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Threshold Concepts in Neuroscience: Identification Challenges, Educational Opportunities and Recommendations for Practice

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Threshold concepts are recent, yet already established, aspects of medical education. However, they represent a new area in neuroscience education, especially given the recency of neuroscience as a field of research in its own right when compared to more established STEM disciplines. In this article, we reviewed the existing literature on threshold concepts in clinical/translational neuroscience education and argued the relevance and the importance of biomarker as a new threshold concept. Moreover, we included a set of recommendations for practice that has the potential to improve the students' experience by offering them an authentic journey and, ultimately, to build a community of practice with shared goals and an enhanced diversity, with beneficial effects at several societal levels.

Keywords: threshold concepts, educational research, learning, neuroscience education, teaching

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INTRODUCTION

Threshold concepts are recent, yet already established, aspects within medical education. Identified by Jan Meyer and Ray Land in 2003 in "Enhancing Teaching-Learning Environments in Undergraduate Courses", and then more widely in different disciplines, they represent a transformed way of understanding, which is essential and required for the progress of a learner (Meyer and Land, 2003). The understanding of a threshold concept, therefore, results in a transformed view of the subject or transformation of the worldview, or even the identity of a learner (Meyer and Land, 2003, 2006b). They have been likened to a portal, opening up a new and previously inaccessible way of thinking about a topic or an entire discipline (Meyer and Land, 2003).

A threshold concept meets specific criteria (**Figure 1**): it is "(likely to be) transformative, (probably) irreversible, (potentially and possibly inherently) troublesome" and has "the capacity to be integrative and bounded", but is different from a core concept as does "not take the learner into a new realm, but rather build layers upon the learning foundations already possessed" (Barradell, 2013, p 266). The qualifiers mentioned above present flexibility, difficulty or subjectivity in identifying disciplinary threshold concepts. Besides this, one of the criticisms against threshold concepts is their putative lack of sophistication to be characterized as a theory, and their repackaging of, or shortcuts to, other theories (Cousin, 2008). Some critics have questioned the validity of the labeling theories, concepts or ideas as being inherently threshold. Lack of defining characteristics, leading to unclear or fuzzy classification methods, has been highlighted (O'Donnell, 2010). In the absence of clear-cut, well-defined criteria, and of additional qualifiers, these criticisms might be valid. On the one side, the popularity in the use of threshold concepts in education has been growing exponentially, and, according to some authors, even the most ardent critics agree there is a kernel of truth in them (Wilkinson, 2014). Also, most critics do not object to the practical use of threshold concepts as a pedagogical tool whose use in several disciplines has indeed become increasingly popular in recent years (Land et al., 2016). However, on the other side, it has recently been observed that "even if the definitional problems were solved" to the extent of being able "to identify some threshold concepts, their scientific importance would be limited if not nil" (Salwén, 2019, p 1). In other words, even if the existence of the threshold concepts were to be demonstrated, the dismissal of the usefulness of the concept might still be possible.

Despite the lack of strong empirical support for the existence of threshold concepts, if they do exist, they could take a prominent place at the center of curriculum redesign. In light of this, it might be worthwhile to attempt to identify them. While addressing the debate on the existence of threshold concepts is well-beyond the scope of this article, here we reviewed the previously proposed threshold concept in neuroscience and argued the relevance and the importance of the biomarker as a new threshold concept in clinical/translational neuroscience education. Moreover, we included a set of recommendations for practice that has the potential to improve the students' experience by offering them an authentic journey and, ultimately, to build a community of practice with shared goals and an enhanced diversity, with beneficial effects at several levels.

THRESHOLD CONCEPTS IN NEUROSCIENCE: IDENTIFICATION CHALLENGES

An apparent easiness in identifying threshold concepts in established STEM disciplines (e.g., limit as a threshold concept for mathematics, electrostatic bonds for chemistry and Newtonian rules in Physics) seems to be counterbalanced by the apparent lack of easily identifiable threshold concepts in neuroscience. This might be due to neuroscience being a relatively young discipline, "in its own right" only in the 20th century (Catani and Sandrone, 2015); a multi- and interdisciplinary one, where the act of "defining and structuring threshold concepts" is generally more challenging (Holley, 2018, p 28). In addition to this, although neuroscience can also be considered basic science, branches of medicine such as neurology and psychiatry draw heavily on neuroscience, and threshold concepts in the medical field have been "rarely discussed" when compared to other STEM subjects (Neve et al., 2016, p 850).

