Community-Derived Core Concepts for Neuroscience Higher Education

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ABSTRACT

Core concepts provide a framework for organizing facts and understanding in neuroscience higher education curricula. Core concepts are overarching principles that identify patterns in neuroscience processes and phenomena and can be used as a foundational scaffold for neuroscience knowledge. The need for community-derived core concepts is pressing, because both the pace of research and number of neuroscience programs are rapidly expanding. While general biology and many subdisciplines within biology have identified core concepts, neuroscience has yet to establish a community-derived set of core concepts for neuroscience higher education. We used an empirical approach involving more than 100 neuroscience educators to identify a list of core concepts. The process of identifying neuroscience core concepts was modeled after the process used to develop physiology core concepts and involved a nationwide survey and a working session of 103 neuroscience educators. The iterative process identified eight core concepts and accompanying explanatory paragraphs. The eight core concepts are abbreviated as communication modalities, emergence, evolution, gene–environment interactions, information processing, nervous system functions, plasticity, and structure–function. Here, we describe the pedagogical research process used to establish core concepts for the neuroscience field and provide examples on how the core concepts can be embedded in neuroscience education.

INTRODUCTION

The heterogeneity of neuroscience program structures and institutional contexts creates a set of challenges for curricular development. For example, some neuroscience programs are housed in a biology, psychology, or other department, whereas others are stand-alone programs, and courses in neurobiology and physiological psychology predated these programs. Despite this inconsistent curricular foundation, programs are rapidly increasing. When the first quantitative analysis of undergraduate neuroscience education in the United States was conducted, there were more than 100 programs during the 2008–2009 academic year (Ramos *et al.*, 2011). Since then, the number of undergraduate and graduate programs in neuroscience has continually increased, along with an increase in the number of students graduating with degrees in neuroscience (Ramos *et al.*, 2016; Pinard-Welyczko *et al.*, 2017; Rochon *et al.*, 2019). During the 2017–2018 academic year, 7208 students graduated with a neuroscience major. As of 2019, there were 221 unique institutions offering 223 undergraduate neuroscience programs (Rochon *et al.*, 2019). These challenges underscore the importance of identifying a consensus set of core concepts that can be applied in diverse programs, providing a common organizational framework for understanding content knowledge.

Previous efforts to develop neuroscience higher education programs have focused on curricular structure and competencies. The first national effort to develop "blueprints," or road maps, for undergraduate neuroscience programs occurred only

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25 years ago (Ramirez, 1997). The blueprints provide guidance on developing and sustaining neuroscience major (and minor) programs, including identification of fundamental principles and core competencies necessary for an effective neuroscience education. Periodic revisions of these blueprints and other curricular recommendations have occurred (Ramirez, 1997; Wiertelak and Ramirez, 2008; Wiertelak *et al.*, 2018; Kerchner *et al.*, 2012). Most recently, Ramirez (2020) summarized the following curricular recommendations and competencies for a neuroscience education:

1. promote critical and integrative thinking,
2. develop oral, written, and visual communication skills,
3. articulate the interdisciplinary and interdependent nature of the field,
4. build competency in quantitative reasoning,
5. build competency in experimental design, and
6. promote an appreciation for how neuroscience may contribute to solving pressing societal problems.

Many of these competencies are similar to those recommended for undergraduate biology education in *Vision and Change* (American Association for the Advancement of Science [AAAS], 2010). In his consideration of the opportunities and challenges for undergraduate neuroscience in the 21st century, Ramirez (2020) also emphasized a recommendation from *Vision and Change*: Educators need to focus on considering the foundational concepts that define the field and the fundamental skills that are required to do the science (AAAS, 2010). Similarly, the National Research Council recommended that both undergraduate and graduate students be exposed to concepts that cut across disciplines and learn to think across scales of time and complexity (National Research Council [NRC], 2008, 2009).

Core concepts are the foundational principles that define the field and can be applied to all subdisciplines. Subdisciplines, specializations within neuroscience that typically have some overlap, include behavioral, cellular and molecular, clinical, cognitive, computational, and developmental neuroscience. D'Avanzo *et al*. (2008, p. 71) defined core concepts as "abstract principles that can be used to organize broad areas of knowledge and make inferences in the domain, as well as determining strategies for solving a wide range of problems." Wiggins and McTighe (2005, p. 338) defined core concepts as "meaningful patterns" that are "transferable beyond the scope of a particular unit." In contrast, fundamental facts state basic information that is introduced to novices. Core concepts organize fundamental facts. For example, the steps involved in synaptic transmission are fundamental facts of neuroscience rather than concepts, because this information does not provide a principle that can be used to organize multiple subdisciplines in neuroscience.

Core concepts are also distinct from core competencies (NRC, 2008; AAAS, 2010). Core competencies refer to fundamental skills that are necessary to be an effective practitioner in a field. These core competencies include analytic and scientific thinking and rigorous and responsible conduct of research. Many of the six recommendations (Ramirez, 2020) address core competencies, and a set of core competencies for undergraduate neuroscience education was recently released by the Society for Neuroscience (n.d.).

Organizing neuroscience education around core concepts promotes student learning (Wood, 2008; Koba and Tweed, 2009; AAAS, 2010; Michael *et al.*, 2017a). Foundational, essential principles (core concepts) can be broken into smaller ideas and principles. As such, core concepts provide an organizational structure for the learning of new facts and explanations. New knowledge can be scaffolded within these core concepts to provide students a deeper understanding as they progress through the curriculum. Explicit instruction on core concepts exposes students to the integral role that theoretical and conceptual frameworks play in the practice of neuroscience research (NRC, 2008). If core concepts are used to organize neuroscience education, they can be incorporated into a single course or a course sequence. Core concepts are also useful for assessment, as course instructors, program directors, and department chairs can use core concepts to structure assessment of student learning in specific courses and curricula (Perez *et al.*, 2013; McFarland *et al.*, 2017; Semsar *et al.*, 2019; Scott *et al.*, 2020). Core concepts are useful for organizing knowledge and for structuring curricula and assessments, but they do not prescribe any particular curricular or assessment structure.

While curricular recommendations have been made and revised, and core competencies in neuroscience identified (Kerchner *et al.*, 2012; Society for Neuroscience, n.d.), a community-derived set of core concepts has not yet been developed. The Society for Neuroscience developed and maintains an interactive list of essential principles in neuroscience at BrainFacts.org (2018) (Neuroscience Core Concepts, 2018). These essential principles were developed primarily for outreach to the K–12 population, aligning content and factual understanding with U.S. Next Generation Science Standards for life sciences, physical sciences, and engineering. The work presented here is distinct from the BrainFacts.org (2018) list, because it involves a broader population of contributors and focuses on identifying principles and frameworks for higher education. These community-derived concepts were developed and refined through an iterative process by incorporating feedback from neuroscience educators representing a broad range of postsecondary colleges and universities over surveys and an interactive working session. This work enhances and supplements the ongoing efforts to support and develop curricular blueprints and core competencies for neuroscience higher education and is intended to provide a framework for organizing neuroscience content within and across courses in program curricula.

METHODS

Our goal was to generate a community-derived set of core concepts for neuroscience higher education. To identify concepts that cut across multiple subdisciplines of neuroscience, it was important that experts from different neuroscience subdisciplines were involved in the suggestion, analysis, and revision of core concepts and explanatory paragraphs. This was not intended to indicate unanimous approval of all core concepts, but rather general agreement. Community-provided input and feedback refined the core concepts to a point where all were accepted by the majority of participants.

