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Core concepts: views from physiology and neuroscience

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Core concepts are "big ideas" that are central to a discipline, provide frameworks of understanding for disciplinary content, and aid student transfer of learning. Core concept lists have been developed for increasing numbers of higher education STEM disciplines. This mini-review uses physiology and neuroscience core concepts as examples to inform core concept pedagogies in these and other disciplines. The article reviews the development of physiology and neuroscience core concepts and compares the resulting concept lists. It then provides suggestions or "lessons learned" for educators and researchers who wish to utilize core concept pedagogies or who wish to develop core concepts for other STEM disciplines.

KEYWORDS

core concepts, physiology, neuroscience, STEM higher education, pedagogy

1 Introduction: what are core concepts?

The term "core concepts" is appearing with increased frequency in the science education literature. While it is difficult to formulate exactly what is meant by a "concept" (Michael et al., 2017b) in the field of education the term "core concepts" is usually synonymous with the term "big ideas" defined in the quotations below from leading education researchers.

> *"Each [big idea] is well tested, validated, and absolutely central to the discipline. Each integrates many different findings and has exceptionally broad explanatory scope. Each is the source of coherence for many key concepts, principles, and even other theories in the discipline."* (Duschl et al., 2007, p. 223)
>
> *"By definition, big ideas are important and enduring. Big ideas are transferable beyond the scope of a particular unit...Big ideas are the building material of understanding. They can be thought of as the meaningful patterns that enable one to connect the dots of otherwise fragmented knowledge."* (Wiggins and McTighe, 2005, p. 338–339)
>
> *A big idea is not simply a topic that typically appears in textbooks, but a key concept that cuts across all topics within a discipline. "A big idea can be described two ways: as involving an enduring principle that transcends its origins, subject matter or place in time; and as a linchpin idea—one crucial to a student's ability to understand a subject."* (Wiggins and McTighe, 1998, p. 113)

What "big ideas" or core concepts have in common is that they:

- are applicable to understanding many phenomena within their domain,
- can facilitate student transfer of learning within a current course, across courses making up the curriculum, in one's eventual career, or one's daily life,

- provide tools that can be used in solving problems within the domain,
- can provide faculty with help in organizing courses or curricula.

It is important to note that core concepts (big ideas) are not a list of topics to be learned (Wiggins and McTighe, 1998) and this is true of both the physiology core concepts (Michael et al., 2009; Michael and McFarland, 2020) and the neuroscience core concepts (Chen et al., 2023, 2024).

A core concepts approach to teaching and learning STEM subjects is rapidly growing. Physiology (Michael and McFarland, 2011; Tangalakis et al., 2023), neuroscience (Chen et al., 2023), and pharmacology (White et al., 2023; Guilding et al., 2024) are but three examples.

As neurobiologists with teaching experience in physiology and neuroscience, we frame similarities and differences between core concepts of physiology and neuroscience (with occasional contrasts to pharmacology) to set up the suggestions that conclude this paper.

2 Core concept development: important considerations

When developing core concepts, the process and resulting concept lists are fundamentally shaped by the rationale and goals for the project. The rationale and goals that shaped the physiology and neuroscience core concepts projects (Michael et al., 2017a; Chen et al., 2022, 2023) may, therefore, be instructive for groups who are interested in developing core concepts lists for other fields. Additionally, given that the rationale and process for development fundamentally influenced the content and nature of the existing physiology and neuroscience lists, understanding the rationale and goals for each project may help educators to interpret and effectively implement these core concepts into their courses and programs.

2.1 Core concept development: rationale for development

The physiology core concepts project (see Michael et al., 2017a,b,c,d,e,f,g for a full description of the history of this project) was sparked by a nation-wide movement (Michael, 2007; Michael et al., 2008; AAAS, 2010; Alpern et al., 2009) to transform biology education from a "memorize and regurgitate" pedagogical model to a "concepts-based" model. The goal of this movement was to improve student understanding of biology. It was a movement that aimed to transform pedagogy and hence what and how students learned biology.

