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Promoting Coherent Science Instruction through Coherent Science Teacher Education: A Model Framework for Program Design

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ABSTRACT

Recent research and reform efforts in science education have consistently stressed the importance of coherent science instruction, in which learning opportunities are connected and contextualized by meaningful phenomena, focus on a small set of core ideas over time, and generate a need-to-know about new ideas through a set of connected lessons. Yet, this type of instruction remains uncommon in schools. We argue that science teacher education has the potential to play a powerful role in promoting coherent science instruction in schools, but to reach this potential, science teacher education programs themselves must be coherent. Based on existing literature and our work in an international collaboration focused on effective practices in science teacher education, we identify key features of coherent science teacher education programs and present a new model that we refer to as the Science Teacher Education Programmatic Coherence (STEP-C) model. The STEP-C model illustrates how key elements of science teacher education are situated relative to each other, potentially serving as a powerful tool for program design.

KEYWORDS
Coherence; program design; teacher knowledge

Decades of science education research have contributed to a broad consensus that high quality science teaching includes situating student learning within collaborative investigations of meaningful phenomena and problems embedded within relevant contexts (e.g., Furtak & Penuel, 2019; Lee & Songer, 2003), leveraging these contexts to motivate within students a need to know about new science ideas (e.g., Schneider et al., 2020), and building a relatively small set of core science ideas and practices over a long period of time (e.g., Alonzo & Gotwals, 2012; National Research Council, 2012). Such features are hallmarks of *coherent* science instruction (Fortus & Krajcik, 2012; Kali et al., 2008). There is a robust and growing base of empirical evidence which suggests that coherent instruction is more effective in supporting student learning, motivation, and equity than more traditional didactic approaches (Beier et al., 2018; Geier et al., 2008; Harris et al., 2015; OECD, 2016; Schneider et al., 2020). Consistent with this evidence base, the importance of coherence in

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science instruction is reflected in science standards documents that are intended to guide and inform classroom instruction (e.g., KMK [Sekretariat der Ständigen Konferenz der Kultusminister der Bundesrepublik Deutschland], 2005; NGSS Lead States, 2013; Vahtivuori-Hänninen et al., 2014).

Despite the promise of coherent science instruction and the widespread emphasis on its underlying principles in science education research and science standards documents, it is relatively uncommon in schools (e.g., Banilower et al., 2018). This so-called research-practice gap (or theory-practice gap) may have many sources, such as teachers' perceptions about the utility of academic research and their experience using research in practice (Cain, 2017; Joram et al., 2020; Lysenko et al., 2014; van Schaik et al., 2018). New teachers in particular struggle to implement the pedagogical tools and strategies they learned within preservice science teacher education and often adopt more traditional instructional, and less coherent, approaches in their own teaching (Fulton et al., 2005; Roehrig & Luft, 2004).

Preservice science teacher education represents an opportunity to mitigate the dichotomy between the type of coherent instruction emphasized within the science education research literature and the instruction commonly enacted in schools. Yet, many preservice teachers experience a challenge in bridging the gap between the ideas advocated in formal learning opportunities during university teacher education and their enactment in schools (e.g., Allen & Wright, 2014; Braaten, 2019). In this paper, we argue that in order to begin supporting new teachers in enacting coherent science instruction, science teacher education itself should become more coherent. Canrinus et al. (2017) indicated the need for coherence in teacher education with well-aligned courses that help preservice teachers to make connections enabling them to bridge campus courses with what they learn from their field experiences. To meet this need, researchers have emphasized the importance of supporting preservice teachers' reflections in order to bridge the gap between university courses and field experiences (e.g., Nilsson, 2008; Schneider & Plasman, 2011). Additionally, a robust research base focuses on the nature of science teacher knowledge and how different components of this knowledge may be developed during science teacher education program (e.g., Hume & Berry, 2013; Loughran et al., 2008; Nilsson & Karlsson, 2019; Sorge, Kröger et al., 2019). Yet, there is much work to be done to specify the essential components of coherent science teacher education and how these components should be related to each other within a science teacher education program.

Recently, we have engaged in a two-year international partnership in which we have shared and explored effective elements of science teacher education programs in seven different European universities. We have iteratively developed the Science Teacher Education Programmatic Coherence (STEP-C) Model which identifies and relates key components of science teacher education that may help new science teachers successfully bridge the gap between what is intended by research and standards documents and what is enacted in classroom practice. In this paper, we present the STEP-C model, illustrate how key components are manifest in partner science teacher education programs, and discuss implications of this model for research and practice.

Theoretical framework

What is coherent science instruction?

Science education research has emphasized the importance of instruction that is designed according to research into how people learn (National Academy of Science, Engineering, and Mathematics [NASEM], 2018). To refer to such instruction, researchers have used terms like *reform-based* (e.g., Veal et al., 2016), *inquiry-based* (e.g., Furtak et al., 2012), and *constructivist teaching* (e.g., Haney & McArthur, 2002), among many other variations. Here, we emphasize the importance of *coherent* science instruction, as this term carries specific meaning with respect to key instructional principles. First among these principles is that coherent instruction focuses on developing a small set of core ideas over a long period of time (Fortus & Krajcik, 2012). Second, coherent instruction is contextualized in connected explorations of meaningful phenomena and problems (NASEM, 2019). Third, coherent instruction motivates a need to know about new ideas based upon their utility in making sense of the phenomena/problems that drive learning (Schneider et al., 2020). Importantly, coherent instruction supports students in taking a primary role in connecting activities and ideas (Sikorski & Hammer, 2017).