Nationwide Survey

Before distribution, survey questions were pilot tested for question clarity and flow. Pilot testers were selected for either their

a

Nationwide Survey Participants	n
Undergraduate Neuroscience Program Director	25
Graduate Neuroscience Program Director	6
Undergraduate neuroscience curriculum development	56
Graduate neuroscience curriculum development	15
Faculty teaching undergraduate neuroscience coursework	95
Faculty teaching graduate neuroscience coursework	30
Staff teaching neuroscience coursework	2
Pre-faculty teaching neuroscience courework	8
Research position	21

c

Pre-working Session Survey Participants	n
Undergraduate Neuroscience Program Director	25
Graduate Neuroscience Program Director	4
Undergraduate neuroscience curriculum development	50
Graduate neuroscience curriculum development	10
Faculty teaching undergraduate neuroscience coursework	77
Faculty teaching graduate neuroscience coursework	16
Staff teaching neuroscience coursework	2
Pre-faculty teaching neuroscience courework	1
Research position	17

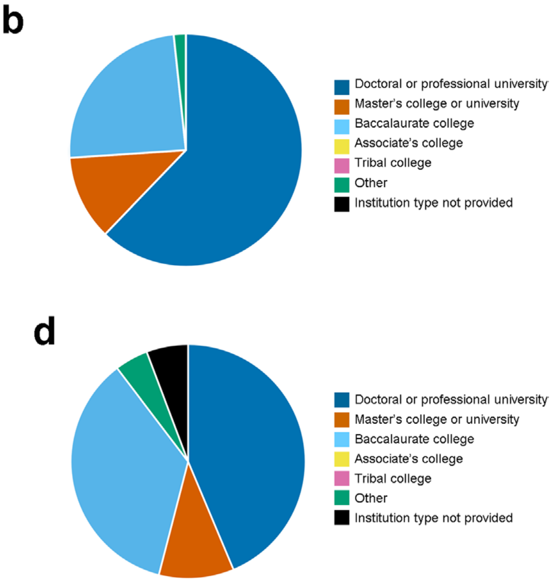

FIGURE 1. Demographics of participants in nationwide survey and pre–working session survey. Representation of neuroscience educators and education researchers in the nationwide survey (a, b) and pre–working session survey (c, d). (b) Of 119 participants in the nationwide survey, 61% were primarily affiliated with a doctoral or professional university, 12% with a master's college or university, 25% with a baccalaureate college, and 2% with an institution not classified under the Carnegie Classification of Institutions of Higher Education. (d) Of 87 participants in the pre–working session survey, 44% were primarily affiliated with a doctoral or professional university, 10% with a master's college or university, 36% with a baccalaureate college, and 4% with an institution not classified under the Carnegie Classification of Institutions of Higher Education; 5% declined to provide their institution type.

familiarity with neuroscience or prior experience in identifying core concepts in other disciplines and were not associated with the institutions represented in our research group. Two biology education researchers with doctoral training in the neurosciences agreed to participate in the pilot study. Feedback from this sample group was used to refine and improve the items. Neuroscience educators were invited to participate in the process of suggesting core concepts through American Physiological Society (APS), Faculty for Undergraduate Neuroscience (FUN), and Society for the Advancement of Biology Education Research (SABER) Listservs, word of mouth, and social media. We collected core concept suggestions between February 25, 2020, and May 31, 2020, using the Qualtrics survey software. The survey consisted of the following sections: 1) demographic data, 2) primer to explain what qualifies as a core concept, and 3) generation of one or more core concepts (survey available in the Supplemental Material). We collected demographic data on survey respondents' role(s) in neuroscience education, areas of expertise in neuroscience, institutions, and institution types (Figure 1). In some cases, respondents opted out of providing demographic information. Individuals who were unable to identify as at least one of the following roles in neuroscience education were excluded: undergraduate neuroscience program director (major or minor), graduate neuroscience program director, undergraduate neuroscience curriculum development, graduate neuroscience curriculum development, faculty teaching undergraduate neuroscience course work, faculty teaching graduate neuroscience course work, staff teaching neuroscience course work, pre-faculty teaching neuroscience course work (e.g., postdoc), or research position. The explanatory primer gave participants definitions of core concepts and examples of core concepts for biological literacy in general biology and differentiated core concepts from fundamental facts, topical subdisciplines, and core competencies. One hundred nineteen faculty participated at this stage. For each core concept suggestion, participants were also asked to explain why they suggested it as a core concept.

Survey Analysis and Drafting of Proposed Concepts

We used an inductive, data-driven coding approach to identify recurrent themes from the survey (Birks and Mills, 2015). To ensure that our coding fully captured all ideas, we used a simultaneous coding approach that allowed multiple codes to be applied to one suggested core concept. Demographic information was removed before coding; however, information on whether two core concepts were suggested by the same survey respondent was retained. Each coauthor reviewed all participants' justifications and independently coded all responses from the nationwide survey. We did not set a minimum threshold number of respondent suggestions for inclusion of a concept, because it was conceivable that a strong concept could be suggested by a single or few individuals who provided strong rationale. We then examined the overlap of our codes and discussed whether emerged themes met criteria to be considered a core concept. As previously described in Chen *et al.* (2022), we defined the following parameters for neuroscience core concepts:

- Applicable across subdisciplines of neuroscience: A core concept is a principle that transcends across subdisciplines of neuroscience. Any concept that is integral to neuroscience should be applicable to any subfield.

- Clear: Core concept statement should be the simplest statement that conveys the essential nature of the concept. These statements should be concise, readable, complete, and accurate in order to maximize comprehension and minimize misinterpretation.
- Timeless: Core concepts should reflect principles that are enduring. Experimental findings may alter our knowledge base of facts in a dynamic process, such that the scientific consensus shifts on various facts. However, principles are not as liable to change, because they describe a fundamental nature or design of nervous systems. Statements of core concepts should be written to withstand new experimental discoveries.
- Applicable across all species that have a nervous system: Each core concept must be correlated to all creatures that have a nervous system.
- Unpackable (broader than a fact): Concepts connect disparate facts by organizing facts into patterns. The AAAS *Vision and Change* report (2010) recommends that educators use facts to promote understanding of broader concepts. Therefore, concepts can be deconstructed or "unpacked" into smaller ideas (Michael *et al.*, 2017b), some of which may be more tightly connected to a given subdiscipline of the field.
- Distinguishable from skills: Concepts are different than competencies. Competencies are characterized as soft and hard skills that can be taught. Core concepts, however, are overarching principles encompassing the knowledge across all subdisciplines in a field.

Responses that identified facts were not eliminated but were coded according to the larger concept theme(s) illustrated by those facts. For example, "Neural development (neural tube, dorsal ventral patterning, SHH signaling)" illustrated the role of genes in development and were binned under the core concept "gene–environment interactions"; and "Perception is an active process, so some of the distortion or discrepancy between percept and measured physical energy arises not just through the limits of sensory organs, but through their active function, which changes with experience and intention" illustrated both "information processing" and "nervous system function." For further examples of raw responses, see the Supplemental Material.

After independent coding and identification of emerged themes, the themes were converted into core concepts across five iterations. In the first iteration, a preliminary statement was crafted to convey the essential nature of the core concept that emerged from the data. Language from survey responses was used to identify the specific components that should be encapsulated within each core concept. We discussed whether the preliminary statement fully captured the breadth of data collected within an identified code. In the second iteration, the summary statement was refined and a descriptive paragraph was composed in order to summarize the full breadth of data in a comprehensible narrative. The focus of this round of reliability check was to ensure both the statement and explanatory paragraph fully captured the data collected within the identified code. These first two rounds were followed by three iterations that primarily focused on refining verbiage for clarity, accuracy, and completeness. Each of these iterations involved all four coauthors in discussions on how to maintain clarity while preserving the intended meaning conveyed by survey respondents. We rotated as lead editors and lead reviewers on each core concept in order to rigorously check core concepts for clarity, accuracy, and completeness with each iteration.

Working Session

A working session to refine core concepts was hosted over Zoom as a satellite event to the FUN Summer Virtual Meeting in 2020. The satellite event allowed us to capture the FUN audience while also inviting education researchers outside of the FUN membership, such as those from SABER. Neuroscience educators were invited to participate in the working session through APS, FUN, and SABER Listservs, word of mouth, and social media. The virtual format of the working session allowed international participation from a broad array of neuroscience educators. One week before the working session, registrants were given a draft of the eight proposed core concepts and were asked to complete an associated survey. The pre–working session survey consisted of the following sections: 1) demographic data; 2) primer on the criteria used to determine core concepts; 3) five-point Likert-scale questions that asked participants whether a core concept met the criteria for a core concept, served an important role in neuroscience education, and served a unique role from the other seven proposed core concepts; and 4) an open-ended question to solicit missing core concepts. Details about the working session, midsession survey, and debrief survey have been previously described in Chen *et al.* (2022).

