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Integrating neuroscience and immunology core concepts to develop a neuroimmunology curriculum

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Training students in interdisciplinary thinking is critical for the future of scientific discovery and problem-solving more generally. Therefore, students must have early opportunities to grapple with knowns and unknowns at the frontiers of interdisciplinary inquiry. Neuroimmunology challenges students to think at the intersection of two rapidly evolving fields, neuroscience and immunology. As these disciplines focus on complex systems, their intersection represents a unique opportunity for students to witness the nature and process of interdisciplinary collaboration and synthesis. However, the fast pace of research and specialized knowledge in both disciplines present challenges for instructors interested in teaching the subject to undergraduate students. In this article, we share and describe a curriculum developed using a backward-design approach to analyze core concepts in both neuroscience and immunology, which were articulated by disciplinary experts in collaboration with their respective education communities. We determine overlaps between these conceptual frameworks, identify key prerequisite knowledge, and suggest example activities to introduce neuroimmunology to undergraduate students. This curriculum may be used for an entire course, or modified into shorter units that instructors can use within diverse educational contexts. We hope that this effort will encourage instructors to adopt neuroimmunology into their curricula, provide a roadmap to forge other such interdisciplinary educational collaborations, and prepare students to develop creative solutions to current and future societal problems.

KEYWORDS

vision and change, undergraduate, interdisciplinary, multiple sclerosis, depression, learning outcomes, backward-design, prerequisites

1 Introduction: background and rationale

Neuroimmunology is an interdisciplinary field that brings together knowledge from neuroscience and immunology to examine the complex, bidirectional interactions between the nervous and the immune systems. It was long thought that the brain is largely "immune-privileged," that immune cells do not cross the blood-brain barrier (BBB), and that the brain lacks a lymphatic system. However, we now know that even though the immune response in the brain differs from that in other tissues, it is not absent (Rustenhoven and Kipnis, 2022). The nervous system and immune system are intertwined via complex mechanisms (Editorial, 2020; Walsh and Kipnis, 2024), and immune cells are indeed found in the brain in both physiological and pathological situations, thereby contributing critically to health and disease.

Neuroimmune interactions have a notable influence on human health and disease-associated morbidity and mortality. For example, Multiple Sclerosis (MS) is a neuro-immunological condition that affected approximately 1 million people in the United States in 2019, and the total economic burden associated with this disease was estimated to be $85.4 billion (Bebo et al., 2022). As another example, the immune system is implicated in traumatic brain injury (TBI), of which there were 27 million cases worldwide in 2016 (GBD 2016 Traumatic Brain Injury and Spinal Cord Injury Collaborators, 2019), and the total global estimated economic burden associated with TBI ranges from tens to hundreds of billions of dollars (Matney and Berwick, 2022). Accordingly, a conceptual understanding of how the nervous and immune systems interact is crucial for our trainees who are future healthcare professionals, researchers, policy makers, and public health officials; and may be patients and/or caregivers during their lifetimes.

With the rise in neuroimmunology-based disease diagnoses and immunotherapies, graduate- and professional-level training in neuroimmunology is being recognized as critical (Obeidat et al., 2020; Gallien et al., 2014; López-Chiriboga and Clardy, 2017; Caldwell et al., 2020; Mackenzie et al., 2021). Even though medical schools recognize the importance of neuroimmunology, literature pertaining to undergraduate neuroimmunology education is sparse.

However, there are several compelling reasons to introduce an upper-level course focused on neuroimmunology in an undergraduate curriculum, especially one that caters to majors who are interested in pursuing healthcare-related careers. The field itself is relatively new, exciting, and rapidly growing. Due to the interdisciplinary nature of neuroimmunology, research findings are frequently complex. This offers students opportunities for higher-order thinking as they have to apply foundational concepts in both neuroscience and immunology to gain a comprehensive understanding of the discoveries in neuroimmunology. Additionally, it fosters an appreciation for collaboration across disciplines. As with most rapidly-growing fields, there are, unfortunately, several exaggerated claims made either by scientists themselves, or journalists trying to simplify the implications of discoveries in neuroimmunology for non-expert audiences, for example, the link between microbiome and mental health (Marcon et al., 2021). Such potentially controversial topics provide a tremendous opportunity for incorporating discussions on the scientific method, rigor, reproducibility, and responsibility in science, and science communication. As the hype surrounding these topics makes its way to social media, the topics become relatable, therefore engaging, to undergraduate students who encounter spurious claims on a daily basis. Even though the involvement of the immune system in the pathophysiology of conditions such as TBI or pain may come as no surprise to undergraduate students, its role in psychiatric disorders, such as depression, would be rather unexpected—unlikely to be a "gut feeling," thus providing new research avenues for students to consider as they map out their future career paths. Similarly, recent findings demonstrate the role of the brain-body axis in regulating peripheral immune responses and maintaining immune homeostasis (Jin et al., 2024). Accordingly, a fundamental understanding of neuroimmunology will be essential for the ideation of novel strategies to diagnose and treat diseases that have been recognized for decades as exclusively neurological or immune disorders.