So far, only one study has attempted to explore the landscape of threshold concepts in neuroscience by interviewing 40 PhD students from US neuroscience programs (Holley, 2018). On the surface, it might seem that no specific concepts were identified. But, factually, Holley did propose a threshold concept that is not *content-based* as she shed light on system perspective as a threshold concept in neuroscience, one requiring as previous content knowledge anatomical (core) concepts, focusing in particular on its transformative and integrative properties. In her own words, a "potential relationship between a systems perspective and anatomy should be acknowledged" (Holley, 2018, p 26). Holley's work takes into account the impact and the implications of the multidisciplinary nature of neuroscience in determining the type of thresholds concepts in this discipline and their difficulty of identification (Holley, 2018). This multidisciplinarity might have an impact on the features of the threshold concepts of this discipline and might affect the quest itself. It is generally assumed that the first threshold concepts to be identified in most disciplines tend to be content-based (Timmermans and Meyer, 2019). But, practically, this was not the case in neuroscience, as a non-content-based threshold concept was identified first (Holley, 2018). This might be particularly relevant and deserving to be noted in the multi- and interdisciplinary context of neuroscience. In fact, while educators often produce content-based teaching materials, similar aspects cannot be neglected or underestimated. If these are threshold concepts, they might be essential for the students themselves.

By considering not only the multidisciplinarity, but also the novelty and the complexity of neuroscience as a field, the reasons why most concepts might meet one or more criteria for being threshold concepts, but not all of them, can be more evident. For example, the relative novelty and the research-in-progress nature of several concepts make them inherently troublesome, and, due to the interdisciplinary nature of the field, many concepts form the borders to, or are integrated within, terminal frontiers of new conceptual areas. However, not every difficult concept can be regarded as a threshold concept, and some fail to be defined transformative, as in any other discipline. In defining discipline-specific threshold concepts, the core criteria need to be revisited and adjusted for the discipline itself. For instance, while the threshold concepts of physics are often troublesome, those in biology might not be difficult or troublesome, but rather the tacit understandings of some aspects of the discipline (Ross et al., 2010; Wilson et al., 2010). Still, neuroscience threshold concepts might, or might not, be troublesome *per se*, and the other criteria might even be met to various degrees. For example, the elegant and straightforward concept of action potential presents a difficulty to a minority of students, yet is potentially transformative, irreversible, bounded and integrative. On the contrary, the gating of ion channels is difficult to grasp for many learners, and it might be a threshold concept that forms the basis for understanding the action potentials. Both concepts can be explored and addressed in future educational works.

With these difficulties in mind, it might be easier to exclude, rather than include, potentially new concepts. Some, but not all, among the Nobel Prize-worthy discoveries in the neuroscience field, as the concept of the synapse (Bennett, 1999; Burke, 2007; Molnár and Brown, 2010) or neurotransmission (Karczmar, 1996; Todman, 2008) might potentially be threshold concepts, but these are also more similar to "core concepts", and not necessarily threshold concepts. As neuroscience education encompasses a variety of domains (Carandini, 2019), from affective to clinical neuroscience, from cellular to computational research, we decided to focus on, and discuss, an example of a potential threshold concept that is