Teachers are the primary agents in how intended standards/curriculum are enacted, and professional learning opportunities play a substantial role in how teachers design or adapt instructional materials to meet the needs of their students (Penuel & Gallagher, 2009; Wilson et al., 2018). Professional learning opportunities in preservice science teacher education play a key role in shaping new teachers' predispositions toward teaching practice (Stroupe et al., 2020) and the manner in which they adapt instructional materials (Forbes, 2013; Forbes & Davis, 2010), thus the design of science teacher education programs plays a key role in whether and how coherent science instruction is enacted in classrooms.

The role of science teacher education in promoting coherent instruction

Many years of classroom experience are required for teachers to develop the type of knowledge and skills for teaching that are the hallmarks of expertise. Teacher education can play a critical role for setting teachers on the path of developing such expertise (Darling-Hammond & Oakes, 2019). Expertise in any field is characterized by well-organized knowledge, in which ideas are richly connected around a small set of powerful core ideas (Linn, 2006; Schwartz & Goldstone, 2016), and adaptive expertise, in which experts efficiently respond to non-routine and novel situations that arise through practice (Bransford et al., 2000). Science teacher education should therefore set the stage for new teachers to both develop robust knowledge for teaching and to authentically engage with the practice of teaching (Stroupe et al., 2020).

To begin down a path toward effectively planning and enacting coherent science instruction new science teachers need more than science content knowledge; they must know, for example, how learners construct understanding of science ideas over time and which phenomena and representations are particularly useful at various grade bands. This special amalgam of knowledge for teaching is commonly called pedagogical content knowledge (PCK; Shulman, 1986). PCK has been linked to teachers' ability to design, enact, and reflect on coherent learning experiences (Park et al., 2011; Wilson et al., 2018).

PCK is just one of a host of characteristics that are important for effective science teaching. Blömeke et al. (2015) highlighted affective-motivational factors (e.g., beliefs) as well as situation-specific skills that also substantially affect teachers' performance (see also Gess-Newsome, 2015). In the following sections, we briefly review current thinking on the PCK construct and discuss the role of teachers' beliefs and goals in influencing their enactment of coherent science instruction. We briefly discuss the role of teachers' beliefs and goal-orientations, as these factors are seen as key amplifiers and filters of teacher actions (Gess-Newsome, 2015; Hutner & Markman, 2017) and are often in conflict due to the dual role that preservice science teachers (PSTs) hold as students at the university and teachers at a school (e.g., Poulou, 2007).

Pedagogical content knowledge

Since it was first proposed by Shulman (1986), researchers have sought to specify the nature and various components of PCK for teaching science (Berry et al., 2015; Magnusson et al., 1999; Nilsson, 2008; Park & Oliver, 2008). These discussions and efforts have recently been incorporated into the so-called Refined Consensus Model (RCM) of PCK for teaching science (Hume et al., 2019). The RCM (Figure 1) identifies the different types of PCK in science teaching and the relationships between them.

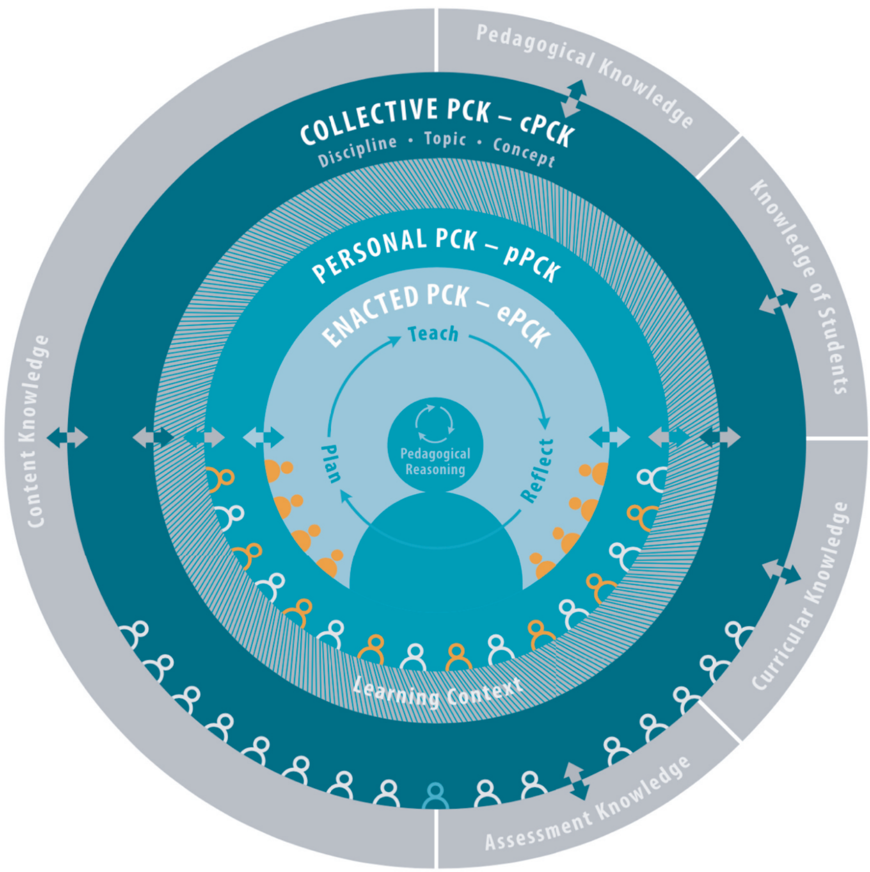

Figure 1. Representation of the Refined Consensus Model (RCM) of pedagogical content knowledge (PCK) for teaching science (Hume et al., 2019).