Revision of Concepts to Produce Final Document

Data from the working session were collected through a transcript of the written chat, recording of the Zoom session, and three Qualtrics surveys.

Statistical Analysis

Descriptive statistics are provided for the evaluation of the proposed core concepts. Pre–working session survey responses were analyzed for association of responses with respondent area(s) of expertise using the Fisher-Freeman-Halton test Monte Carlo method (SPSS v. 28) and a significance level of $p < 0.05$. When a respondent listed a combination of multiple areas of expertise, the combination of areas was used in the analysis. The alternative method of splitting a respondent's areas of expertise would have resulted in nonindependence of rows in the Fischer-Freeman-Halton analysis, because a single individual listing three areas of expertise would have been counted three times—once under each area of expertise.

This study was determined to be exempt from the College of Saint Benedict/Saint John's University Institutional Review Board, Trinity University Institutional Review Board, University of California Irvine Institutional Review Board, and Wright State University Institutional Review Board.

RESULTS

We used an empirical approach to identify neuroscience core concepts based on neuroscience educator recommendations. The initial nationwide survey from February–May 2020 generated 195 proposed higher education core concepts from 119 neuroscience educators. Table 1 summarizes the number of participants involved in each stage of the development of the core concepts. Following the multiple iterations by the researchers to combine and categorize similar proposed themes, eight

TABLE 1. Outline of activities and summary of participants involved in developing core concepts for neuroscience

	Activity	Purpose	Sample
1	Nationwide survey	Collect core concept suggestions from neuroscience educators who represent the breadth of neuroscience subdisciplines and institution types	119 neuroscience educators
2	Survey analysis and drafting of preliminary core concepts		
3	Pre–working session survey	Asynchronous assessment of proposed core concepts to guide working session discussions	87 neuroscience educators and education researchers
4	Participation at working session	Collectively discuss and brainstorm strengths of preliminary core concepts and suggest revisions	103 neuroscience educators and education researchers
5	Midsession survey	Small group assessment of individual preliminary core concepts for importance and comprehensiveness	56 neuroscience educators and education researchers
6	Postsession debrief survey	Assess how proposed core concepts fit with one another and gather remaining concerns	27 neuroscience educators and education researchers
7	Analysis of working session feedback to finalize the core concepts		

preliminary core concepts were identified, and associated conceptual statements and explanatory paragraphs were developed for each concept.

As noted in the *Methods*, survey responses represented stakeholders across different roles in neuroscience education (Figure 1). In addition, the demographics of contributors from the multiple activities (Table 1) included 133 different institutions representing a diverse complement of institutions, including nine Asian American Native American Pacific Islander–serving institutions (AANAPISIs), three historically Black colleges and universities (HBCUs), 11 Hispanic-serving institutions (HSIs), and two primarily Black institutions (PBIs). The minority-serving institution classifications come from the U.S. Department of Education. The large majority of contributors were faculty from institutions in the United States. Eleven participants in the nationwide survey were from outside the United States, and five participants in the working session were from outside the United States. We did not collect information about institutions or countries represented among participants in the pre–working session survey, midsession survey or postsession survey.

These preliminary core concepts were distributed to participants of the 2020 working session of the FUN Summer Virtual Meeting, and participants were asked to complete a survey before attending the working session. One portion of the survey asked whether the participant agreed that each concept met the criteria of a core concept, as previously described (Figure 2a). A strong majority of survey participants thought each proposed concept met the criteria of a core concept, with a positive response (moderately agree or strongly agree) ranging from 79.1% to 97.7% of respondents. The survey also addressed the importance of the core concept to neuroscience higher education (Figure 2b), whether the core concepts were unique from the other core concepts (Figure 2c), the rank importance of each concept to neuroscience education (Figure 2d), and whether the participants believed any core concepts were missing. Of the respondents, 73.3–97.7% indicated that the proposed core concepts were important or absolutely essential, and between 72.1% and 89.8% indicated that each proposed core concept was probably or definitely unique. Furthermore, when asked whether any core concepts were missing, 70% of respondents indicated that the list was complete and did not suggest additional items for inclusion in an open-ended question. The remaining respondents suggested a few additions to the core concepts but did not agree upon core concepts that should be added. Many suggested additions were incorporated into the existing concepts, and some, such as ethical issues in neuroscience, were determined to be competencies rather than concepts. Overall, the results from the pre–working session survey supported the assertion that these were core concepts, that they were important in neuroscience higher education, and that there were not any other concepts missing.

To examine whether support for each concept differed based on respondents' neuroscience backgrounds, we examined whether responses to pre-working session survey questions were associated with respondent area(s) of neuroscience expertise (cellular and molecular, systems, behavioral, etc.) using the Fisher-Freeman-Halton test. We chose the pre-working session survey over the postsession debriefing survey (which also collected respondent expertise) for this analysis, because it provided a larger sample size. Respondents were able to select more than one area of expertise, resulting in the 87 respondents identifying 43 combinations of areas of expertise. For the question asking whether each concept met the criteria for a core concept, the only significant association between response and area(s) of expertise was for the structure–function core concept ($p = 0.017$). However, 81 out of 87 respondents "agreed" or "strongly agreed" that the structure–function concept met the criteria for a core concept. So, while individuals with varying expertise may have evaluated the core concept differently at this stage, there was strong support that the concept met the criteria for a core concept. For the question asking whether a core concept was distinct from the other seven concepts, responses for the evolution concept associated with respondent expertise ($p = 0.049$), but 75 out of 86 respondents indicated that it was "probably" or "definitely" unique. Finally, for the question asking how important a core concept was, only responses for the plasticity concept associated with respondent area(s) of expertise ($p = 0.003$). All respondents indicated that the concept was "moderately important" or "important" (15) or "essential" (72), so the difference of opinion between respondents with different expertise related to the strength of support for the concept rather than whether they supported the concept.

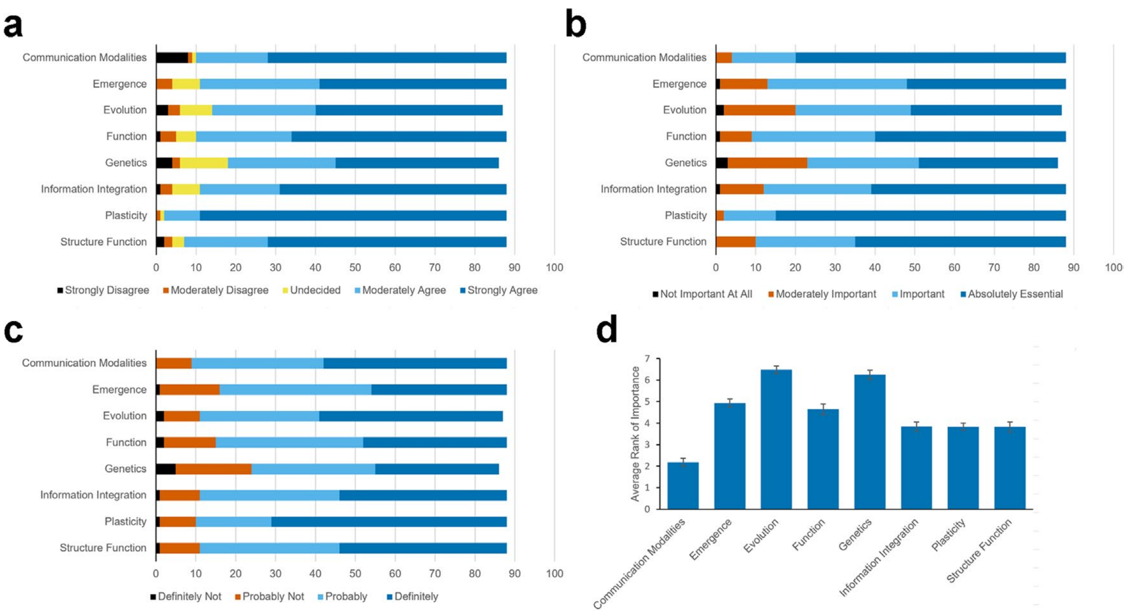

FIGURE 2. Survey results from participants of the 2020 working session at the FUN Summer Virtual Meeting. (a) Level of agreement with the proposed core concept meeting the criteria set forth for being a core concept. Each response is color coded to indicate the number of participants who selected that choice. (b) Importance of each core concept to neuroscience higher education. Responses are color coded and represent the number of participants who indicated that choice. (c) Uniqueness of each core concept from the other. Results reflect the number of respondents who voted for a given choice. (d) Core concepts ranked for importance to neuroscience higher education. Respondents ranked all eight concepts (1 = most important to 8 = least important), which are reported as the mean ± SE.