In the absence of curricular resources, educators may feel unsure how to answer questions related to these rapidly evolving disciplines. Education-based literature has advanced significantly for undergraduate neuroscience. This correlates with a journal dedicated to undergraduate neuroscience education (Journal of Undergraduate Neuroscience Education) and stand-alone neuroscience majors across the United States (Pinard-Welyczko et al., 2017). Similar efforts for undergraduate immunology education are emerging (Bruns et al., 2019, 2021; Mixter et al., 2023; Porter et al., 2021; Pandey et al., 2024). For an undergraduate neuroimmunology curriculum, literature is sparse but emerging. The increasing pertinence of neuroimmunology in an undergraduate curriculum is supported by the inclusion of an entire chapter dedicated to this topic in a recently published open education resource on OpenStax, titled, Introduction to Behavioral Neuroscience, a National Science Foundation (NSF)-funded textbook intended for undergraduate courses in psychology, biology, neuroscience, and similar departments.[1] Previously, Watanabe documented their design and teaching of an undergraduate neuroimmunology course, and shared resources for the educator community (Watanabe, 2021). Their approach to the course included six modules, namely: (1) The Immune System; (2) Immune Molecules in the Nervous System, and Vice Versa; (3) Immune System and Injury to the Nervous System; (4) Diseases with Neurological Symptoms; (5) Autoimmune Disease; and (6) Stress and the Immune System. The article details the content of each module, includes literature review and relevant primary literature for each topic, and grading rubrics for scoring oral presentations. Students develop conceptual knowledge about neuroimmunology and oral presentation and written communication skills for scientific and non-scientific audiences. Brownell et al. (2013) developed a neuroimmunology course that focuses on the core competency of science communication, and documents how a writing-intensive neuroimmunology course helped improve biology undergraduates' perception and confidence of their abilities to read scientific literature and communicate science. Chivero (2024) shared a series of published, primary articles field tested to teach principles in neuroimmunology in an undergraduate neuroimmunology course. Mesmer and Gaudier-Diaz (2022) designed and implemented a psychoneuroimmunology-focused course-based undergraduate research experience, where students showed increased self-efficacy and research identity. This collection of literature illustrates the promise of teaching neuroimmunology to undergraduates and invites further elucidation of the learning objectives of an undergraduate-focused neuroimmunology course.

1 OpenStax (2024). Chapter 17: Neuroimmunology; Introduction to Behavioral Neuroscience. Available at: https://openstax.org/books/introduction-behavioral-neuroscience/pages/1-introduction (accessed January 7, 2024).

In this manuscript, we adopted a concepts-focused approach to design a neuroimmunology course and its modules (Figure 1). Neuroimmunology's parent disciplines, neuroscience and immunology, are themselves relatively newer disciplines that build on the fundamentals of basic biology, chemistry, physics, social and computer sciences. Both disciplines have unique historical trajectories, vocabulary, and concepts. Our work builds on the recent, separately developed community reviewed core concepts for neuroscience (Chen et al., 2023) and immunology,[2] respectively. In addition, we leveraged community of practice (Wenger-Trayner and Wenger-Trayner, 2015; Pandey et al., 2022b) fundamentals to collaborate and communicate among one immunology and two neuroscience educators over the span of a year. The authors teach undergraduate-level introductory and advanced courses in biology, neuroscience, and/or immunology in a primarily undergraduate setting, albeit at diverse institution types (a small public liberal arts college, a public R1 university, and a public master's degree granting university). The authors of this manuscript believe that to help students develop interdisciplinary thinking, curriculum design should adopt an integrated approach instead of a fragmented one (Redish and Cooke, 2013; Gouvea et al., 2013). This intentional collaboration among scientists from different disciplines who appreciate the interdisciplinary nature of science helps: (1) develop a common language between the two disciplines pertinent to their work, and (2) foster a community where educators from diverse disciplines learn and support each other for the ultimate benefit of their students. This approach of intentional collaboration is one of the guiding principles for ImmunoReach Community of Practice (Pandey et al., 2022a). Our curriculum may serve as a blueprint for educators to develop an entire course in neuroimmunology or modify it into shorter modules for use within diverse educational contexts.

2 Frameworks

2.1 Vision and change core concepts

Neuroimmunology cuts across core concepts in the life sciences. By using cross-cutting concepts as a unifying framework, students can see how disciplinary experts, scientists and engineers tap into the interdisciplinary nature of science to solve problems, and that science is not fragmented into disciplinary silos but is highly interconnected.[3] Well-designed assessments focused on a cross-cutting concept or two, and based on real-world, relatable, neuroimmunology based examples (e.g., gut microbiome and mental health) can help students to think critically and practice communicating science to a diverse set of audiences (Ebert-May and Emery, 2017). To establish fundamental statements for neuroimmunology, as described in this paper, we were guided by the *Vision and Change* in Undergraduate Biology Education: A Call-to-Action report published by the American Association for the Advancement of Science (AAAS),[4] which describes five core concepts that undergraduate biology students must understand: (1) Evolution; (2) Pathways and Transformation of Energy and Matter; (3) Information Flow, Exchange and Storage; (4) Structure and Function; and (5) Systems (Woodin et al., 2010). Subsequently, several educator communities designed learning frameworks that unpacked these five core concepts for their specific disciplines. This allows educators to adopt a backward-design approach to curriculum design, which was first recommended by Wiggins and Mctighe (2005) and Fink (2013), and enables instructors to focus on conceptual depth and enduring understandings instead of the breadth of content or excessive disciplinary jargon (Petersen et al., 2020; Roth, 2007).

To develop the neuroimmunology curriculum described in this manuscript, we adopted a backward-design approach, where we utilized concepts for immunology (see text footnote[2]) and neuroscience disciplines (Chen et al., 2023) and created a hierarchical framework with neuroimmunology specific statements. These statements integrate the neuroscience and immunology concepts and we nested them under the five core concepts noted in the *Vision and Change* report. We provide example learning outcomes for these statements in the context of neuroimmunological conditions, Multiple Sclerosis and Depression (Tables 1–5).

