Table 3). Further, inputs and activities of designers were analyzed in light of their discipline-based contributions towards particular PCK components and educative features. During this process, the project documents helped "corroborate and augment" (Yin 2014, p.107) the interview data, confirming and elaborating those with examples and culling information not yielded by the interviews.

Inductive analysis

Undertaken across the entire coded data set, the inductive analysis yielded two main themes. The first theme pertained to the nature of designer contributions, which can be viewed as proactive and reactive. The proactive contributions involved: (i) producing outputs for specific PCK components (e.g., essays by the physicist explaining scientists' understanding of target concepts) and/or (ii) undertaking specific design measures (e.g., reviewing existing formative assessment frameworks). By contrast, the reactive contributions involved providing feedback on colleagues' outputs (e.g., the science educators providing feedback on drafts of unit outlines based on consideration of children's capacities). The second theme can be characterized as intermeshing, which revealed how an output created by designers from a specific disciplinary background was shaped by proactive and/or reactive input(s) of designers of another disciplinary background (e.g., the science educators drafted key scientific ideas for teacher knowledge to be highlighted in essays developed by the physicist and cognitive psychologist respectively). This term was chosen (over similar others, such as interlinked or connected) to highlight a certain characteristic of the operations of the design team – specifically, that designer inputs from different areas of expertise enabled and specified the work such that the varied disciplinary contributions

Table 3 Codes for design process phases related to PCK components and educative features

Code	Description	Example
Analysis	Designer work to generate overall goals, initial design requirements, and specifications	*The [cognitive psychologists] fleshed [the original learning progressions framework] out, and they made this much more explicit roadmap about how they actually thought things were going to grow. And so that happened at the beginning of the project*
Development	Designer work to plan target content, instructional activities and sequences, and create written materials	*I would put together a sequence that I thought would work towards developing a better understanding of material properties, for example. Just an outline. And then I would sit down with P3 and P2, and they would think about it, and troubleshoot it*
Evaluation	Designer work to test and refine prototypes and more advanced versions of the curriculum	*I remember seeing so vividly [in pilot classrooms] was that you'd tell them to make observational drawings, and we thought that they were going to very carefully sketch. But they weren't doing any careful observation. Their drawings didn't reflect the data at all. So you come back and you say, there's got to be something about observational drawings [in the written curriculum]*

Table 4 Educative features supporting (development of) PCK components

Educative Feature and frequency[a]	Description	Samples
Student Thinking-Child Essays (ST-CE) (n = 13)	Explain children's understandings and difficulties with target concepts and scientific practices; presented separately from lesson plans for each section of a grade unit	Excerpt from Grade 5 essay describing children's challenges in understanding evaporation and condensation of water: *[Children] must use the existence of invisible entities—gases—which they do not clearly understand and may not even believe exist—to explain visible events. Some may say that the water has "gone into the air" or even use the word "evaporated." They no longer think it retains its identity as water* Excerpt from a Grade 4 essay on the challenges of developing explanations based on data and evidence: *Young children are constantly moving from evidence (specific observations) to claims (generalizations based on these observations) in their everyday lives. But children are not conscious of what they are doing in this process. One challenge, then, is to get them to reflect on and conceptualize the process itself, explicitly distinguishing "the claims" from "the evidence." This can be hard for children because for them claims and evidence blend seamlessly together into simply "the way things are." When asked to explain an observation (Why do you think this cylinder is heavier?), they might just repeat the observation (because it feels heavier) rather than proposing a deeper explanation. Another challenge for teachers is that, left unguided, children may notice or pay attention to things in a situation that the teacher thinks are irrelevant and fail to notice things that the teacher thinks are highly relevant. For example, when exploring a data table in search of patterns in the numbers, students might be looking for patterns based on addition or subtraction rather than multiplication or division; hence they may fail to find any meaningful generalization (such as when I double the volume of the water, I double its weight too)*
Student Thinking-Boxed Notes (ST-BN) (n = 30)	Highlight student difficulties or alternative ideas to expect in-the-moment of teaching; embedded in lesson plans	Note from Grade 4 investigation on measuring volumes of irregularly shaped objects: *Fourth graders will sometimes confuse volume with surface area, counting the two-dimensional "faces" of the cubes on the outside of the block instead of the three-dimensional cubes that make up its volume*
Instructional Strategies-Boxed Notes (IS-BN) (n = 32)	Provide topic-specific strategies to address students' initial ideas or difficulties and subject-specific strategies to enact scientific practices; embedded in lesson plans	Note from Grade 5 investigation on comparing the properties of ice and water: *A common misconception is that the condensation is water that leaks through the plastic. If someone suggests this, show the class the bottle holding room temperature water and point out that no water is leaking through that plastic*

Table 4 (continued)

Educative Feature and frequency[a]	Description	Samples
Instructional strategies-consistent tripartite structure (IS-CTS) (n = 47)	Structure embedded in lesson plans to integrate concepts with scientific practices: Ask the Question (AQ), Investigate and Share (IS), and Make Meaning Discussions (MM); color-coded text distinguishes procedural steps and tips from recommended teacher language for specific questions, explanations or examples to guide students' thinking	In a Grade 4 investigation on water displacement, teacher poses the question in AQ: *What causes the water level to rise?* Supporting questions include, *What do you predict will happen when I add this larger rock to this container of water? What will happen when I put this smaller rock into the second container? Why do you think one rock displaced more water than the other?* In IS, students record their predictions, data, conclusions and share data with the class. In MM, teacher restates the question and prompts students to discuss data and construct explanations. The supporting questions include, *Can you claim it's the volume that causes the water level to rise? Or do you claim it's the weight? And what is your evidence (from the class data chart) that supports your claim? And what is your reasoning? How do you explain the results?*
Curriculum-concepts chart (C–C) (n = 1)	Common across three grades; summarizes how understandings of a network of key concepts are built in each grade unit (3–5) and across three grade units; presented separately from lesson plans	The target understanding of the concept of weight in Grade 3 is: *The weight of objects can be compared using a pan balance and standard (gram) weights*. The target understanding expands to include the following in Grade 4: *The weight of solids and/or liquids can be compared using a digital scale and can be represented on a weight line or a table*
Curriculum-overview (C-O) (n = 3)	The "Curriculum at a Glance" table summarizes learning activities of investigations in a grade-level unit; shows how activities in different sections within a unit build students' understandings; presented separately from lesson plans	An example from the Grade 3 table features an investigation question, learning goals and activities *How good are our senses at comparing the weight of cubes? Order the material cubes by felt weight. Create need for a measurement and introduce the pan balance*

