THE UNIVERSITY *of* EDINBURGH

Edinburgh Research Explorer

Insights into teaching a complex skill

Insights into teaching a complex skill:
Threshold concepts and troublesome knowledge in electroencephalography (EEG)

Jeremy J. Moeller, MD, MSc, FRCPC[1] and Tim Fawns, PhD[2]

Affiliations
1. Department of Neurology, Yale School of Medicine
2. College of Medicine and Veterinary Medicine, University of Edinburgh

Short Title: Threshold Concepts in EEG

Corresponding Author:
Jeremy Moeller, MD, MSc, FRCPC

Abstract

Background: Threshold concepts (TCs) are defined as ideas within a discipline that are often conceptually difficult ("troublesome"), but when learned, transform a learner's understanding. Electroencephalography (EEG) has been recognized as a conceptually difficult field in neurology, and a study of threshold concepts in EEG may provide insights into how it is taught and learned.

Methods: Semi-structured interviews were performed with 12 EEG experts in the US and Canada. Experts identified potential TCs and troublesome knowledge, and explored how these concepts were taught and learned. Interview transcripts were coded and analyzed using a general thematic analysis approach, based on the core elements of the threshold concepts framework.

Results: One concept (polarity) emerged most clearly as a threshold concept. Other troublesome areas included pattern interpretation and clinical significance, but these lacked some of the characteristics of TCs. Several themes emerged, including the role of TCs and troublesome knowledge in determining expertise and the role of prior experience.

Conclusions: We have used the threshold concepts framework to explore potential barriers to learning, suggest ways to support learners, and identify potential points of emphasis for teaching and learning EEG. A similar approach could be applied to the study of teaching and learning in other conceptually difficult areas of medical education.

Acknowledgements

Declaration of Interest

The authors report no declarations of interest.

Glossary

Threshold concepts: Concepts within a discipline that are conceptually difficult ("troublesome"), but when learned, transform a learner's understanding of the field, opening up new ways of thinking (Meyer, J. H. F., & Land, R. 2003. Threshold Concepts and Troublesome Knowledge: linkages to ways of thinking and practising within the disciplines. In C. Rust (Ed.), *Improving Student Learning - Ten Years On*. Oxford: Oxford Centre for Staff and Learning Development).

Practice Points

- Threshold concepts are areas within a discipline that are often conceptually difficult ("troublesome") but when learned, transform a learner's understanding of the field.
- In EEG education, polarity is the clearest example of a threshold concept.
- The process of identifying threshold concepts can also reveal other types of troublesome knowledge. In EEG, pattern interpretation and clinical significance were identified as troublesome.
- Exploring how threshold concepts and troublesome knowledge integrate with each other can allow the formulation of a "threshold conception" of learning within a field, which may guide curriculum design.
- The learner's background plays a role in their ability to understand threshold concepts, and should also be considered in curriculum design.

Introduction

The framework for threshold concepts (TCs) was first proposed in 2003 by Meyer
and Land, and was first tested in a study of higher education in economics. Since
then, there have been studies of threshold concepts in a broad range of disciplines,
at all levels of education. In their original article, Meyer and Land (2003) described
threshold concepts as "akin to a portal, opening up a new and previously
inaccessible way of thinking about something . . . without which the learner cannot
progress (p. 1)." They propose that the framework can be used as a method of
understanding how learners obtain expertise in conceptually difficult fields. The key
elements of threshold concepts are outlined in Box 1. Much has been written about
the "troublesome" nature of TCs, and about troublesome knowledge in general, and
the main types of troublesome knowledge are also outlined in Box 1

During the process of learning TCs, students occupy a "liminal space," described by
Meyer and Land (2006) as a state of inauthentic understanding. While in the liminal
space, students may resort to mimicry to approximate a deeper understanding. This
can be "compensatory" (e.g. the student defers understanding and opts for a
superficial approach in order to pass an examination) or "conscious" (the student
uses a superficial approach to survive day-to-day activities while working toward
genuine understanding) (Meyer and Land 2006). As learners progress through the
liminal space, they not only internalize TCs, but also become more engaged in the
discourse of their discipline, learning to think like an expert.

Meyer and Land (2006) suggest that understanding exactly *why* and *how* some
concepts are troublesome may be critical in understanding how they are learned,
and how teachers and curricula can support students to move beyond the liminal
space. Among other things, this involves an understanding of the students' "pre-
liminal variation" or the different understandings with which students enter the
liminal state (Meyer and Land 2006).

Threshold Concepts in Health Professions Education

In the years since their introduction, there has been research into TCs in many disciplines, at all levels of educational practice (Flanagan 2016). Compared to some other fields, there has been relatively little published in the medical education literature on TCs, despite the call from some authors for more research in this area (Neve et al. 2016). Threshold concepts could be a particularly useful approach to understanding the transformation of learners as they engage with complex skills and troublesome ideas in medicine, and anticipating areas where learners might get "stuck" in the learning process. As Neve et al. (2016) argue, the threshold concepts framework also encourages a non-linear and individualized approach to learning, an approach that fits well with current trends of integrated medical school curricula and competency-based assessment. The small number of studies involving medical trainees (Blackburn and Nestel 2014; Wearn et al. 2016; Collett et al. 2017) focused mainly on the non-technical aspects of healthcare (e.g. psychology and ethics, emotional engagement, communication management), and we did not find studies in medical education with a focus on more technical cognitive tasks like EEG interpretation.