	Key features of a threshold concept	Biomarker as a threshold concept
Transformative	"Occasioning a significant shift in the perception" (Meyer and Land, 2005, p 373)	Biomarker links previously siloed aspects, such as the olfactory system and the loss of neurons in Parkinson's disease
Irreversible	"Unlikely to be forgotten" (Meyer and Land, 2005, p 373)	Neuroscience appears as a new discipline through the 'lens' of biomarkers, and this landscape of knowledge cannot be reverted
Troublesome	"Learning of certain concepts difficult" (Meyer and Land, 2005, p 375)	Deactivating an area of the frontal lobe during a recognition task can be a biomarker for obsessive-compulsive disorder, despite a non-intuitive, logical connection among these
Integrative	"Exposing the previously hidden interrelatedness of something" (Meyer and Land, 2005, p 373)	Biomarker integrates seemingly independent aspects across different levels: molecular to cellular, system to behaviour
Bounded	"The new 'conceptual space' (…)' has 'terminal frontiers, bordering with thresholds" (Meyer and Land, 2005, p 374)	Threshold concepts are possibly, but not always, bounded; for biomarker, this is due to the interdisciplinary nature of neuroscience as its recency
Discursive	"Indissoluble interrelatedness of the learner's identity with thinking and language" (Land et al., 2014, p 201)	It provides new information and new linguistic and graphical representations made of 'signs' and 'endpoints'
Reconstitutive	Integration and reconfiguration, leading to a shift within both the learners' identity and the knowledge	It discards disciplinary boundaries (biology to physiology, pharmacology to medicine) and reconfigures topics and learning

FIGURE 1 | Key features of a threshold concept.

relevant to most, if not all, neuroscience domains: the concept of biomarker.

BIOMARKERS AS A THRESHOLD CONCEPT IN NEUROSCIENCE EDUCATION

By adopting a simple but effective generalization, neuroscience is initially taught as a 1:1 "mapping" of different cerebral regions, where, for example, the frontal lobe is responsible for action planning and Broca's area is essential for language. This is very similar to a phrenological-like approach (Jones et al., 2018), where knowledge can be represented as a series of maps with known functions and uncharted territories. Then, at a certain point in the curriculum, more often in the late stages of the BSc or directly within the MSc, the concept of biomarker is being taught.

The concept of biomarker goes beyond 1:1 mapping. A biomarker, which is technically a *crasis* between the words "biological" and "marker", is a characteristic that is "objectively measured and evaluated as an indicator of normal biological processes, pathogenic processes, or pharmacologic responses to a therapeutic intervention" (Biomarkers Definitions Working Group, 2001, p 91). The discovery of biomarkers constitutes an extremely promising field of study for neuroscience and neurology, as they can inform us about disease diagnosis, progression, and phenotypical heterogeneous variations. Broadly speaking, a biomarker can be, for example, an "early sign" of pathology, e.g., the loss of the sense of smell in neurodegenerative disorders, such as Parkinson's disease (Trivedi et al., 2019). It can also assist in the differential diagnosis (Bowman, 2017). Biomarkers have the advantage of being able to provide the information "earlier, more quickly, and more cheaply" (Aronson, 2005, p 494). However, despite a large number of candidates proposed, few among them have been adopted in clinical practice (Mondello et al., 2020). Furthermore, there are several complexities, confusions and misconceptions associated with the definition of biomarkers, although explaining them goes beyond the scope of this work. Yet it is worth to report that, in addition to the definition of biomarker itself, other expressions such as "medical signs, symptoms, surrogate endpoints, clinical endpoints, validation—are still under discussion, as are their relationships to each other", and with the concept of biomarker itself, within the broad scientific community (Strimbu and Tavel, 2010, p 463; but see also Mondello et al., 2020).

DISCUSSION

As stated in the introduction, there are no universally agreed criteria to identify threshold concepts nor a precise methodology to do so. Therefore, we chose the following set of criteria as these were put forward by Meyer and Land in their original paper published in 2003: transformative, irreversible, troublesome, integrative. We also discussed the "bounded" feature, although this is often, but not necessarily always, an essential element for threshold concepts. In addition to these features, we briefly discussed the discursiveness and reconstitutiveness, which were introduced almost a decade after their original work (Land, 2011). Our reflection emerged from our own experience as neuroscience students and educators, but also in discussion with neuroscience students. While our experience mostly revolves around postgraduate neuroscience education, considering that the concept of biomarker is also increasingly being introduced in undergraduate degrees, we think it can be applied to neuroscience education in the broad sense, hence being valid both before and after graduation.

