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Threshold Concepts in the Engineering Educator's Journey: A Systematic Review

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ABSTRACT

CONTEXT

Many engineering educators recognize and emphasize the key concepts and skills that are considerably more difficult and that hinder their learners' progress through their undergraduate studies. Many of these topics are considered threshold concepts and make the difference in a student's ability to do engineering things versus being an engineer. What many engineering educators don't recognize is that they too encounter threshold concepts that hinder their own journey to becoming effective educators.

PURPOSE OR GOAL

Unfortunately, there is no analysis of studies of threshold concepts that identify those associated with teaching in either undergraduate engineering programs or post-secondary education in general. This study seeks to answer two questions about teaching-related threshold concepts: (1) what threshold concepts are identified as part of an educator's growth? and (2) what threshold concepts may cause a transformation in the way engineering educators carry out their day-to-day practices?

APPROACH OR METHODOLOGY/METHODS

This paper reports the findings of a qualitative evidence synthesis (qualitative systematic review) of 20 journal articles and conference papers that study threshold concepts related to teaching in the post-secondary system. An initial search for studies of any design that examined threshold concepts related to teaching practice identified 1011 potential papers, 82 of which met the criteria for initial review. A deeper secondary review narrowed the list to 20 papers.

ACTUAL OR ANTICIPATED OUTCOMES

Final review identified 14 threshold concepts associated with post-secondary educators' professional growth ranging from care and authenticity to course-related threshold concepts. These 14 threshold concepts were mapped to categories of Science, Technology, Mathematics and Engineering (STEM) educator practices and conceptions. Four clusters were identified in which mastery of the threshold concept could facilitate a change in day-to-day practice of engineering educators: teaching / pedagogy, learning, assessment, and teaching with technology.

CONCLUSIONS/RECOMMENDATIONS/SUMMARY

This study fills a gap in the literature by identifying teaching-related threshold concepts that may hinder the instructional development of engineering educators. It is hoped that these results will encourage engineering educators, and those responsible for their educational development, to recognize and support professional growth related to these potential thresholds.

KEYWORDS

Threshold concepts, engineering education, teaching.

Introduction

Many engineering educators recognize and emphasize the key concepts and skills that are considerably more difficult for learners, hindering their progress through their undergraduate studies. What many engineering educators don't recognize is that they too often encounter gateway concepts that can hinder their own journey to becoming effective educators. This qualitative systematic review sets out to determine what, if any, threshold concepts are identified that pose intellectual barriers to post-secondary engineering educators in the way they perceive and perform their day-to-day teaching practices.

Background

Educators and researchers have long discussed discipline-specific topics that act as bottlenecks or choke points in a learner's progression. Students follow the steps they're taught but don't seem to understand. Then one day there is an 'aha' moment and everything makes sense; it becomes part of the learner's disciplinary way of thinking and practicing.

Threshold Concepts

Perkins introduced the term 'troublesome knowledge' to address the challenges that students experience in constructivist learning environments (Perkins, 1999). He recognized that there are different types of knowledge, each of which provides a unique challenge for learners. He proposed that knowledge that is 'inert', 'ritual', 'conceptually difficult' or 'foreign' can impede learners as they attempt to grasp concepts required in their profession.

Meyer and Land suggested that Perkins' types of troublesome knowledge should include 'tacit knowledge', the personal and practical knowledge that is shared within a community or discipline. This knowledge is often difficult to explain to others because it is ingrained into one's 'being' (Meyer & Land, 2003) (Hill, 2010). They realized that there are certain topics within every discipline that are gateway or key turning points. When students grasp those topics, they go from simply doing discipline-specific things, to thinking and practicing like a professional in that field. These turning point topics became known as threshold concepts.