Threshold concepts have been studied more extensively in other health professions, including nursing (Levett-Jones et al. 2015; McAllister et al. 2015), occupational therapy (Clouder 2005; Rodger et al. 2015) and physiotherapy (Barradell 2013; Barradell and Kennedy-Jones 2015; Barradell and Peseta 2016). Barradell and Peseta (2016) in particular have written about the challenges in identifying threshold concepts, and distinguishing them from key concepts, competencies or learning outcomes.

EEG as a focus of threshold concepts research

The electroencephalogram (EEG) is one of the central diagnostic tests in neurology, and is a central aspect of neurological graduate medical education. Basic proficiency in EEG is required by most groups that provide accreditation for neurologists (ACGME 2013). In spite of these requirements, misinterpretation of EEG has been

identified as a major problem (Klass and Westmoreland 1985; Williams et al. 1985; Benbadis and Lin 2008; Tatum 2013). Several explanations for EEG misinterpretation have been proposed, and the problem may relate to the complexity of EEG interpretation as a clinical skill or to deficiencies in how this clinical skill is taught. Little has been written about EEG education, and in particular, there is little insight to be gained from the existing literature into how or why EEG might be difficult, where learners run into difficulty, or what should be emphasized in EEG teaching. The identification and exploration of threshold concepts could provide some of these insights and could serve as a starting point in curriculum design.

Aims of our research

Our goal was to identify and explore potential threshold concepts and other troublesome knowledge in EEG learning. Further, we aimed to understand teachers' perspectives on barriers to learning and ways in which students could be supported as they engage with TCs and troublesome knowledge in EEG. Although our primary aims were to explore TCs and troublesome knowledge in EEG learning, we hoped that our findings could provide insights into teaching and learning of other conceptually difficult topics in the health sciences.

Methods
Study Setting and Design
Between August 2015 and February 2016, one of the authors (JJM) conducted interviews with 12 neurologists in US and Canadian academic medical centres who have expertise in EEG interpretation and teaching. The semi-structured interview with experts was chosen as a form of what Cousin describes as the "elite" interview, in which the participant provides expertise and authority on a specialized subject (Cousin 2009). These interviews have the potential to harness experts' passion for teaching in order to generate deeper understandings of threshold concepts (Cousin 2009). The individual expert interview is a method that has been used in several studies of threshold concepts, either alone or in combination with other methods (Jordan et al. 2011; Barradell 2013; Quinlan et al. 2013).

Although focus groups have been used in many studies of TCs (Cousin 2009), this method would have imposed limits on our results. Our aim was to obtain a broad perspective on EEG education, from multiple centres, and from people with a range of teaching and learning experiences. As a starting point, it was much more feasible to get such a broad sample of perspectives with individual interviews. In addition, although focus groups may have been helpful in providing consensus, they can also lead to convergence of an opinion that might not accurately reflect the opinions or experiences of all the members (Cousin 2009).

Participants
For the purposes of this study, we generated an operational definition of expertise in EEG interpretation and teaching, as no recognized formal definition was available. We considered those to have expertise in EEG interpretation if they had post-residency training in EEG and certification through a national subspecialty body. We considered subjects to have expertise in EEG *teaching* if they had at least 2 years of EEG teaching experience and a leadership role in EEG education or had produced scholarly work in EEG.

Within these parameters, we recruited a convenience sample of experts, taking several steps to gather diverse perspectives. Both junior and senior faculty members were interviewed, in order to account for changes in learning and practice that may have arisen from technological changes over the last 25 years, including the advent of digital EEG and continuous EEG monitoring (Collura 1993; Gavvala et al. 2014). We invited interviewees who trained, practice and teach in different institutions, in order to avoid interviewing only members of a particular "school" of EEG interpretation. We interviewed both Canadian and US experts in order to broaden the perspectives on learning beyond a single health care system or culture. In order to enrich the sample and invite a range of perspectives, we specifically asked early interviewees to identify experts who might have a different perspective or opinion (Lingard and Kennedy 2010).

Interview Process

Semi-structured interviews were conducted using a standardized interview script, based on the 5 original features of threshold concepts (Box 1). Our interview script was developed around some of the early work in threshold concepts, and we chose not to include the three additional elements in Box 1, which we thought were more conceptually complex and difficult to explain to those without prior knowledge of TCs. However, these elements were evident in the interviewee's responses, and have been included in the analysis and discussion. The interviews started with a brief outline of the TC framework, followed by an explanation that the purpose of the interview was to address two questions: what are some threshold concepts in EEG interpretations; and how might we (as EEG educators) design curricula and teaching strategies to help learners understand these threshold concepts? The initial questions focused on experts' perceptions of the areas of EEG that are fundamental to the grasp of the topic, and areas that are perceived as most troublesome to learners. Follow-up questions about each concept explored the process of acquiring troublesome knowledge and helpful ways of supporting learning. The goal was to understand not only what the threshold concepts are, but how they are learned, why

they might be troublesome, and what role the teacher and/or curriculum might play in facilitating learning.

