Adv Physiol Educ 50: 32–38, 2026.
First published November 18, 2025; doi:10.1152/advan.00160.2025

american physiological society

ADVANCES IN PHYSIOLOGY EDUCATION

TEACHING INNOVATIONS

Implementing an integrated epistemic framework: a multimodal active learning approach in translational neuroscience

Kambiz N. Alavian

Department of Brain Sciences, Faculty of Medicine, Imperial College London, London, United Kingdom

Abstract

The theoretical and practical aspects of science education are often uncoupled, resulting in decontextualized learning. To address this concern, the present work adopts the view that scientific discovery is a form of learning and that its hypothetico-deductive and transformative processes are essential for learning in scientific disciplines. This article presents an educational practice developed for a graduate-level translational neuroscience module, centered on the process of scientific inquiry through student-led, hypothesis-driven research design. The project adopts a multimodal framework, based on multiple pedagogical and philosophical concepts including transformative learning, threshold concepts, social constructivism, and the philosophies of Popper and Kuhn, to integrate content knowledge with epistemological development. By mirroring the logistics and logic of scientific discovery, and through iterative cycles of discussion, reflection, and critical evaluation, the students navigate both cognitive and affective domains and engage with complex and often troublesome topics in translational neuroscience.

NEW & NOTEWORTHY Grounded in Popper's hypothetico-deductive logic, Kuhn's focus on anomalies, threshold concepts, and transformative learning, the Virtual Research Project (VRP) turns the scientific method into pedagogy.

active learning; multimodal learning; neuroscience; social constructivism; transformative learning

INTRODUCTION

A key concern in the design of science education, especially at the postgraduate level, is how best to introduce students to the epistemologically rich nature of the scientific discovery process. Conventional methods of science education emphasize content delivery and protocol-driven laboratory exercises and often stop short of capturing the complexity and uncertainty that characterize scientific inquiry. Such methods result in decontextualized learning, especially in applied and translational disciplines (1, 2). Here I introduce a method based on the view that scientific discovery is a form of learning and the collective processes underpinning it mirror the structures of learning itself. Education in sciences should, therefore, actively simulate the processes of knowledge production, not merely its outcomes. The Virtual Research Project (VRP) has been implemented since 2016 as an essential component of the Cellular and Molecular Neuroscience module within the MSc Translational Neuroscience program at Imperial College London. It was designed to immerse students in the process of scientific inquiry, engage them in the scientific method and the full cycle of research design and critical analysis, and introduce them to the transformative aspects of scientific discovery. The practice addresses the common gap in postgraduate neuroscience education that although students might gain exposure to experimental procedures in the practical phases of their training, the experimental and theoretical aspects of science are often decoupled and the curricula lack structured opportunities to formulate hypotheses, design projects, and critically evaluate methodological approaches before entering a laboratory environment.

The practice utilizes a multimodal framework, integrating elements of several pedagogical and philosophical concepts, including transformative learning, social constructivism, threshold concepts, Popperian falsification, and Kuhnian paradigms (3–7). This theoretical foundation is supported by key aspects of various educational methodologies, including scaffolding, flipped classroom pedagogy, discovery learning, as well as team-, problem- and group-based learning (8–13). Through integration of these theoretical and practical approaches, the VRP has fostered active, collaborative, reflective, and analytical engagement with complex and transformative neuroscientific concepts among students from diverse educational backgrounds.

PROJECT DESIGN AND RATIONALE

To fully understand the cellular and molecular basis of neurological conditions, a deep understanding of the underlying processes of scientific discovery is required. The Virtual Research Project was designed to immerse students in the hypothetico-deductive and revolutionary processes of scientific discovery. In this practice, discovery-based

Correspondence: K. N. Alavian (k.alavian@imperial.ac.uk).
Submitted 27 June 2025 / Revised 22 August 2025 / Accepted 6 November 2025

1043-4046/26 Copyright © 2026 The Authors. Licensed under Creative Commons Attribution CC-BY-NC 4.0.
Published by the American Physiological Society.

Downloaded from journals.physiology.org/journal/advances at Imperial Col London (2A0C:5BC0:0040:1008:DE4A:3EFF:FE6A:56AD) on January 23, 2026.

instruction, flipped classroom techniques, and the incorporation of research into teaching were employed to their fullest extent. Within this project, the formulation of pointed and important questions, hypothesis-driven inquiry, iterative cycles of failed and alternative hypotheses, and the progressive discovery of subject matter were utilized to embed otherwise difficult (and potentially unengaging) concepts into students' learning (14). By fostering advanced competencies such as project design, literature review, and hypothesis formulation, the project serves as a practice missing from most graduate-level neuroscience courses, i.e., the exercise of conceiving a project from scratch, pitching it to others, and defending it, essentially what occupies scientists while they are immersed in discovery or when applying for funding, publishing, or presenting their work. It encourages creative thinking and reinforcement of the new concepts learned in the module.