A threshold concept has five characteristics that distinguish it from a core concept: (1) it is uniquely troublesome, challenging the way learners think, often making the concept mentally and emotionally uncomfortable to master, (2) it is integrative, pulling discrete concepts and ideas together into a new way of thinking or understanding, (3) it transforms the way learners think about their discipline, (4) it is considered irreversible, and (5) it is bounded to a one's discipline and dependent on context. Mastering a threshold concept is different for each learner. The experience of moving from not knowing to knowing is called liminality and is often quite disorienting (Meyer & Land, 2003) (Rhem, 2013).

Although many engineering educators may not refer to them as threshold concepts, most recognize and emphasize the key concepts and skills that are considerably more difficult to learn. Many of these topics are considered threshold concepts that can make the difference in a student's ability to merely carry out engineering duties versus thinking and acting as an engineer. And while focusing on student learning is understandable, many engineering educators don't recognize that they too encounter threshold concepts that can hinder their individual journeys to becoming effective educators.

Engineering Education Practices

Engineering remains one of the most traditional and didactic disciplines in higher education (Stains et al., 2018). The reluctance of many engineering educators to incorporate research-based instructional strategies is reflected in undergraduate student engagement rankings that place engineering lowest among the disciplines (Nelson & Brennan, 2019). Low adoption of evidence-based practices is common across Science, Technology, Engineering, and Mathematics (STEM) disciplines (Laursen, 2019). Extensive research finds that, while most

STEM educators have tried at least some of these practices, many return to their traditional lecture-based approach (Henderson, Dancy, & Niewiadomska-Bugaj, 2012). Stains reports that fewer than 20% of engineering classes incorporate any student-centred instructional strategies (Stains et al., 2018) and Allen suggests that this may be attributed to an ingrained belief that sticking to traditional teaching outweighs the benefits that may result from such a change (Allen, 2018).

Dancy and Henderson developed a framework for articulating the instructional practices and associated conceptions of individual educators (Dancy & Henderson, 2007). This framework identifies ten categories of practices, differentiating between traditional and alterative instruction: (P1) interactivity, (P2) instructional decisions, (P3) knowledge source, (P4) student success, (P5) learning mode, (P6) motivation, (P7) assessment, (P8) content, (P9) instructional design, and (P10) problem solving. The ten categories of conceptions include: (C1) learning view, (C2) expertise, (C3) knowledge view, (C4) nature of the discipline, (C5) role of school, (C6) students, (C7) teacher role, (C8) diversity, (C9) desired outcomes, and (C10) scientific literacy.

Analysis of educators using this comprehensive framework found that the practices and conceptions of educators were often misaligned (Henderson & Dancy, 2007). While their conceptions about teaching and learning leaned toward evidence-based aspects of alternative instruction, their practices tended toward the traditional. This suggests that an educator's transformation to an alternative instructional approach may require mastery of one or more teaching-related threshold concepts. Unfortunately, there is no present analysis of threshold concepts associated with teaching in either undergraduate engineering programs or post-secondary education in general. This study seeks to answer two questions about teaching-related threshold concepts: (1) what, if any, threshold concepts are identified as part of an educator's growth? and (2) what threshold concepts may cause a transformation in the way engineering educators perceive and perform their day-to-day practices?

Methodology

A qualitative systematic review (QSR), also known as a qualitative evidence synthesis (QES), was conducted to locate primary research studies that identify teaching-related threshold concepts. An initial analysis of the purpose, strengths, weaknesses, and methodologies associated with myriad review types indicate that a QSR/QES is the optimal review type for this research (Grant & Booth, 2009).

The processes used to conduct a QSR/QES are similar to those of a classic systematic review (Flemming & Noyes, 2021) and begins with question formulation. A modified version of the PICO criteria for framing a research question (Petticrew, Roberts, & Ebrary, 2006) (Borrego, Foster, & Froyd, 2014) established the qualitative review question to be 'What concepts are identified as teaching-related thresholds in the professional growth of post-secondary educators?'