All interviews were conducted either in person or by video chat, with the exception of one interview that was conducted by telephone because of technical limitations.

Data Analysis

One author (JJM) coded and analyzed the interview transcripts using a general thematic analysis approach (Lingard and Kennedy 2010) in NVivo. Initial units of analysis included examples of potential threshold concepts and the five original characteristics of threshold concepts, as outlined in our interview script (Meyer and Land 2003). Other units of analysis were terms that are linked to threshold concepts such as different types of troublesome knowledge and the liminal state. The discursive nature of threshold concepts was also explored (Meyer and Land 2006). We also included specific topics within EEG learning, as outlined in the interview script. After the first three transcripts were coded, a preliminary analysis was performed which was reviewed by the second author (TF), and the approach to analysis was refined as a result of review and discussion between the authors. Subsequent coding and analysis was performed iteratively, 2-3 interview transcripts were analyzed at a time, and at each stage, the coding framework was modified as needed. When possible, new nodes were reviewed, merged or connected, with constant return to the 5 core elements of threshold concepts.

Results

Through the iterative recruitment process described above, 12 EEG experts were invited to participate, and all agreed to be interviewed. Selected characteristics of the interviewees are contained in Table 1. *Polarity* emerged as a threshold concept that was identified in every expert interview, usually as the first concept that was discussed. Two other themes of troublesome knowledge - *pattern interpretation* and *clinical significance* - contained some features of threshold concepts, but we felt that they did not clearly satisfy all criteria. Experts discussed the role that TCs and troublesome knowledge might play in the learning process and barriers to learning, such as variability in learners' experiences prior to first engaging in EEG interpretation (pre-liminal variation) and the discursive nature of TC learning.

Polarity as a threshold concept

Broadly defined, polarity refers to the direction and extent of an electrical field generated by the brain, and this can be determined by visual analysis of EEG signals. This is important clinically because an understanding of the polarity and electrical field of an abnormality can provide specific insights into the location and potential etiology of an epileptic focus within the brain. Polarity contained the essential elements of threshold concepts, as outlined by the original work of Meyer and Land (2003), and examples of these elements are shown in Table 2. Experts identified that there was some troublesome language related to polarity. Terminology like "sharply contoured" or "phase reversals" are used to describe EEG findings most commonly associated with epilepsy, and many experts observed that EEG learners look for these findings without really understanding why. Several experts suggested that the use of these terms – and especially an inability to elaborate on their physiological relevance – revealed a superficial, incomplete understanding of polarity.

> *"I think that for many of the newbies, they're looking for* sharply contoured *waves. That's the only thing that they've heard about or* phase reversals *or something and that's what they're looking for without any concept of what it really is that we're looking at" (Expert #3).*

Other experts suggested that while the term was problematic, it was possible to find evidence of deeper understanding by probing the student.

> *"... it's a very superficial term. ...You have to ask them, okay, what's the concept behind that phase reversal. If they can understand polarity, they'll tell me. If they don't understand polarity, they can't tell me." (Expert #8)*

This expert suggested it is not necessarily the term "phase reversal" that is troublesome, but whether or not the term is used to compensate for a lack of understanding.

There was extensive discussion of the role that prior educational experiences might have in understanding polarity. Many experts observed that polarity might be troublesome because of its foundation in physics and electronics: topics that may be intimidating to some learners, and may prevent full engagement in the learning process.

> *"I think there's a certain bit of technophobia ... they automatically think because there are pictures of resistors and capacitors in the textbook chapter, that they're not going to get it" (Expert #10)*

A few experts suggested that a strong knowledge of physics and electronics was essential for mastery of the concept of polarity, but others disagreed. Experts discussed their own discomfort with the technical side of EEG, and reflected on how the EEG teaching community may be missing opportunities to make these concepts relevant to students who don't have a strong background in the physical sciences or engineering:

> *"... I think it's frankly dry for many people or most people. I think we don't necessarily as a whole make it that exciting ... We give the same dry lectures about positive and negative charges. It's very easy to fall asleep." (Expert #12)*

Thus, experts did not all agree about why polarity (and the underpinning physical and technological principles and knowledge) was troublesome. Views about the

role of physics might have depended upon the expert's personal experience. Many experts who felt strongly that students should have a deep understanding of the physics and technology talked about how their own approach was rooted heavily in the fundamentals of physics, and some spoke of having some training in physics before entering medicine. Those who felt that it was possible to have some level of expertise without a deep understanding of physics emphasized that it is important to make physics relevant to the task at hand.

> *"I always struggled with [physics] when I was in high school, and undergrad, so I'd always shied away from it. Then just trying to understand more about the basics of the electricity behind EEG led me to read more about the polarity itself" (Expert #9).*

Emphasizing the relevance of the underlying principles may have the effect of encouraging the learner to return to the foundational principles with renewed interest. Some experts suggested that initial engagement with polarity might not require mastery of physics or electronics, but as students advance, and begin to understand more about why the physics is important, they may return to the foundational principles.

