

REVIEW

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Building bridges: a review and synthesis of research on teaching knowledge for undergraduate instruction in science, engineering, and mathematics

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Abstract

Here, we systematically review research on teaching knowledge in the context of undergraduate STEM education, with particular attention to what this research reveals about knowledge that is important for evidence-based teaching. Evidence-based teaching can improve student outcomes in undergraduate STEM education. However, the enactment of promising evidence-based teaching strategies depends greatly on the instructor and potentially on the teaching knowledge they are able to deploy. The review includes an overview of prevalent teaching knowledge theory, including pedagogical content knowledge, mathematical knowledge for teaching, and pedagogical knowledge. We compare and contrast teaching knowledge theory and terminology across STEM disciplines in order to build bridges for researchers across disciplines. Our search for peer-reviewed investigations of teaching knowledge in undergraduate science, engineering and mathematics yielded 45 papers. We examined the theoretical frameworks used in each study and analyzed study approaches, comparing across disciplines. Importantly, we also synthesized findings from research conducted in the context of evidence-based teaching. Overall, teaching knowledge research is sparse and siloed by discipline, and we call for collaborative work and better bridge-building across STEM disciplines. Though disciplinary divergences are common in discipline-based education research, the effect is magnified in this research area because the theoretical frameworks are themselves siloed by discipline. Investigations of declarative knowledge were common, and we call for increased attention to knowledge used in the practice of teaching. Finally, there are not many studies examining teaching knowledge in the context of evidence-based teaching, but the existing work suggests that components of pedagogical content knowledge, pedagogical knowledge, and content knowledge influence the implementation of evidence-based teaching. We describe implications for future teaching knowledge research. We also call on those who develop and test evidence-based strategies and curriculum to consider, from the beginning, the teaching knowledge needed for effective implementation.

Keywords: Pedagogical content knowledge, Mathematical knowledge for teaching, Pedagogical knowledge, Teaching knowledge, Evidence-based teaching, Undergraduate STEM education

Introduction

Evidence-based teaching can improve outcomes for all students in undergraduate STEM (science, technology, engineering, and mathematics) and can disproportionately benefit students from historically underrepresented groups (e.g., Freeman et al., 2014; Laursen et al., 2014; Theobald et al., 2020). As a result of this potential, there

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have been repeated, high-profile calls for substantial reform in teaching practices in undergraduate STEM (e.g., Holdren & Lander, 2012; Rosenberg et al., 2018). While evidence-based strategies *can* be highly effective at improving student outcomes, the results instructors achieve vary substantially (Andrews et al., 2011; Johnson et al., 2020; Laursen et al., 2014). Furthermore, education research contains many examples of how carefully crafted teaching materials and strategies can fall short of their potential to improve student learning when implemented (e.g., Cohen & Ball, 1990; Dancy et al., 2016; Ganter, 2001). We define evidence-based teaching as the use of teaching strategies that are supported by high-quality evidence that they can positively impact students. A broad definition is appropriate for this work because different STEM disciplines prioritize different evidence-based strategies.

Achieving widespread adoption and effective use of these teaching strategies demands attention to the role of teaching knowledge (i.e., pedagogical content knowledge, mathematical knowledge for teaching, pedagogical knowledge) in evidence-based instruction. Extensive evidence from K12 levels demonstrates that teaching knowledge informs instructional practices (e.g., Keller et al., 2017; Park et al., 2010), and is associated with positive student outcomes in STEM (e.g., Hill et al., 2005; Kanter & Konstantopoulos, 2010; Sadler et al., 2013). Additionally, research and theory focused on teaching knowledge and practices among K12 teachers has been central to shaping professional learning opportunities for teachers (see, e.g., Fennema et al., 1993; Hill et al., 2005), suggesting that careful consideration of key components of knowledge can usefully inform teaching professional development. Yet, despite what we know about the role of teaching knowledge in effective teaching practice, numerous studies have found that instructors commonly adapt evidence-based teaching strategies in ways that compromise their effectiveness (Chase et al., 2013; Daubennire et al., 2015; Turpen & Finkelstein, 2009), and scholars have repeatedly suggested that lack of knowledge contributes to these unsuccessful adaptations (Dancy et al., 2016). For example, Stains and Vickrey (2017) reviewed literature about peer instruction and hypothesized that instructors need knowledge of students' prior knowledge to develop effective questions. Similarly, Offerdahl et al., (2018) proposed that instructors need specific teaching knowledge to design effective formative assessment and to diagnose student learning of a particular topic.

Yet an assumption inherent in systems of higher education is that disciplinary expertise prepares faculty to be effective undergraduate educators. This disconnect between how we approach teaching in higher education

and what has been learned about the importance of specialized teaching knowledge among K12 teachers suggests there is much to be pursued, especially in the context of calls for reform in undergraduate STEM education. Our primary research question is: What is known about teaching knowledge used in the context of undergraduate STEM instruction? Analysis of the body of research into teaching knowledge conducted in undergraduate STEM contexts can aid researchers and practitioners. Taking stock of what is currently known can provide valuable insights into findings and theory. In addition, doing so across multiple STEM disciplines can enable us to leverage the limited number of such studies in any single discipline to help undergraduate STEM instructors to achieve the promise of evidence-based instruction for their students.

In this paper, we systematically reviewed existing research on teaching knowledge in the context of undergraduate STEM, with particular attention to what this research reveals about knowledge that is important to evidence-based teaching. We compare work across STEM disciplines because identifying similarities across disciplines can strengthen our confidence in theory and findings and noting differences can advance efforts by bringing to light areas that have been under-examined in particular disciplines. For the purposes of this review, we use teaching knowledge as an umbrella term to refer to pedagogical content knowledge, mathematical knowledge for teaching, and pedagogical knowledge, which are described in detail in the following section. In the remainder of the introduction, we describe theoretical frameworks of teaching knowledge, articulate the need for studies of teaching knowledge in undergraduate STEM contexts, and end by presenting our research goal.

Theoretical frameworks of teaching knowledge

Teaching knowledge theory development has largely occurred in K12 educational contexts, and much of this work is siloed by discipline. Broadly, teaching knowledge theories address either topic-specific knowledge or more generalizable knowledge. In this section, we introduce teaching knowledge theories, with particular attention to similarities and differences across STEM disciplines in theory and terminology. Table 1 provides an overview of various teaching knowledge components, their theoretical origin, and terminology that varies across and within disciplines. Though it has been useful for researchers to define separate knowledge components, we expect instructors to draw on multiple knowledge components at once in planning, enacting, and reflecting on teaching.

Table 1 Descriptions of teaching knowledge components, the theoretical frameworks that describe them, and other terms sometimes used¹

Knowledge component (theory)	Brief description	Other terms for the same component
Knowledge of student understanding (MKT & PCK ²)	Topic-specific knowledge that encompasses awareness of students' prior knowledge; common difficulties, naive ideas, and misconceptions; variation in student thinking; and how students' thinking can be expected to change	Knowledge of content and students (Ball et al., 2008); knowledge of students' understanding of science (e.g., Park & Oliver, 2008), knowledge of learners (Sickel & Friedrichsen 2018), knowledge of student thinking (Ziadie & Andrews 2018), knowledge of students (Chan & Yung, 2015), and knowledge of student ideas (Robertson et al., 2017)
Knowledge of instructional strategies and representations (MKT & PCK)	Topic-specific knowledge about useful examples, case studies, analogies, visual representations, activities, and other approaches to facilitate student learning	Knowledge of content and teaching (Ball et al., 2008)
Knowledge of curriculum (MKT & PCK)	Topic-specific knowledge that encompasses awareness of standards for teaching a topic, curricular programs and resources, and appropriate topic sequencing within a course and across courses in the curriculum	Knowledge of content and curriculum (Ball et al., 2008)
Knowledge of assessment (PCK)	Topic-specific knowledge that encompasses awareness of the dimensions of learning to assess and methods that can be used to assess that learning	–
Common content knowledge (MKT)	Knowledge of the discipline that is not specific to teaching and that is used by diverse disciplinary experts, including teachers	Subject matter knowledge (e.g., Chan & Yung, 2018), content knowledge (Hale et al., 2016)
Specialized content knowledge (MKT)	Knowledge of the discipline that is specific to the work of teaching but is not knowledge of students or teaching	–
Horizon content knowledge (MKT)	Knowledge of the discipline regarding how disciplinary ideas appear in different areas of the discipline or grade levels	–
Pedagogical knowledge	Knowledge about teaching and learning that is not topic-specific, including knowledge of how people learn, instructional approaches, and other knowledge about learners and learning	–