Table 4 (continued)

Educative Feature and frequency[a]	Description	Samples
Curriculum-narratives (C-N) (n = 69)	Provide overviews of learning goals and activities within a grade unit, clarifies how investigations build on one another. Content coherence presented at three levels: Unit Level (start of each unit), Section Level (start of each section comprising a series of investigations in a unit), Lesson Level (start of each investigation)	Overview of Grade 3 unit: *The first [section], Investigating Materials, helps students distinguish between objects and materials. The second [section], Investigating Weight, focuses on weight as a property of matter. Students make the transition from felt weight, perceived with their hands, to measured weight using a pan balance* Section on Investigating Materials: *By exploring the similarities and differences between materials, students begin to see why some materials are better suited for some objects than others. Students begin to distinguish objects by their properties with particular attention to weight and material* Lesson on Investigating Materials: *Students likely encountered difficulty in their quest to order the cubes by felt weight. In this investigation, they get help from a scientific instrument: the pan balance. By the end of this investigation, students will better understand the limitations of felt weight and the value of instruments for careful measuring*
Assessment-oral and written (A-OW) (n = 35)	Formative assessments draw on students' thinking evidenced in whole class discussions, small group investigations, student notebooks and responses to written 'concept cartoons'; address both scientific concepts and inquiry practices; provide questions, criteria for interpretation, suggested next steps; embedded in lesson plans	In a Grade 4 investigation on changes in weight and volume when a ball of clay is reshaped, prompts ask teachers to consider students' predictions, accuracy of measurements recorded in notebooks, students' use of data and reasoning; suggest using class data to discuss possible sources of error in measuring weight and volume

Table 4 (continued)

Educative Feature and frequency[a]	Description	Samples
Subject matter-scientist Essays (SM-SE) (n = 13)	Scientist's perspective clarifying nuances of target concepts and scientific practices; presented separately from lesson plans for each section of a grade unit, appear side-by-side with corresponding Child Essays	Excerpt from Grade 5 essay on evaporation and condensation: *On the microscopic level we think of evaporation as a process in which an occasional molecule in the liquid (or solid) happens to get enough energy from random thermal motion to break its bonds to its neighbors and escape. It's not a collective phase transition, like melting, freezing, or boiling, so it happens at any temperature* Excerpt from Grade 4 essay on the importance of reasoning and evidence in science: *There are really only two valid ways to support a scientific claim: empirical evidence and logical reasoning from well-established principles. In ordinary life, we rely on analogy, anecdote, higher authority, and on hunch and intuition. To be called "scientific" an explanation must rest on the twin pillars of reasoning and evidence. To offer an explanation in science is to claim that one phenomenon arises as a result of some other phenomenon or process. A good scientific explanation accounts for, or is at least consistent with, all the relevant evidence. Scientists often come up with tentative explanations (hypotheses) that account for one observation or a few, but then try to consider whether other facts contradict the hypothesis or are explained or clarified by it)*
Subject matter-boxed notes (SM-BN) (n = 32)	Elaborate the scientific concepts to be introduced to students; sometimes explain additional complexity beyond intended student understanding; embedded in lesson plans	Boxed note explaining the complexities of evaporation and condensation in a Grade 5 investigation: *Condensation is related to both humidity and temperature difference. When air that includes water vapor is cooled to a lower temperature, the particles of water vapor draw closer together. If the air is sufficiently cooled, drops of condensation will form. Heat energy is necessary for evaporation to occur. Water can evaporate at very low temperatures, particularly when the humidity of the air is low*

[a]Frequency means number of instances across all three grade-level units of the curriculum

Table 5 Nature of designer contributions across phases

		Design Process Phases								
		Analysis			Development			Evaluation		
	Designers' Disciplinary Backgrounds	CP	SE	P	CP	SE	P	CP	SE	P
PCK Components (and Educative Features)	Student thinking (child essays; boxed notes)	Dark grey			Dark grey	Black		Dark grey	Dark grey	
	Instructional Strategies (boxed notes; consistent tripartite structure)		Dark grey					Dark grey	Dark grey	
	Curriculum (concepts chart; overviews; narratives)	Dark grey	Dark grey	Light grey	Black	Black			Dark grey	
	Assessment (oral and written assessments)		Dark grey		Dark grey	Dark grey				
	Subject Matter (scientist essays; boxed notes)					Black	Dark grey		Dark grey	

CP Cognitive Psychologist, SE Science Educators, P Physicist; See Table 4 for educative feature codes