The core concepts of physiology project was an offshoot of this movement. Michael and McFarland (2011) surveyed faculty from a wide spectrum of institutions of higher education (McFarland and Pape-Lindstrom, 2016), asking respondents to "…describe the big ideas that you want your students to understand." The core concepts were from the outset aimed at providing all physiology students, at whatever educational level, tools that would facilitate their learning of the physiology that their instructors expected them to learn. One way in which the physiology core concepts project aimed to do this was by emphasizing concepts that facilitate transfer of learning (Michael, 2022; Doherty et al., 2023) from one topic already mastered (e.g., blood flow in the circulation) to a new topic being studied (e.g., air flow in the airways). Transfer of learning is difficult (Bransford et al., 1999; Wiggins and McTighe, 2005) and students need help to learn to do this.

On the other hand, a subsequent Australian group (Tangalakis et al., 2023) started with the Michael and McFarland (2011) list of core concepts and selected six that they thought best suited physiology curricular structure in Australian universities. They have gone on to describe their approach to incorporating core concepts in physiology curricula for undergraduate majors (these papers can be found in the core concepts collection of articles on the *Advances in Physiology Education* website at http://journals.physiology.org>journals>advances). Briefly, the goals of this project emphasized curriculum mapping in a particular educational context.

The neuroscience project, like the original physiology project, aimed to develop core concepts that help students to transfer learning across topics and courses. However, the context in which the core concepts need to be utilized is somewhat different for neuroscience than physiology, meaning that the process and nature of the resulting concept list is also somewhat different. Neuroscience research and education are founded in a wider breadth of disciplinary underpinnings compared to physiology. Neuroscience is not only psychology and biology, but is also a computational, philosophical, and cognitive discipline. Neuroscience and neuroscience education increasingly prioritize psychological and other non-biological perspectives, as well as transdisciplinary learning (Akil et al., 2016).

Further, while physiology instructors have long agreed upon fundamental body systems to be covered (albeit with changing emphasis and detail), neuroscience education is newer. The first blueprints for undergraduate neuroscience programs were developed by Faculty for Undergraduate Neuroscience (FUN) and Project Kaleidoscope (PKAL) and included models for programs housed in psychology, programs housed in biology, freestanding neuroscience minors, and freestanding neuroscience majors (Ramirez, 1997). These blueprints were expanded and updated in 2005 and 2018 (Wiertelak and Ramirez, 2008; Wiertelak et al., 2018).

Today, neuroscience higher education is delivered in widely varying contexts, from programs with structures represented in the blueprints to free-standing courses in a range of home departments (Pinard-Welyczko et al., 2017). The relative recency of neuroscience education expansion, coupled with the integrative and expanding nature of neuroscience, can make it challenging to identify key big ideas that we should prioritize for student learning or that students should be able to transfer across topics and coursework. This problem served as the impetus for developing core concepts for neuroscience higher education.

2.2 Core concept development: educational approaches

Educational contexts in which core concepts will be implemented should also inform both the development and nature of the core concept lists. Physiology is a mechanistic discipline with boundaries defined by organ systems. It generally takes a reductionist approach to investigation and education in which phenomena are deconstructed into increasingly smaller physical components to understand how they occur. Here, we use a narrow definition of "mechanism" explained by Ross and Bassett: "mechanism is narrow in that it refers to causal systems with particular features that are often reductive. These mechanisms "underlie," "underpin," or "implement" higher-scale systems and are characterized by microscale processes, physical–causal interactions, spatial-geometric features and an emphasis on fine-grained detail" (Ross and Bassett, 2024, p. 84).

Many physiology core concepts are mechanistic given the reductionist nature of physiology education (for example, flow down gradients, cell theory, mass balance, etc.). Neuroscience can be mechanistic and reductionist, as exemplified by cellular and molecular neuroscience. But neuroscience education also emphasizes emergent outputs and behaviors at the circuit and system levels—a challenging task due to the complexity and changeability of nervous systems and brains. For example, parallel processing, neuromodulation, large-scale activity patterns, dendritic computation, and the impact of experience on future outputs continue to present challenges both in investigative limits (technological and analytical) and in defining their contributions to behavior and cognition (Bargmann and Marder, 2013; Gjorgjieva et al., 2016; ACD BRAIN Initiative Working Group 2.0, 2019; Sanbonmatsu and Johnston, 2019).

Ross and Bassett (2024) distinguish causal systems from mechanisms, as causal systems:

> *do not include lower-scale factors or physical-impact, mechanical connections. Examples of this usage include "network mechanisms," "large-scale mechanisms", "systems'-level mechanisms", "circuit mechanisms", "global mechanisms", "top-down mechanisms"... as they reveal causal connections without lower-scale or physical detail.* (Ross and Bassett, 2024, p. 84).