¹ These differences in terminology may sometimes represent subtle differences in meaning, but we understand these researchers to be referring to some or all of the definition provided above

² MKT = mathematical knowledge for teaching; PCK = pedagogical content knowledge

Pedagogical content knowledge (PCK) and mathematical knowledge for teaching (MKT)

Pedagogical content knowledge (PCK) and mathematical knowledge for teaching (MKT) are two separate theoretical frameworks that conceptualize topic-specific teaching knowledge. PCK was first conceptualized in science education by Lee Shulman (Shulman, 1986). Researchers further defined this type of teaching knowledge (Magnusson et al., 1999; Park & Oliver, 2008), and their models were widely used. Eventually the breadth of PCK work made it challenging to compare across studies and to offer useful findings for teacher educators (Settlage, 2013). In response, a group of K12 scholars developed the PCK consensus model (Berry et al., 2015). The model reaffirmed critical aspects of the original model, including its relationship to other components of teacher's professional knowledge base (Gess-Newsome, 2015). The consensus model builds on prior models by separating orientations and beliefs from knowledge, distinguishing and emphasizing the role of PCK that is embedded within and cannot be separated from the acts of teaching and explained the linkages between PCK and student outcomes (Gess-Newsome, 2015). These K12 scholars continued their work, eventually producing the Refined Consensus Model of PCK, which further distinguished realms of PCK to emphasize the differences between knowledge held by the field, knowledge held by an individual, and knowledge deployed in the act of teaching (Carlson et al., 2019).

Concurrently, in mathematics education, Deborah Ball and colleagues developed MKT, which included but extended beyond PCK (Ball et al., 2008). MKT divides topic-specific teaching knowledge into two main components: PCK and content knowledge. The PCK framework used in science education overlaps in some, but not all ways, with the PCK half of the MKT framework (Table 1). We first describe the similarities between the conceptualization of PCK within mathematics and science education, and then describe differences.

Across disciplines, scholars define PCK as knowledge of teaching and learning that is specific to a topic (e.g., natural selection, bonding, slope, energy, etc.) and to a grade level. This knowledge goes beyond content knowledge developed through disciplinary coursework or scholarship. This knowledge is specific to the work of teaching. Importantly, content knowledge is necessary, but insufficient to support the development of PCK (Depaepe et al., 2013; Wilson et al., 2002). Scholars have focused extensively on identifying and describing components of PCK (Chan & Hume, 2019), and two components are most often studied: knowledge of student understanding and knowledge of instructional strategies and representations (Chan & Hume, 2019; Depaepe et al.,

2013). See Table 1 for other names sometimes used to refer to these PCK components.

Knowledge of student understanding includes awareness of students' prior knowledge of a topic, knowledge that is prerequisite to understanding a topic, common difficulties students encounter as they learn a topic and the source of these difficulties, and variation in student thinking about a topic (Table 1; Ball et al., 2008; Magnusson et al., 1999; Park & Oliver, 2008). Instructors need knowledge of student understanding for each topic they teach. For example, as biology instructors plan lessons for natural selection, they benefit from knowledge that undergraduates commonly think that individuals evolve. As another example, in chemistry, students may draw the sulfate dianion incorrectly because they do not understand the limitations of Lewis dot structures as 2-dimensional models. Chemistry instructors who recognize why students struggle, and how to help them navigate limitations of the model, possess PCK for teaching the Lewis dot structure model.

PCK also includes knowledge of instructional strategies and representations (Table 1). This encompasses knowledge used in identifying and designing examples, case studies, analogies, visual representations, activities, and other approaches to facilitate student learning of a topic (e.g., Ball et al., 2008; Magnusson et al., 1999; Park & Oliver, 2008). It may also include sequencing of particular examples or cases. For instance, when introducing a rule for differentiation in a calculus class, an instructor draws on her knowledge of instructional strategies and representations to select which examples to use first. This component of PCK includes knowledge of which features of examples should be avoided because they may not highlight the key ideas. For example, when introducing the product rule (i.e., that if $f(x) = g(x) * h(x)$, then $f'(x) = g(x) * h'(x) + h(x) * g'(x)$) if one uses $f(x) = e^x * \sin(x)$ as a first example, the nature of the rule is obscured because the derivative of e^x is itself e^x . An example from biology is knowing that students need to complete problems using double-stranded DNA as they learn about DNA replication and the central dogma because otherwise they will not develop accurate ideas about the directionality of DNA.

Though it has been studied less frequently, both mathematics and science education scholars include knowledge of curriculum within PCK frameworks (e.g., Ball et al., 2008; Magnusson et al., 1999; Park & Oliver, 2008). Knowledge of curriculum includes awareness of standards related to a topic, curricular programs and resources for teaching a topic, and appropriate sequencing of topics within a course and across courses in the curriculum, among other things. Teachers rely on this knowledge to differentiate between big ideas and less important or

more peripheral ideas related to a topic (e.g., Magnusson et al., 1999; Park & Chen, 2012). The PCK framework from science education has one component not typically ascribed to MKT: knowledge of assessment. Knowledge of assessment includes knowledge of the dimensions of learning to assess related to a topic and methods that can be used to assess that learning (e.g., Magnusson et al., 1999).

The other half of mathematical knowledge for teaching (MKT)

In the MKT framework, PCK represents one of two main components of teaching knowledge. The other component is content knowledge, which is knowledge of mathematics that is used to do the work of teaching but does not rely on knowledge of students or teaching (Ball et al., 2008). Thus “the other half of MKT” goes beyond the PCK framework used in science education. The MKT framework includes three distinct teaching knowledge components: common content knowledge, specialized content knowledge, and horizon content knowledge (Table 1).

Common content knowledge is not specific to teaching and is used by both other experts in the discipline and teachers. This knowledge is developed via courses at K12 and higher levels, and by engaging as a professional in a discipline. This is the knowledge we have traditionally assumed that teachers need to be effective.

Specialized content knowledge is disciplinary knowledge that is specific to the work of teaching, but does not require knowledge of students or teaching (Ball et al., 2008). This knowledge is used to reason through disciplinary problems, but in the specific context of teaching. Examples of mathematical work a teacher does include determining whether a particular student-generated procedure is mathematically valid or figuring out whether a procedure that works in one context (e.g., whole numbers) is also mathematically valid in another context (e.g., rational numbers). Another example of deploying specialized content knowledge would be a biology instructor reasoning through a non-typical experimental design proposed by a student to determine its strengths and weaknesses. The instructor is relying on disciplinary expertise, but in a context unlikely to be encountered outside of teaching or mentoring.

Horizon content knowledge is disciplinary knowledge of particular mathematical ideas that appear in different mathematical areas or grade levels. Horizon content knowledge comes into play in a variety of teaching situations including when an instructor is discussing a topic that students will encounter again, in a more sophisticated way, at a later grade level. An initial presentation of a topic needs to be at an appropriate level for those

students, but also needs to be done in ways that are an accurate portrayal of the more sophisticated ideas. This work of teaching, which is enabled by horizon content knowledge, is referred to as “trimming” (McCrory et al., 2012). An example of trimming that indicates a lack of horizon content knowledge is when an elementary school teacher explains to students that “multiplication makes things bigger.” Students will eventually encounter multiplication involving values less than one, which does not make things bigger. Therefore, using this “simplified” rule may make it harder for students to learn content in later years. This knowledge is tied to content knowledge of the discipline and is distinct from the knowledge of curriculum that includes the grade level or curricular sequencing of the ideas.

Generalizable teaching knowledge: pedagogical knowledge

There are also components of teaching knowledge that are applicable across topics rather than specific to particular content. These knowledge bases have received less empirical and theoretical attention than topic-specific knowledge and are not as clearly defined. Notably, theory surrounding topic-specific knowledge has blossomed over the last 40 years, which was an important shift toward recognizing that teaching requires knowledge within the discipline that goes well beyond content knowledge. One result of this shift, however, is that more generalizable knowledge has remained undertheorized.

We have a few reasons to believe that pedagogical knowledge deserves particular attention within the context of undergraduate STEM education, even though it is not currently a focus in many studies of K12 teaching knowledge. First, unlike K12 teachers, many undergraduate instructors have little or no professional preparation for teaching and thus may lack general, formalized knowledge that is common in professional learning for K12 teachers. Second, undergraduate STEM instructors often teach in challenging pedagogical contexts, such as “industrial-sized” classrooms, which necessitate scaling teaching approaches considerably. Third, undergraduate STEM instructors are being called upon to change their pedagogical approaches (e.g., Freeman et al., 2014), and it is reasonable to think this requires particular expertise to enact effectively (e.g., Andrews et al., 2011).