In all three significant cases identified, there was no clear pattern in which a single area of expertise answered differently than the other areas, because respondents were able to choose more than one area of expertise, such that individuals' responses may have been influenced by the combination of expertise areas that they represented.

During the working session, we hosted 103 educators who offered comments and suggestions, both orally and via the Zoom Chat feature. Upon review of the feedback, we determined that there were three main suggestions for revisions to the preliminary core concepts list. First, we needed to more directly incorporate behavioral, cognitive, computational, and clinical subdisciplines of neuroscience into the explanatory paragraphs. Second, it was recommended that we create a preamble to introduce key aspects of the core concepts, including the targeted audience, a description of how the core concepts might be used, explanations of the terminology, and an acknowledgment of the interdisciplinary foundations of neuroscience as well as some overlap between the core concepts. Finally, based on the feedback offered during the working session, we attempted to balance the incorporation of neuroscience-specific language with broad applicability for each explanatory paragraph. We created explanations that encompassed the multitude of facets and subdisciplines under the umbrella of each core concept while maintaining neuroscience-centric specificity to ensure that the neuroscience core concepts could be differentiated from other branches of science.

Participants were asked to provide feedback on each proposed core concept throughout the working session and in a postsession debrief survey. In the postsession debrief survey, participants were asked whether they felt each core concept should be eliminated, kept with modifications, or kept as is. Twenty-seven participants completed the survey and each indicated favorably that each core concept should be kept with modifications or kept as is (Figure 3). Approval of individual concepts varied from 66.7% to 100%. "Genetics" and "evolution" received the most votes to eliminate (9 and 7, respectively), as some participants felt that these were general biology core concepts rather than neuroscience-centric. It was clear in both the survey and working session that there were a variety of views on whether genetics and evolution should be included and on how best to include them. During the working session, participants debated whether genetics and evolution each warranted a stand-alone core concept. Participants presented views supporting incorporating evolution and genetics into other existing concepts. For example, "Like evolution, genetics could easily be integrated with the other core concepts." Another participant said, "The genetics concept could also be axed, for the same reason as the evolution concept—unless we feel that genetics function differently in Neuroscience." Others argued that genetics was an overarching principle required for neuroscience literacy. For example, one participant said, "You can't understand the nervous system without understanding genetics. The point of this list of concepts is not to explain how/where neuroscience is different from biology or chemistry or physics. It's to include the main concepts needed to understand the nervous system." Another participant argued, "It seems even the more biological concepts, evolution and genetics, have there [*sic*] place among these concepts." As a compromise, we adapted the evolution and genetics core concepts to have more explicit connections to the neuroscience-specific context, as suggested by a spokesperson for a subcommittee of participants: "Evolution and Genetics sections should … be written a little more neuro-specific." Participants also suggested incorporation of environmental influences that affect genetics. For example, a

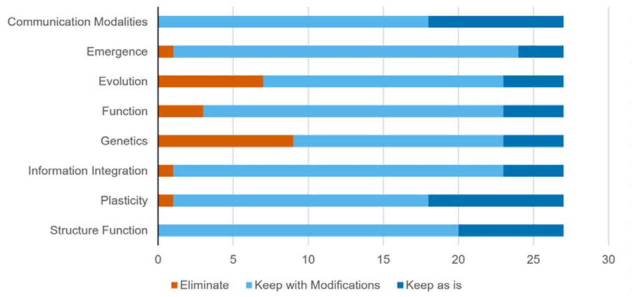

FIGURE 3. Debrief survey results following 2020 working session at the FUN Summer Virtual Meeting. The survey asked whether each preliminary core concept should be kept, revised, or eliminated. Results from 27 participants are color coded for each concept and indicate the number of respondents who selected that choice (reprinted from Chen *et al.*, 2022, with permission from the publisher).

spokesperson from a subcommittee said, "Environmental factors were under emphasized, but genetic factors were over emphasized. Should be a focus on a combination of environmental and genetic factors." As a result, the genetics core concept was adapted to form the core concept "gene–environment interactions." The evolution core concept was similarly revised.

In addition to asking whether individual core concepts should be eliminated or modified, participants were also asked whether additional core concepts needed to be added (question 4 in the Postsession Debrief Survey, Supplemental Material). Twenty people responded. Six responses indicated that no additional core concepts were needed. Six responses indicated that behavior/cognition needed to be added as its own concept or better incorporated into the existing concepts. Similarly, there was one suggestion to incorporate clinical neuroscience into the core concepts. As mentioned earlier, we more directly incorporated examples from these subdisciplines into the explanatory paragraphs of the existing core concepts, given that many of the suggestions to enhance behavioral and clinical aspects of neuroscience also directly tied clinical and behavioral neuroscience to existing concepts. There were four responses indicating that neuroscience is an interdisciplinary field and should be added as a core concept. The interdisciplinary nature of the field was added as part of the preamble to Table 1, given that these suggestions seemed to focus on the structural organization of the field of neuroscience and its many overlapping branches/niches, rather than discrete core concepts that frame the knowledge in the field. As well, six responses suggested including methods and ethics as a core concept. However, these are competencies that, while important, are outside the purview of core concepts. As such, the interdisciplinarity of neuroscience, methods, and ethics were excluded from the final core concepts. One response was not an addition, but rather a suggestion for expanding upon the evolution concept.

Revisions were made to the preliminary core concepts based upon the collective feedback of all of the constituents involved in the various surveys and the working session, resulting in eight final core concepts, conceptual statements, and explanatory paragraphs (Table 2). Additionally, a preamble was added describing the purpose of these core concepts, intended audience, and clarification of terminology used throughout. To help neuroscience educators consider how core concepts can be naturally integrated into common topics already in curricula, we provide example applications in Table 3.

DISCUSSION

Summary

We provide the first set of core concepts vetted by a robust neuroscience education community (Table 2). As such, these core concepts can be widely adopted by program chairs and curriculum directors with confidence that they represent wide community support. The core concepts for neuroscience higher education are based on multiple rounds of input from national and international neuroscience educators. Among participants who disclosed their institutions, the countries participants in the survey came from included Canada, Japan, Germany, Mexico, the Philippines, the United States, and the United Kingdom, with approximately 91% of participants from the United States. Ninety-five percent of working session participants came from institutions located in the United States, with the remaining participants from Austria, Canada, and the United Kingdom.

The core concepts are broadly applicable across subdisciplines of neuroscience and are able to accommodate future discoveries in the field. They can be applied by programs housed in biology, psychology, and other departments, as well as interdepartmental programs, to meet their institution- and program-specific needs.

The field of neuroscience is inherently interdisciplinary. Thus, it is no surprise that some of these neuroscience core concepts draw upon and overlap with core concepts identified for biology, physiology, and microbiology higher education (AAAS, 2010; Michael and McFarland, 2011; Merkel, 2012). Neuroscience core concepts also overlap to some degree with "crosscutting concepts" that have been identified as applicable and fundamental to all STEM fields (NRC, 2012). While we value the overlap of neuroscience core concepts with other disciplines, we considered it critical that this core concepts document emphasize the unique nature of neuroscience in the concepts and supporting explanations.