2.2 Benchmarks for science literacy

Because both neuroscience and immunology are disciplines rooted in life sciences, many parallels can be drawn between the two, such as the reliance on cellular and molecular concepts, and a strong relevance for current therapeutics and diagnostics. The key difference between the two disciplines stems from discipline specific terminology, and we identified that this could be one of the biggest barriers to student comprehension of neuroimmunology. The Benchmarks for Science Literacy report published by the AAAS[5] recommends avoiding the excessive use of technical language and jargon, both to reduce the sheer burden on students, and to prevent knowledge of vocabulary from being mistaken for conceptual understanding. In support of this recommendation, a previous report found that students articulate their understanding better when exposed to concepts first and jargon second, instead of the other way around McDonnell et al.

2 Pandey, S., Bruns, H. A., Condry, D. L. J., Justement, L. B., Kleinschmit, A. J., Liepkalns, J., et al. (2023). CourseSource Immunology Learning Framework. CourseSource. Available at: https://qubeshub.org/community/groups/coursesource/courses/immunology/ (accessed February 23, 2024).

3 San Diego County Office of Education. Using the Crosscutting Concepts to Build Student Sense-Making and Reasoning. Available at: https://www.sdcoe.net/ngss/evidence-based-practices/using-the-crosscutting-concepts-to-build-student-sense-making-and-reasoning (accessed January 7, 2024).

4 The American Association for The Advancement of Science. (2011) Vision and change in undergraduate biology education: A call to action. Available at: https://web.archive.org/web/20240330071209/https://www.aaas.org/sites/default/files/content_files/VC_report.pdf (accessed February 22, 2024).

5 The American Association for The Advancement of Science. (1993) Benchmarks for Science Literacy - A tool for curricular reform. Available at: https://web.archive.org/web/20241205145127/https://www.aaas.org/resources/benchmarks-science-literacy (accessed September 21, 2024).

TABLE 1 The concept "systems" in the context of life science (Brownell et al., 2014), Neuroscience (Chen et al., 2023), and Immunology (see text footnote[2]) and their application in Neuroimmunology.

Systems	
Life science core concepts	
• Biological molecules, genes, cells, tissues, organs, individuals, and ecosystems interact to form complex networks. A change in one component of the network can affect many other components. • Organisms have complex systems that integrate internal and external information, incorporate feedback control, and allow them to respond to changes in the environment.	
Neuroscience concepts	**Immunology concepts**
Emergence • Nervous system functions are constructed from the combined interactions of smaller constituent components. **Nervous System Functions** • Nervous systems function to coordinate survival responses to the environment, permit behavior in a timely manner, and maintain homeostatic regulation.	**Systems** • The immune system is an interconnected and coordinated network of macromolecules, cells, tissues, and/or organs within an organism. • Cellular and molecular processes maintain homeostasis of the immune system, and loss of homeostasis may result in a variety of immune-mediated disorders. • Immunological memory plays a critical role in protective immunity.
Neuroimmunology context	
• The nervous and immune systems communicate bidirectionally and can influence each other's activity in the context of the environment. • Dysregulation of homeostatic neuroimmune systems can cause disease.	
Multiple sclerosis specific example learning outcome	
Explain the cross-talk between nervous and immune system to mediate the neurodegenerative processes in multiple sclerosis.	
Depression specific example learning outcome	
Describe the cross-talk between the hypothalamus-pituitary-adrenal (HPA) axis and the immune system in depression.	

TABLE 2 The concept "structure and function" in the context of life science (Brownell et al., 2014), Neuroscience (Chen et al., 2023), and Immunology (see text footnote[2]) and their application in Neuroimmunology.

Structure and function	
Life science core concepts	
• Biological structures exist at all levels of organization, from molecules to ecosystems. A structure's physical and chemical characteristics influence its interactions with other structures, and therefore its function. • Natural selection leads to the evolution of structures that tend to increase fitness within the context of evolutionary, developmental and environmental constraints.	
Neuroscience concepts	**Immunology concepts**
• **Structure-function Relationship:** Structure permits and constrains nervous system function, and function shapes structure. • **Plasticity:** Nervous system reorganize their structure, function and connections in response to experience.	• Immune responses are influenced by the presence, location and organization of lymphoid organs/tissues within an organism. • Immune cell function is characterized by the presence of macromolecular features. • Macromolecular interactions influence the outcome of an immune response.
Neuroimmunology context	
The presence, location and physical organization of nervous and immune system components (organs, cells, molecules) within an organism can affect and are affected by neuroimmune interactions.	
Multiple sclerosis specific example learning outcome	
Explain the role of an autoantigen and its receptors in facilitating this neuroinflammatory process underlying multiple sclerosis.	
Depression specific example learning outcome	
Explain how modifications in microglial structures impact their functions and contribute to neuroinflammation that may underlie the development and/or progression of depression.	

(2016). Nonetheless, mastering discipline-specific vocabulary is a critical component of comprehension (Malatesha Joshi, 2005; Case, 2002), and allows students to develop effective scientific communication skills. Therefore, in this manuscript, we identify general biology, neuroscience- and immunology-specific terms and topics that we consider essential for student comprehension (Table 6).

2.3 Interdisciplinary understanding

National conversation and call for action underscored the importance of interdisciplinary thinking in reports such as *Vision and Change* in Undergraduate Biology Education: A Call to Action (see text footnote[4]). These calls have been amplified by funding agencies such as the National

TABLE 3 The concept 'information flow, exchange and storage' in the context of life science (Brownell et al., 2014), Neuroscience (Chen et al., 2023), and Immunology (see text footnote[2]) and their application in Neuroimmunology.