Though theory about pedagogical knowledge is less developed, scholars agree that pedagogical knowledge includes expertise about how people learn, instructional approaches, classroom management, and other knowledge about learners (e.g., Auerbach & Andrews, 2018; Grossman & Richert, 1988; König et al., 2014; Morine-Dersheimer & Kent, 1999). The most recent framework, and the only one focused on undergraduate instructors,

outlined seven distinct components of pedagogical knowledge (Auerbach & Andrews, 2018). This framework focused particularly on knowledge relevant to active-learning instruction in large undergraduate biology courses. At the core of the framework is knowledge of creating opportunities for legitimate generative work. This includes awareness that students learn from cognitively engaging in challenging work during class, that students must construct (not just receive) knowledge, and that engagement in legitimate scientific practices is important for learning in the sciences (Auerbach & Andrews, 2018). Additionally, this pedagogical knowledge framework includes knowledge about monitoring and responding to student thinking, increasing equity, motivating students, prompting metacognition, building links between tasks, and managing active-learning logistics.

The need for research on undergraduate STEM teaching knowledge

Though research investigating teaching knowledge among K12 teachers provides a strong theoretical and empirical foundation for research on teaching knowledge in undergraduate STEM education, we see a need for investigations set in the context of undergraduate-level teaching and learning. The teaching knowledge that is important to effective instruction may be different for undergraduate instructors due to the undergraduate-specific classroom environments where they teach, the norms and practices for teaching at the undergraduate level, and the different depth and level of content that they teach. For example, many undergraduate faculty teach courses that enroll hundreds of students in a single lecture course that is held in a large auditorium which stands in contrast to the context for most K12 instruction.

The ways in which undergraduate instructors develop as teaching professionals is also distinct. Professional development for undergraduate teaching, when it is provided, is often brief and non discipline-specific. For example, mandatory teaching professional development for graduate teaching assistants in the life sciences is often fewer than 10 h and focused on policies and classroom management (Schussler et al., 2015). Additionally, faculty often do not receive sufficient mentoring or feedback on their teaching (e.g., Brickman et al., 2016). On the other hand, college instructors have many additional years of training in their discipline compared to K12 teachers and thus likely have more expansive and well-organized content knowledge. Overall, undergraduate faculty likely have fewer opportunities to develop deep and well-organized teaching knowledge and more opportunities to develop content knowledge that they can use

in their teaching (Anderson et al., 2011; Deshler et al., 2015; Luft et al., 2004; Seymour, 2005).

Finally, the content that undergraduate instructors teach may differ in depth, level, and scope. Developmental STEM courses may be most similar to secondary content. On the other hand, senior-level courses may be highly focused on a particular area of the discipline and on authentic engagement in the practices of the discipline (e.g., reading and critiquing peer-reviewed papers). Furthermore, whereas K12 teachers often rely on research-based curricula that can promote the development of teaching knowledge, undergraduate instructors often develop the majority of their teaching plans and materials.

These differences between the K12 and undergraduate teaching contexts pose challenges but also create opportunities as we work to advance research on teaching knowledge for undergraduate STEM. Caution is called for when adopting theories and findings derived from research on K12 teachers since they may not generalize to undergraduate teaching due to the differences discussed above. However, as research in this area accumulates, we may learn that much of existing theory does have descriptive and explanatory power for undergraduate teaching. The payoff of research on those who teach undergraduate STEM may ultimately be an overall richer understanding of theories of teaching knowledge as current theories are augmented to be descriptive of teaching knowledge across a wider range of grade levels.

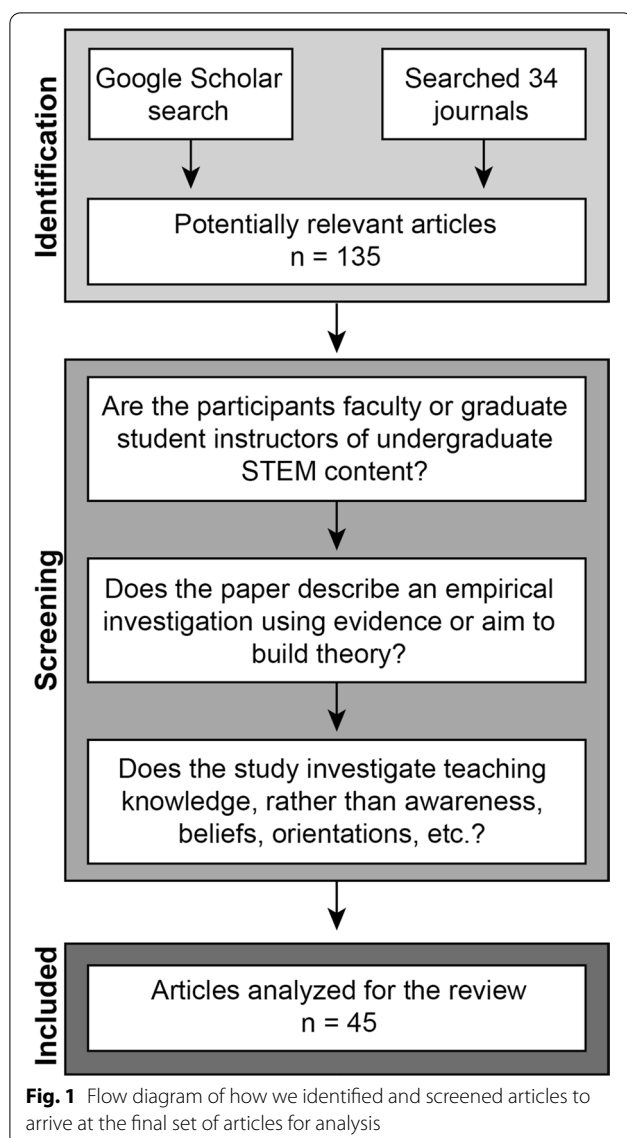
Research goals

The goal of this work was to systematically review existing research on teaching knowledge among undergraduate STEM instructors, with particular attention to what has been learned about important knowledge for evidence-based teaching.

Methods

Identifying candidate works for review

Our goal was to identify peer-reviewed works about teaching knowledge relevant to undergraduate STEM instruction (Fig. 1). We included both journal articles and published conference proceedings in our search, but excluded books, dissertations, reports, and other grey and white literature. Grey and white literature includes information produced outside traditional academic publishing venues, such as reports, working papers, white papers, policy documents. We searched initially in 2018 and repeated these searches in 2021. Therefore, this review focuses on work published prior to June 2021. We did not set an early date limit, but almost all papers returned in our searching were published in 2000 or later.



We used Google Scholar to identify potentially relevant articles. We conducted multiple searches using a combination of search terms to indicate educational level (college, undergraduate, university), STEM discipline (biology, mathematics, chemistry, physics, engineering), and a teaching knowledge term (pedagogical content knowledge, mathematical knowledge for teaching, pedagogical knowledge, teaching knowledge, knowledge for teaching). We relied on these search terms to be both specific and comprehensive. We read titles, abstracts, and skimmed papers as necessary to determine if they focused on the undergraduate level, studied STEM instructors, and were related to teaching knowledge. In reviewing the Google Scholar result list (organized by relevance to our search terms), we

stopped reading titles and abstracts when items on the list no longer met our minimum search criteria.

We also examined journals to collect potentially relevant articles that might have been missed in Google Scholar searches. This approach added 19 articles that were potentially relevant beyond what had been recovered using Google Scholar searches. We focused on journals that publish discipline-based education research (DBER) in the undergraduate context in a single STEM discipline or multiple disciplines. We scoured a total of 34 journals and conference proceedings (see Additional file 1). We used search terms for educational level and for teaching knowledge within journal search engines. We omitted STEM discipline search terms when searching within a discipline-specific journal (e.g., *Journal of Chemical Education*, *Journal of Geosciences Education*). Journals that were not specific to STEM (e.g., *Higher Education*) returned so few papers that we could screen them for a STEM focus by hand.

The result from this phase of our work was a set of 135 articles and conference proceedings that were potentially relevant to our review (Fig. 1). As we began a closer inspection of these candidate works, it became apparent that many items in our candidate set were not research on teaching knowledge in undergraduate STEM contexts. This prompted a second phase where we screened the works and further refined our inclusion and exclusion criteria.