A core idea behind the Virtual Research Project is that all the students, regardless of their background knowledge and by the virtue of joining the course, have questions about the inner workings of the mind and brain. These questions would form the basis for construction of new knowledge. The questions and topics of the project on the mechanistic underpinning of neurological and neurodegenerative diseases, of unknown root causes, are inherently complex and troublesome.

Through posing pointed, important, and timely questions and navigating cycles of hypothesis testing, encountering failures and development of alternative hypotheses, the students immerse themselves into very difficult topics of neurological conditions and essentially (re)discover the topics for themselves. Learning such topics requires more than a mere consideration of cognitive processes. The practice considers behavioral and affective domains, such as the students' interests, values, and motivation (15, 16).

STRUCTURE AND PROCESS

The VRP centers around small-group, inquiry-led learning and is structured to simulate the collaborative and investigative nature of real-world scientific research. Groups of four to six students are formed and assigned a distinct but interrelated cellular or molecular process involved in or considered as part of the etiology of neurological or neurodegenerative conditions. These overlapping (but not identical) topics serve as the central inquiry themes and typically include key pathological mechanisms such as genetic risk factors, mitochondrial dysfunction, neuroinflammation, protein aggregation and mishandling, synaptic plasticity, and potential therapeutic strategies. Each student within the group takes responsibility (ownership) for researching and learning about the role of the group's overarching theme in a specific neurological or neurodegenerative disease condition, such as Alzheimer's disease, Parkinson's disease, or traumatic brain injury (Fig. 1). This division of labor ensures comprehensive coverage of the topics and different aspects of disease pathology while fostering interdependence and social constructive learning among group members, as collective understanding of the group becomes essential to formulating a plausible research question.

After reviewing the literature on the topics, the students come together and start discussing their understanding of as well as their opinions and level of interest in and related to the involvement of the cellular or molecular process in their assigned disease conditions. Driven by curiosity and creativity, each member of the group is required to pose an important, interesting, and timely question related to the connection between their assigned disease and the group topic. In subsequent discussion sessions, the questions are discussed and critically evaluated by the entire group, which then constructs what they consider to be the most interesting, important, and timely question focusing on the role of the topic in a single disorder. In addition to the three core criteria, the question is required to be within the domain of cellular and molecular neuroscience, related to a critical gap in knowledge within the field, and relatively specific. For instance, a question related to outcomes of a clinical trial fall beyond the scope of this module or practice, but the role of a specific gene or protein in modulation of cellular metabolism during the course of multiple sclerosis (as long as it meets the criteria of timely, important, and interesting), would be an appropriate question (Fig. 2).

The groups then collaboratively develop their hypotheses, considering the empirical content and Karl Popper's criteria of consistency, universality, and falsifiability (5). The critical assessment of different hypotheses and formulating a single one often requires several days of contemplation, reading, and discussion. The groups then design up to three aims and identify the most appropriate methodologies for testing their specific hypothesis. The experimental procedures and protocols appropriate for achieving each aim are discussed in detail, and the most appropriate methods are chosen based on published work and discussions among the group and with the instructor. The students then predict the most likely logical outcomes and results, based on carefully considering the conceptual and topical boundaries and envisioning the possible and probable scenarios. A very important part of the project is carefully considering the conceptual and methodological pitfalls and alternatives that might result in fundamentally changing the conceptual framework or tweaking or redesigning different aspects of the question, hypothesis, aims, or project design (Fig. 2). The students are cautioned that a linear and straightforward thinking process and results affirming the original hypotheses often result in incremental change within the existing paradigms or normal science (Kuhn's terminology) (17). It is the ability to engage with controversial outcomes that results in more sophisticated questions and hypotheses, increasing the likelihood of breakthroughs or paradigm shifts. The design and reflective process within this context and in the social constructive setting is iterative. With each iteration, student learning deepens, the concepts are improved, and the project becomes stronger.

INTEGRATION OF EPISTEMOLOGICAL AND PEDAGOGICAL FRAMEWORKS

Distinct elements from several philosophical and pedagogical concepts have been integrated into the theoretical foundation of the VRP. Karl Popper's philosophy and hypothetico-deductive model for scientific inquiry, including conjectures, refutations, and systematic elimination of error

Downloaded from journals.physiology.org/journal/advances at Imperial Col London (2A0C:5BC0:0040:1008:DE4A:3EFF:FE6A:56AD) on January 23, 2026.