Pattern interpretation

Many experts used the term "pattern recognition" in the interviews, but then talked about a process that was more than simple recognition, and for this reason, we have applied the term "pattern interpretation" to this process. This process includes interpretation of the polarity of an electrical field, combined with visual recognition of a pattern and classification of the pattern so that it can be put into clinical context. Pattern interpretation was thought to be troublesome in several ways: it can be tacit, conceptually difficult or alien. Examples of these aspects are shown in Table 3.

Clinical significance

Experts also discussed the troublesome nature of determining the clinical significance of an EEG pattern. This process involves pattern interpretation (and,

thus, an understanding of polarity), but also involves an understanding of the clinical context, disease processes, and the ability to communicate the meaning of the EEG findings to non-experts. Some examples of the troublesome nature of clinical significance are shown in Table 3.

One expert (Expert #10) discussed how it can be particularly difficult for learners to take into account the "audience and the implications" when generating an impression of EEG findings: that is, an EEG report should be modified depending upon who is receiving it, in order to ensure that the findings are not taken out of context or over-interpreted. While many experts observed the tendency of inexperienced EEGers to overstate the significance of EEG findings, almost all expressed a desire that the least skilled EEGers should do the exact opposite. Most experts expressed the opinion that a patient was much more likely to come to harm with over-interpretation of findings. This is troublesome because it is counter-intuitive: in many diagnostic testing modalities, greater harm occurs when a finding is missed, while in EEG, there may be greater harm with over-interpretation. As such, many experts discussed a situation in which they would ensure, at the very least, that learners who did not develop a deep understanding of clinical significance, could remain "safe" by limiting their clinical conclusions.

A "threshold conception" of EEG interpretation
While not necessarily fitting the description of TCs, the themes of pattern interpretation and clinical significance emerged from many of the expert interviews as areas that were troublesome to learners. To varying degrees, both of these activities were rooted in an understanding of polarity, and each of these concepts built on each other. Figure 1 illustrates how polarity was identified as the core threshold concept: a fundamental understanding of polarity is necessary for expertise in EEG interpretation, and learners need to understand pattern interpretation in order to understand clinical significance. Pattern interpretation incorporated an understanding of polarity, but also incorporated other knowledge

and skills. An understanding of clinical significance was seen to build upon

knowledge of polarity and pattern interpretation.

Discussion

As we related our results to the existing knowledge and understanding of threshold concepts and troublesome knowledge, several themes emerged. We believe that these themes could provide useful insights to support teaching and learning in EEG interpretation.

Troublesome knowledge and learning as discourse

Experts acknowledged that some EEG concepts and terminology can be tacit, counter-intuitive or conceptually difficult, and this can impose barriers in EEG learning. Some of the terminology used in EEG interpretation is subject to disagreement, and there is a lack of agreed-upon definitions for some EEG findings. For learners, this can be frustrating, and they may struggle to understand how an expert makes decisions. Learners may oscillate between periods of apparent understanding and moments of frustration when faced with a particularly ambiguous pattern or troublesome terminology (Meyer and Land 2006). Developers of curricula could acknowledge that this oscillation will be a normal part of learning, and should provide maximal opportunities for discourse between expert/teacher and student. In this way, the learner will have the opportunity to move beyond memorizing rules and begin to understand what it is to think and communicate like an expert (Land et al. 2005).

When a learner is not functioning at the level that the teacher expects, there could be many different explanations. By probing for understanding of troublesome knowledge, the teacher may be able to "diagnose" difficulties and thus provide more specific support. Is the problem that the learner is not grasping polarity, for example? Or if the learner does grasp polarity, is the problem related to the student's inability to understand the ambiguities of pattern interpretation? Depending upon the problem, the teacher may be able to recommend readings, resources and exercises, and may choose to focus on the problematic concept in subsequent teaching.

Addressing variation in learners' prior experiences

In order to support learners as they wrestle with threshold concepts and troublesome knowledge, some acknowledgement of pre-liminal variation can be built into the curriculum. For example, it may be useful to inform learners *a priori* that some of them will grasp some concepts quickly, while others may take longer. Learners who do not grasp the concepts as quickly should be reassured that with time, they can eventually get it; their difficulty is not necessarily related to a lack of ability, but also to differences in background and prior knowledge. While lack of prior experience can be seen as a barrier to learning, because TCs involve transformation and reconstitution, learners should also be advised that understanding these concepts may require abandoning or reshaping their preconceptions about the topic. Learners can be further encouraged by being reminded that the process of understanding TCs is often non-linear, with repetition as part of the learning process.

Threshold capabilities

Ultimately, expertise may be determined not only by whether the concepts are understood, but also how that knowledge is applied in practice. Baillie et al. (2013) have proposed combining elements of the TC framework with capability theory to focus on applications of threshold concepts to novel situations, within a framework of "threshold capabilities." Within this framework, the focus is on what the learner should be capable of doing in a novel situation, and then determining what threshold concepts are central to these capabilities. In much the same way as we outline above, educators and curriculum developers can focus on these capabilities to inform all aspects of curriculum design, from learning objectives to the teacher's role, to assessment. In our work, it may be possible to consider some aspects of pattern interpretation and determination of clinical significance as capabilities, rooted in the threshold concept of polarity, as outlined in our threshold conception of EEG teaching and learning.