The RCM is represented as a series of concentric circles (see Carlson et al., 2019). The outermost circle identifies the professional knowledge bases that serve as the foundation for the work of expert teaching. Immediately inside of this circle is a construct identified as collective PCK (cPCK), which represents a shared knowledge base among a community of science teaching professionals (e.g., teachers, researchers). Individual teachers hold personal PCK (pPCK), which serves as a set of knowledge and skills that a teacher may draw upon when designing and enacting instruction. The elements of pPCK that are activated during planning, teaching, and reflecting are identified as enacted PCK (ePCK). The quality and nature of the cycle of planning, teaching, and reflection is driven by individual teachers' pedagogical reasoning, which is a process represented at the center of the RCM.

PSTs encounter learning opportunities during university teacher education addressing different components of PCK. Explicit instruction in science method courses supports preservice teachers' knowledge exchange between cPCK and pPCK (Sorge, Stender et al., 2019), and field experiences provide opportunities for preservice teachers to enrich their pPCK (van Driel et al., 2002) and develop their ePCK for planning, teaching and reflecting (Alonzo et al., 2019; Kulgemeyer et al., 2020).

The RCM delineates between different realms of PCK and other factors that influence teaching—such as teacher beliefs, attitudes, and goals—and does not include them specifically in the model. However, the different realms of PCK are connected through knowledge exchanges that are driven by contexts and other influencing factors such as beliefs and goals. In order for science teacher education to support teachers' enactment of coherent science instruction, programs must attend to more than science teacher knowledge.

Teacher beliefs and goals

Teachers' beliefs influence practice by serving as a filter of information and a guide for problem-solving (Fives & Buehl, 2012). While teachers' beliefs influence practice, it is important to note that observed practice is frequently misaligned with teachers' stated beliefs. New teachers in particular may profess beliefs that stand in stark contrast with their classroom actions (Caleon et al., 2018; Davis et al., 2006).

Science teacher education may play a critical role in bridging the gap between beliefs and practice, yet, many preservice teachers struggle to connect the theory they learn in coursework to practice in classrooms (Levine, 2006). Even when PSTs adopt pedagogical beliefs that align with normative consensus, new science teachers are often quick to abandon such beliefs as they begin inservice practice (Fletcher & Luft, 2011; Saka et al., 2009, 2013).

Hutner and Markman (2017) apply a goal-driven model of teacher cognition to explain the mismatch between beliefs and practice, arguing that knowledge and beliefs about teaching are only activated when they align with an active goal. Thus, while a teacher may hold knowledge and/or beliefs that correspond with coherent science instruction, they may not be activated if they do not correspond with an active goal (e.g., achieving a high student pass-rate on a standardized test). Hutner and Markman (2017) observe that the goals of preservice and practicing teachers often do not correspond. For example, preservice teachers may be focused on impressing their professors while practicing teachers may prioritize school or district goals like raising standardized test scores. In this case, it is important for teacher educators to provide supports for preservice teachers in order to resolve such goal conflict (Hutner et al., 2019).

Defining coherence in teacher education

Science teacher education programs play a critical role in helping PSTs to form a consistent set of knowledge, beliefs, and goals that apply across the university and school contexts in which science teacher education is situated. In order to promote such a consistent set of PSTs characteristics, science teacher education must itself be coherent. Coherent teacher education programs are those that present a consistent vision of good teaching that is revisited across a range of teacher education experiences (Darling-Hammond & Oakes, 2019). The value of coherence in teacher education has long been recognized (Darling-Hammond et al., 2005; Richmond et al., 2019; Smeby & Heggen, 2014). Yet, coherence in teacher education, particularly concerning connections between university-based and school-based experiences, has been elusive (Canrinus et al., 2017; Grossman et al., 2008; Zeichner, 2010).

In an effort to define coherence in teacher education, Hammerness (2006) argued that coherence may be broken down into "conceptual coherence"—describing a shared vision among those who work with preservice teachers—and "structural coherence"—in which key assignments and experiences are aligned. Darling-Hammond and Oakes (2019) stressed that coherent programs' core ideas and theoretical frameworks are reiterated across courses and experiences, highlighting the importance of integration between university coursework and clinical work in schools.

Importantly, coherence in teacher education is not an endpoint that is achieved, but rather a continuous process of negotiation and communication between a diverse group of relevant stakeholders (Hammerness, 2006; Richmond et al., 2019). This process of coherence-seeking would benefit from a common framework which identifies key programmatic elements that are particularly promising for putting a common vision into practice and ensuring that this vision is apparent to learners as a coherent vision.

Developing a model of coherent science teacher education

Scholars have previously contributed to a definition of coherence in teacher education and identified general characteristics of coherent programs, and our intent is to build on this foundation in order to: (1) specifically address the issue of programmatic coherence in science teacher education and (2) go beyond identifying general characteristics of coherence to represent how these characteristics may be manifest in terms of complementary programmatic elements.

Recently, we (an international group of science teacher educators) collaborated to identify components of science teacher education programs that show particular promise for promoting the enactment of coherent science instruction in schools and to construct a model that represents the particular role of these components within coherent science teacher education programs. In the next sections, we describe the collaborative project and introduce the model of coherent science teacher education that we developed during the course of our collaboration. A central goal of this model is to guide the design and ongoing reflection and evaluation of science teacher education programs that support the enactment of coherent science instruction in schools.