Screening for inclusion

Our aim was to include all articles that directly investigated or theorized about teaching knowledge that is used by instructors of undergraduate STEM courses (Fig. 1), and we made inclusion decisions collaboratively. Our initial search generated a set that included works outside these bounds and our further reviewing of the works helped us clarify our criteria. There were several ways that works in the candidate set failed to match our criteria. One was based on who the instructor participants were and what they were teaching. For example, we included works focused on faculty and graduate student instructors of undergraduate STEM content, and excluded work focused on instructors of pre-service teachers and work focused on undergraduate learning assistants. We included one paper that involved STEM instructors and instructors from other disciplines (e.g., Fernández-Balboa & Stiehl, 1995), because many of the participants were STEM instructors.

We also defined the bounds of the review by the type of scholarship. We included investigations that utilized empirical evidence about teaching knowledge and papers aiming to build theory. We excluded opinion pieces and essays. We then further refined what constituted

empirical work on teaching knowledge, resulting in the exclusion/inclusion criteria discussed below.

We aimed to review work focused on the teaching knowledge that instructors employ in the work of teaching. Therefore, we excluded articles that investigated an array of adjacent cognitive constructs. We excluded studies of whether instructors were familiar with specific instructional approaches or pedagogical terminology because we did not consider this to be knowledge that instructors could use to do the work of teaching (e.g., Hanauer & Bauerle, 2015; Henderson & Dancy, 2009). We also excluded papers that investigated content knowledge among instructors if the goal was not to understand how that content knowledge was used for teaching. We also excluded papers describing studies of teaching beliefs or orientations. Contemporary teaching knowledge theory positions beliefs as distinct from knowledge, acting as a filter or amplifier of how instructors apply knowledge to practice and what knowledge instructors construct from reflection on their practice (e.g., Gess-Newsome, 2015). Previous models included teaching orientations as a component of PCK (e.g., Magnusson et al., 1999; Park & Oliver, 2008), and some papers in our candidate list focused primarily on teaching orientations (Mack & Towns, 2016). We retained papers that studied orientations alongside knowledge components of PCK (e.g., Padilla & Van Driel, 2011).

We determined that a few papers in our candidate set were studies of teaching knowledge in undergraduate STEM, even though the authors did not frame their investigation as focused on knowledge (e.g., Baldwin & Orgill, 2019). We included these papers because the foci of their work aligned closely with contemporary conceptualizations of teaching knowledge. We may have missed other papers that did not frame their work as studying knowledge because they would not have been returned on our searches. We recognized this paper in journal scouring because the title strongly suggested alignment with contemporary conceptualizations of PCK.

Analysis of articles

We analyzed each paper with the ultimate goal of characterizing the full collection of papers. The screening process reduced the number of papers and conference proceedings to 45. We analyzed each to determine (1) whether the work investigated declarative knowledge and/or knowledge-in-use; (2) the participant population and whether and how researchers considered participants' teaching experience; (3) the knowledge components investigated, which follows from teaching knowledge theory, and (4) whether researchers studied teaching knowledge in the context of evidence-based teaching. We then further analyzed the subset of papers

that examined teaching knowledge in the context of evidence-based teaching to synthesize key findings. We relied on abstracts, full papers, and our own written summaries of papers for these analyses. We analyzed papers independently and collaboratively, with at least two authors contributing to all analyses.

We characterized the approaches used in each paper, dividing them into whether they studied declarative knowledge or knowledge-in-use. Declarative knowledge is something a teacher can possess and can be developed within or beyond the classroom (e.g., Alonzo & Kim, 2016). Knowledge-in-use is embedded within and cannot be separated from the acts of teaching (e.g., Gess-Newsome, 2015). These two approaches have been used in teaching knowledge research in K12 contexts (e.g., Chan & Hume, 2019). The most recent model of PCK in science education, the Refined Consensus Model of PCK, places knowledge-in-use as most closely linked to teaching and therefore most able to influence student outcomes (Carlson & Daehler, 2019). The Reformed Consensus Model refers to this as enacted PCK (Carlson & Daehler, 2019). We use the term knowledge-in-use because it captures the meaning but is not specific to PCK.

We considered research to be focused on declarative teaching knowledge if the approach to eliciting teaching knowledge was not directly tied to the participant's personal teaching practice. These studies generally collected data using surveys or interviews. We considered research to be focused on knowledge-in-use if the approach to eliciting teaching knowledge relied on an instructor's personal teaching practice. Like Chan and Hume (2019), we defined "teaching practice" as the full teaching cycle of planning to teach, enactment in the classroom, and reflection on teaching experience. These studies gathered data about teaching knowledge by observing instructors in the acts of teaching, including developing lessons and implementing them in the classroom. Most commonly researchers both observed instruction and then elicited instructor's thinking about their teaching through interviews, surveys, or written reflections. This aspect of our analysis applied only to papers that collected and analyzed data, excluding those focused solely on extending theory.

We also characterized the participant population for each study and how researchers considered the participant's experience. Research studying K12 instructors indicates that teaching experience can foster the development of teaching knowledge (e.g., Chan & Yung, 2018), so the experience level of participants may influence what can be learned in a research study. Therefore, we determined the experience level of the participants in each study that collected data about teaching knowledge. We first determined if a study investigated teaching

knowledge among graduate teaching assistants or undergraduate faculty. We further examined how the researchers defined the experience level of faculty. Experience was characterized in different ways across papers, including years of undergraduate teaching experience, years using a particular curriculum or teaching approach, and evidence of effectiveness. We divided these according to whether and how experience was defined and captured.

Given the robust teaching knowledge theory from K12 education that characterizes different components of teaching knowledge, we analyzed each paper included in the review to determine the teaching knowledge component(s) studied. Most papers explicitly state this information and ground the work in specific teaching knowledge theory. In a few cases, we made our own judgments about the knowledge components studied using the contemporary conceptualizations of these components, as described in the introduction of the paper.

A key goal of this review was to determine what existing research reveals about teaching knowledge for evidence-based teaching in undergraduate STEM. Therefore, we determined which papers examined teaching knowledge in that context and synthesized their findings. We considered a paper to examine teaching knowledge in the context of evidence-based teaching if the goals of the study and the approaches to data collection focused explicitly on evidence-based teaching and related teaching knowledge. We then wrote summaries of the findings of each paper. Using these summaries, we organized the findings across papers according to the teaching knowledge component addressed in the finding, synthesized these findings, and wrote summaries. Lastly, we looked across all of the findings of this work for emergent, big picture themes. We each individually reviewed the summaries and recorded notes (i.e., qualitative memos) about patterns that we observed. We discussed each memo and considered them in light of recent reviews on teacher knowledge, specifically Chan and Hume (2019) and Depaepe et al. (2013), and our research questions. Finally, we collapsed these into the themes that are presented here.

Limitations

This systematic review has limitations that are important to keep in mind. First, we reviewed peer-reviewed articles and conference proceedings, excluding dissertations, books, and reports. Thus, our review may not fully represent the existing scholarship. Importantly, our approach privileges researchers who have access and support to shepherd their work to journals and conferences, and thus may disproportionately underrepresent scholars who have been denied equal professional access.

Second, as with any review, we cannot ensure that we found every article and proceeding that met our inclusion criteria. In particular, we may have missed work that was not framed using existing theoretical frameworks of teaching knowledge. We sought to identify relevant work that used different theoretical framing, and found some work like this (e.g., Baldwin & Orgill, 2019), but we may have missed other relevant work that did not use any of the search terms.

Lastly, we chose to focus our review on specific aspects of the collected work, which necessarily narrows what can be learned from this systematic review. We reviewed aspects of methodology that we expect to be important to making useful discoveries; the components of knowledge investigated, as defined in existing theoretical frameworks; and findings related to teaching knowledge for evidence-based teaching. There may be other important aspects of methodology, theory, and findings that we have not reviewed. We encourage scholars to capitalize on the collection of papers to investigate other questions relevant to their teaching knowledge research programs (see full list in Additional file 2).

Results

We describe five main findings from our systematic review of research on teaching knowledge in undergraduate STEM, in order of increasing complexity. Our findings include a broad quantification of this body of literature, characterizations of the research methods and teaching knowledge components studied, and a synthetic summary of research findings from studies examining teaching knowledge in the context of evidence-based teaching. Discoveries in the context of evidence-based teaching are particularly relevant given the interest and energy surrounding evidence-based teaching in undergraduate STEM education.

Finding 1: teaching knowledge research is scarce

Across STEM disciplines, we identified 29 peer-reviewed papers and 16 conference proceedings that met our inclusion criteria (Table 2). The greatest number of peer-reviewed papers has been published in Chemistry, and Mathematics has the most work inclusive of conference proceedings (Table 2). This review confirms that there is considerably less teaching knowledge research in undergraduate contexts than K12 contexts. In comparison, studies of teaching knowledge in K12 science and mathematics number at least 289 based on reviews published in the last five years (e.g., Chan & Hume, 2019; Hoover et al., 2016).