Information flow, exchange, and storage	
Life science core concepts	
• Organisms inherit genetic and epigenetic information that influences the location, timing, and intensity of gene expression. • Cells/organs/organisms have multiple mechanisms to perceive and respond to changing environmental conditions.	
Neuroscience concepts	**Immunology concepts**
• **Communication modalities:** Nervous systems encode and transmit information in various modalities. • **Gene-environment interactions:** Unique patterns of gene expression underlie the organization and function of a nervous system and are altered by environmental factors. • **Information processing:** 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.	• Antigen recognition and associated cellular signaling result in differential gene expression, which shapes the organism's targeted immune response. • During development, immune cells differentiate to acquire characteristic phenotypes. • Gene expression and regulation influence the recognition of diverse antigens by the immune system.
Neuroimmunology context	
The gene expression pattern for cell-to-cell communication and cell differentiation in nervous and immune systems can be inherited and influenced by the changes in environmental conditions.	
Multiple sclerosis specific example learning outcome	
Describe how the brain microenvironment in multiple sclerosis can influence expression of pro- and anti-inflammatory cytokines.	
Depression specific example learning outcome	
Using examples from the immune system, explain how inherited gene expression patterns or epigenetic changes can increase an individual's vulnerability to depression.	

TABLE 4 The concept "pathways and transformation of energy and matter" in the context of life science (Brownell et al., 2014), Neuroscience (Chen et al., 2023), and Immunology (see text footnote[2]) and their application in Neuroimmunology.

Pathways and transformation of energy and matter	
Life science core concepts	
• Energy and matter cannot be created or destroyed, but can be changed from one form to another. • Energy captured by primary producers is necessary to support the maintenance, growth and reproduction of all organisms. • Natural selection leads to the evolution of efficient use of resources within constraints.	
Neuroscience concepts	**Immunology concepts**
Not available	• Immune system activation is an energy-intensive process that can influence and can be influenced by other metabolic demands (e.g., stress, malnutrition, reproduction, circadian rhythm disruption, exercise etc.)
Neuroimmunology context	
Neuroimmune interactions require energy and resource allocation that can compete with other metabolic demands within an organism.	
Multiple sclerosis specific example learning outcome	
Explain how the metabolic needs of a CD4+ T cell may change as it differentiates from naive to an effector cell to mediate neuroinflammatory processes in multiple sclerosis.	
Depression specific example learning outcome	
Describe how inflammation-induced changes in the kynurenine pathway, which transforms tryptophan into various metabolites, can impact neurotransmitter balance and potentially contribute to the development of depression.	

Science Foundation and National Institutes of Health. These calls stem from the realization of the fact that complex societal problems will need interdisciplinary collaborations for proposing and implementing solutions. The inherently interdisciplinary neuroimmunology curriculum offers a perfect opportunity to bring this competency into the undergraduate curriculum. In addition, we were informed by previous work on interdisciplinary understanding by Tripp and Shortlidge (2019, 2020), who reported a working definition of interdisciplinary science as follows: "A collaborative process of integrating knowledge/expertise from trained individuals of two or more disciplines—leveraging various perspectives, approaches, and research methods/methodologies—to provide advancement beyond the scope of one discipline's ability (Tripp et al., 2020)." They proposed a conceptual framework called Interdisciplinary Science Framework (IDSF) to guide students to tap into the interdisciplinary nature of science. This framework describes five elements: disciplinary humility, disciplinary grounding, different research methods, advancement through integration and collaboration across

TABLE 5 The concept "evolution" in the context of life science (Brownell et al., 2014), Neuroscience (Chen et al., 2023), and Immunology (see text footnote[2]) and their application in Neuroimmunology.

Evolution	
Life science core concepts	
• All living organisms share a common ancestor. • Species evolve over time, and new species can arise, when allele frequencies change due to mutation, natural selection, gene flow, and genetic drift.	
Neuroscience concepts	**Immunology concepts**
• The similarities and differences in nervous systems between organisms are constrained and defined by their evolutionary backgrounds.	• Immune defenses vary based on organism's evolutionary timeline.
Neuroimmunology context	
Neuroimmune interactions may change or remain conserved across the evolutionary timeline.	
Multiple sclerosis specific example learning outcome	
Compare and contrast between mouse, fish and human as research model organisms for studying multiple sclerosis.	
Depression specific example learning outcome	
Justify the use of rodent models for studying depression, a complex human psychiatric disorder.	

TABLE 6 Life science, neuroscience and immunology specific terms and topics that students should know before embarking on a neuroimmunology module/course.

Life science terms and topics	Neuroscience terms and topics	Immunology terms and topics
• Tissues and Cells • Organisms and Organ systems • Cells and Macromolecules (e.g. DNA, RNA, Protein, Lipid) • Gene and Gene Regulation • Receptor and Ligand • Host and Pathogen • Normal cell and Tumor cell • Replication, Transcription and Translation • Metabolism and ATP • Mutation, Natural Selection and Evolution	• Central Nervous System and Peripheral Nervous System • Meninges, Blood Brain Barrier, the Ventricular System, and Cerebrospinal Fluid • Neurons and Glial Cells (Microglia, Astrocytes, Oligodendrocytes, Schwann Cells, Ependymal Cells) • Parts of a Neuron • Electrochemical Communication a) Ion Channels b) Membrane and Action Potentials c) Myelin and Saltatory Conduction d) Neurotransmitters, Neuropeptides, and their Receptors • Plasticity	• Innate and Adaptive • Antigen and Antibody • Antigen and Immunogen • Self and Non-self • Autoantigen and Altered self-antigen • Cytokine and Chemokine • Recruited and Structural Cell • Central and Peripheral Lymphoid organs/tissues • Defense and Tissue Repair • Memory and Tolerance

disciplines. These five elements guided our collaboration for the neuroimmunology curriculum.