Helping students understand nervous system function can require a causal approach for which mechanistic details have not been distilled or for which molecular and cellular mechanisms may not be the best scale for understanding (Ross and Bassett, 2024). Given this causal approach, and given the requirement that neuroscience core concepts be applicable across all subdisciplines (cellular, computational, cognitive, etc.) (Chen et al., 2023), it is perhaps not surprising that core concepts for neuroscience education are more thematic—akin to Vision and Change core concepts—than mechanistic (AAAS, 2010).

Core concepts do not describe content, facts, topics, or textbook units in either physiology or neuroscience. In both disciplines, core concepts provide unifying themes across which student knowledge can be built without prescribing courses and curricula or defining research fields and disciplinary boundaries. For example, students may learn about long term potentiation (LTP) as a synaptic mechanism underlying learning or hyperalgesia. Students may also learn about cognitive development of adolescents and its relation to white matter. Plasticity, as a core concept, unifies these seemingly separate content items to help students understand plasticity as fundamental to nervous system function rather than seeing them as two compartmentalized events. This framework then helps students approach new problems and contexts, such as applying plasticity concepts toward spinal cord injury treatment or neural mechanisms of trauma.

3 What has been learned?

As other science fields begin to consider adopting a core concept approach to teaching their discipline, is there something to be learned by comparing the experiences of physiology and neuroscience in doing the same? Does the story of the development of core concepts by the pharmacology community shed any additional light on this process of educational change? Below, we consider lessons that may inform future use of core concepts and future developers of core concepts in other STEM disciplines.

3.1 Define the problem you are trying to solve

The starting point for identifying core concepts of any discipline is recognizing the problem you are trying to solve. The biology/physiology core concepts movement (see Michael et al., 2017b) was a consequence of the realization that students were memorizing large volumes of facts but were not building robust mental models with those facts.

The neuroscience faculty (Chen et al., 2022, 2023) wanted to identify big ideas that are critical for understanding nervous system function in the face of widely varying curricular and institutional contexts.

Other groups may have different problems that they hope core concepts will solve. For example, the pharmacology community (White et al., 2023; Guilding et al., 2024) is explicitly responding to reduced hours in the curriculum for their discipline and the need to identify what the most essential topics are in this field. They were attempting to answer the question "what do students need to know to be successful in their chosen profession."

In each case the specific problem being addressed necessitated a somewhat different solution as can be seen in the differences in the core concepts of physiology, neuroscience, and pharmacology.

3.2 Identify the audience you are addressing

Another lesson is the need to define the intended audience and context for the core concepts. The list of core concepts of physiology published by Michael and McFarland (2011) was based on the responses of a wide spectrum of physiology teachers at all levels of higher education to this request: "describe the big ideas that you want your students to understand." Thus, the initial steps in the project clearly addressed the question of what teachers thought physiology students should know. This question and its answer affected decisions made about all aspects of the core concepts and their deployment in the physiology classroom.

For example, the conceptual frameworks (see "unpacking" discussion in 5.6 below) that have been written and validated for Flow-Down Gradients (Michael and McFarland, 2011), Homeostasis (McFarland et al., 2016), Cell Membrane (Michael and Modell, 2019), and Cell-Cell Communications (Michael et al., 2017g) are formatted as either "flat" hierarchies of ideas or items organized in deep hierarchies, depending on which structure was deemed most appropriate for student and instructor use. In all cases, the language of the core concepts and the language of the conceptual frameworks was chosen to be understandable by students.

The Australian physiology group (Tangalakis et al., 2023), on the other hand, was addressing a perceived curricular problem: the need for consistency of physiology majors (programs) in all Australian universities. They were addressing physiology program or curricular leaders. The decisions they made about what core concepts to include on their list reflects this audience and problem this audience was trying to solve. The group started with the list of core concepts published by Michael and McFarland (2011) but did not include those core concepts learned in other STEM courses taken by their students and opted to keep core concepts that will serve as tools for student learning of physiology as well as inform curricula decision-making.