Project structure and participants

The project was structured to leverage the opportunities provided for learning about teacher education in one's own country by learning in detail about what is done in other countries (see Darling-Hammond, 2017). Over the course of two years, partners from Denmark, Finland, Germany, Norway, Sweden, and Turkey participated in a collaborative project, called "Promoting Instructional Coherence through Science Teacher Education" (PICoSTE). Project activities were designed according to the principles of coherent instruction. Toward this end, we focused on the guiding question "How can science teacher education better prepare new teachers to implement coherent science instruction in school?" To address this question, we designed a series of eight connected meetings that focused on different aspects of science teacher education and how they are connected. Throughout the project, we visited partner institutions to: learn about the local educational context, read and discuss relevant literature, observe science teacher education in practice, and learn in-depth about a key element of the science teacher education program that supports coherent science instruction. Each partner visit took place over the span of three days and included site visits to local partner schools, observations of teacher education courses, observations of school science instruction by PSTs, and structured reflective and brainstorming discussions. Core project participants included thirteen scholars, working in university-based science teacher education, and seven master level mentor teachers, supervising student teachers during the teaching practice. In addition to these core participants, each partner visit involved local stakeholders including PSTs, university and school administrators, science teachers, and other science teacher educators.

As a central artifact of our collaboration, we developed and iterated upon a model that connected promising practices from partner institutions within a broader framework. This model was initially proposed and discussed during our fourth project meeting, and was revisited and revised in accordance with our new learning in every subsequent project meeting.

Method of model development

To document and reflect upon our learning in each project meeting, we created and retained artifacts such as: notes, agendas, lesson plans, PST work samples, background papers, photographs, presentations, and collaborative documents generated during reflective and sensemaking discussions. Additionally, after each partner visit, we constructed a narrative describing key activities, theoretical perspectives, and outcomes that emerged from our collaboration. Using these documents, we conducted document analysis as described in Corbin and Strauss (2008). Such analysis is intended to elicit meaning, gain understanding, and develop empirical knowledge from the corpus of collected documents. Our goals in this analysis were: (1) to identify key themes in our emerging group consensus regarding how science teacher education can promote coherent science instruction and (2) to describe relationships between these key themes such that these relationships can be represented in a model. To reach these goals, we engaged in an iterative process of skimming, thorough reading, and interpretation (Bowen, 2009) in order to organize information from the documents into categories, identify themes, and describe relationships between them.

Bowen (2009) identifies several limitations of the document analysis approach, including insufficient detail in documents which were not created for research purposes and bias selectivity resulting from the likelihood of available documents to align with organizational policies and procedures. We addressed these limitations by triangulating data sources. For example, we conducted small group informal interviews between PSTs and visiting project participants during site visits that simultaneously provided more vivid detail regarding key programmatic components and allowed for the inclusion of perspectives of stakeholders who were not directly responsible for science teacher education program design. Further, as our document analysis was iteratively conducted over several meetings, we were able to counter the insufficiency limitation by identifying areas where more information was needed and to address selectivity bias by engaging with the perspective of various external stakeholder groups as consensus emerged. Model development was similarly iterative. During site visits, we elaborated and revisited the initial model in order to include the shared understanding how coherence in science teacher education appear in the each context. Therefore, the local visits served as conceptual test for the initial model and facilitated revisions to better grasp the local context.

A model for Science Teacher Education Program Coherence (STEP-C)

In developing the STEP-C model (Figure 2), we endeavored to go beyond simply listing characteristics of coherent science teacher education to identify key programmatic elements that are most critical for coherence and situating these elements relative to each other within a broader programmatic perspective. The ultimate goal of a programmatic perspective that focuses on coherent science teacher education is to put new teachers on a pathway to develop the knowledge bases, beliefs, and goal-orientations that are necessary for enacting coherent science instruction in their own classrooms. As such, we align our work in particular with the RCM for PCK; while the RCM represents how various knowledge bases and stakeholder groups contribute to science PCK, the STEP-C model represents how science teacher education programs might be designed to support PSTs in developing robust science PCK. The STEP-C model is also intended to foster supportive beliefs and goals to put that knowledge into action. Such a focus on putting knowledge into action strongly aligns with the perspective of practice-based science teacher education (Stroupe et al., 2020), which emphasizes the indispensable role of engaging in the practices of planning, enacting, and reflecting upon instruction.

The STEP-C model includes three major elements: (1) overlapping circular fields that indicate the two primary contexts in which science teacher education occurs (university and school), (2) a triangular "reflective dynamo"—situated both in the university and school contexts—that represents engaging in planning, teaching, and reflecting using a set of core ideas about coherent science instruction, and (3) arrows representing key "bridging elements" that are critical for activating the core ideas for teaching science consistently across the university and school contexts.

Contexts for science teacher learning

Roughly speaking, the university context is where PSTs learn about intended science instruction, as represented by exemplary curriculum, standards documents, and seminal research in the field; in the school context, PSTs observe and participate in enacted science instruction through mentor observations, shorter-term teaching practica, and longer-term student teaching experiences. The contexts identified in the STEP-C model are less about location than they are about different foci. Even if university courses meet on K-12 school