Implications for further research

The framework of threshold concepts may be particularly useful for understanding how conceptually difficult or "troublesome" knowledge and skills are learned. Ultimately, the goal is to ensure that students understand difficult concepts on an "expert" level, and refrain from either giving up or resorting to superficial understanding. Too often, curricula are filled with educational objectives that are either vague or very specific, and the overall "conception" of the field remains obscure to new learners, until they have gained specific knowledge and experience. As others have written, students may be more comfortable with struggle and ambiguity – and may be less likely to give up – if they are aware of the existence of an overall "conception" of the topic, and if they are reassured that they will eventually understand it (Land et al. 2005). Perhaps the most important next step will be to investigate how to operationalize threshold concepts and troublesome knowledge in curriculum design in medical education, to determine how this approach can inform approaches to teaching complex skills. In our specific area of EEG, the topic of pattern interpretation could be explored further, possibly by comparing and contrasting approaches in EEG with other fields where pattern interpretation is a central element (e.g. radiology or pathology).

Limitations of this study

There may be limitations in including only experts in our analysis. Several authors (Davies and Mangan 2007; Loertscher et al. 2014) have emphasized the importance of confirming the validity of threshold concepts by engaging students in the process. It may not be possible for experts to remember or fully understand why a concept is troublesome, or how it felt to exist in a liminal space (Barradell and Peseta 2016). While we did not include students, we made efforts to include subjects who included EEG teaching as a major component of their professional roles. These subjects were able to reflect on years of experiences with students' struggles, and we believe we obtained some on the challenges that students face in learning EEG.

Barradell & Peseta (2016) have described some of the methodological challenges in engaging content experts in the identification of threshold concepts. The TC framework is complex, and arguably troublesome in itself. In our study, we were less focused on creating a definitive list of TCs in EEG, and more focused on using a unique approach to understanding how EEG could be taught and learned. Therefore, the TC framework functioned to set the stage of the subsequent interview, and arguably a full understanding of TCs was not necessary to generate useful insights.

It is also important to address some of the criticisms of the threshold concepts framework itself. Importantly, the original 5 "defining" characteristics of TCs include several qualifiers, including the words "probably," "often" and "potentially" (Wilkinson 2014). As a result, critics argue, it is difficult to know what are the essential features of a threshold concept (Rowbottom 2007), and how such a concept might differ from similar terms like "core," "fundamental" or "key" concepts (O'Donnell 2010). In addition, even if we accept that threshold concepts exist as distinct entities, they are "agent-relative:" the definition of a threshold concept (particularly the transformative, irreversible, and troublesome aspects) depends upon the experience of the learner (Rowbottom 2007; O'Donnell 2010). Thus, what might be a threshold concept for one learner might not be for another. In our research, there was disagreement between experts about how troublesome certain EEG concepts were, which may provide support for the "agent-relative" argument. However, we do not think that these criticisms detract from our findings or insights. While much of the debate in the literature centres on how a list of threshold concepts is derived, in our research, TCs were not the end itself. Rather, they served as a foundation of an exploration of the teaching and learning of a complex skill.

Reflexivity

We considered several issues raised by the fact that the interviewer and primary author (JM) was both a content expert and a member of the EEG community from which participants were recruited. We addressed recruitment bias by approaching interviewees in an iterative fashion, specifically asking each interviewee to identify

other experts who might have divergent perspectives. We also recruited participants who were both known and unknown by the interviewer, as well as participants who were both junior and senior in academic rank. We hoped that by ensuring a range of relationships between interviewer and interviewees, we would get a broader range of responses.   We also acknowledge that the primary author's position as a content expert could also affect data analysis, which could be biased by the author's preconceptions about EEG teaching and learning. To address this, we ensured that both authors (one a content expert and one not) were involved in data analysis and interpretation. We also considered a potential advantage to the position of interviewer as content expert: in a field as technically complex as EEG, if the interviewer was not an expert, much of the interview time may have been consumed by explanations of the technical aspects of the field. This could have limited the depth of discussion, and even prevented the emergence of the themes outlined in our work above.

Conclusion

We identified one potential threshold concept in EEG education (polarity), and also explored two major troublesome themes: pattern interpretation and clinical significance. We have shown how each of these concepts may relate to each other as a threshold conception of EEG learning: polarity forms the core of EEG understanding, and needs to be understood before learners can understand pattern interpretation or determine clinical significance. Our hope is that these findings have clarified potential barriers to learning EEG, ways in which learners can be supported, and potential areas of emphasis in curriculum design. Learners may oscillate between mimicry and genuine understanding, and the learning process requires an acknowledgment of this, with frequent opportunities for repetition and discussions with experts. An acknowledgement of the variability in experiences that students bring to the learning process (pre-liminal variation) can go a long way to supporting students in overcoming barriers to learning. In addition, these TCs and troublesome knowledge may get to the root of expertise; determining whether a student has truly understood a threshold concept may be a useful foundation for assessment of the very highest levels of knowledge and skills in EEG interpretation.