Given that core concepts are unifying principles that organize knowledge across disciplines, we have provided examples of how each core concept may be applied to different neuroscience fields of study and at different levels of organization (Table 3). As noted in the preamble (Table 2), a single example might be used to illustrate more than one core concept, depending on how the example is approached in an educational setting. The example of reflexes is identified to illustrate emergence and nervous system function. The application of a single example to multiple core concepts may help students understand how the set of core concepts interact during nervous system operations.

Practical Applications for Neuroscience Core Concepts

Neuroscience core concepts are intended for use by neuroscience educators, including program directors, department chairs, and instructional faculty in neuroscience higher education. The core concepts can be used to inform curricular and course development, as well as curricular and programmatic assessment, given that they represent input from a diverse group of neuroscience educators.

This set of core concepts for neuroscience higher education provides a framework that may help individual programs

TABLE 2. Neuroscience core concepts for higher education

Preamble to neuroscience core concepts: Core concepts are overarching principles that organize knowledge and can be applied to all subdisciplines in neuroscience. This set of neuroscience core concepts was generated based on input from neuroscience educators and education researchers from more than 100 institutions across the globe. These core concepts were developed for neuroscience program directors, department chairs, and other university stakeholders who are involved in evaluating programs and assessing student learning gains and to guide faculty decisions on course curricula. They may also be useful as a starting point for education researchers designing assessment tools. Core competencies are not included, as these have been previously identified by the Society for Neuroscience. Therefore, important competencies such as quantitative reasoning, ethics, scientific literacy, and methodology are not directly addressed in the core concepts. The core concepts presented here interrelate and are not mutually exclusive. Multiple core concepts may apply to a single topical example. Given that each core concept can be applied to all neuroscience subdisciplines, we use the term "unit" to allow for scalability to any level of analysis. In a cellular neuroscience context, a "unit" may refer to a neuron, while in the computational neuroscience context, a "unit" may refer to a complete circuit. The term "neural" refers to both neurons and glia.

Communication modalities
Core concept: Nervous systems encode and transmit information in various modalities.
The communication of information within cells, between cells, and across regions is essential for nervous system function. Nervous systems use activity patterns, electrical signaling, and chemical signaling as communication modalities. Information is encoded and transmitted as timing, frequency, and patterns of neural activity. Neural cells transmit information through the regulated movement of ions across their membranes and through intracellular biochemical signaling, and electrical and chemical processes permit information transmission between neurons, glia, and nonneural tissues. Various modalities enable nervous system communication to vary in speed and range.

Emergence
Core concept: Nervous system functions are constructed from the combined interactions of smaller constituent components.
Complex nervous system functions such as cognition, behavior, perception, and emotion are the outcome of interactions between many smaller units. Unique nervous system functions emerge at higher organizational levels through the interaction of smaller, autonomous biological units. System-level functions emerge from discrete cell-, circuit-, and network-level mechanisms and interactions. At the cellular level, neuronal and glial behavior arises from the function of individual organelles and proteins. Some features require the combination and interaction between smaller constituent components. Dysfunction in a smaller unit can disturb higher-order function.

Evolution
Core concept: The similarities and differences in nervous systems between organisms are constrained and defined by their evolutionary backgrounds.
Evolutionary processes produce shared functions and homologous nervous system structures, as well as adaptations that generate differences between organisms. The shared phylogenetic history of animals allows the use of animal models in neuroscience experimentation to understand the neural basis of behavior. Genetic changes and developmental mechanisms generate differences between species at biochemical through ecological levels. Similarities in neural mechanisms between species may be due to inheritance from a common ancestor or convergent evolution. Differences in behavior between species may be due to selection for differences in neural mechanisms or to genetic drift. Nervous systems are subject to evolutionary forces and therefore must be understood within the phylogenetic history and ecological context of an organism.

Gene–environment interactions
Core concept: Unique patterns of gene expression underlie the organization and function of a nervous system and are altered by environmental factors.
Genes and environmental factors combine to create unique patterns of gene expression that underlie the organization and function of the nervous system. Nervous systems develop into an organized arrangement of functional regions as dictated by the expression of necessary and appropriate genes. Genetic expression determines morphological and functional properties of nervous systems at all life stages and levels, from subcellular to single cells to networks, and alterations in gene expression can be retained across the life span to produce long-lasting changes in nervous system structure and function. Nervous system mechanisms that produce behavior, cognition, and physiological processes depend on gene expression patterns, which can be modulated by internal and external forces through molecular and epigenetic mechanisms. Analysis of gene–environment interactions in the nervous system can reveal mechanisms of pathology.

Information processing
Core concept: Outputs from a unit in the nervous system depend on the inputs it receives as well as information filtering and modulation performed by the unit.
Information processing can be studied at multiple levels of granularity, including synapses, subcellular arbors, circuits, and systems. At each level, the output of a unit in the nervous system is dependent upon the inputs it receives and processes. A unit integrates inputs from select external and internal conditions. The probability of a particular output is determined by the combinations of inputs and the current state. In some cases, a processing unit detects a change rather than an absolute level. Before producing an output, a unit may actively filter information. Information processing within a unit of the nervous system follows computational, statistical, mathematical, engineering, and physical principles and allows the nervous system to coordinate its own functions as well as functions of other body systems.

(*Continues*)

TABLE 2. Continued

Nervous system functions
Core concept: Nervous systems function to coordinate survival responses to the environment, permit behavior in a timely manner, and maintain homeostatic regulation.
Nervous systems detect and monitor external and internal environmental conditions, in conjunction with using stored information, to direct an appropriate response. Although functions of nervous systems vary across species, all nervous systems permit behavior, such as movement and memory. Nervous systems also homeostatically regulate neural function and other body systems. These functions of a nervous system depend upon its specialized ability to mount rapid local and systemic responses. When normal nervous system function is disrupted, disease symptoms and functional deficits can arise.
Plasticity
Core concept: Nervous systems reorganize their structure, function, and connections in response to experience.
The nervous system is malleable. From early developmental stages and throughout life, the nervous system strengthens and weakens components and connections in response to experience. This modulation, or plasticity, occurs in response to intrinsic and extrinsic experiences, such as sensory input, behavior, and pathological processes. Intrinsic and extrinsic experiences stimulate plasticity at molecular through behavioral levels. This malleability increases nervous system flexibility, enhances or dampens existing processes, and enables nervous systems to change in sensitivity and output. Nervous system plasticity is a dynamic process that allows the nervous system to flexibly meet functional demands.
Structure–function relationship
Core concept: Structure permits and constrains nervous system function, and function shapes structure.
Nervous system structures and functions bidirectionally inform each other at all levels of organization. For example, structural properties of proteins enable proteins to function effectively. Neurons and glia have protein compositions and essential morphological specializations that differentiate them from other cells and determine their functional properties. The architecture of the connections between neurons and glia in circuits and networks underlies and is constrained by requirements for efficient information flow that produces specific behaviors. Conversely, activity levels and functional demands of nervous systems can stimulate alterations of circuit connectivity, cell morphology and protein expression. Structure and function can be influenced by processes both internal, such as physiological demands, and external, such as behavior and the environment, at cellular through systemic levels.

organize their unique strengths and offerings. Each program serves a particular set of student needs and is built upon a unique set of faculty strengths. This work does not advocate for standardized or homogenous programs. The core concepts provide a set of foundational principles that can be used to map, organize, and frame content knowledge in courses and curricula in a manner befitting individual circumstances (Stanescu *et al.*, 2020; Clemmons *et al.*, 2022).

To help educators understand a strategy they might use to deploy the core concepts in their own courses and curricula, we provide an example outline of the essential elements of the "plasticity" core concept (Table 4). This list draws on key content and topical areas that survey respondents and workshop participants identified as being part of the plasticity concept. The plasticity conceptual elements are tentative, in that they have not yet undergone multiple phases of validation with a broad base of experts, such as the process we used to identify the neuroscience core concepts and develop explanatory paragraphs and that other biology education researchers have used to "unpack" concepts into conceptual elements. A full unpacking of all eight concepts is beginning and will be provided in future publications. After community input, educators can use such a list to examine how their courses or curricula can introduce all or a subset of the essential components of the core concept.