Table 2 Count of included peer-reviewed papers and peer-reviewed conference proceedings, by discipline

Discipline	Count of papers	Count of conference proceedings
Mathematics	5	13
Chemistry	12	0
Physics	5	3
Biology	5	0
Engineering	1	0
Multiple disciplines	1	0
Total	29	16

Table 3 Count of research approaches by discipline¹

Discipline	Declarative knowledge	Knowledge-in-use
Mathematics	4	10
Chemistry	12	0
Physics	7	1
Biology	2	3
Engineering	1	0
Multiple disciplines	1	0
Total	27	14

¹ Four theorizing papers from mathematics were excluded from these counts: (Delgado-Robolledo et al., 2020; Hauk et al., 2013; Liang, 2019; Nuzzi et al., 2020)

Finding 2: teaching knowledge research has investigated both declarative knowledge and knowledge-in-use, using a variety of data collection approaches

To understand how researchers have investigated teaching knowledge for undergraduate STEM education, we examined the research approaches used. More than half (60%) of these works investigated declarative teaching knowledge (Table 3). In these studies, researchers aimed to elicit teaching knowledge, but not in the context of participants' own classroom practice. The majority of these studies used interviews or open-response surveys that were informed by teaching knowledge theory. Researchers used a variety of interview methods, including semi-structured interviews (e.g., Padilla & Van Driel, 2011, 2012; Zotos et al., 2020), task-based interviews (Frank & Speer, 2012), think-aloud interviews (Maries & Singh, 2016), and Content Representations (an established approach to eliciting PCK (Loughran et al., 2004). In addition to interviews, researchers elicited declarative teaching knowledge using a variety of questionnaires (e.g., Connor & Shultz, 2018; Hale et al., 2016; Lutter et al., 2019) and concept inventories (e.g., Maries & Singh, 2013), sometimes alone and sometimes in combination with an interview (e.g., Maries & Singh, 2016).

Interviews generally addressed teaching knowledge about specific content and/or reflection on corresponding assessments. For example, Zotos et al. (2021) captured undergraduate chemistry instructors' PCK for teaching organic reaction mechanisms using a task-based interview protocol. Participants examined authentic student responses to content questions and considered what the student was thinking and how they would respond instructionally. This approach provides highly context- and content-specific information about instructors' declarative knowledge, but it does not provide direct data about how participants apply this knowledge in their own classroom practice.

About one-third (31%) of the reviewed work investigated knowledge-in-use (Table 3), which are studies of knowledge enacted in practice. These studies primarily used teaching observations in combination with another method, such as an interview, to examine how instructors applied their knowledge during the teaching cycle (e.g., planning, implementing, reflecting). Most of this work investigated mathematics instructors ($n=10$). Johnson and Larsen (2012), for example, studied how instructors addressed student contributions to in-class mathematical discussions, using an iterative video analysis technique. They identified instances of "teacher listening," which included student contributions and instructor responses and determined whether the instructor response was supported or constrained by their mathematical knowledge for teaching. This work, and other scholarship like it, can reveal teaching knowledge that instructors rely on while teaching. Prevalence of studies of knowledge-in-use varied across disciplines, with studies in chemistry and physics rarely examining knowledge-in-use and studies in mathematics preferentially studying knowledge-in-use.

Finding 3: teaching knowledge research often does not explicitly consider teaching experience

Studies of novice and experienced instructors can reveal what teaching knowledge develops over time. Such findings can also inform professional development for novice instructors and reveal how knowledge development occurs. Therefore, we characterized whether and how teaching experience was taken into account in studies of teaching knowledge. Most generally, studies investigated graduate teaching assistants ($n=18$) and faculty ($n=21$). Only one study compared instructors across these two career levels (Zotos et al., 2021). We assume that most graduate teaching assistants are relatively inexperienced compared to faculty and may be comparable to pre-service teachers in K12 contexts in terms of their development of teaching knowledge. Thus comparisons between graduate students and faculty may reveal what teaching knowledge develops as a

result of experience. Only one study examined adjunct faculty (Nuzzi et al., 2020) and no studies focused on community college faculty and thus very little is known about teaching knowledge in these instructor populations.

Most studies did not explicitly consider teaching experience among participants, but a few did so strategically. Most commonly, researchers reported participants' semesters or years of teaching experience (e.g., Lawrie et al., 2019; Maries & Singh, 2019; Padilla & Van Driel, 2011, 2012), but level of experience did not appear to be a factor in participant recruitment. Convenience sampling appeared to be the primary strategy used by researchers, which may be the result of unique challenges associated with recruiting instructors as a subject population (i.e., small numbers, cultural prioritization of research over teaching) (Robert & Carlsen, 2017). A subset of studies defined teaching experience in specific ways aligned with particular study goals. Some studies ($N=9$) deliberately focused on instructors with substantial experience (Auerbach & Andrews, 2018; Auerbach et al., 2018; Fernández-Balboa & Stiehl, 1995; Johnson & Larsen, 2012; Viiri, 2003; Weber, 2010). In other cases, researchers examined participants who had no prior experience with a particular practice or curriculum in order to understand what teaching knowledge a novice needed (Johnson, 2012; Speer & Wagner, 2009; Wagner et al., 2007). Other work specifically recruited participants with some evidence of teaching effectiveness, such as recommendations by administrators, student evaluations, performance outcomes, and teaching awards (Fernández-Balboa & Stiehl, 1995). Lastly, at least one study aimed to compare instructors with different levels of experience and expertise. Auerbach et al. (2018) compared teaching knowledge among expert and novice active-learning instructors, defining experts based on both years of experience and either demonstrated effectiveness or demonstrated purposeful reflective practice. These studies may serve as examples for researchers considering how to define experience and to purposefully recruit participants when designing a teaching knowledge study.

There are few interpretable trends in how teaching experience was defined and studied across disciplines. However, consistent with other findings in this review, research in mathematics education seemed somewhat distinct from that in science education, including a greater fraction of studies focused on faculty. Investigations of participants' teaching knowledge related to a particular approach or curriculum were primarily in mathematics and biology, and generally aimed to

understand the role of teaching knowledge in implementing some form of evidence-based teaching.

Finding 4: different disciplines have relied on different theoretical framing in teaching knowledge research, resulting in some convergences and key divergences

As described in the introduction, different theoretical frameworks about teaching knowledge have been developed in the context of K12 mathematics and science education. Our systematic review indicated that most research into teaching knowledge in undergraduate STEM has adopted the theoretical frameworks developed for K12 educational contexts, including pedagogical content knowledge (PCK) and mathematical knowledge for teaching (MKT). In addition, some research has developed and relied on a pedagogical knowledge (PK) framework that is specialized to undergraduate STEM education. Table 4. represents the number of papers investigating particular components of teaching knowledge, organized by theory, for each discipline. To see the sets of papers corresponding to the rows, columns or cells in Table 4., please consult Additional file 2. This spreadsheet can be searched and sorted to locate, for example, papers on a particular knowledge component from a particular discipline. A few papers did not explicitly align their work with established frameworks of PCK, MKT, or PK, yet studied components of knowledge described in these frameworks. Therefore, we grouped these papers with the aligned knowledge components.

Research in both undergraduate mathematics and science has investigated PCK.

Thirty-three of the 45 (73%) reviewed papers examined one or more PCK components. Knowledge of student understanding (see Table 1 for definitions and alternative terms) was the only knowledge component that researchers in all included STEM disciplines investigated, and thus represents a key convergence in teaching knowledge research in undergraduate STEM. It was also the most frequently investigated component (Table 4). Disciplines varied more for other PCK components, with biology and chemistry examining knowledge of instructional strategies and representations as often as knowledge of student understanding, and physics with few papers studying other PCK components. Investigations of knowledge of curriculum and knowledge of assessment were rare outside of chemistry, which stands apart from other disciplines by having more papers across the different components of PCK.