Dark grey = proactive contributions

Light grey = reactive contributions

Black = both proactive and reactive contributions

White = no detailed data available/not applicable

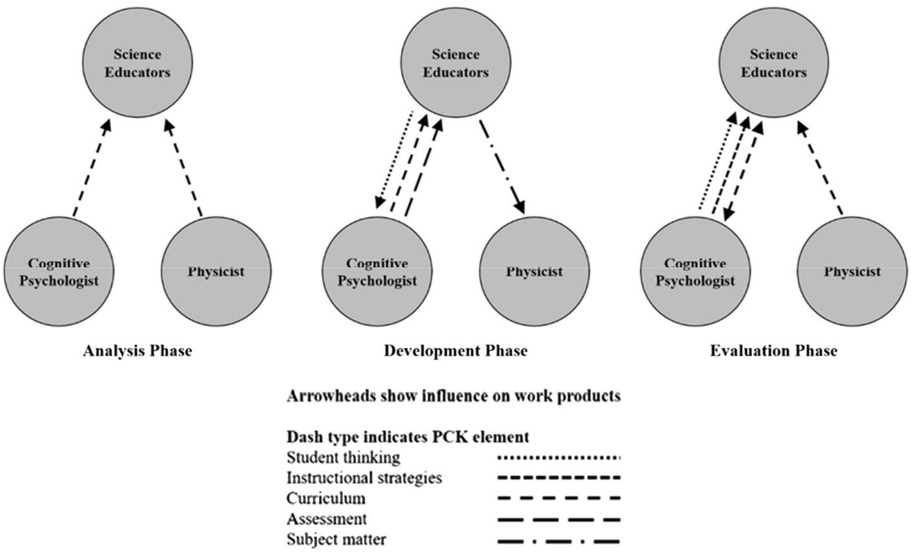

Fig. 1 Intermeshing of designer contributions across design process phases and in relation to PCK components

blended together to result in a coherent output. The authors discussed all mapping in the data until 100% consensus was reached.

Results

As stated before, the data analysis revealed that designers created 10 educative features to support the PCK components. This section presents findings about how designers with different disciplinary backgrounds contribute to creating the educative features throughout phases of the design process (analysis, development, and evaluation). Table 4 depicts the educative features, including their descriptions, samples, and the frequency with which they appeared in the teacher guide.

The inductive analysis revealed that, with regard to the nature of contributions, designers contributed proactively and reactively to various PCK components and educative features. Table 5 presents a synthesis of these contributions.

There was also intermeshing of designer contributions. A synthesis of the intermeshing interactions across the design process phases and in relation to the PCK components is depicted in Fig. 1. The circles depict the three areas of designer expertise and the arrows indicate the contribution of inputs from designers of one expertise area to those of another area towards creating educative features. The direction of the arrows indicates the flow of proactive and/or reactive inputs for designing specific educative features. By depicting the expertise areas and the flow of inputs between them, the figure provides at once a view of the whole team contributions and those of designers from individual expertise areas towards various PCK components across phases of the design process.

The design process phases are used to organize the remainder of the findings in this section.

Analysis phase

Student thinking

The *cognitive psychologist* (P5) had previously co-authored a white paper describing a hypothetical learning progression for matter, containing research-based insights into young children's common conceptions and misconceptions about matter and the role of instruction in developing their understanding. P5′s prior research was an important proactive contribution to help the design team understand children's ideas and to later develop the child essays (ST-CE).

Instructional strategies

The *science educators* contributed proactively by crafting a vision of teaching science through inquiry to include in the grant proposal. They were also aware that primary school teachers may be unfamiliar with science inquiry practices; therefore, teachers would need scaffolding in order to pose questions pertinent to both the science discipline and students' interests; to help students develop testable predictions; to guide students' observations during investigations; and to interpret evidence and articulate ideas through argumentation. This vision was later formalized in the consistent tripartite structure (IS-CTS) during evaluation and redesign phases. As P2 recalled during the interview,

> We came up with this [lesson] structure of what we thought [scientific practices] looked like in investigations, that was going to be repeated again and again, that we have that framework of ask the question, do an investigation, and then do the make meaning discussion. And so that had to do with our deep sense of how you could really engage in [scientific] practices. It was the way that we understood [scientific] inquiry, and it was something that we really lived, that we really did that for all those activities.

Curriculum

Designer contributions were intermeshed and designers with different backgrounds contributed both proactively and reactively in supporting this component. First, the *cognitive psychologist's* (P5) white paper mentioned before, which detailed a research-based, hypothetical learning progression on matter for primary and secondary school students, provided the science educators with the first roadmap for the present curriculum's goals and conceptual focus. In proactively designing this component, the *science educators* outlined a sequence in the grant proposal, beginning with rocks and soil in Grade 3, and proceeding to liquids in Grade 4 and finally gases in Grade 5. Drawing on the prior research on learning progression and related in-house projects, they emphasized introducing the concepts through solid materials because these were more familiar, tangible and observable to students than liquids and gases. This sequence, manifested in the C–C, diverged from typical curricula on matter (involving short investigations of unrelated objects and examples of concepts) by supporting inquiry through a sustained six-week study at each grade level. Each proposed grade-level sequence also reflected the main conceptual focus of the hypothetical learning progression.

Second, the original learning progressions work by P5 had proposed versions of standards-based science ideas suitable to teach at broad grade ranges and suggested scientific practices for students in those grade ranges. For this curriculum, however, a finer-grained progression was needed to help the science educators craft curricular goals and conceptual foci for each of grades 3, 4 and 5. At the beginning of the curriculum project, the team brainstormed and refined the framework to undergird the science educators' work for developing the present curriculum and to guide P5′s work on the associated research for this curriculum. P5 prepared a more detailed map of conceptual understandings for each grade within the 3–5 range to help the science educators later develop separate grade level units. This output crystallized into the science concepts chart (C–C) to support teachers' understanding of the curricular goals.

Furthermore, while designing the Grade 5 unit, the team revisited the underlying framework to identify which of two parallel directions to pursue: the concept of density or that of phase change, where density as a concept was included but the emphasis was on understanding gases as a phase of matter. Whereas the cognitive psychologist advocated starting from density, the science educators argued for focusing on phase change, considering students' prior knowledge of mathematics, alignment with the schools' science curriculum and standards, and limited implementation time. This was indeed a crucial point in the design process, and the team finally chose the phase change direction. The following interview quotes from science educators P1 and P2 respectively highlight the team's dilemma, negotiation of different perspectives, and their rationale:

> The hypothetical [learning] progression addressed both [density and phase change]. But we began to realize within the scope of the curriculum. we couldn't address both

> of those. One of the things that we saw when we made the decision to focus on phase change and transformations in 5th grade, as opposed to density, was that students just didn't have the mathematics to do an in-depth study of density in the 5th grade.
>
> There is a trade-off between the cognitive psychologist's idea about how [children's] ideas develop, and the scientist's idea about, what are big, important ideas [in science]? And maybe just the realities of the classroom, like how much time do you have here? A whole lot of the standards to do with weight, volume, and density, are in math, not in science. You begin to realize that if this is something that's an important science concept when you're thinking about matter, you have to squeeze it in to so few hours in the week to get that in.