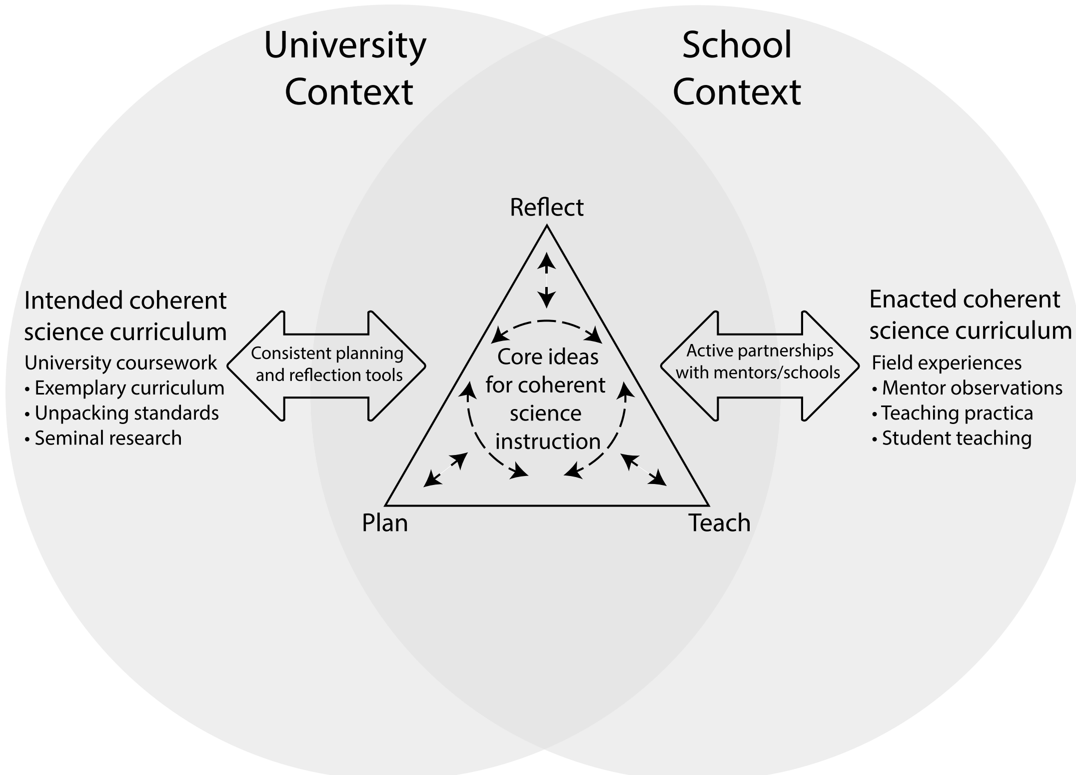

Figure 2. The Science Teacher Education Programmatic Coherence (STEP-C) model.

campuses, there is typically still a distinction between learning the theory of coherent science instruction and participating in the enactment of science instruction. This distinction resembles the difference between cPCK and ePCK in the RCM. The university context, represented on the left side of the STEP-C model, is the primary opportunity for PSTs to learn about the publicly-held knowledge that is shared among the broader community of science educators (Sorge, Stender et al., 2019). Such publicly-held knowledge includes, for example, empirically-supported perspectives on how students learn science (e.g., "three-dimensional" learning in the NGSS), the role of effective representations in supporting science learning, empirically-based learning progressions for core science ideas etc. The university context represents the primary opportunity for PSTs to encounter ideas of cPCK from the broader science education community and to begin the work of incorporating these ideas into their pPCK by engaging with peers, university faculty, and other stakeholders (e.g., master teachers, policymakers) (Kleickmann et al., 2013). The school context, represented on the right side of the STEP-C model, is the primary opportunity for PSTs to gain experience teaching certain topics to specific students. The purposeful reflection of for example, unexpected student questions, conceptions or the perceived effectiveness of using a representation in turn can also enrich the pPCK and ePCK of PSTs (Alonzo et al., 2019).

Reflective dynamo

At the center of the STEP-C model are the core ideas for coherent science instruction, contained within both the university and school contexts. These ideas include the central principles for what makes science instruction coherent, including: a focus on students collaborating to figure out relevant and accessible phenomena and/or problems (Schneider et al., 2020), motivating a need-to-know about new ideas through, for example, the construction of coherent storylines (Hanuscin et al., 2016; Nordine et al., 2019), and a sustained focus on building students' understanding of the most central explanatory ideas of science over time (Kali et al., 2008; Kesidou & Roseman, 2002).

We identify the importance of focusing on relevant phenomena/problems, motivating a need-to-know through connected activities, and focusing on core ideas over time as core ideas for coherent science instruction because these ideas are broadly supported within the literature. However, the specific core ideas emphasized within each program may vary in their nature and makeup. For example, Roth et al. (2017) elaborate upon two "lenses" for effective science teaching—"Student Thinking Lens" and the "Science Content Storyline Lens"—that form the conceptual core of a video-based approach to designing coherent science teacher preparation (Stennett et al., 2020). Whatever their form, core ideas for coherent science teaching should be both grounded in research and specific to teaching science. That is, the core ideas go beyond specifying programmatic commitments to pedagogy in general (Hammerness, 2006) to identifying critical aspects of coherent science teaching that have been shown to support student learning.

The position of the reflective dynamo at the center of the STEP-C model reinforces the importance of PSTs encountering the same ideas within each context. Learning is inseparable from the context in which it occurs (Lave & Wenger, 1992), and encountering and using the same core ideas across contexts is a key part of developing expertise (Bransford et al., 2000; NASEM, 2018). Similarly, beliefs are dependent upon the contexts in which they are formed (Pajares, 1992), and adjustment of beliefs may be particularly sensitive to positive experiences (Sharot & Garrett, 2016), e.g., receiving positive feedback from students, mentors, and/or professors. Thus, science teacher education programs should be organized around a small set of core ideas about teaching and learning science that can be used consistently across both school and university contexts. In the cycle of planning, teaching, and reflecting, core ideas should not only inform teaching and learning activities, but also be made explicit to PSTs across contexts. While this seems to be an obviously critical part of science teacher education, this is often not the case (Canrinus et al., 2017; Fazio & Volante, 2011; Zeichner, 2007, 2010). Many faculty located in university or school contexts are largely unaware of what takes place in the other context (Zeichner, 2007, 2010), and PSTs often do not perceive that learning experience in the school and university context are underpinned by the same set of core ideas about teaching and learning (Canrinus et al., 2017; Fazio & Volante, 2011).