3 The learning environment

The proposed neuroimmunology curriculum is intended for undergraduate students in life, health, or allied health sciences. The course may be adopted as a one-semester (13–15 weeks) intermediate or advanced elective course in a biology or neuroscience curriculum. Alternatively, an instructor may decide to implement a neuroimmunology module within their existing neuroscience or immunology courses.

3.1 Neuroimmunology learning objectives

Our ultimate learning goals for a neuroimmunology course are for students to: (1) develop a deeper level of conceptual coherence, and (2) practice problem-solving skills that utilize the conceptual understanding of both disciplines. More specifically, students should develop an understanding that the nervous and immune systems are not disparate but are interconnected and interacting systems within an organism, and that these interactions can influence health and disease outcomes.

Learning Objectives are defined as specific and measurable articulations of what a learner should be able to do as a result of engaging with the course or a module (Orr et al., 2022). Accordingly, we note the following Learning Objectives:

At the end of the neuroimmunology course/module, students will be able to:

(i) Describe the mechanisms by which the nervous and immune systems integrate and communicate bidirectionally to regulate homeostasis and respond to challenges (Overarching Core Concept: Systems) (Table 1).
(ii) Identify the relationship between key components of the nervous and immune systems and their functions (Overarching Core Concept: Structure and Function) (Table 2).
(iii) Explain how the components of the nervous and immune systems interface and communicate with each other in health and diseased states (Overarching Core Concept: Information Flow, Exchange and Storage) (Table 3).

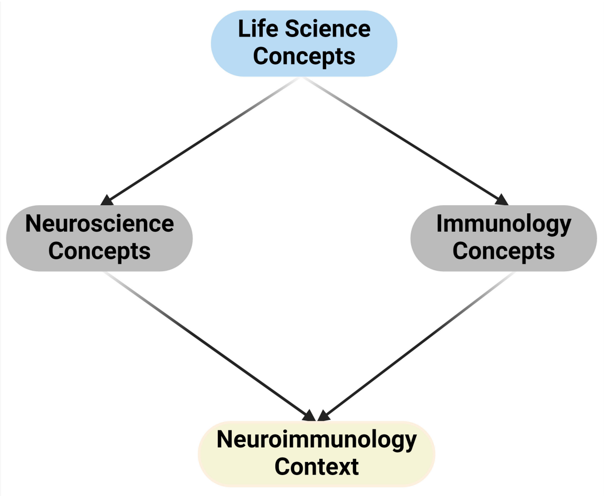

FIGURE 1
Workflow that describes our concept-focused approach to neuroimmunology curriculum design. Neuroimmunology statements are grounded in the understanding of neuroscience and immunology concepts, which are in turn derived from basic biology (life science) concepts. Image created by S.P. using www.biorender.com.

(iv) Discuss how energy trade-offs influence nervous and immune system development and function (Overarching Core Concept: Pathways and Transformation of Energy and Matter) (Table 4).
(v) Discuss how diversity in nervous and immune systems across organisms informs neuroimmunology research (Overarching Core Concept: Evolution) (Table 5).

3.2 Prerequisite knowledge for the neuroimmunology curriculum

Upper-level biology courses often require significant prerequisites and/or corequisites. For example, a stand-alone course in neurobiology or immunology builds on principles covered in introductory biology, chemistry, cell biology and genetics courses. Disciplinary norms and course rigor may dictate the choice of prerequisites, though it is debated whether prerequisites effectively serve the purpose(s) that they are intended for (Taylor, 2013; Shaffer et al., 2023; Sato et al., 2017). While designating prerequisites are important for an instructor to ascertain the starting point for their classes, it cannot be assumed that all students are at the same level of conceptual understanding and knowledge before engaging with the neuroimmunology content.

In most educational contexts, students will have already completed an introductory biology course sequence before encountering an intermediate or advanced elective course such as this one. Knowledge of core introductory biology should thus be considered prerequisite knowledge and not be covered in depth, though instructors may want to reinforce and remind their students of such foundational concepts as they arise. It is much less likely that undergraduate biology or neuroscience students would have completed intermediate courses in both neuroscience and immunology before encountering a neuroimmunology elective course, especially at smaller colleges. Therefore, instructors may find it helpful to include a "crash course" in immunology and/or neuroscience depending on how the course is situated in the curriculum and what kind of student audience the course draws. In the following sections, we describe the three subsections for prerequisite knowledge that an instructor may cover or review first.

3.2.1 Introductory biology prerequisite knowledge

Students who have taken an introductory biology course may already be familiar with the general categories of content knowledge as described in *Vision and Change* and the subsequent BioCore interpretations (Brownell et al., 2014). For example, they would likely be familiar with the basics of structure and function relationships at the macromolecular, subcellular, and cellular levels, as well as receptor-ligand interactions. Subsequently, instructors can expand on general concepts surrounding foundational structure/function when discussing structure/function relationships among and between neural and immune cells. Students should also be familiar with the basics of information flow within systems, such as how genetic material is stored, replicated, transcribed, and translated, and how it changes through mutation. With respect to systems, students should be familiar with how a system's complexity in structure and function progresses across levels of organization, from subcellular and cellular levels to tissues, organs, organ systems, and organisms. As one example, most students will be familiar with the idea of homeostasis as a system's ability to self-regulate in response to perturbation. Students should be well-acquainted with the idea that evolution is a unifying framework that can be applied to biology at all scales of organization. The introductory biology (life science) core concepts that students must understand are listed in Tables 1–5, and the relevant terms and topics are listed in Table 6.