Transformative

The first and foremost characteristic of the threshold concepts is of being fundamentally transformative. Meyer and Land identified correlations and drew parallels between their definition of transformation and Mezirow's concept of perspective transformation, as "the process of becoming critically aware of how and why our presuppositions have come to constrain the way we perceive, understand, and feel about our world" (Mezirow, 1990, p 14). They particularly refer to Mezirow's idea of disorienting dilemma or challenging perspective involving a phase of withdrawal before re-engagement and integration of a different perspective, corresponding with the instigative effect of threshold concepts (Land et al., 2010). The emphasis of mainstream transformative learning is on liberation from limited ways of being in the world (Kasworm and Bowles, 2012; Hodge, 2018). While a threshold concept is likely to be transformative, not every transformative concept is considered a threshold concept. Grasping the concept of biomarker can be difficult, challenging and transformative. Many students struggle for weeks, "hanging out" in the liminal space to understand the definition and the practical implications of the biomarkers. Similar to a catalytic enzyme in a chemical reaction, this new understanding is transformative in the sense that it re-frames the clinical/translational neuroscience landscape by equipping the students with a new viewpoint. As a result of this, students move from a descriptive view to an active usage of the building blocks. They can "connect the dots" among scientific aspects that, before grasping this concept, seemed siloed, such as the olfactory system and the loss of neurons in the example mentioned above of Parkinson's disease. They are equipped with new maps. As educators, we can see that the students embrace this concept, in all its transformative power, when they start to "play" with it. We can assess this, for example, while reading a review on the potential role of a specific biomarker in translational neuroscience written by them.

Irreversible

The second criterion is irreversibility, as (probably) the new knowledge cannot be easily forgotten or unlearned. In other words, a concept is not likely to be unlearned once it results in a change in identity or perspective and it is used. Neuroscience students seem to "dance", and not necessarily enjoy the dance while it happens, but possibly retrospectively, within the liminal space. This is metaphorically similar to the tribal dances depicted in the pioneering ethnographical works by Van Gennep (2011) and Turner (1969). Its *rite de passage* touch is further reinforced by the inexorable destiny of failure that awaits the students that do not grasp it in a reasonable time. This is useful in clustering the knowledge: the concept of biomarker is not a concept they can strategically memorize, but something that changes their learning experience. Clinical/translational neuroscience itself appears as an almost entirely new discipline that arguably can be defined through the "lens" of biomarkers, and this landscape of knowledge cannot be reverted. Students struggle to look back at neuroscience through the previous mapping, as, at this post liminal stage, embracing the discipline with a biomarker-powered awareness seems to occur as a "more natural" option. Understanding the concept of biomarkers can, therefore, be considered irreversible in the sense that "the change of perspective occasioned by the acquisition of a threshold concept is unlikely to be forgotten" (Meyer and Land, 2003, p 4).

Troublesome

Students report, vocally and in feedback, the difficulty they experience after being exposed to this concept for the first time, and while going through the learning process. This process does not have the same timing for each student. This is not part of the inert neuroscientific knowledge as it does not "sit in the mind's attic" (Perkins, 1999, p. 8): to sit in their mind's attic, people need to have been exposed to it, which is unlikely for its very low-to-null frequency of occurrence in our society. But it is conceptually difficult knowledge as per the definition that Perkins (1999) provided for scientific disciplines. Moreover, it can be described as a sort of tacit knowledge where "emergent (. . .) understandings are often shared within a specific community of practice" (Wenger, 1998, cited in Meyer and Land, 2003), i.e., the neuroscientific community at large. Biomarkers do not exist just within the neuroscience community, but in neuroscience they have found a new definition. They are highly heterogeneous and can feature a mix of behavioral phenotypes and neuropsychological evidence, imaging evidence (Sandrone, 2012) or even being non-neuroscience-related and still having a neuroscientific relevance, with no obvious underlying links. The underpinning process encompasses a learning trajectory from specific mapping to higher-order/abstract (and, possibly, undiscovered) connections. Its knowledge can be counterintuitive. For instance, it has been recently demonstrated that the ability to deactivate a portion of the frontal lobe while doing a simple recognition task could be an early biomarker for Obsessive-Compulsive Disorder (Hampshire et al., 2020), despite a non-existent intuitive, logical connection among these elements. And this also applies to the first example linking the sense of smell to the loss of neurons which, before embracing the concept of biomarker, might seem to belong to two different territories. Overall this reinforces Holley's viewpoint of threshold concepts in neuroscience as being challenges to the learners "while considering new ways of knowing that may even appear to be counterintuitive" (Holley, 2018, p 26) to the previous knowledge.