Different sets of core ideas in varying contexts could also lead to the activation of different goals depending on the context (Hutner & Markman, 2017). Different goals presented in the university context and the school context further substantiate the "two-worlds pitfall" (Braaten, 2019) forcing PSTs to balance conflicting ideas in each context (Hutner et al., 2019) and making it difficult to experience consistent feedback across contexts that shape beliefs about teaching and learning. When preservice teachers do encounter the same set of explicated ideas about teaching across contexts, it seems that they are indeed more likely to demonstrate these core ideas in their own teaching practice after the conclusion of the teacher education program (Hammerness, 2006).

Bridging elements

Ensuring that PSTs encounter the same set of core ideas about coherent science teaching across university and school contexts is far easier said than done. The STEP-C model includes bridging elements, represented by double-headed arrows connecting the university and school contexts with the reflective dynamo, which serve as explicit tools and activities that are critical to providing PSTs and faculty with opportunities to activate core ideas consistently across contexts. The idea behind bridging elements is to make practitioner knowledge public and commonly shared and, consequently, to support PSTs' learning from their experiences.

Consistent planning and reflection tools

On the left side of the STEP-C model, bridging elements connect the university context to the reflective dynamo. Here, we emphasize the importance of a consistent set of planning and reflection tools for activating core ideas for coherent science teaching. These tools—such as the CoRe (Hume & Berry, 2011; Nilsson & Loughran, 2012), coherent storyline planning tools (e.g., Nordine et al., 2019; Reiser, 2014), and the EEE+A (Engage, Experience, Explain+Argue) framework (Davis & Marino, 2020)—are important scaffolds for PSTs as they begin to consider how to design their own coherent science instruction based on the theoretical ideas discussed in the university context. For example, CoRes are useful for systematically considering key content ideas, common alternative ideas, assessment strategies, and ways of framing ideas for students (Loughran et al., 2008). There is evidence that CoRes can be effective for increasing teachers' pPCK and ePCK (Carpendale & Hume, 2019), and when used in conjunction with video analysis, CoRes may be particularly helpful in engaging PSTs in a plan-teach-reflect cycle that facilitates bridges between cPCK, pPCK, and ePCK (Nilsson & Karlsson, 2019). Structured reflection has also been found to support PSTs in perceiving connections between science content learned at the university and the knowledge needed for teaching (Lorentzen et al., 2019).

Planning and reflection tools appear on the left side of the STEP-C model because they are particularly helpful for connecting the learning at the university (e.g, content knowledge) with the plan-teach-reflect cycle as it is manifest in the school setting. Further, these tools appear on the left side of the reflective dynamo because these planning and reflection tools are often first encountered during formal university coursework. To be bridging elements, it is critical that planning and reflection tools have practical utility in both the university and school setting. Thus, these tools should elicit and make explicit key aspects of both cPCK and pPCK and also be feasible for use in the context of full-time teaching.

To be successfully used within a science teacher education program, planning and reflection tools should be used to support engagement in teaching practices (e.g., planning, teaching, reflecting) across a range of university courses and field experiences. Thus, the tools need to be sufficiently flexible to be applicable in a wide variety of courses and teaching experiences and be useful for activating various knowledge bases of PCK, e.g., science content, student learning, and strategies for motivating student interest. Tools like CoRes and storyline planning tools fit this criterion, whereas tools that are more narrow in scope, such as concept maps (McClure et al., 1999)—which are primarily designed to make conceptual understanding visible—are less useful as bridging elements. Many tools for science teaching are useful for planning and implementing science instruction (e.g., concept maps), and should be introduced as part of a comprehensive teacher preparation program, but these tools should be implemented in a more targeted fashion while a very small number of more comprehensive planning and reflection tools (tuned to the core ideas for coherent science instruction) are seen consistently across programmatic elements and contexts, and always in service of engaging in authentic teaching practices (Stroupe et al., 2020).

Active partnerships

On the right side of the STEP-C model, bridging elements connect the school context to the reflective dynamo. Here, we emphasize the importance of active partnerships in supporting PSTs in planning, teaching, and reflecting using core ideas for coherent science teaching across both contexts. Key to the formation of active partnerships is the recognition that effective science teacher education relies on the contributions of various stakeholders, including university-based science faculty, university-based science teacher educators, school-based mentor teachers and administrators, and preservice teachers themselves.

Active partnerships between university and school stakeholders are critical for supporting programmatic coherence by maintaining a consistent vision across university-based and school-based learning experiences. Importantly, these partnerships should emphasize the bi-directional nature of learning between university and school partners and the expertise held by school partners (Zeichner, 2010). Thus, the aim of these partnerships is not to "train" school-based faculty in order to enact the science teacher education program as designed at the university, rather, to leverage the expertise of mentor teachers and partner school administrators in constructing programmatic coherence. These partnerships should be geared toward generating consensus around a shared vision of effective science teaching, which informs the identification of core ideas for coherent science teaching that PSTs will encounter across contexts. In addition to promoting programmatic coherence, active partnerships are critical for cultivating relationships that align and enhance the efforts of school-based mentor teachers and university faculty in their support for PSTs (Nordine et al., 2015; Thompson & Larkin, 2020).