Finally, students should also have beginner-level conceptual knowledge of science as an iterative process, including the scientific method, hypothesis testing, and visualization and interpretation of data. Some introductory concepts and competencies may vary depending on the structure of the introductory course and whether it includes a laboratory. Depending on whether students have taken an introductory biology laboratory and how that laboratory was designed, they may also have direct experience with engaging in the process of scientific inquiry, including collecting and analyzing data and communicating their findings in the style of a lab report or scientific manuscript. Students may also have experience reading and analyzing scientific literature. Our proposed neuroimmunology curriculum is amenable to opportunities to discuss primary literature as a means of developing skills in reading and critical thinking. Instructors should be aware of their course context and, when appropriate, either teach or reinforce skills for reading scientific literature through direct instruction or assigning and discussing readings on this topic such as guides authored by Carey et al. (2020) and Harrington (2020).

3.2.2 Neuroscience specific prerequisite knowledge

Because neuroimmunology emphasizes the interconnectedness of the nervous system with other systems in the body, it would be helpful for students to have a good understanding of foundational neuroscience concepts via prior neurobiology or neuroscience courses or a crash course at the beginning of a neuroimmunology course. Referring to the Core Concepts for Neuroscience (Chen et al., 2023), students should be familiar with the structure of the nervous system and its major divisions, and how these structures relate to functions at the systemic level to elicit behavior. They should also be able to relate structure to function at the cellular and molecular levels. For example, neurons and glial cells have distinct and specialized structural characteristics that enable these cells to perform specific functions. Students should also be well-acquainted with how neurons receive information from their immediate environments, generate graded or action potentials and transmit various signals to target cells that are either in the immediate vicinity or more distant. They should be aware that gene-environment interactions can influence nervous system structure and function throughout life and that these connections within the nervous system are plastic, changing in response to internal and external stimuli. Students should appreciate that cellular and molecular mechanisms underlying core neurobiological phenomena are evolutionarily conserved, allowing us to address research questions that concern human health using animal models. Moreover, the evolutionary relationship between any particular species and humans dictates not only the types of research questions that can be addressed using that species as an experimental model but also the translatability of the findings. Lastly, students should be familiar with the idea that higher-order functions and complex behaviors arise from interactions of brain areas in functional networks and cannot be attributed to any one specific brain area.

3.2.3 Immunology specific prerequisite knowledge

Typically, a stand-alone undergraduate course in immunology is an upper-level elective. Students may have been exposed to some immunology in the context of human anatomy and physiology or microbiology, and instructors may conduct a formal or an informal assessment to gauge their students' prior knowledge. AAAS's assessment site is a helpful resource to test students' basic knowledge.[6] If students have a good understanding of the five core concepts in life sciences - systems, structure-function, information flow, exchange and storage, pathways and transformation of energy and matter, and evolution—these concepts could be introduced in the context of immunology. An example activity is to have students sort immunology-specific learning outcomes based on the core concept that they align with Branchaw et al. (2020). These immunology specific core concepts and learning outcomes are noted in the immunology learning framework (see text footnote[2]). An immunology unit could introduce immune system-specific terms and concepts that are sufficient to understand neuroimmunology. In our respective classes, we have used one or more of the following resources to provide an introduction to immunology: (a) An Interactive Classroom Icebreaker and Parting-Ways Activity to Introduce and Review the Effector Functions of Cellular Players Associated with Immune Response (Kleinschmit et al., 2020); (b) HHMI's Biointeractive Resources on the Immune System[7] and other HHMI resources[8] (Basta, 2024). The intent is to cover the basic principles in immunology, identified in the Immunology Learning Framework (Tables 1–5) and introduce immunology specific terms in a compare-and-contrast format (Table 6).

In order to introduce these details, instructors may devise activities based on time available at hand. These could range from self-assigned reading to an in-class overview using public response/polling systems, or card sorting or worksheet-based activities. The above-listed concepts and terms could then be reinforced with the neuroimmunology modules/topics, and they could be expanded based upon the need of the neuroimmunology specific topic. For example, a paper on CD4+ T lymphocytes in multiple sclerosis, may require additional knowledge of the Major Histocompatibility Complex (MHC) or T-Cell Receptor (TCR).

3.3 Course content and resources

Here we provide the weekly schedule for a semester-long neuroimmunology course (Table 7). Additional neuroimmunology topics that could be incorporated into a course are listed in Supplementary Table 1. We also provide a curated list of resources categorized by topic, level, and resource type[9] to introduce students to neuroimmunology, neuroscience and immunology. This list includes a variety of case studies, popular science books, textbooks, podcasts, videos, primary and secondary literature, educational games etc. This resource list is a living collection, and we invite instructors to suggest resources through our online form.[10]

Working from the learning objectives, our proposed curriculum for a semester-long neuroimmunology course (Table 7) begins with covering the basics of neural and immune structure and function and their interactions. In the second half of the course, instructors can choose disease case studies to illustrate

6 BSCS. Science Assessment: AAAS Project 2061. Available at: https://assess.bscs.org/science/pages/about (accessed September 24, 2024).

7 Howard Hughes Medical Institute. HHMI Biointeractive: The Immune System. Available at: https://www.biointeractive.org/classroom-resources/immune-system (accessed September 20, 2024).

8 ImmunoReach. Basta, H. (2024) What's the Big Picture? Contextualizing an Immunology Course Using HHMI BioInteractive's Immune System Resource. Available at: https://immunoreach.net/dr-holly-basta/ (accessed September 20, 2024).

9 Shah, A., Pandey, S., and Leininger, E. (2024) ImmunoReach: Neuroimmunology Pedagogical Resource Database. Available at: https://airtable.com/appByDaPB0xscz75V/shr365EuVJchXatIs (accessed September 23, 2024).