To resolve this dilemma, the *physicist* (P6) contributed reactively by clarifying what was important to teach from a disciplinary perspective. He identified salient science ideas in each strand and explained how the strands related to previous grade units and to the schools' curricular goals. He also reiterated addressing the big science idea that gases are a form of matter because it prefigured the particulate model, which was the ultimate student learning goal of the present curriculum. His input was reflected in the C–C. Here is how P6 summarized his perspective:

> [The density direction] didn't match at all the [science] standards and the curriculum in the actual school. And the other major problem I recall we ran into was that all the stuff that we'd wanted to begin with about measurement and standard units and comparing quantities, and even volume - those were all topics that were under the mathematics curriculum in the schools. Another issue was that [the schools'] curriculum in [fifth] grade focused heavily on the water cycle. You can't understand the water cycle if you don't understand that gases are matter. From my point of view, sort of an overarching goal of this was really to prepare students to be ready to talk about atoms and molecules in middle school. And it seemed really important to me to be able to get there, that you needed to understand that gases are matter. Because usually, the first place you want to talk about atoms and molecules is in the context of gases. You can't do that if you don't already believe that gases are something.
>
> Reflecting on the team's decision, P5 stressed its collaborative nature:
>
> That shows you the value of how closely we worked together and thought about these. It's not like [science educators and physicist] were saying [density direction] was unimportant. I think we agreed these [directions] are not necessarily either or, but they only had time for one. We all agreed this seemed like a good way to go. It wasn't where we were envisioning going, necessarily, at the start, as [cognitive psychology] researchers.

Assessment

Drawing on their own prior work, the *science educators* emphasized formative assessments in the grant proposal as a core component of the proposed curriculum. In producing this output, they proposed embedding assessments into students' learning activities (as opposed to providing teachers with a separate set of instruments); in so doing, they

PCK Components	**Designers**	**Nature of contributions**	
Specific output	*Disciplinary Background*	*Proactive*	*Reactive*
Student Thinking *Child Essays*	Cognitive Psychologist	Prior research describing students' typical thinking	NA
Instructional Strategies *Consistent Tripartite Structure*	Science Educators	Crafted vision in grant proposal for structuring inquiry-based lessons	NA
Curriculum *Concepts Chart*	Cognitive Psychologist ↓	White paper on hypothetical learning progression; detailed map of grade-level learning progression; feedback on emphasizing density over phase change in learning progression framework for Grade 5 unit design	NA
	Science Educators ↑	Crafted vision in grant proposal for sequence of conceptual understanding; feedback on emphasizing phase change over density in learning progression framework for Grade 5 unit design	NA
	Physicist	NA	Clarified rationale for emphasizing phase change over density in learning progression for Grade 5 unit design
	Whole Team	NA	Brainstormed, refined detailed, grade-level learning progressions framework
Assessment *Oral and Written Assessments*	Science Educators	Crafted vision in grant proposal for embedding formative assessments in student learning activities	NA

Fig. 2 Nature of contributions and intermeshing in the analysis phase

stressed assessments about both science content and inquiry practices. Finally, they proposed collecting student work during curriculum implementation to build developmental criteria for the learning progression, and to create systematic and less teacher-subjective assessments.

To summarize, during the analysis phase, designers contributed in various ways to the PCK components of student thinking, instructional strategies, curriculum, and assessment. The proactive contributions included preliminary ideas to craft their vision, and the reactive contributions included consideration of possible science content for the curriculum. Finally, designer contributions were intermeshed for the curriculum component, as the cognitive psychologist's prior work and feedback on learning and the physicist's clarification of science content to emphasize guided the science educators' work on subsequent unit development (see Fig. 2).[3]

[3] The up and down arrows in Figs. 2, 3, and 4 indicate intermeshing of designer contributions.

PCK Components	**Designers**	**Nature of contributions**	
Specific output	*Disciplinary Background*	*Proactive*	*Reactive*
Student Thinking *Child Essays*	Science Educators ↓	Identified key ideas to address in child essays	Provided feedback on language, clarity of child essays
	Cognitive Psychologist	Explained in child essays children's typical conceptions, difficulties	NA
Curriculum *Concepts Chart; Narratives; Overviews*	Cognitive Psychologist ↓	Identified intermediate conceptual understandings to target in learning progression	Provided feedback about conceptual focus, learning activities, student learning in grade-level unit plans
	Science Educators	Prepared grids for concept sequences, grade-level learning activities, cross-grade unit planning	Provided feedback on children's capacities, supporting scientific ideas, inquiry practices in lesson plans
Assessment *Oral and Written assessments*	Cognitive Psychologist ↓	Identified children's alternative conceptions for Concept Cartoons	NA
	Science Educators	Reviewed formative assessment frameworks; identified learning goals, student ideas, criteria, next steps, examples; gathered feedback on assessment criteria from field test teachers	NA
Subject Matter *Scientist Essays*	Science Educators ↓	Identified key ideas to address in scientist essays	Provided feedback on clarity, elaboration in scientist essays
	Physicist	Explained in scientist essays importance of target concepts, practices to science discipline, rationale for teaching those	NA

Fig. 3 Nature of contributions and intermeshing in the development phase

Development

Student thinking

From a conceptual change perspective, the *cognitive psychologist* (P5) contributed proactively by explaining how children may hold initial and/or alternative conceptions and experience difficulties with specific concepts related to matter. These explanations manifested in the child essays (ST-CE). Designer contributions were intermeshed as P5 created this output based on proactive input provided by science educators P2 and P4, identifying key scientific ideas for teachers' background knowledge. Further, *science* educator P1 provided reactive input through feedback on language and clarity to help revise the essays.