Building on the essential elements in Table 4, the following is an illustrative example of how educators might embed the neuroscience core concepts into a sequence of courses that builds increasingly more sophisticated thinking on the concept. Students are likely introduced to the idea of synaptic plasticity in an introduction to neuroscience course. When covering learning and memory, instructors can describe connectivity changes that generate information change when teaching the basic principles of long-term potentiation (Table 4, elements 1.2, 2.5). Plasticity can be expanded upon in a neuropsychopharmacology course, such as discussing the calcium cascade following N-Methyl-D-aspartate (NMDA) receptor activation that leads to a stronger synapse, including protein kinase M Zeta (PKMZeta) and the mechanisms of brain-derived neurotropic factor (BDNF) in relation to several disorders and treatments to illustrate additional conceptual elements within plasticity (Table 4, elements 1.1, 1.2, 2.3, 4.1, 5.1, 5.3, 6.1). In the same course, plasticity can be discussed as a component in addiction with changes in receptor expression (e.g., DA receptor up-/down-regulation, and subunit changes in α-amino-3-hydroxy-5-methyl-4-isoxazolepropionic acid (AMPA) receptors). In a laboratory course, students could complete an experiment investigating the neuroscience of exercise, and measure BDNF and cortisol after completing an acute workout, to evaluate changes (Table 4, elements 2.6, 3.2, 4.2). A written lab report on the experiment, including a literature review and discussion, could be assigned, with the expectation that students would demonstrate an enhanced understanding of the concept of plasticity. Finally, an upper-level neurobiology course could delve deeper into this concept when covering the development of synapses in the visual system, including both activity-independent and activity-dependent development. Activity-dependent plasticity is covered when discussing creation of ocular dominance columns, as well as creation of visual maps in the superior colliculus/optic tectum, the thalamus, and visual cortex and can be used to highlight conceptual elements (Table 4, elements 1.1, 1.2, 2.1, 2.4, 3.1, 4.2, 5.3).

Neuroscience core concepts could also be used to design assessment activities. For example, an end-of-term project could require students to introduce, explain, and apply a neuroscience core concept of their choosing. First, students produce an

TABLE 3. Example strategies for applying neuroscience core concepts during instruction on common neuroscience topics

Example applications of neuroscience core concepts: Core concepts are overarching principles that organize knowledge and can be applied to all subdisciplines in neuroscience. The following examples are intended to help educators consider how the core concepts might be applied to unify courses and curricula across neuroscience subdisciplines.

Communication modalities

Core concept: Nervous systems encode and transmit information in various modalities.

Example topics where core concept can be integrated:

- Chemical synaptic transmission: Communication between neurons can occur via release of chemical neurotransmitters from presynaptic vesicles. Neurotransmitters cross the synaptic cleft and bind to fast ionotropic or slower metabotropic receptors, causing modulation of the postsynaptic membrane across different timescales. The postsynaptic response to the chemical message is mediated by alterations to ion movement across the membrane and/or intracellular biochemical signaling.
- Neuromodulators inform switching of states in circuits: Neuromodulators use a chemical modality to alter circuit activity both locally, through intrinsic circuits, or over long distances, through extrinsic circuit modulation. The presence and combinations of neuromodulatory chemicals direct reconfiguring of circuits, such that the circuits can have variable outputs under modulatory control. For example, in the crustacean stomatogastric ganglion (STG), the neuropeptide Red Pigment Concentrating Hormone (RPCH) has been shown to switch STG neurons from separate cardiac sac and gastric mill circuits to a combined cardiac/gastric circuit.
- Cerebellar Purkinje cells: In the cerebellum, long-term depression is sensitive to the temporal order in which the parallel fiber and climbing fiber coactivate the Purkinje cell. Repetitive coincident activity leads to gradual synaptic weakening that can last for many hours. Therefore, the relative timing of the two inputs is a modality that communicates future alterations to Purkinje cell synapses. The cerebellum also uses firing patterns as another communication modality. Purkinje neurons communicate with simple spikes or complex spikes. Advances in cerebellar learning theory examine the dynamic interplay between complex spikes and simple spikes as information is coded in patterns of neural activity.
- Neuronal coherence: Communication between brain regions may rely on temporal frequency of firing as a communication modality. One theory of how distant brain regions communicate is through coherence: Neurons go through cycles and are more or less likely to fire at different points during the cycle (Fries, 2005, 2009). When two distant brain regions have coordinated cycles of low and high firing, communication between these regions is strong. According to coherence, synchronized neuronal oscillations within and across brain regions encode a form of information that is crucial for communication between or across networks of the brain.

Emergence

Core concept: Nervous system functions are constructed from the combined interactions of smaller constituent components.

Example topics where core concept can be integrated:

- Monosynaptic stretch reflex arc: Reflexive contraction arises from the interaction of many smaller units. As a muscle is stretched, mechanically gated protein channels in the muscle spindle are opened and generate a graded receptor potential. This subcellular transduction is required for the emergence of the motor behavior. Cellular electrical properties and intracellular communication are also constituent components that allow for the reflex to emerge. The receptor potential activates action potentials in afferent and then efferent fibers via a monosynaptic pathway. Reflexive contraction of the muscles is stimulated by the neurotransmitter acetylcholine at the neuromuscular junction. If any constituent component of the anatomical circuit is damaged, the reflexive behavior will be diminished.
- Memory storage: Memory formation and storage results from the interaction of nervous system units at molecular through circuit levels. Activity-dependent interactions between neurotransmitters and receptors at single synapses, along with activity-dependent activation of nearby synapses, lead to durable changes in synaptic strength. Circuit plasticity emerges from changes in synaptic strength across neurons, making future circuit outputs in response to a previously encountered input more or less likely. For example, the firing rate of hippocampal place cells encodes a specific location in the environment of a rat, and place cell responses can be updated by synaptic changes stimulated by experience with the environment. Thus, place cell responses represent memory traces at the neuronal ensemble level that emerge from discrete electrical and chemical events.

Evolution

Core concept: The similarities and differences in nervous systems between organisms are constrained and defined by their evolutionary backgrounds.

Example topics where core concept can be integrated:

- Comparative neuroanatomy: Animals have developed varying anatomical approaches across evolution to maintain similar functions of the nervous system. For example, in many invertebrate species, axons are unmyelinated. However, these creatures maintain a rapid action potential conduction velocity by expressing axons with large diameters. Conversely, in vertebrates, certain classes of glial cells (oligodendrocytes and Schwann cells) enwrap some axonal processes in myelin to enhance action potential conduction velocity while maintaining small axonal diameters. Other invertebrates have a myelin-like substance surrounding their axons to increase conduction velocity. Some vertebrate neurons, such as alpha motor neurons and proprioceptive axons, generate very fast conduction velocities via heavy myelination combined with large axonal diameters.
- Comparative sensory systems: The ecological context and phylogenetic history of platypus (*Ornithorhynchus anatinus*) have selected for a unique electromechanical system that uses electroreceptors and mechanoreceptors when diving in search of prey. Platypuses belong to the family of monotremes and are semiaquatic mammals native to freshwaters of eastern and southeastern Australia. When swimming, platypuses essentially shut down their senses of vision, audition, and olfaction. The bill of the platypus is packed with three distinct types of receptor cells that enable the animal to detect movement and subtle electrical fields produced by prey. Without the use of vision, audition, and olfaction, electroreception has evolved to become most critical to survival. Other monotremes, such as echidnas, also have electroreception, but this sense is most specialized in the platypus.
- Model organisms in research: Fundamental discoveries in neuroscience have relied upon the study of organisms such as squid, crayfish, sea snails, zebrafish, frogs, rodents, and primates. Scientists leverage specific traits of animal species, selecting the most appropriate model system to address the scientific question. Our understanding of fundamental processes such as how neurons fire action potentials, how neurons communicate with other neurons at synapses, and how neurons encode information were all made using traditional or nontraditional model organisms. Findings from model organisms can then be applied to other organisms based on conserved genetic and physiological properties. Diverse and appropriate model systems are essential for not only validating or disproving the generalization of scientific discoveries, but also for the generation of novel information.