10 ImmunoReach. Shah, A., Pandey, S., and Leininger, E. (2024) *ImmunoReach: Neuroimmunology Pedagogical Database Contribution Invitation*. Available at: https://docs.google.com/forms/d/e/1FAIpQLSeoq-ARMvaYeJyDpfzMOwwhAH3YsGqAyT_Q8lr0Ymj3FRECgg/viewform?pli=1 (accessed September 23, 2024).

TABLE 7 Proposed semester curriculum for an undergraduate upper level neuroimmunology course.

Weeks	Theme	Topics	Learning objectives
1	What are the physical components of the nervous and immune systems?	Central Nervous System and Peripheral Nervous System; Meninges, Blood Brain Barrier, and the Ventricular System; Neurons and Glial Cells; Parts of a Neuron; Central and Peripheral Lymphoid organs/tissues; Recruited and Structural Cells	(i)
2	What are the chemical components and processes of the nervous and immune systems?	Membrane and Action Potentials; Saltatory Conduction; Neurotransmitters, Neuropeptides, and their Receptors; Electrochemical Communication; Antigen and Antibody; Antigen and Immunogen; Cytokine and Chemokine; Autoantigen and Altered self-antigen	(i)
3-6	How do the nervous and immune systems interact and regulate each other?	The brain's immune system; CNS lymphatic system; The role of microglia in neural development; The role of the immune system in synaptic plasticity; Immune-brain interactions during sickness (e.g., fever, sickness behavior); The gut-brain axis; Neuroplasticity; Immune memory and tolerance	(ii), (iv)
7-8	Disease Example 1: Multiple Sclerosis	Autoimmunity; Demyelination in the central nervous system; Symptoms: sensory and motor systems; Treatment strategies: corticosteroids, interferons, antibody therapies	(ii), (iii)
9–10	Disease Example 2: Myasthenia Gravis	Autoimmune vs. congenital causes; Neuromuscular synaptic transmission; Symptoms: muscle weakness; Role of animal models in elucidating mechanism; Treatment strategies: acetylcholinesterase inhibitors and thymectomy	(ii), (iii), (v)
11–12	Disease Example 3: Narcolepsy	Autoimmunity; Role of neuropeptides in hypothalamic homeostatic systems (Emergence); Symptoms: excessive sleepiness, cataplexy; Role of animal models in elucidating mechanism; Treatment strategies: stimulants	(ii), (iii), (v)
13–14	Disease Example 4: Depression	Heterogeneous etiologies, Multiple inflammatory mechanisms related to neuroplasticity, HPA axis dysfunction, gut-brain dysbiosis; Symptoms: mood dysregulation; Treatment strategies: SSRIs, ketamine	(ii), (iii), (iv), (v)
15	Wrap-up/Synthesis	Possible activities could include concept mapping, short presentations from student groups, peer review of final assignments, discussion of recent news articles relating to neuroimmunology topics, etc.	variable

Course learning objectives are mapped to the themes and topics of each module in the course.

how neural-immune interactions can become dysregulated during disease states, how perturbations of structure and function lead to disease symptoms, and mechanisms of common or proposed treatments. The proposed course curriculum includes four examples of neuroimmunological diseases covered in 2 weeks each. The first two diseases, multiple sclerosis and myasthenia gravis, are classic examples of autoimmune neurological diseases that students may be familiar with from introductory immunology or neuroscience courses, as these diseases target core features of immune or neural structure and function, respectively. Multiple Sclerosis is caused by the autoimmune demyelination of axons, perturbing the core process of action potential propagation and resulting in sensory and motor symptoms (Mahad et al., 2015; Bando, 2020). Myasthenia gravis is an autoimmune disease that attacks nicotinic acetylcholine receptors at the neuromuscular junction, impairing the core process of synaptic transmission and resulting in muscle weakness (Gilhus and Verschuuren, 2015; Paz and Barrantes, 2019). Several published teaching case studies can be used in the classroom to help students learn about multiple sclerosis (Field et al., 2019) and myasthenia gravis (Brown and Ellerton, 2011; Russo et al., 2005). The other two diseases narcolepsy and depression, are likely diseases that students have heard of but are unaware of as being connected to neuroimmunology. We propose including these conditions as ways to highlight the complexity of neural and immune systems in creating emergent properties of behavior and cognition (Sarno et al., 2021; Latorre et al., 2022). In particular, students may be familiar with the "serotonin hypothesis" of depression but may not be aware of the additional possible etiologies of depression including the potential role of the immune system (Réus et al., 2023).

While we chose four possible diseases to highlight as examples in the sample curriculum, instructors could choose from a myriad of neuroimmune disease examples depending on their interests and the interests of their students (Supplementary Table 1). In particular, the role of neuroimmune interactions in Traumatic Brain Injury and COVID-19 may be especially compelling and relevant to college students' lived experiences. Instructors could also incorporate additional neuroimmune diseases into their course through independent project work, as described by co-author A.S. in Section 5.

4 Assessment of student learning

Student knowledge and understanding can be assessed in the following three domains.

4.1 Testing prior knowledge

The prerequisite concepts and terms-related knowledge identified in Section 3.2 can be assessed in the 1^{st} week of class in various ways: (i) Quizzes and tests; (ii) Concept Maps, and (iii) Student self-assessment. The misconceptions unraveled during the prior knowledge assessment can then inform further lesson plans, as described here (Shi et al., 2017).

4.2 Testing conceptual knowledge gains

Writing clear and measurable/observable learning outcomes aligned with the neuroimmunology concepts (see example in Tables 1–5) is critical for this step and an iterative, collaborative process may help with this task (Orr et al., 2022).

4.3 Testing the students' understanding of importance of interdisciplinary communication and collaboration

As noted in Section 2.3, the neuroimmunology curriculum is well suited to meet the competency of interdisciplinary scientific understanding with undergraduate students. Toward this end, Tripp and Shortlidge (2020) propose the development of essay prompts and assessing those with the help of the Interdisciplinary Science Rubric (IDSR).