Curriculum

Designer contributions were intermeshed as the *cognitive psychologist* (P5) stressed a learning progressions perspective, which focused on the child's network of concepts and beliefs (as opposed to the experts'). Her proactive input involved identifying intermediate

PCK Components	**Designers**	**Nature of contributions**	
Specific output	*Disciplinary Background*	*Proactive*	*Reactive*
Student Thinking *Boxed Notes*	Cognitive Psychologist ↓	Examined progress in students' understandings during field tests; communicated findings to science educators	NA
	Science Educators	Created boxed notes in lesson plans for anticipating students' typical conceptions	NA
Instructional Strategies *Consistent Tripartite Structure; Boxed Notes*	Cognitive Psychologist ↓	Examined progress in students' understandings during field tests; communicated findings to science educators	NA
	Science Educators	Observed classroom testing; refined structure, supports for enacting inquiry; created boxed notes in lesson plans for addressing students' typical conceptions, enacting scientific practices	NA
Curriculum Concepts Chart, Overviews, Narratives	Science Educators ↕ ↑	Conducted early trials at workplace; observed classroom testing; prepared, revised unit outlines, lesson plans; proposed revisions to underlying learning progressions framework	NA
	Cognitive Psychologist; Physicist	NA	Feedback on learning goals, activities in unit outlines
Subject Matter *Boxed Notes*	Science Educators	Observed classroom testing; created boxed notes in lesson plans to clarify concepts	NA

Fig. 4 Nature of contributions and intermeshing in the evaluation phase

steps as targets to move children's understanding forward instead of destabilizing it. As P5 explained,

> Your goal in a curriculum is to move the network [of concepts] forward, transforming it without destabilizing it. So a lot of traditional science instruction tries to define learning goals by the expert understanding. Let's break it into little pieces. And a learning progression's approach says that's not how you define the goals. The expert pieces are in terms of concepts that are miles away from where the kids are. You have to think much more creatively about it, and imagine intermediate steps that are targets, that are in terms of their own network of concepts, that aren't going to just match it but are moving it forward.

P5 also offered reactive input by critiquing written plans of grade-level units developed by the *science educators*. In so doing, she attended to the conceptual foci, learning activities, and anticipated issues and strategies in students' learning. The *cognitive psychologist's* contributions were manifested in the science concepts chart (C–C) and the curriculum overviews (C-O).

The *science educators'* contributions were manifested in educative features C–C, C-O, and the curriculum narratives (C-N). With respect to proactive contributions, they developed grids describing sequences of concepts and learning activities for grade-level units, aligned with the learning progression framework. They used the grids to also envision conceptual build across the grades. Further, working reactively in critiquing drafts of lesson plans, the *science educators* drew on their primary school teaching experience and their background in science and engineering. They considered target grade-level students' capacities, shedding light on what was reasonable to expect for activities like writing or manipulating materials. From a scientific perspective, the *science educators* pondered suitable approaches for developing science ideas within short timeframes of single lessons or sequences of lessons. They also critiqued the drafts with a focus on how key scientific ideas and inquiry practices may be integrated and played out during classroom enactment. P3 and P4 respectively described the *science educators'* contributions thus:

> So plotting out target understandings and brainstorming possible activities, things that we knew that kids of that age could do, and then really brainstorming the content sequences it might possibly build, making sure that there always was this little grid of the progression and some of the ideas that seemed essential to be included. And then [P4] would bring his drafts to the meeting and we would go over them and critique them, and make suggestions. I think that one of my roles was that I had a lot of experience in the classroom at that age level. So I knew what kids typically could and couldn't do when they were 8 years old or 9 years old or 10 years old, so I had a pretty good sense of what was reasonable to expect in terms of, for example, manipulating materials or writing. And then P2 would often take what had been done and put it into some kind of a grid, more of a conceptual chart.
>
> P2 would say, do you think doing these two [lessons] first is better, or do you think doing this first and then doing that—and then she'd say why she thought that was a better approach for the science, the development of the science idea.

Assessment

Designer contributions were intermeshed as the *cognitive psychologist* (P5) worked with science educators to develop 'concept cartoons'—a type of written formative assessment (A-OW) in which students respond to scenarios and alternative ideas about scientific concepts presented in cartoon-style drawings (Keogh and Naylor, 1999). The cartoons depict characters debating different explanations of scientific phenomena. One character's explanation is consistent with the scientific perspective, whereas other explanations reflect children' common understanding or confusions. Students are prompted to respond to each character's explanation. See the following excerpt from an external evaluation report of the Grade 4 unit:

> One of the strengths [of the curriculum design process] identified by [the designers] was the inter-connectedness among team members. This resulted in several collaborations across fields of expertise. For example, a collaboration between one of the cognitive [psychologists] and a [science educator] resulted in innovative curriculum-embedded assessment items: Concept Cartoons that became an integral part of the [Grade 4 unit] and that will presumably continue into the [Grade 5 unit]. These assessments were particularly well-received by the [Grade 4] class teachers.

To develop the concept cartoons, P5 contributed proactive input based on research on children's thinking, as described in this interview quote:

> The concept cartoons were a place of meeting a need for formative assessment in the classroom using [learning progressions/conceptual change] research, what we found to have the alternative [cartoon character] responses be things that kids might find - things that a teacher might not think that the kids would think, but we could put them in, that

> would be things [students] would go for in a big way, and that would then therefore generate an interesting class discussion.