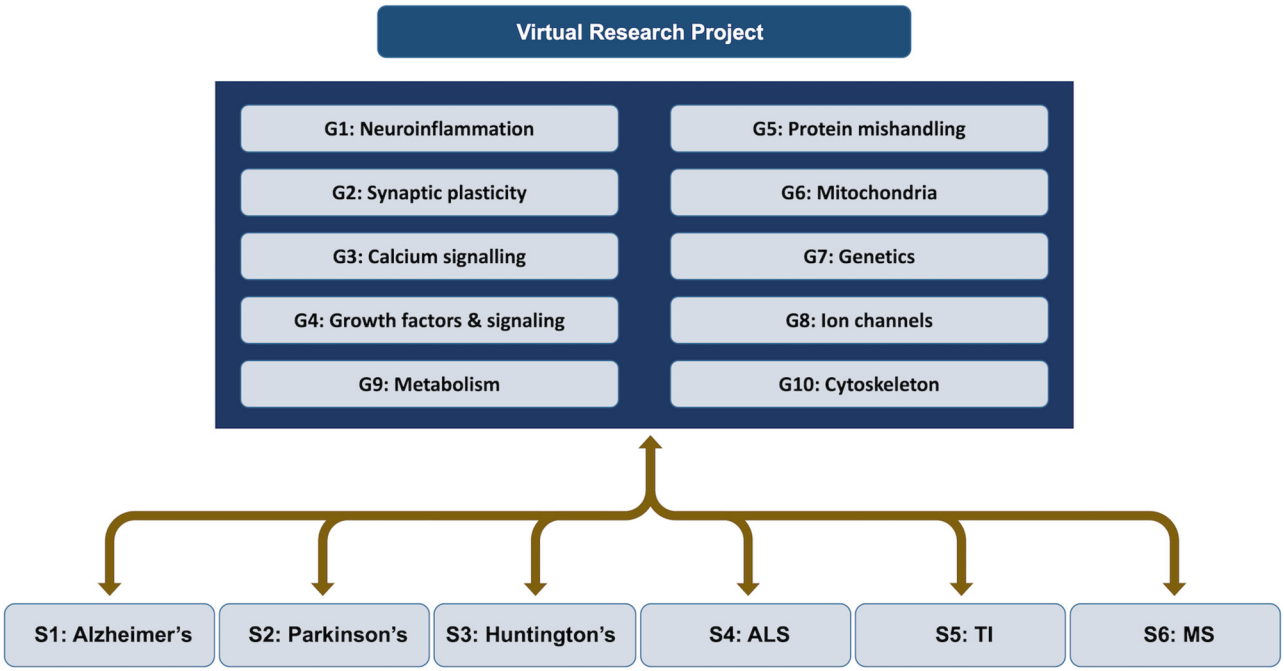

Figure 1. Overview of the Virtual Research Project (VRP) group structure. Each row represents a student group (*G1–G10*) focused on a cellular or molecular mechanism, and each column at *bottom* indicates a specific neurological or neurodegenerative disease assigned to individual students. Within each group, students (*S1–S6*) investigate the role of their shared mechanism across different disease contexts. The layout illustrates how overlapping scientific topics are mapped onto distinct pathological conditions. ALS, amyotrophic lateral sclerosis, MS, multiple sclerosis, TI, traumatic injury.

(18), are built into the VRP. The iterative cycles of formulating, challenging, and refining hypotheses based on critical analysis of data and systematic reasoning are meant to simulate real-life scenarios following this model. In this guided process, once the research question for each group is clearly defined, different deductive inference tools of analysis such as abduction or retroduction are used to generate tentative explanations or solutions and to test them against the prior knowledge of the groups (19, 20). Popper's structure is complemented by Kuhn's patterns of crisis and paradigm shift. At different stages of the project and by implementing these philosophical viewpoints, the VRP attempts to mirror transitions across Kuhn's five phases of scientific change, from preparadigm to normal science, crisis, paradigm shift, and formation of new paradigms (6, 17, 21, 22). The transition between the normal and transformative phases at this micro level (in the context of VRP) is continuously monitored and tailored to the content and context of the projects. The