Instructors should also consider equity and inclusion, principles of universal design and scaffolding while designing course assessments. Assessment design can be one of the most exclusionary factors in a classroom setting, where assessments may disadvantage students because of characteristics or abilities extraneous to the outcomes being judged. For example, a closed book exam is not necessarily a test of conceptual understanding, but of students' ability to memorize and recall information under pressure. Similarly, an oral presentation can be anxiety inducing for some students. As Tai et al. (2023) state, "an authentic assessment must create space for students to integrate their values, capabilities and their future aspirations." Instructors can leverage Universal Design for Learning guidelines to design rigorous, authentic, and inclusive ways for students to demonstrate their learning (CAST, 2024). Drew et al. (2021) note ten different types of assessments, with their advantages and disadvantages, and their appropriateness for face-face, blended, and online modalities. For lengthy or complex assignments, scaffolding can help clarify the necessary intermediate steps for a successful assignment and ensure that students engage with the process of the assignment consistently. For example, in two different multidisciplinary courses on sex, gender, and the brain, instructors used scaffolded research proposal assignments and public-facing science communication assignments to assess students' conceptual knowledge as well as communication and scientific reasoning skills (Tan and Leininger, 2024). As another example, assignment scaffolding in a microbiology course was introduced to help students build conceptual knowledge alongside data interpretation and communication skills (Joyner and Parks, 2023). We encourage educators to purposefully integrate assessments into their courses, scaffolding assignments when necessary and modifying them as needed for their educational setting.

5 Discussion, limitations, and constraints

An interdisciplinary neuroimmunology curriculum offers the advantage of encouraging real-world problem-solving capabilities in our students. We offer this curriculum as an example, and note that when implementing this curriculum, instructors must mold it to their own educational context, considering the available resources (personnel, faculty expertise, and funding), course modality (online vs. face-to-face, synchronous vs. asynchronous), students' likely prerequisite knowledge and integration within the program curriculum. An important takeaway for instructors adopting this approach is to maintain conceptual focus, limit the use of disciplinary jargon in the lesson plans, and scaffold progression of concepts. While our approach was to nest the neuroscience and immunology concepts under life science core concepts identified in the *Vision and Change* report, and integrate the two for neuroimmunology applications, we acknowledge that this is not the only approach to curriculum design. For example, in addition to life science concepts, the course learning outcomes could be aligned with competencies [for example, using this (Pandey et al., 2024)], and/or incorporate a societal or policy-based approach to neuroimmunology topics. It is important to note that appreciation for the interdisciplinary nature of science is a step after disciplinary understanding. Therefore, instructors should expect that students become increasingly proficient in this competency toward the end of the curriculum rather than right at the start.

While the neuroimmunology curriculum proposed here is designed as a semester-long endeavor, instructors may opt to adapt this larger curriculum into a neuroimmunology module within another course. For example, co-author A.S. has developed and taught an upper-level elective for neuroscience majors at her institution called *Brain-Body Interactions in Health and Disease*, which includes a module on neuroimmunology. In the most recent iteration of this course from last spring with ∼50 students enrolled; this module spanned 4 weeks. As student responses to a pre-course survey indicated that over 90% of the class had not taken a course on immunology during their time in college thus far, the 1st week of the module was spent on introducing general immunology and vaccines in a flipped-classroom style. Students were provided an interactive online module on the immune system (see text footnote[7]), an associated problem set, and videos on the cells of the immune system. In-class time was spent reviewing this content via mini tutorials using whiteboard illustrations led by student groups. The 2nd week focused on illustrating how the immune and nervous systems are structurally and functionally intertwined and involved activities such as annotation of a news feature and discussion of novel findings on immunological memory in the brain presented in a *This Week in Neuroscience* podcast.[11] Student knowledge was assessed with a collaborative two-staged quiz (Giuliodori et al., 2008; Khong and Tanner, 2021) before proceeding to brief (5-min) group presentations on ten neuroimmunology topics from a list that was made collaboratively with students, during the last 2 weeks of the module. As noted above and based on experience teaching this module over the years, it is highly recommended to conduct a pre-course survey to assess students' prior exposure to immunology and adapt the course/module content accordingly.

11 MicrobeTV. (2024) Immunological memory in the brain. Available at: https://www.youtube.com/watch?v=LRcpJ3fP2dU (accessed September 26, 2024).

This information can also be used as one of the criteria when creating student groups to ensure balanced prior background. While student feedback suggests that the course was effective overall, future assessments will be designed and implemented to evaluate the extent to which the neuroimmunology learning objectives, as described in this paper, are met.

By designing and proposing the neuroimmunology curriculum described in this manuscript, we hope to share resources with faculty looking to incorporate the interdisciplinary nature of science as a learning goal for their students, and invite educators to our neuroimmunology community of practice,[12] where we can learn from each other, and vet this curriculum collaboratively.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

AS: Conceptualization, Data curation, Writing – original draft, Writing – review & editing, Investigation, Methodology, Resources, Visualization. EL: Conceptualization, Data curation, Writing – original draft, Writing – review & editing, Investigation, Methodology, Resources, Visualization. SP: Conceptualization, Data curation, Funding acquisition, Project administration, Resources, Visualization, Writing – original draft, Writing – review & editing, Investigation, Methodology.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declare that no Gen AI was used in the creation of this manuscript.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/feduc.2025.1502521/full#supplementary-material

12 ImmunoReach. (2024) Neuroimmunology Community of Practice. Available at: https://immunoreach.net/neuroimmunology/ (accessed September 26, 2024).

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