Regarding proactive work by the *science educators*, P3 recalled, based on a review of existing formative assessment frameworks (e.g., Harlen, 2006), that they highlighted learning goals, varied sources of evidence of students' thinking, specific criteria for interpreting students' thinking, and identification of next steps to attain the goals. They mined project resources like videos of classroom enactment to exemplify oral assessments of students' discussions and investigations and excerpts from students' notebooks to exemplify authentic written work. Additionally, as evidenced in external evaluation reports, proactive tasks by the *science educators* included gathering feedback from field test teachers during monthly PD meetings to develop assessment criteria for interpreting students' thinking. They prepared and revised drafts of the assessments based on the team's feedback.

Subject matter

Designer contributions were intermeshed in supporting this PCK component. The *physicist* (P6) contributed proactively by explaining why concepts and scientific practices about matter were important to the discipline and explicated a rationale for teaching those to their students. The explanations were manifested in the scientist essays (SM-SE). P6 developed this output based on proactive input provided by *science educators* P2 and P4, identifying key scientific ideas for teachers' background knowledge. The essays were revised following reactive feedback about clarity and elaboration from *science educator* P1. As P6 described:

> [P1] wanted from me a statement about why do scientists care about matter? Why is this something that we're hammering into our students? No one ever tells them where it's going, why science invented this idea and why we're hammering it on them. From the perspective of someone who's been through the whole thing and uses these ideas, but written, hopefully, in a way that would make sense to people who were not scientists but are engaging with the same materials. So the first thing I would have to do is to really think about it, and come up with an answer that satisfied me about why is it scientifically an important concept.

To summarize, during the development phase, designers contributed to the PCK components of student thinking, curriculum, assessment, and subject matter. The proactive contributions included identifying target concepts, preparing sequences of concepts and activities, and reviewing existing frameworks. The reactive contributions included providing feedback on drafts of child and scientist essays to improve clarity. Finally, intermeshing was noted in all four components, with the science educators contributing both proactively and reactively to shape the essay outputs produced respectively by the cognitive psychologist and scientist, and the cognitive psychologist contributing proactively to shape the curriculum and assessment outputs produced by the science educators (see Fig. 3).

Evaluation and redesign

Student thinking

Proactive contributions from the *cognitive psychologist* (P5) involved conducting clinical interviews for research to iteratively inform the curriculum design, based on the underlying learning progressions framework. Specifically, the interviews examined students' conceptual understandings during field tests of the curriculum enactment. Designer contributions were also intermeshed as the results about student understandings were communicated to the science educators to provide insights into strengths and limitations of their understandings of target concepts. For example, in revising the Grade 3 unit, P5 pointed out that students erroneously believed light material cubes were hollow inside compared to heavy material cubes. This finding was subsequently represented in a boxed note (ST-BN) for a Grade 3 investigation, stating, "students commonly think wood or plastic cubes are light because they are hollow inside. While sometimes objects are hollow or filled with other materials, it is not true in this case."

Instructional strategies

The *cognitive psychologist's* (P5) proactive input about students' conceptual understanding based on the curriculum field tests helped the science educators create tips for teachers to address alternative conceptions. These contributions were represented in boxed notes on instructional strategies (IS-BN) embedded in lesson plans, thus indicating the intermeshing of designer tasks. For example, P5 noted:

> We gave [science educators] feedback on what we were seeing in the interviews, which suggests students didn't really understand volume too much in grade 3. And so we would bring up issues that [science educators] would focus on, and then the kids made a lot of progress with volume. We told them a lot of [students] think it's hollow in some of those light [cubes of different materials used in curriculum activity]. [The science educators] added to the curriculum cuts of [the cubes] just so they could show the kids that.

Based on this feedback, a boxed note was added to a Grade 3 investigation on sorting same sized cubes of different materials, suggesting that teachers "explain that each cube is made of just one material and is solid all the way through."

The *science educators* contributed proactively by observing classroom testing and stressing the need to reinforce classroom discussions with a consistent structure to support teachers' enactment. Consequently, they crafted discussion supports such as questions to elicit and respond to students' predictions and explanations. These contributions were manifested in the consistent tripartite structure (IS-CTS). Additionally, they emphasized the need to provide explicit guidance for enacting scientific practices like constructing, communicating with, and revising explanatory models. To this end, the *science educators* designed tips which were manifested in boxed notes (IS-BN). For example, the notes provide tips for different lines of questioning and conceptual focus for explanatory models. As evidenced in a *science educator's* written observations, key insights included:

> The teacher needs more guidance [for] reviewing [explanatory models], selecting a pair for students to analyze, and helping move the conversation forward in the class the next day as students review and discuss the selected models. When [students] commented on what they thought of the 2 models, how they compared, most of their observations were about how to improve the drawing and not how to improve the model. They just need more experience, and teacher needs more guidance. I had shared with [pilot teacher] the two lines of questioning: clarification questions and evaluative questions. We'll need to provide examples of each.

> Teachers will not be in a position to ask such questions when they have so little experience with them themselves.

Curriculum

Through a series of evaluation and redesign measures taken proactively by the *science educators*, sequences of concepts and instructional activities were formalized and materialized finally in the curriculum overview table (C-O) and narratives (C-N). Specifically, based on early trials of activities with children that were conducted at their workplace, the *science educators* generated unit outlines of student investigations, goals, and key ideas for classroom discussions at specific grade-levels. The whole team provided reactive input by critiquing the outlines with an eye on how the goals and activities served the underlying learning progressions framework, thus intermeshing their contributions. As indicated in an external evaluation report, "finally, after about two months of intense discussion, a consensual agreement on the outline would be reached." During this process, "the learning progression was central to [the team's] conversations about the evolving curriculum". See this excerpt from the evaluation report:

> [The learning progression] was part of all the conversations, no one lost sight of where we all wanted to get to. So when we were talking about activities, we would ask ourselves, "What does this have to do with the [learning progression]?" There was a real effort to lay out charts of each unit and to state for each lesson, "What's the learning goal?" And all the learning goals were aimed towards the progression.