The threshold conception of EEG learning should be considered a starting point: both for novel approaches to teaching, curriculum design and assessment, but also for further validation with future research. A similar approach could be applied to other areas of medical education where identifying and engaging with TCs may provide focus to a curriculum, allowing teachers and curriculum designers to better understand what students need to learn in order to progress and how to determine the extent to which they understand it.

References

ACGME. 2013. The Neurology Milestone Project. [accessed February 4, 2015]. http://www.acgme.org/acgmeweb/Portals/0/PDFs/Milestones/NeurologyMilestones.pdf.

Baillie C, Bowden JA, Meyer JHF. 2013. Threshold capabilities: threshold concepts and knowledge capability linked through variation theory. Higher Education. 65(2):227-246. English.

Barradell S. 2013. The identification of threshold concepts: a review of theoretical complexities and methodological challenges. Higher Education. 65(2):265-276. English.

Barradell S, Kennedy-Jones M. 2015. Threshold concepts, student learning and curriculum: making connections between theory and practice. Innovations in Education and Teaching International. 52(5):536-545.

Barradell S, Peseta T. 2016. Promise and challenge of identifying threshold concepts: a cautionary account of transactional curriculum inquiry. Journal of Further and Higher Education. 40(2):262-275.

Benbadis SR, Lin K. 2008. Errors in EEG interpretation and misdiagnosis of epilepsy. Which EEG patterns are overread? Eur Neurol. 59(5):267-271.

Blackburn SC, Nestel D. 2014. Troublesome knowledge in pediatric surgical trainees: a qualitative study. J Surg Educ. 71(5):756-761. English.

Clouder L. 2005. Caring as a 'threshold concept': Transforming students in higher education into health (care) professionals. Teach High Educ. 10(4):505-517. English.

Collett T, Neve H, Stephen N. 2017. Using audio diaries to identify threshold concepts in "softer" disciplines: a focus on medical education. Practical and Evidence of Scholarship of Teaching and Learning in Higher Education. 12(2):99-117.

Collura TF. 1993. History and evolution of electroencephalographic instruments and techniques. Journal of clinical neurophysiology : official publication of the American Electroencephalographic Society. 10(4):476-504.

Cousin G. 2009. Researching Learning in Higher Education: An Introduction to Contemporary Methods and Approaches. New York: Routledge.

Davies P, Mangan J. 2007. Threshold concepts and the integration of understanding of economics. Studies in Higher Education. 32:711-726.

Flanagan M. 2016. Threshold Concepts: Undergraduate Teaching, Postgraduate Training, Professional Development and School Education: A Short Bibliography. [accessed June 3, 2016]. http://www.ee.ucl.ac.uk/~mflanaga/thresholds.html.

Gavvala J, Abend N, LaRoche S, Hahn C, Herman ST, Claassen J, Macken M, Schuele S, Gerard E, Critical Care EEGMRC. 2014. Continuous EEG monitoring: a survey of neurophysiologists and neurointensivists. Epilepsia. 55(11):1864-1871.

Jordan K, Tracy F, Johnstone K. 2011. Threshold concepts as focal points for supporting student learning. Bioscience Education. 18(1):1-7.

Klass DW, Westmoreland BF. 1985. Nonepileptogenic epileptiform electroencephalographic activity. Annals of neurology. 18(6):627-635.

Land R, Cousin G, Meyer JHF. 2005. Threshold concepts and troublesome knowledge (3): Implications for course design and evaluation. In: Rust C, editor. Improving

Student Learning. Oxford: Oxford Centre for Staff and Learning Development; p. 53-64.

Levett-Jones T, Bowen L, Morris A. 2015. Enhancing nursing students' understanding of threshold concepts through the use of digital stories and a virtual community called 'Wiimali'. Nurse Educ Pract. 15(2):91-96.

Lingard L, Kennedy TJ. 2010. Qualitative research methods in medical education. In: Swanwick T, editor. Understanding Medical Education: Evidency, Theory and Practice. Chichester, West Sussex: Wiley-Blackwell; p. 323-335.

Loertscher J, Green D, Lewis JE, Lin S, Minderhout V. 2014. Identification of threshold concepts for biochemistry. CBE - Life Sciences Education. 13:516-528.

McAllister M, Lasater K, Stone TE, Levett-Jones T. 2015. The reading room: Exploring the use of literature as a strategy for integrating threshold concepts into nursing curricula. Nurse Educ Pract. 15(6):549-555.

Meyer JHF, Land R. 2003. Threshold Concepts and Troublesome Knowledge: linkages to ways of thinking and practising within the disciplines. In: Rust C, editor. Improving Student Learning - Ten Years On. Oxford: Oxford Centre for Staff and Learning Development.

Meyer JHF, Land R. 2006. Threshold concepts and troublesome knowledge: Issues of liminality. In: Meyer JHF, Land R, editors. Overcoming Barriers to Student Understanding: Threshold concepts and troublesome knowledge. London: Routledge; p. 19-32.