The group generating the neuroscience core concepts began with a nationwide survey that asked faculty to identify core concepts for neuroscience, provide rationale, and distinguish why a suggestion was a core concept rather than content, competency, or topic (Chen et al., 2022). The core concepts were then drafted for a faculty audience to maximize precision in vocabulary and ideas. For example, the neuroscience core concepts and/or their explanatory paragraphs reference "units" that are scalable to different levels of analysis including molecular, cellular, circuit, or network rather than enumerating each level of organization in each concept (Table 2 preamble; Chen et al., 2023). Writing for a faculty audience assumes that the instructor will translate a core concept as appropriate for their subdiscipline and topics (i.e. interpret the concept at the neuron level vs. behavioral or network level). Similarly, the pharmacologists (White et al., 2023; Guilding et al., 2024) are addressing faculty but in an attempt to define what students learning pharmacology ought to know.

3.3 Define what you mean by a core concept

It is also important to define what is meant by a "core concept" in any discipline that attempts to identify them. Each of the core concepts of physiology (Michael and McFarland, 2011) can serve as a tool for understanding a wide variety of physiological phenomena and facilitate the transfer of learning (Michael, 2022; Doherty et al., 2023) from one physiology topic already understood to a new topic being learned.

A particular challenge in identifying neuroscience core concepts was reconciling the breadth of sub-disciplines (behavioral, cognitive, computational, cellular, etc.) with the goal of facilitating learning transfer. Therefore, the requirement that an idea be foundational across subdisciplines was imposed when defining neuroscience core concepts. Additional requirements, including that an idea be true across organisms with nervous systems, are detailed in Chen et al. (2023).

In contrast, pharmacology educators (White et al., 2023; Guilding et al., 2024) adopted a definition of a core concept that clearly states that each of the core concepts is a "topic" that students are expected to understand to prepare the students to function in their eventual careers given their goal of identifying the most essential elements of a curriculum.

The definition being used matters because it influences the final products: the list of core concepts, their conceptual frameworks or "unpackings," and any concept inventories that get developed. These definitions also matter in that any discussion about the use of core concepts in a particular discipline must involve a shared understanding by the community about what is meant by a core concept. If one community seeks to learn about the use of core concepts in another discipline it is important that their definition of a core concept be understood. As has been demonstrated here, the definition of a core concept differs in the three domains we have discussed.

3.4 Implementation

The developers of the core concepts of physiology (Michael et al., 2017b; Tangalakis et al., 2023), neuroscience (Chen et al., 2023), or pharmacology (White et al., 2023; Guilding et al., 2024) are clearly suggesting that changes are needed in the way their disciplines are taught. This leads to the following questions to be confronted by these groups and any other seeking similar changes.

What changes in courses or curricula are you advocating? What would the "new" courses or curricula look like? How should these changes be introduced into existing courses or curricula? How can successful strategies for change be shared? Are core concept learning resources available and, if not, who will produce them?

Finally, there is the fundamental question of whether any implementation, either at the course or the curriculum level, is successful, and how would you know? That is, are the proposed changes solving the problem(s) that led to the adoption of a core concepts focus? Questions like these are particularly difficult to answer; educational research is inherently difficult (Berliner, 2002).

3.5 Get buy-in from your community

Adoption and revision of the physiology core concepts has occurred gradually over the course of more than a decade (Crosswhite and Anderson, 2020; Michael and McFarland, 2020; Stanescu et al., 2020). Implementation of core concepts to inform teaching and learning in neuroscience is also likely to occur incrementally through the work of many educators and education researchers. Published examples of implementation, as well as empirical evidence of outcomes, provide real examples for inspiration, adoption, and evaluation.

Professional organizations can play a multifaceted role in promoting adoption of core concepts through their support for educational research and educators' professional development. For example, the Center for Physiology Education (CPE) of the American Physiological Society has promoted core concepts in the past 3 years through the creation of on-line instructional modules (Michael and McFarland, 2022), a conference titled "From Concept to Classroom," and facilitating the creation of a collection of core concept-focused physiology problems.

Conferences and workshops, primarily through the American Physiological Society, have provided physiology educators and researchers and opportunity to discuss advances, difficulties, examples, and theory underlying core concept use. Neuroscience meetings such as the FUN Workshop, Neuroscience Teaching Conference, or Society for Neuroscience Annual Meeting are similar opportunities for neuroscience educators and education researchers. It will be imperative that these conversations derive from a wider group of neuroscience educators than only a core research group. Further, buy-in from neuroscience educators will take time as educators initially make small changes to their courses and pedagogies that, if effective, inform larger changes.