Based on the agreed upon outlines, proactive work by the science educators included preparing lesson plans with learning goals and structure for investigations and 'Make Meaning' discussions. The lesson plans were revised following observations of classroom testing. Additionally, the science educators provided feedback to revise the detailed (hypothetical) learning progressions framework created originally by the cognitive psychologist into an "as enacted" framework (and manifested later in science concepts chart C–C), balancing theoretical considerations with practical needs and constraints. As described in an external evaluation report, the science educators strove to not only produce "a curriculum that maintained the integrity of the [learning progressions] framework, but also one that met the needs of the participating schools," specifically of "teachers in [a statewide standardized assessment] world who don't do hands-on science and don't have a science background." See this interview quote from *science educator* P1:

> It was certainly that the learning progression was guiding the initial development of the curriculum. When we would make revisions, we were trying to hold onto that, always, but we were also thinking about – is this viable for students, and is it viable for teachers? And we were also saying – is this giving students the ideas that the cognitive [psychologists] were hoping for?

Subject matter

Proactive work from the science educators involved observing classroom enactment to redesign supports for particular scientific concepts in the teacher materials. For example, during pilot testing of Grade 5 investigations on water freezing and melting, they noted that the curriculum materials did not clarify to teachers why water expands when frozen nor that this expansion is anomalous compared to other liquid materials. These insights were ultimately manifested in boxed notes (SM-BN) embedded in the revised lesson plans. One note provides a basic explanation for the increased volume of frozen water: In simplest terms, the tiny water particles rearrange themselves to form crystals when they freeze. In their new arrangement, the particles are not as tightly packed together as they are in liquid form and they take up more space.

To summarize, during the evaluation and redesign phase, the designers contributed in various ways to the PCK components of student thinking, instructional strategies, curriculum, and subject matter. The proactive contributions included observing classroom enactment and examining student conceptions through pilot and field tests of the curriculum implementation to inform redesign of supports for student thinking, instructional strategies, and subject matter. The reactive contributions were in the form of feedback on the unit outlines. Finally, intermeshing was noted for the components of student thinking, instructional strategies, and curriculum, as input from field testing by the cognitive psychologist informed additional supports, and the cognitive psychologist and the physicist gave feedback on the unit outlines created by the science educators (see Fig. 4).

Discussion

Reflections on the findings and substantive recommendations

This section presents reflections on the main findings of the study in light of relevant literature on interdisciplinary collaboration, PCK, and educative materials. In addition, distilled from both the findings and literature are recommendations for both research and practice related to collaborative interdisciplinary design to support teachers' PCK and thereby support instruction. Whereas the recommendations emerged from the case of a primary school science curriculum, several implications for designing curricula and instruction seem relevant to other school levels and subject areas.

First, with respect to the nature of designer contributions, the proactive and reactive nature of contributions observed in this study shed light on how different designer expertise can contribute to shaping various educative features over time. This is a notable finding because these kinds of contributions can help members of interdisciplinary teams to systematically offer unique inputs consonant with their areas of expertise (Wang 2014). Indeed, for complex endeavors (as exemplified in the present case of creating longitudinal curricula containing many educative features), the requisite and pertinent knowledge to craft solutions does not lie within the contributions of a single designer but is distributed among the inputs of different designers (Arias et al. 2000). Both proactive and reactive contributions from varied expertise can thus help design teams to attain goals efficiently that cannot be attained through the efforts of individual professionals alone (Bronstein 2003; Bruner 1991). A recommendation then for future research is to map in greater detail the nature of contributions from designers with different expertise for specific PCK components or to understand how designers with differing expertise can work within diverse groups during each phase of design (analysis, development, and evaluation). For instance, what is the role of subject matter experts when designing supports for PCK of instructional strategies or assessments and how can their proactive and reactive contributions shape the designed product? Based on this insight, interdisciplinary design teams can plan for what kinds of proactive and reactive inputs to draw out from its members according to PCK components as well as consistently during different design phases.

Another key finding of this study is that of intermeshing of designer contributions for all PCK components and during different design process phases to coordinate inputs from different areas of expertise and yield coherent educative materials. Thus, not only were the different outputs (educative features) brought together to produce a unified curriculum, but the outputs themselves resulted from varied designer expertise. The interplay of disciplinary inputs is important because while designers may bring specialized disciplinary perspectives to a design task, insights and solutions emerge from communication and integration of different perspectives (Wang 2014). The intermeshing for specific design tasks may help designers take advantage of the available expertise to generate innovative solutions (Barber 2015). This is especially critical to foster interdependence and mutual respect for productive interdisciplinary collaboration as they pursue shared goals (Bronstein 2003).

Additionally, with respect to intermeshing, the inductive findings show how collaboratively created artifacts, such as the detailed learning progressions framework, underpinned the designers' negotiation of the focal science content and their critiques on drafts of the written curriculum. The literature on collaborative interdisciplinary design stresses the role of *boundary objects* – shared design artifacts – which externalize designers' ideas and facilitate reflection and communication (Flood et al. 2015). Boundary objects are especially crucial to build shared understanding among designers working together as a *community of interest* to address problems of shared concern (Fischer and Ostwald 2005), as instantiated in the present design team composed of science educators, practising scientists and cognitive psychologists. Whereas this study shows how a curriculum framework served as a boundary object for the PCK component of curriculum, additional research is needed to investigate how various other boundary objects may contribute to intermeshing of designer interactions for supporting other PCK components. Based on this insight, design teams can plan on incorporating different boundary objects, such as documents of prototypes, to facilitate intermeshing of designer contributions towards shared design tasks.

The findings about intermeshing extend other research on collaborative design. Prior work has documented collaboration of expert designers, highlighting processes such as negotiation of task-specific aspects and interactive evaluation of the outcomes (Kvan et al. 1997). Studies have also described social processes in design teams and tactics by which designers analyze problems and develop solutions. For example, designers are found to externalize their understanding of design requirements and specifications, and co-operatively add to and refine initial design ideas (Cross and Cross 1995). And yet other research has examined the development of shared understanding in design teams, pointing to dynamic patterns in designer focus on the taskwork (i.e., the intended product), the teamwork (i.e., the underlying design process), and specific actions to perform (Cash et al. 2020). Whereas the literature has described these general processes in design teams, the concept of intermeshing provides an analytical lens to unpack and further develop a more fine–grained understanding of the ways in which individual designers contribute, enable, or specify the emergent team work based on their respective expertise during these collaborative design processes.