Neve H, Wearn A, Collett T. 2016. What are threshold concepts and how can they inform medical education? Med Teach. 38(8):850-853.

O'Donnell R. 2010. A Critique of the Threshold Concepts Hypothesis and an Application in Economics. Working Paper No 164. [accessed July 18, 2016]:[1-18 p.]. http://www.finance.uts.edu.au/research/wpapers/wp164.pdf.

Quinlan KM, Male S, Baillie C, Stamboulis A, Fill J, Jaffer Z. 2013. Methodological challenges in researching threshold concepts: a comparative analysis of three projects. Higher Education. 66(5):585-601. English.

Rodger S, Turpin M, O'Brien M. 2015. Experiences of academic staff in using threshold concepts within a reformed curriculum. Studies in Higher Education. 40(4):545-560. English.

Rowbottom DP. 2007. Demystifying threshold concepts. J Philos Educ. 41(2):263-270. English.

Tatum WO. 2013. How not to read an EEG: introductory statements. Neurology. 80(1 Suppl 1):S1-3.

Wearn A, O'Callaghan A, Barrow M. 2016. Becoming a Different Doctor: Identifying Threshold Concepts: When Doctors in Training Spend Six Months with a Hospital Palliative Care Team. In: Land R, Meyer JHF, Flanagan M, editors. Threshold Concepts in Practice. Rotterdam: Sense Publishers; p. 223-238.

Wilkinson L. 2014. The problem with threshold concepts. Sense and Reference: A philosophical library blog. [accessed 2016 June 19, 2014]. https://senseandreference.wordpress.com/2014/06/19/the-problem-with-threshold-concepts/.

Williams GW, Luders HO, Brickner A, Goormastic M, Klass DW. 1985. Interobserver variability in EEG interpretation. Neurology. 35(12):1714-1719.

Box 1. Threshold Concepts and Troublesome Knowledge

Characteristics of Threshold Concepts (Meyer and Land 2003, 2006; Baillie, Bowden and Meyer 2013)
• **_Transformative:_** The understanding of threshold concepts leads to a shift in the student's perception of the subject area. • **_Probably irreversible:_** Once they are learned, threshold concepts change perspective so that learners are unlikely to forget them. • **_Integrative:_** They will show the "hidden interrelatedness" of a subject. • **_Often bounded:_** These concepts may form a boundary or demarcation in levels of expertise, and understanding these concepts may serve as a portal to open up new areas of intellectual exploration. • **_Potentially troublesome:_** Troublesome knowledge is "'alien,' counter-intuitive or even intellectually absurd at face value." • **_Discursive*:_** Learning threshold concepts involves enhanced use of language. • **_Liminality*:_** During the learning process, learners occupy a "liminal space" characterized by incomplete or fragile understanding. • **_Reconstitutive*:_** Related to both the transformative and discursive characteristics, learning threshold concepts involves discarding prior conceptual stances regarding the topic.
Types of Troublesome Knowledge (Perkins 1998, 2006)
• **_Ritual knowledge:_** A type of routine knowledge used for a specific task or social ritual. • **_Inert knowledge:_** Knowledge that is known or understood on some level, but rarely used out of a specific context. • **_Conceptually difficult knowledge:_** Knowledge that is difficult to understand at face value. • **_Foreign or alien knowledge:_** Knowledge arising from a foreign or conflicting perspective. • **_Tacit knowledge:_** Knowledge that is acted upon every day, but about which we may not be entirely conscious or aware.

* The last 3 characteristics were added to the original 5 elements of the threshold concepts framework based on further work by Meyer & Land (2006).

Table 1. Selected characteristics of EEG experts interviewed.

ID	Gender	Years of teaching Experience	Location of EEG training	Location of practice	Number of residents taught	Number of fellows taught
1	F	5-10	USA	USA	40-50	10-20
2	M	20-25	USA	USA	>100	70-80
3	M	30-35	Canada	Canada	20-30	1-5
4	M	30-35	USA	USA	0	>100
5	M	30-35	USA	USA	>200	10-20
6	M	15-20	USA	USA	>100	>100
7	F	5-10	USA	USA	20-30	10-20
8	M	35-40	Canada	Canada	>100	40-50
9	M	5-10	USA	USA	40-50	20-30
10	M	1-5	USA	USA	30-40	0
11	M	10-15	Canada	Canada	20-30	0
12	F	15-20	USA	USA	70-80	10-20

Table 2. Polarity as a threshold concept.