Buy-in can occur at the level of individual faculty and the course(s) they teach. But, buy-in can also be sought at the departmental or institutional level. In some institutions a bottom-up approach may be more fruitful while at other institutions a top-down approach may yield better results.

3.6 Availability of learning resources

Widely shared resources for learning activities, curricular mapping, and course- and program-level assessment will improve effective use of core concepts, conserve energy, improve buy-in, and allow for collaborative improvement of the work.

Various learning activity formats might incorporate core concepts. Empirically identifying characteristics of successful tools will help others construct additional activities. Characteristics that seem helpful to-date include:

- Activities should provide insight into why the core concept matters scientifically and how it helps organize key ideas/topics (Mitchell et al., 2017). To that end, instructors might emphasize the entire concept sentence rather than only the concept title. For example, emphasize *"Nervous systems encode and transmit information in various modalities"* rather than simply "Communication Modalities."
- Embed core concepts throughout the entire course to the extent possible (Etherington et al., 2023). Repeated exposure to concepts in different contexts is important for transfer of learning.
- More is not better. Be specific about which concepts are most relevant to an example and why, given specific course objectives and context. Students tend to apply as many concepts as possible (J. Schaefer, personal observation). However, focused attention to fewer concepts is more productive—core concepts cannot all be addressed simultaneously.

Assessment and curricular mapping resources should also be developed and shared. Assessment resources may include concept inventories to be implemented at the course or program level (Cary and Branchaw, 2017; McFarland et al., 2017). Assessment resources are an important strategy for getting students to focus on core concepts given that assessment tends to orient studying. Curricular mapping resources scaffold big ideas among courses. Each program will do this differently. As such, sharing of curricular mapping resources will provide inspiration for others' work, but will likely not be directly replicated given that core concepts do not prescribe content or topics.

Important support for teaching and assessment tool development comes from "unpacking" core concepts into conceptual frameworks. Unpacking breaks a core concept into its essential conceptual elements (Khodor et al., 2004; Cary and Branchaw, 2017; Michael et al., 2017f). Physiology concepts of Homeostasis (Michael et al., 2017e; Beckett et al., 2023), Flow Down Gradients/Movement of Substances (Michael et al., 2017d; Brown et al., 2023), Cell-cell Communication (Michael et al., 2017c; Chopin et al., 2023), and Physiological Adaptation (Estaphan et al., 2023) have been unpacked to-date. Work is underway to unpack neuroscience concepts of Plasticity, Gene-Environment Interactions, Evolution, and Structure-Function Relationship (Chen et al., 2024). Conceptual frameworks help detail, for instructors and students, what understanding students should take with them into the future. Conceptual frameworks can also assist program scaffolding and alignment (Brownell et al., 2014) and can explicitly identify common misconceptions or barriers to learning (Mitchell et al., 2017).

3.7 One size will NOT fit all

Core concepts, conceptual frameworks, and associated learning resources are tools for improving teaching and learning but there is no "best" way to use them. Ultimately, the most effective use of core concepts and related resources will depend on the learning goals of each program, course, or instructor. It will require intentional use of core concepts to complement course content and competencies. Instructors and program directors should implement and modify pedagogies and resources as best fits their unique contexts and student needs. After all, the teacher's job, at any educational level, is to help the learner to learn (Michael and Modell, 2003).

There is also no "best" way to get buy-in from the faculty who teach a discipline. In some institutions a "top down" approach may be the most effective way to bring about change. In other institutions a "bottom up" approach may prove most effective.

4 Concluding comments

A core concepts approach to teaching STEM disciplines is increasingly evident. The problems that this approach is intended to solve are different in different disciplines but compelling in each of them. Nevertheless, the process of revising the way any particular discipline is taught is complicated and can be difficult. Thus, it is important that STEM educators share ideas about what has been successful and what has not.

What is needed now is data about implementation; what has been tried and what have been the consequences of implementing these new approaches. At the same time, each discipline that attempts to implement a core concepts approach must determine what constitutes success for their reform movement and how best to assess whether, or to what extent, the new approach has been successful. There is much work for all of us to do.

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