Research drawing on non-PCK components of MKT was mostly limited to mathematics, and studies of pedagogical knowledge were limited to science, reflecting divergences among disciplines. Of the 45 reviewed papers, 18 (40%) investigated components outlined in

Table 4. Number of papers ($n = 45$) by discipline and knowledge component(s) studied¹

Theoretical framework	Knowledge component	Biology (n = 5)	Chemistry (n = 12)	Physics (n = 8)	Math (n = 18)	Engineering (n = 1)	Total
Pedagogical content knowledge (PCK)	Knowledge of student understanding	3	9	8	9	1	30
	Knowledge of instructional strategies and representations	3	10	1	3	0	17
	Knowledge of curriculum	1	6	1	2	0	10
	Knowledge of assessment	1	5	0	2	0	8
	PCK as a whole ²	0	1	0	0	0	1
Mathematical knowledge for teaching (beyond PCK)	Common content knowledge	0	0	2	5	0	7
	Specialized content knowledge	0	0	1	6	0	7
	Horizon content knowledge	0	0	0	0	0	0
	MKT as a whole ²	0	0	0	6	0	6
Pedagogical knowledge		4	1	0	0	0	5

Key: Shading indicates number of papers

0	1	2-4	5-8	9+
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¹ This table excludes one paper that crossed multiple STEM disciplines, which studied common content knowledge and pedagogical knowledge. ² This work considered only the framework as a whole, rather than distinguishing among knowledge components

MKT that extend beyond PCK. Most of these papers ($n = 15$) focused on mathematics education and explicitly grounded their work in the MKT framework. Another three studied common content knowledge without reference to MKT. There were no investigations of horizon content knowledge. Interestingly, the one study of specialized content knowledge outside of mathematics resulted from a collaboration between a physics education researcher and a mathematics education researcher. Research on pedagogical knowledge also shows divergences among disciplines. Out of five studies, all were within science and most limited to biology.

Notably, a small number of papers aimed to build or refine teaching knowledge theory in the context of undergraduate STEM education. Most of this work focused on extending the MKT framework. Specifically, some papers engaged in theory-building related

to MKT by linking it to other areas of research (e.g., Hauk et al., 2013; Johnson, 2012), tailoring it to specific teaching contexts (e.g., Firouzian & Speer, 2015; Miller, 2018), developing related theory (e.g., Delgado-Rebolledo & Zakaryan, 2020; Johnson, 2012) or critically reviewing prior work with new lenses to suggest future directions (e.g., Liang, 2019). Some of these papers pursued theory-building by analyzing empirical evidence of specific instructors' knowledge and practice, and others propose arguments that had not yet been tested. Most of this work was disseminated via conference proceedings. One paper aimed to build theory in the context of the PCK framework utilized in science disciplines (Bond-Robinson, 2005) and one paper focused on theory-building related to pedagogical knowledge. Unlike MKT and PCK, pedagogical knowledge is undertheorized, so this work proposed a

framework of components of pedagogical knowledge (Auerbach & Andrews, 2018).

Finding 5: evidence-based teaching relies on pedagogical content knowledge and pedagogical knowledge, in addition to content knowledge

We identified just six peer-reviewed papers and four conference proceedings that investigated teaching knowledge for evidence-based teaching in undergraduate STEM classrooms, which represents 22% of the reviewed work. Seven of these investigated mathematics instructors and three investigated biology instructors. Notably, 8 out of 10 studies examined knowledge-in-use, which is distinct from the larger body of reviewed work in which 31% of papers studied knowledge-in-use. The reviewed papers focused specifically on inquiry-based or active-learning instruction. These terms can have many definitions. The work reviewed here generally studied learning contexts in which students worked on questions and problems during class, collaborated with peers during class, and participated in class discussions facilitated by the instructor (Andrews et al., 2019; Johnson, 2012; Johnson & Larsen, 2012; Speer & Wagner, 2009; Wagner et al., 2007). Next we summarize key findings about teaching knowledge for evidence-based teaching, based on the reviewed work.

Knowledge of student understanding, a component of PCK, can facilitate evidence-based teaching. Several in-depth studies provide convincing evidence that STEM instructors may have insufficient knowledge of student understanding to effectively plan and implement evidence-based lessons (Andrews et al., 2019; Johnson & Larsen, 2012; Speer & Wagner, 2009; Wagner et al., 2007). Additionally, knowledge of student understanding was observed to be more common among expert active-learning instructors than among those newer to this teaching approach (Auerbach et al., 2018).

Knowledge of student understanding informs how instructors plan lessons because it helps instructors anticipate student thinking and plan learning opportunities to shift students toward desired normative conceptions. Biology instructors who successfully implemented evidence-based teaching planned lessons specifically to target difficulties that they anticipated students would have in learning a topic (Andrews et al., 2019). With insufficient knowledge about student understanding, undergraduate mathematics instructors had trouble anticipating students' early and ill-formed ideas about a topic (Wagner et al., 2007). Similarly, these instructors struggled to anticipate how students would respond to certain tasks and problems, including what would be easier and harder for them and the likely consequences of naive ideas as students engaged in new tasks or problems

(Johnson & Larsen, 2012; Wagner et al., 2007). Anticipating common student thinking is particularly important for recognizing how instructional tasks and problems developed by someone else can contribute to the overall trajectory of student learning (Wagner et al., 2007). This knowledge may also be key to having reasonable expectations for student thinking at different stages in learning a topic (Wagner et al., 2007).

Knowledge of student understanding also plays an important role in implementing evidence-based teaching. Evidence-based teaching practices provide instructors with access to student thinking as they circulate the classroom, talk to students, and facilitate discussions. Knowledge of student understanding helps instructors make sense of student contributions, which then allows them to enact immediate instructional responses. Mathematics instructors with this knowledge were able to make sense of student thinking in real-time, whereas instructors lacking this knowledge could not always reason through ill-formed student contributions quickly enough to respond appropriately during class (Johnson & Larsen, 2012; Speer & Wagner, 2009). Anticipating student difficulties made the cognitive task of reasoning through student thinking during class more efficient and therefore more feasible while managing the other demands of leading a lesson (e.g., Speer & Wagner, 2009). After making sense of a student contribution, knowledge of student understanding helped instructors decide whether and how to use or respond to a student's contribution. For example, this knowledge could help an instructor recognize that an inaccurate idea shared by a student is productive for the class to consider further because it can create space for students to grapple with a common difficulty (Speer & Wagner, 2009). As another example, mathematics instructors lacking knowledge of how students are likely to be thinking about a topic may struggle to consider whether an example, counterexample, or explanation they intend to provide will be understandable to students (Johnson & Larsen, 2012).

Instructors may also employ knowledge of student understanding to make decisions about timing during a lesson. This could include deciding what to omit when time is short in a lesson (Wagner et al., 2007), and feeling comfortable moving forward with a lesson when students are still expressing ideas that are not yet fully aligned with normative ideas about a topic (Wagner et al., 2007). That point is particularly interesting because evidence-based teaching can give instructors much more access to student thinking than they have had previously, and what instructors discover may be surprising, and even disconcerting. Students often simultaneously hold both normative and non-normative ideas as they develop more expertise (Opfer et al., 2012), but that may not be obvious

to instructors who have not regularly elicited student thinking throughout the learning process.

Pedagogical knowledge, which is generalizable across topics, can also influence evidence-based teaching. This finding is more tentative than the important role of PCK because pedagogical knowledge only appeared in a few studies, all focused on biology (Andrews et al., 2019; Auerbach et al., 2018). More expert evidence-based instructors use knowledge of how to monitor student thinking as they interact with small groups and circulate the classroom with the intention of accessing student thinking (Andrews et al., 2019; Auerbach et al., 2018). There may also be a role for knowledge of how people learn, which helps instructors to design lessons focused on students generating reasoning (Andrews et al., 2019; Auerbach et al., 2018). More expert evidence-based instructors also display more knowledge about motivating students by holding them accountable for working during class (Auerbach et al., 2018). There may also be other components of pedagogical knowledge used by evidence-based instructors, such as knowledge of metacognition and equitable teaching practices, but further work is needed to understand their role in evidence-based teaching (Auerbach & Andrews, 2018).

Finally, the reviewed research confirms a critical role for content knowledge in evidence-based teaching. To date, this research is limited to the discipline of mathematics, which has a long history of studying content knowledge that is important to teaching. Instructors rely on content knowledge while teaching, especially when they encounter students' thinking. Instructors use common content knowledge (as well as other knowledge components) to take a student's contribution (e.g., answers, explanations, solutions) that is unfamiliar and possibly surprising, make sense of it, and then translate it into something that can further a class discussion (Speer & Wagner, 2009). More generally, common content knowledge can help instructors to recognize student contributions as aligned with normative knowledge (Johnson, 2012). It can also inform an explanation of a topic (Johnson, 2012) and choices about appropriate representations of content (e.g., Lee et al., 2009). More robust specialized content knowledge may allow instructors to more efficiently and effectively make sense of student thinking that is non-normative while teaching so that they can leverage these contributions toward lesson goals; this may involve common content knowledge and specialized content knowledge (e.g., Speer & Wagner, 2009; Wagner et al., 2007). Instructors with underdeveloped content knowledge may only be able to reason through the content of non-normative student answers with more time and thus may miss opportunities to leverage student thinking during a lesson.