Integrative

The word integrative comes from the Latin "integrare", which means "making whole". Threshold concepts would indeed reveal previously hidden (or previously perceived unrelated) interrelations (Meyer and Land, 2003). Uncovering the interrelations between old and new knowledge, the linkage of different aspects of the same concept and revealing the interconnections among knowledge across disciplines are forms of integration. Further expanding on the previously cited example, finding a biomarker for the Obsessive-Compulsive Disorder allowed the scientific community to integrate two different aspects, namely the behavioral outcome and the neuroimaging evidence, hence "making whole" of them. Passing the portal of the biomarker, as a threshold concept, indeed exposes the students to "the previously hidden interrelatedness of something" (Meyer and Land, 2005, p 373).

Bounded

Threshold concepts are possibly bounded, in that they might form the borders to the terminal frontiers of a conceptual space into new conceptual areas (Meyer and Land, 2006a). "Often (though not necessarily always) threshold concepts are bounded in that any conceptual space will have terminal frontiers, bordering with thresholds into new conceptual areas" (Meyer and Land, 2003, p 5). The authors specified that this does not need to be "necessarily always" the case (Meyer and Land, 2003). Boundedness has also been suggested to be central to forming scholarly mindsets particular to a discipline (Barradell and Fortune, 2019). It is challenging to define biomarker in postgraduate clinical/translational neuroscience as a bounded concept, perhaps due to the interdisciplinary nature of the neuroscience as a new field, where knowledge is often framed and contextualized in multiple disciplines.

Discursive and Reconstitutive

As noted by Barradell (2013), while reviewing the theoretical complexities and methodological challenges related to identifying threshold concepts, less than a decade later two more characteristics, "discursive" and "reconstitutive", were added (Land, 2011). The discursive shift occurs during passing through the liminal space, as a result of the discursive *quid* of subjectivity (Ross, 2011) and "an indissoluble interrelatedness of the learner's identity with thinking and language" (Land et al., 2014, p 201). In other words, encountering troublesome knowledge in the liminal spaces, by definition, is discursive as it involves "attempts to derive meaning from symbolic representation, linguistic, mathematical or graphical" (Land et al., 2014, p 203). This aligns well with the reflections of Becker et al., referring to the same aspect of the process in a class of medical students: "students acquire a point of view and terminology of a technical kind, which allows them to talk and think about patients and diseases" in a different way (Becker et al., 2005, p 421).

The inherent troublesomeness of threshold concepts instigates unsettling of prior understandings, which leads to a state of liminality. The integration of new knowledge within this state requires reconfiguration and even discarding of the learner's prior schema and conceptual stance. The reconstitutive feature of the threshold concepts is viewed as integration and reconfiguration, leading to a shift within both the learners' identity and the knowledge ("ontological/epistemic shift", Meyer et al., 2010, p 6).

Moreover, this feature can equally refer to the identity of the learner or the identity of knowledge. If this feature relates to the former, it is difficult to attribute it to the grasping of the concept vs. the natural trajectory of a student at that level of the learning process. Yet, it still seems to strengthen a new "neuroscientist" identity on the students' side. If this feature refers to the latter, it can be better seen as the "volitional" change theorized by James (1902). The volitional type is of interest here as it consists of "a series of step changes" or "jerks and starts" that accumulated over some time, and this is more akin to the experience of an educational programme (Land et al., 2014, p 208).