Transformative	"*They might say they understand it, but then you ask them a question about it and they clearly do not. Then, one day after the right picture on the screen, all of a sudden everything clicks, and your life is beautiful." (Expert #10)*
(Probably) Irreversible	"*[polarity] seems to be a very hard concept to get through, but it always seems like once they get it, they just got it." (Expert #9)*
Integrative	"*how to transform [EEG] into the idea of a three dimensional electrical field like a topographic map of contours and that's not something that comes immediately to mind." (Expert #3)*
Bounded	"*Once they can understand dipoles and where things are coming from, I think that opens up the field of localization for them as well." (Expert #9)*
Troublesome	"*I think that's why EEG is even more difficult to conceptualize [than radiology]… I mean, not to sound too philosophical but we kind of made this up and decided that there's certain conventions and you have to just learn this and there are rules. That absolutely does not apply in radiology." (Expert #12)*

Table 3. Examples of troublesome aspects of pattern interpretation and clinical

significance.

| Troublesome concept	Example	Type of troublesome knowledge
Pattern interpretation	*"I remember my first day trying to read EEG, someone pointed out an artifact, or I asked, 'What is that?' And they said it was an artifact, and I asked, 'Why?' They said it looks 'artifact-y.' That sums up most of my hatred of trying to learn EEG from that first day, is if you can't explain why something is the way it is, it makes it very hard for someone to learn why it is that." (Expert #9)*	Tacit
	"...when I first started it was all a big jumbled mess, I had no idea what I was doing ..." (Expert #7)	Conceptually difficult
	"I think people come and their only prior experience with anything that remotely resembles this is an electrocardiogram and they try and apply some of the same inspection of these waves that they learned from fundamental [ECG] ... and it really isn't the same at all." (Expert #3)	Foreign or alien
Clinical significance	*"... actually writing an impression is quite difficult: knowing how to make something sound either important or not important ... " (Expert #2)*	Tacit
	"making the distinction between the summary of findings and your impression, is one of the things that I try to stress ...Your impression is your impression, but always keep in mind the audience and the implications." (Expert #10)	Conceptually difficult
	"I always say ... leniency comes with experience. The more you see, the more you tolerate normal variants. In addition, the other factor is, the legal environments in which we here in the United States practice, people are so afraid of missing something that they would rather over-diagnose." (Expert #6)	Foreign or alien
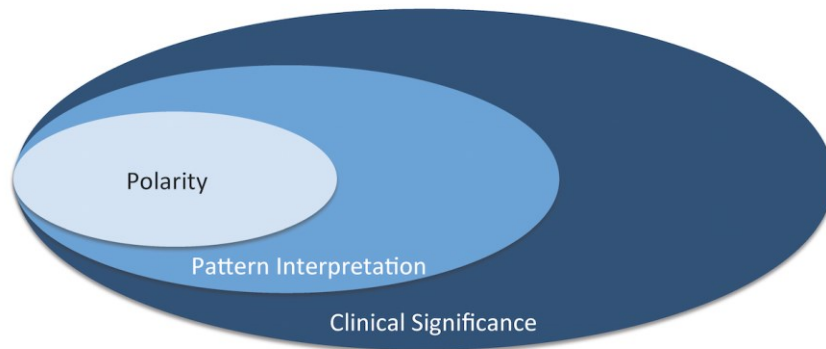
Figure 1. "Threshold conception" of EEG interpretation.

Appendix 1: Interview Script for Threshold Concepts in EEG

Intro:
Threshold concepts are "akin to a portal, opening up a new and previously inaccessible way of thinking about something . . . without which the learner cannot progress"

They are:
1. Transformative: Once understood, their potential effect on student learning and behavior is to occasion a significant shift in the perception of a subject
2. Probably irreversible: The understanding of threshold concepts changes perspective to a point that they are unlikely to be forgotten.
3. Integrative: They will show the "interrelatedness" of a subject.
4. Often bounded: They are a portal through the boundaries or demarcations in levels of understanding of a subject.
5. Potentially troublesome: Troublesome knowledge is "alien" or counterintuitive or even intellectually absurd at face value.

Think about your career as an EEG teacher, and your experiences with students in the context of these ideas as we discuss teaching and learning EEG.

Baseline Data
1. How long have you been involved in the teaching of EEG (including fellowship).
2. How many students have you trained (approximately)?
   a. Residents
   b. Fellows
   c. Others
3. What are the contexts and venues in which you teach (or have taught) EEG interpretation?

Questions about EEG learning
1. What concepts in EEG are fundamental to the grasp of this topic?
2. Of these areas, which have been most "troublesome" to learners, in your experience?
   a. To fellows?
   b. To residents?
   c. To both?
3. [for each concept] Specific to these areas that you have identified, how have you seen learners progress to truly understand these troublesome concepts?
   a. How has the process taken place (gradually or all of a sudden)?
   b. What role have you played as a teacher in facilitating this?
   c. What else has been helpful in getting them to understand troublesome concepts?

        d.   What are barriers to them understanding troublesome concepts?
4. [for each concept] Specific to each of these areas, have they been, and if so how:
   a. Transformative
   b. Irreversible
   c. Bounded (portals)
   d. Integrative
5. What are some overall aspects of the learning environment, teaching strategies, curriculum that are most helpful in allowing learners to truly understand EEG interpretation?
6. What are some general barriers to EEG learning?

Would you like to make any additional comments about EEG learning, troublesome concepts, etc.?

Specific categories [use only if not addressed with answers to questions above]
Please consider troublesome concepts and teaching strategies in the following areas:
- Technical aspects of EEG (montages, polarity rules, filters, etc)
- Normal awake and asleep recordings
- Artifacts
- Normal variants
- Epileptiform discharges
- Seizures
- EEG in critically ill patients.
- Terminology, writing reports