(*Continues*)

TABLE 3. Continued

Gene–environment interactions

Core concept: Unique patterns of gene expression underlie the organization and function of a nervous system and are altered by environmental factors.

Example topics where core concept can be integrated:

- Enriched environments alter gene expression: Hebb (1947) first discovered that environmental enrichment was associated with both structural changes in the brain and improvements in cognitive behavior. Environments that promote enhanced cognitive, motor, and sensory stimulation produce molecular and morphological changes that underlie neural structure and function, and ultimately behavior. Genes that are differentially expressed after enrichment training are linked to neuronal structure, synaptic plasticity, and transmission. For example, a group of genes that encode proteolytic proteins involved in signaling and apoptosis (prolyl oligopeptidase, caspase-6, and protease 4) and genes involved in the formation, reorganization, and strengthening of synaptic connections (e.g., GTPase RhoA) are altered in response to enrichment training. Rodents that are reared in enriched environments display gene expression changes in the cortex and improved performance on spatial and nonspatial memory tasks and recent and long-term memory retrieval.
- Gene–environment interactions in development of psychiatric disorders: Genetic disposition, environmental exposures, and their interactions play important roles in the development of severe mental illness, including bipolar disorder, severe depression, and schizophrenia. The pathogenic effects of many environmental risk factors depend upon the familial disposition to severe mental illness. Recent research has identified gene–environment interactions with specific molecular genetic variants. For example, *SLC6A4*, which encodes the serotonin transporter, has been extensively studied with respect to its relationship to the environment. A functional-length polymorphism in the promoter of *SLC6A4*, known as 5-HTTLPR, has been shown to moderate the effects of childhood maltreatment on depression. The interaction of a short 5-HTTLPR allele and a history of childhood maltreatment is associated with cognitive impairment in those with psychotic disorders.
- Gene–environment interactions in Parkinson's disease: Parkinson's disease (PD), like many other diseases, can rarely be explained by a change in a single gene or even multiple genes. Genes and environmental factors act individually and in concert to determine risk factors for PD. Gene–environment interactions occur when the prospective high-risk genotype and high-risk environment increase risk in a nonadditive manner. Environmental risk factors, such as pesticide exposure, affect several pathways genetically linked to PD. A person's genetics can predict the PD risk from pesticide exposure or the speed at which PD progresses.

Information processing

Core concept: Outputs from a unit in the nervous system depend on the inputs it receives as well as information filtering and modulation performed by the unit.

Example topics where core concept can be integrated:

- Synaptic integration: A tremendous number of synaptic inputs can convey information to a neuron at multiple time points. If a single input is repeatedly active within a close enough time frame, the signals it provides can summate to influence the probability of postsynaptic neuron firing (i.e., temporal summation). If multiple inputs arrive at different locations along a neuron's morphology in close enough proximity to each other, they summate to influence the probability of postsynaptic neuron firing (i.e., spatial summation). Further, the relative locations, densities, and combinations of ionotropic receptors and voltage-gated channels along the neuronal membrane can actively amplify or filter the influence of given inputs during summation events. Temporal and spatial summation are not exclusive from one another. Neurons simultaneously integrate synaptic information along both space and time.
- Basal ganglia: The basal ganglia are a group of subcortical nuclei that modulate the activity of the motor cortex and descending motor pathways. The two distinct pathways of the basal ganglia—the direct pathway and the indirect pathway—have opposite effects on the thalamus. The output to the thalamus from the basal ganglia involves integration of the complex sequences of excitation, inhibition, and disinhibition within both pathways, as well as integrating information from the forebrain in the planning and execution of complex motor behavior.

Nervous system functions

Core concept: Nervous systems function to coordinate survival responses to the environment, permit behavior in a timely manner, and maintain homeostatic regulation.

Example topics where core concept can be integrated:

- Reflexes and movement: The nervous system, in conjunction with the musculoskeletal system, allows for voluntary movements and reflexive responses. While there are many different regions in the brain that contribute to the establishment and modulation of motor control, cortical upper motor neurons are essential for generating voluntary movement through connections with local circuit neurons in the brainstem and spinal cord, which in turn connect with lower spinal motor neurons. These spinal motor neurons provide an efferent connection with peripheral muscle fibers to cause contraction. The nervous system mediates reflexive responses through peripheral sensory receptors that detect various perturbations (e.g., stretch of the muscle or pain) and convey these sensory signals back to the spinal cord to allow for rapid reflexive responses by the lower spinal motor neurons (e.g., reflexive contraction of the muscle or a withdrawal response).
- Fear responses: Survival often requires an appropriate emotional response at an appropriate time. Nervous systems detect and monitor external and internal environments to coordinate an appropriate emotional response, such as fear experienced by mammals during threatening situations. The emotional response also depends on past emotional events. For example, in the case of fear, external stimuli such as aggressive facial expressions from conspecifics are processed and interpreted in conjunction with past emotional events, enhancing survival during threatening situations. Past emotional events are more likely to influence emotional responses, and therefore survival, than are emotionally neutral events. For example, the hormone norepinephrine, released during heightened states of emotion such as fear, “primes” neural cells to remember by increasing their sensitivity at sites of synaptic rearrangement. Together, these processes underlie the formation of new memory circuits and enhance future survival responses.

(*Continues*)

TABLE 3. Continued

Plasticity

Core concept: Nervous systems reorganize their structure, function, and connections in response to experience.

Example topics where core concept can be integrated:

Activity-dependent neurological changes: Motor skill learning and practice, such as juggling, results in a multitude of neurological changes, including reduced energy consumption for the associated task, increased gray matter volume, synaptogenesis, and increased spine formation. Myelin also appears to be regulated by functional activity and participates in nervous system plasticity. Microstructural changes in white matter include changes in axon diameter, packing density of fibers, and myelin thickness.

Exercise-mediated neurogenesis: Exercise, particularly aerobic exercise, enhances hippocampal neurogenesis and sharpens certain cognitive skills. This process is mediated by brain-derived neurotrophic factor (BDNF), which regulates many of the processes within neurogenesis, such as differentiation and survival. In a study of older adults, moderate aerobic exercise, performed three times each week, had a protective effect against volume loss of the hippocampus and improved spatial memory function. Moderate aerobic exercise was correlated with greater serum levels of BDNF (Erickson *et al.*, 2011). Higher levels of BDNF are associated with improved cognitive performance, in both laboratory rodents and humans.

Synaptic plasticity: Synapse strength can increase or decrease in response to repetitive or coincident activity at the synapse. Changes in quantal size (due to postsynaptic receptor behavior) and/or quantal content (due to presynaptic vesicle release probabilities) can be temporary or long-lasting. Long-term plasticity can also produce durable changes to synaptic strength through changes in gene expression that lead to alterations in receptor number. The nervous system also acts as a malleable system to stabilize the neural network. Network stability is maintained through a compensatory, negative feedback mechanism termed "homeostatic plasticity." Homeostatic plasticity protects the nervous system from hyperexcitability and strengthens excitability in cases of chronic inactivity.

Structure–function relationship

Core concept: Structure permits and constrains nervous system function, and function shapes structure.

Example topics where core concept can be integrated:

Dendritic and axonal morphologies: Dendritic arbors and axons have an array of morphological features that contribute to their functional roles. Dendritic spines and multiple branching points along dendrites increase the surface area for synaptic contacts, and spine morphology can be altered in response to activity. The diameter of dendritic branches and axons can impact the velocity at which current is conducted through these structures, and the addition of myelin can further increase conduction velocity in the axon. Interestingly, neural activity can also modulate myelin sheath formation.

Ion channel and receptor protein structures and responses: Potassium channel structures have been well characterized through sequence analysis and protein imaging methods. Potassium channel structural characteristics, such as pore size and charges, voltage-sensor amino acid composition, and inactivation gates determine the channel's responsiveness to stimuli, current amplitude and duration, and selectivity.