Potential Limitations

In addition to the discussed limitations, there are two potentially major limitations to biomarker being a threshold concept in postgraduate clinical/translational neuroscience education. The first one pertains to the definition of biomarker itself, which, according to some observers, is ill-defined (Naylor, 2003; Califf, 2018). While it is true that "clarification of the definitions of different biomarkers and a better understanding of their appropriate application could result in substantial benefits" (Califf, 2018; p 213), this criticism can be dismantled by a more operational, and not merely linguistic, definition of biomarker, one that needs to be "evaluated" and "re-evaluated" (Strimbu and Tavel, 2010) in different contexts. Furthermore, "biomarker discovery is an ongoing process, with (its) translation being tested *de novo* in every single study, providing us with the opportunity to revise our knowledge of the complex scheme of human physiology and pathophysiology" (Puntmann, 2009; p 538). In light of this, the lack of a repository for the neuroscientific biomarkers discovered so far does not diminish its value nor its validity as a threshold concept. Further, it renders this criticism tangential, almost irrelevant. A second possible limitation can be that the pedagogical approaches or teaching methods might influence the "existence" of biomarker as a threshold concept. Another criticism might be that the concept of biomarker can be a threshold (or not) depending on how the curriculum is taught, how much time is dedicated to it and if such a concept is thoroughly explained or not. For example, if there is not enough time for teaching it, mostly due to packed curricula and a limited amount of resources, it might be a rather tricky threshold concept to grasp. However, in several biomedical and life sciences disciplines, including medicine, the concept of biomarker is more foundational and is often introduced very early on in the curriculum. Despite being (extensively) taught early in the curriculum, such a concept still meets most of the criteria for being considered a threshold concept, therefore also the second limitation is way less impactful than what it might seem at first glance.

Recommendations for Practice

Supporting curriculum (re)design has been recently suggested as a primary purpose for identifying threshold concepts (Tucker, 2019). Whilst designing the "ideal" neuroscience curriculum might be challenging due to the numerous neuroscience domains, defining a core/minimum curriculum can help delineate a national/international benchmark. Limiting the analysis to the tools available to social sciences (i.e., without considering a statistical and relative approach to try to reach a consensus to exclude the concepts from being a threshold concept), three actionable aspects, here listed in a gradient from the classroom to the scientific community, can be identified.

1) Conducting a comprehensive study on a large cohort of graduate-level neuroscience students and educators with the goal of identifying candidate threshold concepts in neuroscience. Following the suggestions put forward by Barradell (2013), a consensus approach based on the Nominal Group Technique or the Delphi Technique (McMillan et al., 2016) can be adopted.
2) "A tight cooperation among and between" people "doing research" and those putting "data into a broader perspective" might be required (Sandrone, 2013, p A2). Given the scientific diversity of the neuroscience community, the second step is to perform a study on the stakeholders from the relevant communities to investigate whether the candidate threshold concepts reach a consensus and/or if new ones emerge. This approach will utilize "transactional curriculum inquiry" (Barradell, 2013) and will create an informed viewpoint on both sides of the threshold. Involving the stakeholders can be instrumental in aligning the existing neuroscience curricula to the needs of the job market and the expectations of future employers. Among the stakeholders to involve in this project will be the directors of postgraduate studies, the heads of the neuroscience departments and also representatives from the pharmaceutical and biotech industry, as only a percentage of early-career scientists stay in academia (Royal Society, 2010).
3) The newly identified threshold concepts can be used to (i) design the "core/minimum" neuroscience curriculum for a new, blended course, (ii) to facilitate their transition and progression to becoming young neuroscientists, and (iii) to market the graduate level courses to external constituents, considering that a gap, specifically related to the interdisciplinary programmes, has been identified (Pizarro Milian and Missaghian, 2018).

These recommendations for practice also have the potential to further improve the students' experience by offering them a truly authentic journey. The students will have the chance, in turn, to contribute to building a community of practice with shared goals and an enhanced diversity, which mostly derives from a more inclusive pool of participants, to foster a culture of excellence and respect, with beneficial effects at several societal levels.

CONCLUSIONS

The debate surrounding the existence of threshold concepts across disciplines is extensive and far from being concluded. New curricula can be re-designed based on the "thresholds" that students need to cross in their learning journey. Our article represents a pioneering attempt at initiating the process of identification of threshold concepts in neuroscience education and the first one in identifying a content-based threshold concept for clinical/translational neuroscience.

AUTHOR CONTRIBUTIONS

Both the authors listed have made a substantial, direct and intellectual contribution to the work, and approved it for publication.

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