In addition, the study shows how this mix of various disciplinary inputs throughout phases of the design process helps designers to systematically and iteratively target multiple PCK components in tandem. This is important because the components are interconnected (Magnusson et al. 1999; Park and Chen 2012); hence, addressing them singly may not be ideal in supporting teacher learning. This designer work is consistent with existing heuristics (Davis and Krajcik, 2005) and principles (Davis et al. 2017) in suggesting the importance of designing to support teachers' PCK in multiple ways, and with recent examples of such materials (Arias et al. 2016; Roseman et al. 2017; Schneider 2013). Finally, designer work focused on helping teachers understand curricular content and plan for their teaching (e.g., the child and scientist essays and curriculum narratives and overviews to aid background knowledge of curricular content and organization), as well as to enact their plans in-the-moment of classroom instruction (e.g., boxed notes, consistent tripartite structure including specific language and questions, and oral and written formative assessments). This dual attention is vital because teachers draw on their PCK to plan and reflect on their teaching as well as during enactment (Kirschner et al. 2016), with recent research showing that the PCK held by teachers affects their instructional actions in the moment-of-teaching, i.e., enacted PCK (Kuglemeyer et al. 2020).

Limitations and methodological recommendations

This study involved a retrospective analysis of designer interactions. Related to this approach, three important limitations bear mention. First, the choice to identify a project with successful outcomes meant identifying a project that had been completed long enough for the outcomes to be measured. Given the elapsed time, and the fact that the study relied on participants' memories for describing their design process and interdisciplinary contributions, detailed descriptions were not always possible. Although project documents were used to extract additional information and support respondent recall, some details were challenging to obtain and did not lend themselves to in-depth scrutiny or were excluded from the data analysis. For example, monthly PD meetings and co-teaching the curriculum with field test teachers were important measures taken by the science educators. However, precise details of how these measures shaped various educative supports were lacking.

A second limitation stems from the first. Namely, whereas the inductive analysis revealed the nature and intermeshing of designer contributions for some PCK components in each design phase, a comprehensive overview was not feasible. For example, the data set did not yield adequate information on designer expertise and inputs in supporting teacher knowledge of instructional strategies during the development phase or in supporting knowledge of assessments in the evaluation (and redesign) phase. Furthermore, a similar point may be noted in Fig. 1 depicting intermeshing of designer contributions for different PCK components across design process phases. Specifically, the presence of unidirectional arrows (indicating the flow of proactive and/or reactive contributions) between specific areas of expertise for some PCK components suggests a basic coordination of independently crafted inputs, instead of a process involving back-and-forth and discussions between designers or the team as a whole to yield a more synergistic output (akin to the outputs for the PCK component of curriculum). For example, considering the learning progressions framework underpinning the design work, one could reasonably expect that for the PCK components of student thinking and assessment, there was substantial discussion between the cognitive psychologist and science educators about which student difficulties and alternative conceptions to address and how in the associated educative features (e.g., child essays and concept cartoons). While it is clear that such interactions were limited in our data set, we cannot rule out the possibility that this was a kind of false negative, due to the retrospective nature of the study.

Hence, further verification of such details should be a priority in future research, given that recent reforms (National Academies of Science, Engineering and Medicine 2017) and research in teacher professional learning (Furtak et al. 2016) emphasize formative assessments. The (science) education community would benefit from knowledge of the design process behind such assessments. We therefore recommend that future research study the design processes of ongoing curriculum projects which may enable researchers to collect observations, documentation and interview data at regular time points, thus relying less on participants' memories.

The third limitation is the study's ability to unpack whether or how the nature and amount of designer contributions might have been influenced by the number of hours worked and/or the number of designers who composed the 'sub-teams' of science educators, cognitive psychology researchers, and science experts. The present data were gathered from a subset of the full project team, and contained only partial information on the time devoted to this project by the designers in the team. Whereas one might reasonably expect the science educators to have devoted the most time to this work, considering their relevant expertise in science curriculum design, primay school teaching, and teacher PD, future research could systematically collect data to examine designer contributions in relation to the size of the sub-teams and the length of time of work.

Significance of the study

In closing, this study brings into high relief the painstaking nature of interdisciplinary collaboration during design to produce beneficial supports for teachers and students. Such supports are crucial for enabling teachers to fine-tune learning environments and instructional approaches in ways that engender positive learner outcomes (Pareja Roblin et al. 2018). Furthermore, as evidenced in recent research, educative materials help teachers shape instruction to engage students with important content and practices (e.g., Arias et al. 2016). But high-quality curriculum design is an expensive undertaking and requires significant and sustained funding from various agencies (Burkhardt and Schoenfeld 2003). To aid these endeavors, the study contributes a detailed design case to help other designers learn from precedents, describing both the designed product and the underlying designer rationales and activities (Howard et al. 2012). Moreover, this study yields detailed theoretical insights into collaborative, interdisciplinary design processes, revealing how designers make specialized, discipline-specific contributions, and coordinate varied inputs to systematically shape coherent educative materials. Finally, the study also offers practical recommendations to guide designers engaging in collaborative interdisciplinary design of curriculum materials. The recommendations can serve experienced and novice designers in different educational contexts as well as interdisciplinary educational design teams.

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Data Availability The dataset analyzed during this study is not publicly available due to confidentiality requirements, as established by the research organization's Institutional Review Board.

Declarations

Conflict of interest The authors declare they have no conflicts of interest.

Ethical approval The data collection and analysis procedures employed in this study were granted approval by the Institutional Review Board at TERC.

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