Criteria for the QSR/QES were defined for the type of study, data sources, and search keywords (see Table 1). The screening process followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (PRISMA, 2021) using the inclusion and exclusion criteria specified in Table 1 item 5 (see Figure 1). A search of the SCOPUS database, performed in April 2020, identified and screened 163 primary studies. Of these papers, 25 were accepted for further review. Search of the online bibliography / repository was done in June 2020. 553 primary studies were identified and screened using the same inclusion and exclusion criteria with 59 accepted for further review. A search of the ERIC database was done in January 2021, with 22 of the 295 papers accepted for further review. Duplicate papers were removed from the list, leaving 82 primary studies for secondary review. Of the 82 reports sought for retrieval, 22 were not accessible, leaving 60 reports to be assessed. All screenings were done by the lead author.

Table 1: QSR/QES Criteria

1. Primary research studies: a. must be peer-reviewed and published as a dissertation, in a journal, as part of a conference proceeding, or as a book chapter b. can be of any design: mixed, qualitative or quantitative
2. Data sources for: a. initial search must include: i. a social sciences research database (SCOPUS) ii. an education research database (ERIC) iii. threshold concept online bibliography / repository b. secondary search can include: i. peer reviewed papers cited in studies selected for secondary review
3. Database search of paper title, abstract and keywords must include: a. ‘threshold concept’ AND ‘teaching’ OR ‘pedagogy’ OR ‘expertise’ OR ‘professional learning’ OR ‘transformation’ OR ‘professional identity’ b. ‘decoding the discipline’ AND ‘teaching’ OR ‘pedagogy’ OR ‘expertise’ OR ‘professional learning’ OR ‘transformation’ OR ‘professional identity’
4. Threshold concept bibliography / repository categories must include, but are not limited to: a. ‘change’, ‘evidence-based practice’, ‘exploration’, ‘ways of thinking and practicing’, ‘pedagogic’, ‘professional development’, ‘expertise’
5. Screening inclusion and exclusion criteria state the title, keywords, and if necessary abstract, must: a. relate directly to threshold concepts, teaching, and post-secondary educators b. NOT focus on student-related threshold concepts c. NOT focus on educators recognizing or incorporating discipline-specific threshold concepts d. NOT focus on educational developer-related or curriculum-development related threshold concepts
6. Report assessment notes must include, but are not limited to: a. citation information (title, authors, date, journal) b. research question c. methodology/research design d. findings
7. Report assessment criteria: a. reports must be accepted, rejected, or marked as potentially accepted b. accepted reports must identify a teaching-related threshold concept using a qualitative, quantitative, mixed methodology or evidence-based argument c. reason(s) for exclusion must be specified for rejected reports d. concerns/reasons must be specified for potentially accepted reports

Sixty reports were assessed for eligibility in the study. Each paper was read in full and notes recorded using the criteria specified in Table 1 item 6. Application of report assessment criteria specified in Table 1 item 7 excluded 51 of these studies. Twenty-eight were excluded because they were not teaching-related threshold concepts, six were not threshold concepts, and 17 inadvertently made it through the screening process (see Figure 1). Eleven additional papers were identified from citations in the reviewed reports. These were retrieved, assessed, and included in the study resulting in a final count of 20 papers (see Table 2). All assessments were done by the lead author.

Authors of the final 20 papers were from eight countries in North and Central America, Australasia, Europe, and South Africa. Sixteen papers were published in Higher Education or

Academic Development journals, and two each as conference proceedings and book chapters. Publication dates ranged from 2010 to 2020 inclusive.