Content knowledge may not always be an asset to evidence-based teaching. Interestingly, one study raised questions about the limitations that content knowledge could place on evidence-based teaching. One instructor was more open to using student thinking to drive a lesson forward when teaching content that was not aligned with his research interests (Fortune & Keene, 2019).

Discussion

This systematic review of research on teaching knowledge in undergraduate STEM instruction supports three broad conclusions and has several implications for future research. Here, we describe the emergent conclusions and then detail implications for future work. The first broad conclusion that emerges from this review is that existing research is limited in terms of the number of published papers, and thus there are many opportunities for future research. A second emergent conclusion is that this body of research is siloed by discipline. Though disciplinary divergences are common in discipline-based education research, the effect is magnified in this research area because the theoretical frameworks are themselves siloed by discipline. The convergences and divergences identified in this review point toward productive areas for future research. A third and final broad conclusion is that despite being a limited and siloed body of research, collectively this work adds strength to the claim that teaching knowledge is an important factor influencing evidence-based teaching. Attention to teaching knowledge should be a priority for research, teaching professional developers, developers of evidence-based strategies and curriculum, and funding agencies who aim to promote and support the adoption and effective implementation of evidence-based teaching in undergraduate STEM. Next, we describe seven implications of the findings that we see for future research on teaching knowledge and research focused on evidence-based teaching.

Prioritize studies of knowledge-in-use

Future teaching knowledge research should prioritize studies of knowledge that instructors rely on while engaging in the acts of teaching (i.e., knowledge-in-use, enacted PCK). Knowledge deployed in the context of teaching is what most directly influences instructional practices and instructional practices create learning opportunities for students. As has been true in K12 contexts (e.g., Chan & Hume, 2019; Hoover et al., 2016) studies of teaching knowledge in undergraduate STEM more commonly focused on declarative knowledge, and this was particularly true in some disciplines (Table 3). Though studies of declarative knowledge certainly have value, we cannot assume that the findings reveal

knowledge that undergraduate STEM instructors actually deploy in their teaching.

Theoretical frameworks of teaching knowledge offer useful lenses for future studies of knowledge-in-use. The current predominance of studies of declarative knowledge constitutes a drift from some of the most influential conceptualizations of teaching knowledge. For example, an early conceptualization of PCK considered it to be a “dynamic construct that describes the processes that teachers employed when confronted with the challenge of teaching particular subjects to particular learners in particular settings” (Berry et al., 2015, page 9). The originators of the MKT framework sought to understand the “work teachers do in teaching mathematics” because they saw it as the only direct way to reveal the nature of knowledge needed for teaching (Ball et al., 2008, page 390). These scholars conceptualized teaching knowledge as inextricably linked to teaching practice.

There have also been more recent calls for teaching knowledge research situated in the context of instructors’ own teaching. Recent efforts to build consensus among K12 PCK scholars concluded that “classroom practice is the location of PCK” (Gess-Newsome, 2015, page 36). The most recent PCK model, the Refined Consensus Model of PCK, proposes three distinct realms of PCK: collective PCK, personal PCK, and enacted PCK. Enacted PCK is the knowledge that is deployed throughout the teaching cycle of planning, implementing, and reflecting on instruction and includes the reasoning behind instructional decisions (Carlson et al., 2019). This conceptualization may be useful to researchers as they pursue studies of knowledge-in-use. We also point researchers toward other theoretical frameworks as potential grounding for studies of knowledge-in-use, including teacher noticing (e.g., Sherin et al., 2011, Kaiser et al., 2015) and teacher listening (e.g., Johnson & Larsen, 2012).

Another important reason for studying knowledge-in-use among college STEM instructors is that teacher learning may be closely linked to knowledge deployed while teaching and reflecting on teaching. For example, Chan and Yung (2015) studied experienced high school instructors who were teaching a lesson for the first time, and found that instructors experienced “on site” PCK development as they taught and reflected on that teaching, and that PCK development was facilitated by strong content knowledge and pedagogical knowledge. We identified few studies of knowledge development among undergraduate STEM instructors (Bolitzer, 2021; Frank & Speer, 2012; Seung, 2013), yet investigations of in-the-moment knowledge development and longitudinal development have the potential to contribute to our understanding of how to support instructors’ knowledge growth. College STEM instructors generally have few

formal opportunities to develop as teachers, and ongoing teaching professional development may not be encouraged nor rewarded within STEM departments. Therefore, the development of key teaching knowledge may occur primarily through experience in the practice of teaching and in communicating with colleagues. Studying knowledge-in-use may afford the opportunity to document knowledge development.

Explore the role of teaching experience in knowledge development

In the reviewed work, teaching experience was often under conceptualized. Most commonly, experience was determined based on a single metric, such as self-reported terms or years of teaching. This approach seems based on the assumption that teaching experience results in increased knowledge, but some research indicates that experience is necessary but insufficient for knowledge development (e.g., Chan & Yung, 2018). Therefore, experience cannot be assumed to be a valid indicator of teaching knowledge. We recommend that future work include careful consideration of experience, particularly when aiming to compare across levels of teaching knowledge. This implication applies particularly to studies of teaching knowledge for evidence-based teaching. Most work looking closely at the relationship between evidence-based teaching and teaching knowledge focused on instructors who are inexperienced with evidence-based teaching. Such work has allowed for important discoveries about the ways in which instructors struggle to enact evidence-based teaching when they lack particular teaching knowledge (e.g., Johnson & Larsen, 2012; Speer & Wagner, 2009; Wagner et al., 2007). However, the current body of teaching knowledge research leaves many open questions about the role that teaching knowledge plays in expert practice. Potentially fruitful avenues for future research include investigations of expert evidence-based instructors, comparisons of instructors with different levels of expertise, and studies of whether and how collaborative co-teaching between more and less expert instructors supports knowledge development.

Seek explicit connections and collaborations across STEM disciplines

One key implication of this systematic review is that future teaching knowledge research would benefit from connections and collaborations across STEM disciplines. Work that is siloed by discipline can have more limited impact and may not build upon, nor contribute to, our broader understanding of teaching knowledge and the role it plays in effective instruction in undergraduate STEM education. This review can serve as a resource to researchers, helping to bridge between disciplines. We

have clarified differences in terminology, theory, and methodology that can otherwise make it difficult to leverage research from another discipline (Table 1). We also identified work from multiple STEM disciplines, aiding researchers in finding relevant work outside of their own discipline (see full list of reviewed papers in Additional file 2). We propose that the standard for future teaching knowledge research should be to make explicit connections to relevant work in other STEM disciplines. This call echoes those made by prior reviews in related areas that have similarly called for more communication across research communities and more explicit focus on building on prior work (Beach et al., 2012; Reinholz et al., 2021).

We envision multiple ways that future research can pursue connections across disciplines. The most fundamental step that researchers can take is to explicitly link their research to prior work in their writing. This can occur in the introduction and discussion of research papers and is essential to helping readers recognize how new research findings relate to what is already known. Making these connections explicit for readers also serves authors because it will result in work being read across disciplines, rather than primarily within one discipline.

Another exciting path for making connections across disciplines is investigating components of knowledge that have not yet been studied or are understudied in a discipline. This work could leverage research in another discipline. For example, specialized content knowledge has been studied only in mathematics. This knowledge component (possibly in concert with common content knowledge and knowledge of student understanding) is used to make sense of and determine the validity of students' written and spoken work. Yet there are studies of teaching knowledge in biology and other disciplines that have examined instructor sense-making while teaching without any consideration of specialized content knowledge (e.g., Andrews et al., 2019). In what ways is specialized content knowledge relevant outside of mathematics? What role does it play in teaching planning and lesson implementation? These questions may be highly relevant to evidence-based teaching and yet are uninvestigated.

In addition to connecting findings to other disciplines and investigating understudied knowledge components, there is considerable room for cross-disciplinary work to better understand differences and similarities in teaching knowledge across disciplines. For example, one promising space for future work is investigating how pedagogical knowledge varies across disciplines. This form of teaching knowledge has been conceptualized as generalizable across topics (e.g., Auerbach & Andrews, 2018; König et al., 2014; Morine-Dershimer & Kent, 1999), so it is reasonable to hypothesize that similar pedagogical

knowledge could be useful across STEM disciplines. Alternatively, pedagogies and courses may be sufficiently different across STEM disciplines that, for example, chemistry instructors need distinct pedagogical knowledge from mathematics instructors. Future research should examine the extent to which findings from one discipline can be leveraged in another, as this could create a larger base of findings to inform theory and practice in individual disciplines. The result of such research is also highly relevant to centers and programs responsible for teaching professional development. If pedagogical knowledge is largely discipline-specific, then teaching professional development should be as well. If important pedagogical knowledge is similar across STEM disciplines, then teaching professional development could effectively target broader faculty audiences.