Aphasia: A brain region's physical connectivity determines its interactions with other brain regions, and therefore informs its function. Auditory–motor integration requires a physical connection for information to flow from the auditory system to Wernicke's area, then from Broca's area to motor regions controlling mouth and tongue movement during speech. The architecture of the connections in this network underlies efficient information flow that allows language comprehension and language production. A lesion in the arcuate fasciculus, which connects Broca's and Wernicke's areas, results in difficulty repeating words, as communication between regions controlling language comprehension and regions controlling language production has been disrupted.

infographic that graphically represents their knowledge of the core concept in a way that is understandable to a non-biologist. Then, to assess students' ability to apply core concepts to concrete scenarios, students would be required to accurately and clearly apply the core concept to an instructor-chosen topic. For example, a non-biologist's course on "mind, memory, and the brain" could require each example to be within the realm of the neurobiology of learning and memory.

Finally, the neuroscience core concepts also provide a basis for building assessment instruments. To gauge comprehension of neuroscience core concepts, future assessments can be designed to be more high-throughput similar to the Molecular Biology Capstone Assessment for molecular biology concepts (Couch *et al.*, 2017). Items can be designed as multiple true-false questions following a narrative stem and tested for internal reliability and test–retest stability. This method of testing can provide diagnostic information on specific content areas that a student has mastered or is still lacking, while still allowing ease of administration to a large student population.

Limitations

While we are confident in the overall results of this work, there are limitations that should be acknowledged. In compiling and categorizing participants' examples of core concepts, we attempted to find conceptual ideas that overlapped across responses. We then worked to clarify and refine the verbiage to identify the core concept the participants tried to convey. Along this process, it is entirely possible that some educators have some different ideas or verbiage that is not captured in the core concepts or explanatory paragraphs. As such, we did not obtain unanimous support for all core concepts, as can be seen in the *Results*. However, the core concepts did receive strong support from a large proportion of respondents.

Another limitation is that we were only able to obtain input from a small fraction of neuroscientists or educators globally. However, the process used to develop these core concepts embedded numerous strengths. It invited multiple rounds of input from a variety of stakeholders representing graduate and undergraduate programs and a variety of educational roles, including instructors, program directors, and curriculum developers. The stakeholders represented AANAPISIs, HBCUs, HSIs, and PBIs. As such, we are reasonably assured that the list of core concepts does not miss important ideas or institutional perspectives. Further, the inductive, data-driven approach to coding feedback from the first survey allowed for open-ended outcomes and did not presuppose any concepts based on the researchers' opinions or expertise. On the other hand, it is possible that participants in the survey or other feedback rounds

TABLE 4. Example, tentative essential elements of "plasticity" core concept

Plasticity core concept: Nervous systems reorganize their structure, function, and connections in response to experience.
Plasticity 1. Plasticity alters nervous system structures.
Plasticity 1.1 Structural changes can occur at all levels of organization.
Plasticity 1.2 Structural changes occur at individual components and in the connectivity between components.
Plasticity 2. Plasticity alters nervous system functions.
Plasticity 2.1 Functional changes can occur at all levels of organization.
Plasticity 2.2 Plasticity increases nervous system flexibility.
Plasticity 2.3 Plasticity enhances or dampens nervous system processes.
Plasticity 2.4 Plasticity changes sensitivity and output.
Plasticity 2.5 Plasticity generates information storage, including learning and memory.
Plasticity 2.6 Plasticity helps an organism meet environmental and functional demands.
Plasticity 2.7 Plasticity occurs as a response to injury.
Plasticity 3. Plasticity occurs throughout the life span.
Plasticity 3.1 Plasticity occurs during early development.
Plasticity 3.2 Plasticity continues throughout adult life stages.
Plasticity 4. Plasticity is a result of intrinsic and/or extrinsic influences and experiences.
Plasticity 4.1 Extrinsic influences include sensory input, environmental factors, and social interactions.
Plasticity 4.2 Intrinsic influences include developmental programming, pathologies, and organismal behaviors.
Plasticity 5. Plasticity is a dynamic process.
Plasticity 5.1 Changes can vary in magnitude and are not linear.
Plasticity 5.2 Changes are reversible.
Plasticity 5.3 Timescale of changes can vary.
Plasticity 6. Plasticity events can alter nervous system components in different directions.
Plasticity 6.1 Plasticity strengthens or weakens nervous system structures, functions, and connections.
Plasticity 6.2 Plasticity events can shift away from an existing state (e.g., Hebbian plasticity).
Plasticity 6.3 Plasticity events can return to a prior state (e.g., homeostatic plasticity).

may underrepresent diversity of neuroscience instructors, given that we did not track participants' personal demographics. Other core concept projects have used task forces, survey feedback, or feedback from focus groups to generate core concepts, followed by feedback from focus groups, conference participants, or surveys to inform revisions (AAAS, 2010; Michael and McFarland, 2011; Merkel, 2012). By combining these approaches, we were able to maximize our reach with the initial survey and then receive detailed, nuanced feedback from group discussions in the workshop.

Additionally, while Table 3 provides examples of how each core concept may be applied in different examples in a range of subdisciplines and Table 4 provides a preliminary list of essential elements of the plasticity core concept, we do not attempt a systematic unpacking of the concepts here. Future unpacking, or deconstructing, of the concepts into their critical components will create a conceptual framework to further guide curricular and assessment efforts (Khodor *et al.*, 2004; Michael *et al.*, 2017b).

Future Directions

Future work will focus on tools to help educators employ these core concepts. The conceptual framework provided by the community-derived core concepts for neuroscience higher education will be unpacked to identify the key conceptual elements within each core concept, following a method similar to biology education research conducted for biology and physiology core concepts (Brownell *et al.*, 2014; Cary and Branchaw, 2017; Michael *et al.*, 2017b). By unpacking the complexity and providing examples of each core concept across neuroscience subdisciplines and biological scales, neuroscience educators will be better equipped to establish learning outcomes, assessments, and teaching materials for neuroscience core concepts. The unpacking process will follow the example of efforts in other disciplines that asked disciplinary experts and educators to develop and revise nested, hierarchical structures of the components of each core concept (Khodor *et al.*, 2004, Brownell *et al.*, 2014; Cary and Branchaw, 2017; Michael *et al.*, 2017b; Santiago *et al.*, 2021). As we undertake this process for each of the eight concepts, we will solicit input at the drafting and revising stages from neuroscience educators via surveys and at professional meetings. The essential elements of the plasticity core concept identified in Table 4 need community input, for example, to determine whether the elements identified are accurate, whether elements are missing, whether each item is an element or subelement, and whether each element can be broken into additional, more detailed subelements.

Going forward, we will also provide examples of how instructors and other neuroscience educators can use core concepts in higher education neuroscience course work and curricula. Finally, the list of core concepts will be used to develop learning progressions—cognitive-based progressions in the thinking and understanding of scientific ideas—for neuroscience education, as has been done in other fields, including biology and genetics (Scott *et al.*, 2019, 2020; Castro-Faix *et al.*, 2021). The NRC (2007, p. 214) describes learning progressions as "successively more sophisticated ways of thinking about a topic that can follow one another". Importantly, learning progressions characterize learning over a prolonged time span and distinguish novice from expert thinking. Neuroscience educators can use learning progressions to assess and track student progress, inform curricular development, and assess teaching strategies.

CONCLUSION

This set of core concepts complements previous work that developed undergraduate neuroscience curricular blueprints

(Ramirez, 1997; Wiertelak and Ramirez, 2008; Wiertelak *et al.*, 2018; Kerchner *et al.*, 2012) and identified core competencies for undergraduate neuroscience education (Kerchner *et al.*, 2012; Society for Neuroscience, n.d.). These core concepts provide a unifying framework for organizing neuroscience content understanding, in alignment with the recommendations of *Vision and Change* (AAAS, 2010), and could be addressed in each course of a neuroscience curriculum to help students understand relationships between subdiscipline knowledge and experimental findings. Core concepts can be flexibly integrated into diverse courses at varied institution types, because implementation does not need a particular sequence of courses and pre-existing student knowledge can differ. When concepts are used in the classroom, they lend meaning to the multitude of facts. Ideally, courses and curricula would deploy core concepts and core competencies in parallel during curricular development, instruction, and assessment.

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