There is of course extensive variation with respect to how school-university partnerships may be structured, from formalized professional development school relationships (Dresden, 2016) to local schools that simply accept preservice teachers from the university to complete practicum and/or student teaching experiences. Regardless of how partnerships are structured, we stress within the STEP-C model that in order for science teacher education to be coherent, school-university partnerships must actively involve university-based and school-based personnel in collaboration and co-learning in service of the science teacher education program. We recognize that some active partnerships are easier to maintain, especially when there exists a formalized professional development school relationship or faculty members who are designated as liaisons between the university and school, but the scope of active partnerships may vary while still serving the purpose of supporting coherence in science teacher education. For example, active partnerships may be structured around specific activities to support a community of practice among stakeholders involved in science teacher education, such as collaborating to discuss how new standards inform the development of coherent learning experiences for PSTs (Campbell et al., 2019) or working across faculties to develop assignments, lesson planning tools, and observation protocols for engaging in reflective video analysis (Stennett et al., 2020). No matter what their scope is, it is nevertheless important to recognize that maintaining such active partnerships requires a sustained commitment of resources (e.g., faculty time, meeting space) from both university and school partners and a shared recognition of the benefits of active partnerships for all partners.

Initial use of the STEP-C model

A central goal of the STEP-C model is to guide science teacher educators in ongoing reflection and dialogue about programmatic design. While the model has yet to be fully implemented, it has so far proven useful for PICoSTE partners and stakeholders in guiding systematic discussion about, and revision of, certain features of their own science teacher education programs. Here, we provide two examples of such use.

Example 1: Collaborating on program design across faculties

Science teacher education at the University of Helsinki is organized as a shared program, with faculty of science, faculty of education and schools sharing responsibility for organizing science teacher training. Coherent science teacher education has been approached in the context of the STEP-C model through increasing possibilities for active partnerships among teacher educators at the faculties and schools. In practice, one-day planning meetings in autumn and two-day reflection meetings in spring have been organized for teacher educators. In these collaborative meetings, core aims related to planning, teaching and reflecting, and ideas for PCK-related courses and teaching practice (e.g., conceptual and procedural knowledge) were agreed upon, and a plan for their use in various science teacher education activities was outlined. Such meetings have been helpful for identifying the core ideas of coherent science teaching and sharing them among teacher educators (Darling-Hammond et al., 2005; Klette & Hammerness, 2016), and these meetings have been valuable for planning teacher education activities according to the core ideas and aims at the partner faculties and schools (Canrinus et al., 2017; Grossman et al., 2008; Zeichner, 2010). Collaboratively with mentor teachers, university science teacher educators designed consistent planning and reflection tools to support the use of core ideas learned at the faculty during the teaching practice. For example, a "lesson planning" tool helps student teachers analyze the aims of a lesson, record teachers' and students' actions during the lesson, and guide reflective activities. Further, we designed a "mobile app" (Turkkila et al., 2021) to help PSTs to analyze and reflect together and recognize the core ideas of coherent science teaching. Consequently, collaboration and concrete tools have aimed to support the development of conceptual and structural coherence (Hammerness, 2006) in science teacher education in Helsinki.

Example 2: Guiding program revisions

The STEP-C model guided the process of program revisions at IPN - Leibniz Institute for Science and Mathematics Education. For example, the bridging elements identified in the STEP-C model spurred iterative revisions in a university course organized around a student teaching experience. In previous years, this course focused on research literature related to science practices (e.g., scientific modeling) and the development of opportunities to implement such practices in instruction. In a first step, IPN science teacher educators focused on including planning and reflection tools such as the CoRe and storyline planning tool to support PSTs in planning a coherent instructional unit prior to their student teaching experience and reflecting upon their student teaching experience after its conclusion. In a second step a year later, IPN science teacher educators focused on promoting active partnerships by involving mentor teachers (who are arranged by a separate coordinator) in key course activities prior to the beginning of the student teaching experience. For example, mentor teachers participated in an interactive course seminar designed to promote active exchanges between preservice teachers, university faculty, and mentor teachers. University faculty outlined the course learning goals, preservice teachers introduced their initial attempts in planning coherent instruction and received feedback from mentor teachers, and mentor teachers described their planning process. Such an exchange was designed to tap into the expertise shared by different partners involved in the student teaching experience (Zeichner, 2010). PSTs reported that explicitly involving mentor teachers in the course seminar promoted a feeling of coherence across the different contexts of science teacher education, especially as mentor teachers reinforced several ideas emphasized in the planning and reflection tools used in the course. This illustrative example shows how the elements identified in the STEP-C model can be used to develop specific learning opportunities in teacher education in order to increase the coherence between the different realms of teacher education.

Discussion

The STEP-C model was developed in the course of a two-year international project that focused on the role of science teacher education in promoting coherent science instruction in schools. As such, the purpose of the model is to represent key programmatic features of science teacher education that supports not just preservice teacher knowledge about coherent science instruction, but opportunities to use and reflect upon this knowledge in practice. We make no claims that the elements of the STEP-C model are easy to realize—in fact, no partners involved in its development feel that their current science teacher education program fully aligns with the model. The utility of the STEP-C model, therefore, is as a guide for science teacher educators to reflect upon their own science teacher education programs for the purpose of iterative design and ongoing conversation to support the process of coherence-seeking (Richmond et al., 2019).

Our purpose in developing the STEP-C model was to build upon existing literature that broadly defines coherence in teacher education in order to identify—and illustrate relationships between—key programmatic elements that promote the knowledge, beliefs, and goal-orientations that are critical for enacting coherent science teaching in schools.

Science teacher knowledge

The STEP-C model is well-aligned with recent work on science teacher PCK, such as the RCM (Hume et al., 2019). One key alignment between these two models is the corresponding positions of the "reflective dynamo" in the STEP-C model and "pedagogical reasoning" in the RCM. The centrality of pedagogical reasoning in the RCM signifies the central role that this component of PCK plays in influencing all aspects of planning, teaching, and reflecting (Carlson et al., 2019). The centrality of the reflective dynamo and the core ideas for coherent science teaching emphasizes that a small set of ideas that drive planning, teaching, and reflecting should be central to all programmatic activities. By encountering and using the same core ideas across contexts while engaging in planning, teaching, and reflecting, PSTs may be more likely to successfully integrate these ideas into their own pedagogical reasoning.