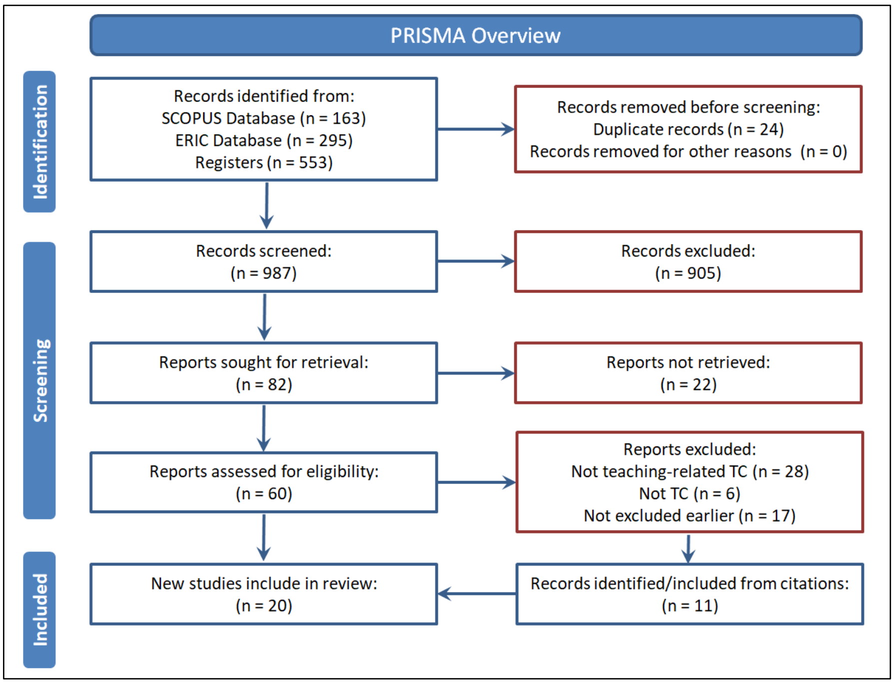

Figure 1: Overview of PRISMA screening process

Results

Final review identified 14 threshold concepts associated with post-secondary educators' professional growth ranging from care and authenticity to learner-centred practices and recognition of threshold concepts themselves (see Table 2). These 14 threshold concepts were mapped to Henderson and Dancy's categories of STEM educator practices and conceptions (Henderson & Dancy, 2007) (see Table 2).

Educator Practices

Ten of the 14 threshold concepts were categorized as educator practices, three related to instructional design, three associated with assessment, two related to teaching with technology, and one each connected to student learning and content.

Six studies report three threshold concepts related to instructional design: (1) inquiry into student learning, (2) teaching for transfer of knowledge, and (3) need for a growth mindset.

Four studies report that inquiry into student learning is a teaching-related threshold concept. Cook-Sather and her colleagues talk about the value of faculty-student partnerships when making pedagogical decisions. This shared exploration is troublesome because it "is at once counterintuitive for many faculty and contradictory to norms in higher education". While expanding educators' perspectives, the "partnership can be threatening, disappointing, and/or (potentially) productively unsettling" yet transformative (Cook-Sather, 2014, p. 189). For this partnership to work educators must "believe that students both know and care about their own learning – a threshold that represents a high, but most worthwhile, crossing to take" (Werder, Thibou, & Kaufer, 2012, p. 38). Howson and Weller recognize the distinctiveness of student perspectives, but note that the "benefit of student involvement in the enhancement of teaching is dependent on the perceived authenticity of student voice within a circumscribed idea of student expertise" (Howson & Weller, 2016, p. 10). Bunnell and Bernstein focus on an inquiry-based approach where the educator "serves not only as a source of knowledge but also as an active pursuer of knowledge about how learning progresses" (p. 15). This form of