To truly break down silos, we likely need researchers reaching across disciplines. With that in mind, we strongly encourage cross-disciplinary collaborations among researchers interested in teaching knowledge. The collaboration that we undertook to complete this work has helped each of us to expand and refine our thinking. It has informed our ongoing research and opened our eyes to future research avenues. We have also come to appreciate differences in the discipline-based research histories, cultures, and communities, which can be hard to notice and account for as an outsider.

Test how theory developed in K12 contexts does and does not apply in undergraduate STEM

A fourth implication of this review is that future work should explicitly consider the ways in which theory developed in K12 contexts applies and does not apply in undergraduate STEM contexts. As described in the introduction, both PCK and MKT frameworks were developed based on studies of K12 teachers. The fact that these theories guided most of the work reviewed herein demonstrates that researchers have found these theories valuable in understanding teaching knowledge among undergraduate STEM instructors. However, differences in the educational background, instructional context, and teaching preparation of college instructors compared to K12 teachers may result in relevant differences in the use and development of teaching knowledge. Thus, there is a need to inquire into whether and how teaching knowledge theories represent and provide explanatory power for teaching in an undergraduate STEM context. A few papers considered how teaching knowledge theory translates to undergraduate contexts (e.g., Nuzzi et al., 2020; Speer et al., 2015), but this has not yet been the explicit focus of empirical work. Future work should aim to go beyond adopting some or all of a theory as a guiding lens, and instead test whether and how an existing framework

of teaching knowledge characterizes, predicts, or explains new evidence. What is learned from deliberate inquiries into theory can help advance our collective understanding of undergraduate teaching, as well as advancing theory in a way that is relevant at all educational levels.

Expand research on teaching knowledge for evidence-based teaching

Research examining teaching knowledge in the context of evidence-based teaching is sparse, but creates a solid foundation on which researchers can build. The reviewed work most strongly supports the role of the knowledge of student understanding (i.e., a PCK component) in effective evidence-based teaching, but there are many open questions about what knowledge is crucial. The existing research studied mathematics and biology courses, and bears replication across disciplines and with a greater diversity of faculty. Importantly, knowledge of student understanding may seem to be most important to evidence-based teaching only because it has most often been studied. Other unexplored knowledge may be just as important. For example, much of the existing work studied mathematics instructors who were implementing research-based curricula, and therefore were not designing lessons themselves. Most undergraduate courses lack such rigorously developed curricula and therefore instructors design their own lesson materials, potentially relying heavily on knowledge of instructional strategies and representations. Therefore, this PCK component warrants further exploration. Similarly, only one study has examined pedagogical knowledge-in-use (Andrews et al., 2019), leaving many questions about which pedagogical knowledge is important to which practices and in which contexts.

There are also bodies of knowledge yet uninvestigated that may be particularly important to new and growing efforts to support inclusive teaching and culturally responsive teaching, which we see as two kinds of evidence-based teaching. At the K12 level, teachers' awareness and understanding of culture is critical for the success of these pedagogies (Gay, 2002; Gay & Kirkland, 2003; Sheets, 2004; Sleeter & Thao, 2007). Relatedly, researchers have considered the role of STEM instructors' racial consciousness and racial noticing in creating equitable and just learning environments for all students (e.g., Haynes & Patton, 2019; Shah & Coles, 2020). Considering this work, we hypothesize that knowledge of culture, identity, and systems of oppression are likewise essential to realizing the positive impact of inclusive and culturally responsive practices at the undergraduate level. These teaching knowledge domains have not yet been the subject of research, but we look forward to future

insights about the role of such knowledge, alone and in relation to the components of teaching knowledge.

Use research on teaching knowledge in design and efficacy testing of evidence-based teaching practices

The results of this review also have a critical implication for researchers who develop, refine, and test the efficacy of evidence-based teaching practices. Understanding college instructors' teaching knowledge as it relates to evidence-based practices is necessary for the successful development and dissemination of these approaches. However, teaching innovations are often designed without consideration of the knowledge teachers will need to successfully use them and how the requisite knowledge varies by context. Careful studies of the implementation of evidence-based teaching practices show tremendous variation across instructors (e.g., Chase et al., 2013; Dancy et al., 2016; Turpen & Finkelstein, 2009; Waugh & Andrews, 2020). These differences in implementation matter because often instructors are adapting or eliminating components of a strategy that are essential to improving student learning (e.g., Dancy et al., 2016), potentially rendering the strategies no better than traditional lecturing. Further, teachers may need to adapt evidence-based practices because their teaching context differs from the context in which the practice was developed (Brown et al., 2009). For this reason, it is essential that we also understand the choices that teachers make when adapting these practices and how their choices relate to the teaching knowledge they hold, as well as knowledge about their students and their teaching context (Buxton et al., 2015). Careful attention to the teaching knowledge needed to effectively implement evidence-based strategies may considerably broaden their effective use and thereby the positive impact on student outcomes.

Given the important role that teaching knowledge can play in evidence-based teaching, as synthesized in this review, we advocate for careful attention to the teaching knowledge that will be needed to effectively use new teaching innovations and evidence-based strategies. Developers and researchers can increase the impact of their work by considering teaching knowledge from the beginning. Evidence of the effectiveness of a teaching innovation or strategy should routinely include documentation of the essential teaching knowledge as well as guidance and resources to help develop this knowledge. As a scholarly community, we value evidence-based practices for their potential to improve student outcomes, but the actual impact of these strategies on students depends greatly on their implementation by STEM faculty. Therefore, we cannot advance STEM education if we do not

attend directly to the teaching knowledge that instructors need to help students achieve improved outcomes.

Examine how teaching knowledge influences student outcomes in undergraduate STEM

A pivotal avenue for future research is investigating the relationship between teaching knowledge and student outcomes. Testing this association is key to determining which teaching knowledge helps instructors to achieve the potential benefits of evidence-based strategies and understanding which students benefit as a consequence of their knowledge when applying these strategies. Furthermore, examining this relationship can help us understand how teaching knowledge plays a role in achieving positive student outcomes. Studies of the relationship between teaching knowledge and student outcomes are also rare in K12 education, but a few seminal studies have demonstrated a relationship between teaching knowledge and student outcomes, and thereby raised important questions about how we should be preparing and supporting teachers in their work (e.g., Hill et al., 2005; Kanter & Konstantopoulos, 2010; Sadler et al., 2013).

We offer a few notes of caution for those interested in pursuing fundamental research about teaching knowledge and student outcomes. It is tempting to consider the development of a survey instrument to measure teaching knowledge because surveys can be easily administered to many participants. Yet the effect of teaching knowledge on student outcomes must be mediated by instructional practices, and therefore studies of knowledge-in-use, which tend to involve more labor-intensive data collection and constrained sample sizes, are likely to provide more insights into how teaching knowledge influences student outcomes. Another challenge of such research will be the topic-specific nature of PCK, which narrows the sample of instructors whose knowledge can be meaningfully compared. Lastly, students' learning and other experiences are impacted by many factors beyond teaching knowledge, and research designs will need to account for this variation in order to detect an effect of teaching knowledge on student outcomes.

Conclusions

This systematic analysis of existing work highlights innumerable avenues for future research on teaching knowledge in the context of undergraduate STEM education. We propose that fostering the development of teaching knowledge in undergraduate STEM instructors is essential to achieving the promised benefits of evidence-based teaching for diverse undergraduates. Therefore, it is imperative that researchers pursue questions in this area and collaborate with those responsible for teaching professional development to translate their foundational

discoveries into real changes in students' learning opportunities.

Abbreviations

STEM: Science, technology, engineering, and mathematics; PCK: Pedagogical content knowledge; MKT: Mathematical knowledge for teaching; PK: Pedagogical knowledge; K12: Kindergarten through 12th grade in American education system.

Supplementary Information

The online version contains supplementary material available at <https://doi.org/10.1186/s40594-022-00380-w>.

Additional file 1. List of journals and conference proceedings.

Additional file 2. Full list of reviewed papers.

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Author contributions

All authors conceived of the work, conducted the search for articles, completed analyses, and contributed to writing the manuscript. All authors read and approved the final manuscript.

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Availability of data and materials

The final list of papers included in this review, and the results of our analyses of those papers are included in additional materials.

Declarations

Competing interests

The authors declare that they have no competing interests.

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