The RCM model also stresses that PCK has both individual and shared components (e.g., pPCK and cPCK), and that science teachers must be able to coherently connect shared knowledge bases to their own classroom and context. Well-developed PCK therefore relies on science teachers' ability to make connections across contexts and communities of stakeholders. A central purpose of the STEP-C model is to map programmatic components that have high potential to support preservice teachers in seeing connections across contexts and stakeholder communities. In order to support beginning teachers to develop pedagogical reasoning that is consistent and align ePCK, pPCK, and cPCK, the relevant community of science teacher education stakeholders must explicitly identify the core ideas for effective science teaching and ensure that these ideas are consistently represented across contexts and stakeholder communities.

Finally, the RCM model includes arrows that represent "knowledge exchanges", but as Park (2019, p. 124) notes, "the knowledge exchanges in the RCM do not clearly demonstrate mechanisms through which shared pPCK can be publicly examined, verified, refuted, or modified." The STEP-C model takes a step in the direction of identifying, in the form of bridging elements, how science teacher education programs may include programmatic elements that provide more explicit support for such knowledge exchanges between, for example, pPCK and cPCK as well as knowledge bases among different communities of science educators (e.g., school and university faculty) which may have distinctive cPCK.

Science teacher beliefs and goal-orientations

Teacher beliefs and goal-orientations play a critical role in determining how teacher knowledge is (or is not) utilized within enacted instruction (e.g., Hutner & Markman, 2017). Preservice teachers are more likely to develop a set of consistent beliefs and goals about the enactment of coherent science instruction if they encounter consistent messages from faculty and mentors across stakeholder groups and contexts, and science teacher educators must consider how science teacher education programs can promote a consistent set of beliefs and goals across contexts (Hutner et al., 2019). Luft (2009) showed that new teacher induction programs that included collaboration between university and school district personnel and the use of science-specific supports for instruction positively influenced new teachers' beliefs about science teaching and the likelihood of enacting more coherent instruction; this finding reinforces the role of the bridging elements in the STEP-C model. Science-specific planning and reflection tools (e.g., CoRe, storyline planning tool) play a key role in providing concrete supports for planning and reflecting upon coherent science instruction, while the active partnerships between university-based and school-based stakeholders support opportunities for enacting coherent science instruction while receiving consistent feedback from faculty and mentors. These bridging elements effectively support preservice teachers in productively engaging in the plan-teach-reflect cycle when they are designed according to a consistent set of core ideas about coherent science instruction. Seeing the same set of core ideas about science instruction reflected across contexts, learning experiences, and stakeholder groups is critical for supporting preservice science teachers in developing a set of beliefs and goal-orientations that align with enacting coherent science instruction.

Utility of the STEP-C model

Preservice science teacher education represents a powerful opportunity to improve teachers' ability to guide student learning through meaningful and coherent instruction, though the extent to which science teacher education programs have accomplished this is questionable (NASEM, 2019). The central aim of the STEP-C model is to represent key programmatic components that support coherence in science teacher education, which we argue is critical for preparing science teachers who possess the mutually-reinforcing knowledge bases, beliefs, and goal-orientations that are critical for effective science teaching. The two implementation examples discussed earlier highlight the possible utility of the STEP-C model as a framework that continuously guides the refinement of learning opportunities in science teacher education programs. It is our hope that science teacher educators find utility in the STEP-C model for framing the perpetual work of designing and maintaining coherence in science teacher education.

In arguing for the importance of coherence, we wish to distinguish between coherence and uniformity; embracing diverse perspectives are as essential to effective science teacher education as they are to effective science instruction. The STEP-C model was developed in the context of an international project in which partner countries varied substantially in their approaches to science teacher preparation and credentialing; this variation forced us to focus on elements that were meaningful and potentially effective across contexts. Even within individual science teacher education programs, diversity of ideas, contexts, and coursework provide students with a more robust set of experiences that lead to durable outcomes. By specifying the boundaries of what must cohere, science teacher educators in the same program have great freedom to be creative and to include a range of learning opportunities without threatening basic programmatic coherence, and preservice teachers' perceptions thereof. Thus, the STEP-C model focuses not only on programmatic elements that are promising, but those that are also likely to be directly perceived by PSTs. Using the same high-quality planning and reflection tools across a range of learning experiences, encountering the same core ideas for coherent science teaching, and experiencing complementary (rather than conflicting) messages from various stakeholder groups may promote programmatic coherence and potentially lead to the knowledge, beliefs, and goal-orientations that are necessary to enact coherent science teaching in schools.

Limitations and next steps

The STEP-C model was developed in a collaboration focused on partner institutions—largely in the Baltic region—learning from each other and synthesizing their key findings; as such, it has yet to be fully implemented or empirically tested, and its relevance beyond partner institutions has not been established. While project partners have successfully used the model to inform program design, reflection, and revision, we are unable to make claims about its utility in other contexts or effectiveness relative to other design paradigms. Project partners have recently initiated a new collaboration to identify core ideas for coherent science instruction that span local contexts, design and test a suite of planning and reflection tools based upon these core ideas, and to investigate the use of these tools across courses and contexts as well as PSTs' perceptions of programmatic coherence. Though robust empirical support for the STEP-C model has yet to be established, it has already proven useful for partners involved in its development, and our hope is that the STEP-C model may prove useful to other science teacher education practitioners and researchers to guide reflections, design discussions, and empirical research.

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