Table 2: List of Threshold Concepts Identified in Primary Studies

Author, Year	Study Design	Teaching-Related Threshold Concept(s)	Mapping to STEM Educator Practices and Conceptions	Threshold Concept Category
Adler-Kassner, L., & Majewski, J. (2015)	qualitative - interview	acknowledging student threshold concepts	C9 – outcomes	Pedagogy – threshold concepts
Blackie, M.A.L., Case, J.M. and Jawitz, J. (2010)	argumentative essay	learner-centred focus	P5 – learning mode C9 – outcomes	Learning – learner-centred
Boyd, Diane E. (2014)	qualitative - reflective practice	growth mindset	P9 – instructional design	Pedagogy – knowledge types
Bunnell, S. and Bernstein, D. (2012)	qualitative - reflective practice	inquiry-based teaching teaching as public act	P9 – instructional design	Pedagogy – knowledge types
Cook-Sather, A. (2013)	qualitative - reflective practice	student-faculty partnership in pedagogy	P9 – instructional design	Pedagogy – knowledge types
Devitt, A., Kerin, M. and O'Sullivan, H. (2014)	qualitative - interview	learner-centred focus	P5 – learning mode C9 – outcomes	Learning – learner-centred
Howson, C. K., & Weller, S. (2016)	qualitative - interview	student expertise as learner	P9 – instructional design	Pedagogy – knowledge types
Kinchin, I. M. (2019)	argumentative essay	care	C7 – teacher role	Pedagogy – knowledge types
Kinchin, I. M. and Miller, N. L. (2012)	qualitative - concept mapping	learner-centred focus (structural transformation of knowledge)	P5 – learning mode C9 – outcomes	Learning – learner-centred
Kilgour, P., Reynaud, D., Northcote, M., Gosselin, K. P., & McLoughlin, C. (2018)	mixed method	online learning	P11* – teaching with technology	Teaching with Technology
McGowan, S. (2012)	qualitative - reflective practice	educational technology	P11* – teaching with technology	Teaching with Technology
Meyer, J. (2012)	qualitative - reflective practice	variations in student learning	C6 – students	Learning – learner-centred
Mills, R. and Wilson, A. (2014)	qualitative - interview	learner-centred focus	P5 – learning mode C9 – outcomes	Learning – learner-centred
Moore, J. L. (2012)	qualitative - concept mapping	teaching for transfer of knowledge (course to course)	P9 – instructional design	Pedagogy – knowledge types

Author, Year	Study Design	Teaching-Related Threshold Concept(s)	Mapping to STEM Educator Practices and Conceptions	Threshold Concept Category
O'Brien, M. (2013)	qualitative - grounded theory	acknowledging student threshold concepts (theory of difficulty)	C9 – outcomes	Pedagogy – threshold concepts
Simper, N. (2020)	qualitative - interview	assessment – constructive alignment with learning outcomes assessment standards	P7 – assessment	Assessment – alignment & authenticity
Timmermans, J. A., & Meyer, J. H. (2019)	argumentative essay	acknowledging student threshold concepts	C9 – outcomes	Pedagogy – threshold concepts
Timmermans, J. A., Bruni, C., Gorbet, R., Moffatt, B., Stubley, G., Williams, D., & Holmes, T. (2018)	qualitative - reflective study	care	C7 – teacher role	Pedagogy – knowledge types
Werder, C., Thibou, S., & Kaufer, B. (2012)	qualitative - reflective practice	student-faculty partnership in pedagogy	P9 – instructional design	Pedagogy – knowledge types
Wilcox, S., & Leger, A. B. (2013)	qualitative - questionnaire	formative assessment learner-centred focus context-driven practice student diversity	P7 – assessment P5 – learning mode C9 – outcomes P8 – content C6 – students	Assessment – formative Learning – learner-centred Pedagogy – knowledge types

*items marked with an asterisk are not included in Henderson and Dancy's categories of practices and conceptions. They were added to fill gaps reflective practice implies that educators “have much greater responsibility for students’ learning than has traditionally been assumed” (Bunnell & Bernstein, 2012, p. 16).

One study reports context-based practice as a threshold concept. Wilcox and Leger note that to gain a “better understanding of what kind of learning is required by students” there is “no one best way to teach in all circumstances” (Wilcox & Leger, 2013, p. 7).

Educator Conceptions

The remaining four threshold concepts were categorized as educator conceptions, two related to an educator’s role, and one each connected to outcomes and students. Three studies report two threshold concepts related to educator roles: (1) care, and (2) teaching as a public act.

Two studies report care as a threshold concept. Kinchin identifies that Clouder’s phases in the development of care (Clouder, 2006) “may be helpful in supporting contextually appropriate levels of teacher development of a caring perspective” (p. 3). He notes that “students regard care as a key marker of good teaching, and good teachers as people who care about their discipline, about teaching as a professional activity and about their students” (Kinchin, 2019, p. 4). Timmermans and her colleagues report that care could be a teaching threshold concept “transforming the ways we conceive of, design, and enact initiatives”. They suggest care includes care for the discipline, care related to students and their learning, and care among Faculty Learning Community (FLC) members (Timmermans et al., 2018, p. 371).

Bunnell and Bernstein report that teaching as a public act, or making the teaching and learning visible, is a threshold concept. It challenges educators to recognize that “content knowledge is not sufficient” and opening their classrooms to peer feedback is a “challenge to a professor’s identity as an expert” (Bunnell & Bernstein, 2012, p. 16).

Three studies report acknowledgement of threshold concepts as a threshold concept. Adler-Kassner and Wardle report that educators’ “realization that there are threshold concepts critical for understanding and practicing their discipline was itself a threshold concept (Adler-Kassner & Wardle, 2015, p. 188). O’Brien identifies that “theories of difficulty are woven into the pedagogical thinking and reasoning of teachers” and “can vary between teachers, in ways that potentially influence significant differences in the student learning experience” shedding light on how educators practice and teach (O’Brien, 2013, p. 39). Timmermans and Meyer note that as “teachers do the work of uncovering TCs (sic), we have noticed that some experience transformative shifts in their conceptions of their disciplines, their teaching, and their understanding of their students’ learning” (Timmermans & Meyer, 2017, p. 360).

Finally, two studies report variation in student learning as a threshold concept. Meyer reports that crossing this threshold “opens up a new and empowering theoretical perspective of reflexive teaching practice” based on “how and why students vary in their engagement of the content and context of learning” (J. Meyer, 2012, p. 10). Wilcox and Leger report that in appreciating “the variation in students’ learning needs, capacities, styles” (p.7) there must be recognition of an “accommodation for diversity” (Wilcox & Leger, 2013, p. 8).

Discussion

These 14 threshold concepts identified in the practices and conceptions of post-secondary educators can be clustered into four categories of teaching-related threshold concepts: teaching or pedagogy, learning, assessment, and teaching with technology (see Table 1).

Pedagogy-related Threshold Concepts

There are seven pedagogy-related threshold concepts: (1) inquiry into student learning, (2) teaching for transfer of knowledge, (3) need for a growth mindset, and (4) context-based practice, (5) care, (6) teaching as a public act, and (7) acknowledgement of threshold concepts.

Shulman identifies four type of teaching knowledge required by proficient educators: (1) subject-matter expertise, (2) pedagogical knowledge (PK), a grasp of the general principles of teaching, (3) pedagogical content knowledge (PCK), the ability to organize, represent, and convey discipline-specific knowledge and skills in a way that facilitates student learning, and (4) curricular knowledge (CK), the way specific topics can, and should, be taught depending on where and when they appear in a program of study (Shulman, 1986). The threshold between competent and proficient educators requires acquisition of PCK and CK which encompass the seven pedagogy-related threshold concepts.

Engineering educators begin with subject-matter expertise, but the majority receive little or no instructional development, reporting that they learned to teach by teaching and through informal discussions with their peers (Nelson & Brennan, 2018). The same study reports that 40% of these engineering educators place some to no emphasis on continued development of their teaching skills. The same percentage rarely or never attends workshops offered by their teaching and learning centres. Such low participation may be caused by a lack of incentive or a perceived lack of relevance to their courses, subjects, students, or challenges (Felder, Brent, & Prince, 2011). Felder and his colleagues note that engineering educators are more likely to participate in instructional development workshops that are designed for them and delivered by a teaching expert with an engineering background. Any opportunities for engineering educators to explore pedagogical and pedagogical content knowledge will facilitate their crossing of the pedagogy-related thresholds and provide an educationally-sound learning experience for their students.

Learning-related Threshold Concepts

There are two learning-related threshold concepts: (1) learner-centred focus, and (2) variation in student learning. Educators who cross these thresholds provide effective learning environments for each of their students.

Research into effective learning environments identifies six broad themes for ensuring student success and value-added learning: (1) academic rigour, (2) a focus on learning, (3) supported instruction, (4) quality of teaching, (5) relationships, and (6) student engagement (Nelson & Brennan, 2019). The focus on learning brings together myriad benchmarks associated with “active and collaborative learning, learning strategies, reflective and interactive learning, higher order thinking, skills development and quantitative reasoning. Each of these directly involves students in, and with, their learning” (p, 2). For students to be successful, educators must make instructional decisions that are “informed by a deep understanding of the learners, along with their active involvement in selecting solutions that work for them” (Higher Learning Commission, 2018, P. 7). Any opportunities for engineering educators to explore how students learn, what motivates them, and ways to offer different pathways to success will facilitate crossing learning-related thresholds resulting in a more effective learning environment for each student.

Assessment-related Threshold Concepts

There are three assessment-related threshold concepts: (1) constructive alignment of assessments with learning outcomes, (2) differentiation of standards and minimum competence, and (3) formative assessment. Educators who cross these thresholds objectively and authentically assess clearly-defined learning outcomes. They also provide ongoing, informative feedback to their students.

In their critical review of assessment practices in engineering education, Subheesh and Sethy report that “most of the engineering faculty members across the globe have a little or inadequate experience in formulating measurable course objectives, assessing students’ performance, and providing appropriate and unambiguous feedback to students” (Subheesh

& Sethy, 2020, p. 13). They recommend engineering educators access appropriate educational development opportunities to help them move from norm- to criterion-referenced assessment practices and provide prompt, appropriate and unambiguous feedback to help students become self-regulated learners and achieve course learning objectives.

Teaching with Technology-related Threshold Concepts

Finally, there are two teaching with technology-related threshold concepts: (1) experimentation with educational technology, and (2) online learning. Educators who cross these thresholds stretch their current pedagogical models and broaden their approaches to teaching to include technological solutions to learning challenges.

Koehler and Mishra extended Shulman's construct of pedagogical content knowledge to include technological knowledge. "The interaction of these bodies of knowledge, both theoretically and in practice, produces the types of flexible knowledge needed to successfully integrate technology use into teaching" (Koehler & Mishra, 2013, p. 62). A review of the use of educational technology in engineering education reports challenges in STEM programs with a "lack of faculty members with the right digital skills and the aversion to change by some" (Hernandez-de-Menendez & Morales-Menendez, 2019, p. 715). They note important benefits for using educational technology including improved acquisition of technical knowledge, better use of pedagogical strategies, and increased student motivation.

Limitations

This QSR/QES is not free from limitations. Although the exploration of threshold concepts is fairly new, there are many papers related to threshold concepts in tertiary education. Few, however, focus on the thresholds that educators themselves encounter in their teaching practices, and none are specific to engineering educators. The review, conducted from April 2020 to March 2021, was limited to three primary sources, and may inadvertently exclude studies relevant to this work. Exclusion decisions, mapping and clustering represent a single point of view and may vary if analyzed by different researchers.

Conclusions

This study fills a gap in the literature by identifying 14 teaching-related threshold concepts that may hinder the instructional development of engineering educators. Recognizing that these pedagogical, learning, assessment, and teaching with technology related threshold concepts exist may facilitate a transformation in the way engineering educators perceive and perform their day-to-day practices.

This research lays the foundation for further work. Study could be done to determine if these threshold concepts are equally important and necessary for the growth of engineering educators, or if certain thresholds hold the key to transformative teaching practices. This study could also provide the basis for an engineering- or STEM-focused educational development program that helps educators consider and cross any or all of these thresholds.

It is hoped that adding these results to the existing body of evidence will encourage both engineering educators and those responsible for their educational development, to support professional growth related to these potential thresholds.

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