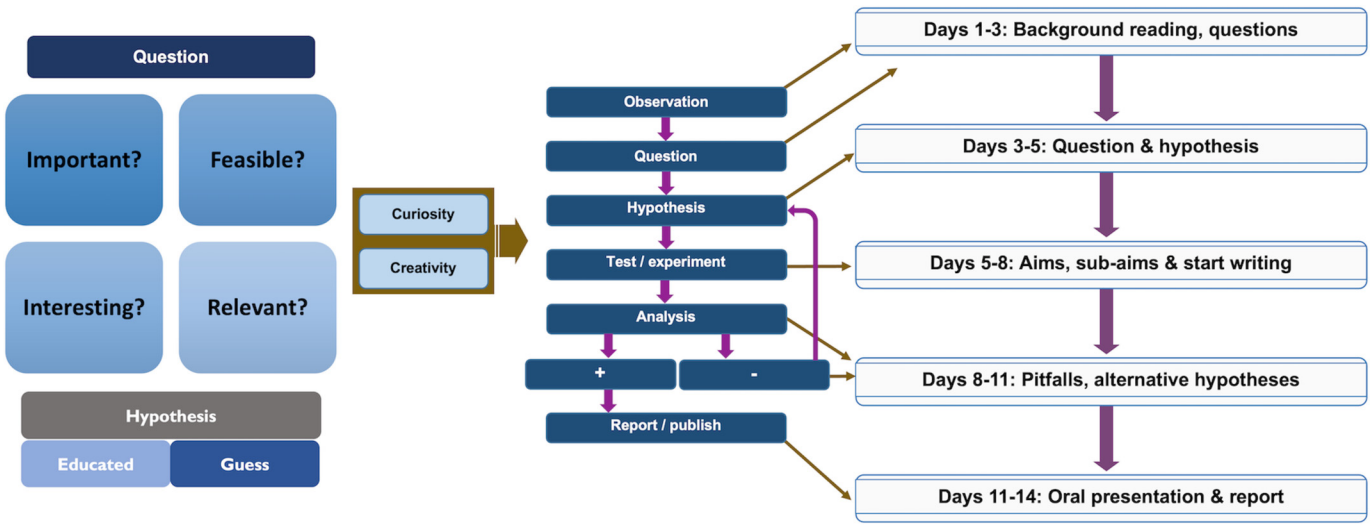

Figure 2. Flow chart of the Virtual Research Project (VRP) timeline and learning process. The sequence and logic of the VRP from the criteria for formulating an adequate question (important, feasible, interesting, and relevant; *left*) alongside the role of curiosity and creativity in initiating inquiry to the scientific process from observation and question formulation to hypothesis generation, testing, analysis, and dissemination (*center*). A rough timeline of the project, aligned with the stages of the project over a 2-wk period, is shown on *right*.

Downloaded from journals.physiology.org/journal/advances at Imperial Col London (2A0C:5BC0:0040:1008:DE4A:3EFF:FE6A:56AD) on January 23, 2026.

students initially operate within the accepted paradigms of their assigned cellular and molecular topics and disease areas, or within the Kuhnian normal science phase. Once they encounter and engage with conflicting and contradictory data, intellectual dissonance of the crisis stage emerges. The iterative cycles of hypothesis revision and reconceptualization push students toward a shift in their understanding, leading to the construction of new frameworks of thinking. These shifts, whether modest or transformative, are meant to emulate the conceptual leaps seen in Kuhn's scientific revolutions or irreversible shifts in perspective in threshold concepts (Fig. 3) (23–27).

The VRP happens in a flipped classroom setting and utilizes group-based inquiry and several aspects of team-based learning to foster interdependence and social constructivism. Students explore cellular and molecular mechanisms and hypotheses through problem- and inquiry-based methods, constructing knowledge through iterative engagement with complex problems at the juncture of basic and clinical neuroscience. The collaborative reasoning that follows individual preparation and the constructivist principles at the core of this process enable formation of a zone of proximal development through scaffolding of knowledge across diverse academic and disciplinary backgrounds (28). Reflective practice, discovery learning, and cycles of self and peer feedback are anchored in Popper's and Kuhn's epistemological models of scientific discovery (Fig. 3) (6, 29).

In addition to fostering deep engagement through social constructivism, the VRP provides a valuable pedagogical (liminal) space for the recognition and crossing of threshold concepts. These are concepts that, once understood, transform perception of a subject and are difficult or impossible to unlearn. The experience of grappling with threshold concepts often involves a liminal stage, characterized by uncertainty, repositioning and reconfiguration of the learner's prior schema, and reconstitution of understanding. The reconfiguration and integration of knowledge results in an ontological and epistemic shift, representing the reconstitutive feature of the threshold concepts. The liminal state resonates closely with Kuhn's notion of scientific anomaly resolution (30–32). The epistemological transformation of the students, along with their cognitive, affective, and identity-level shifts, begins to take place in these uncertain, uncomfortable stages (6, 30, 33–35). These processes align

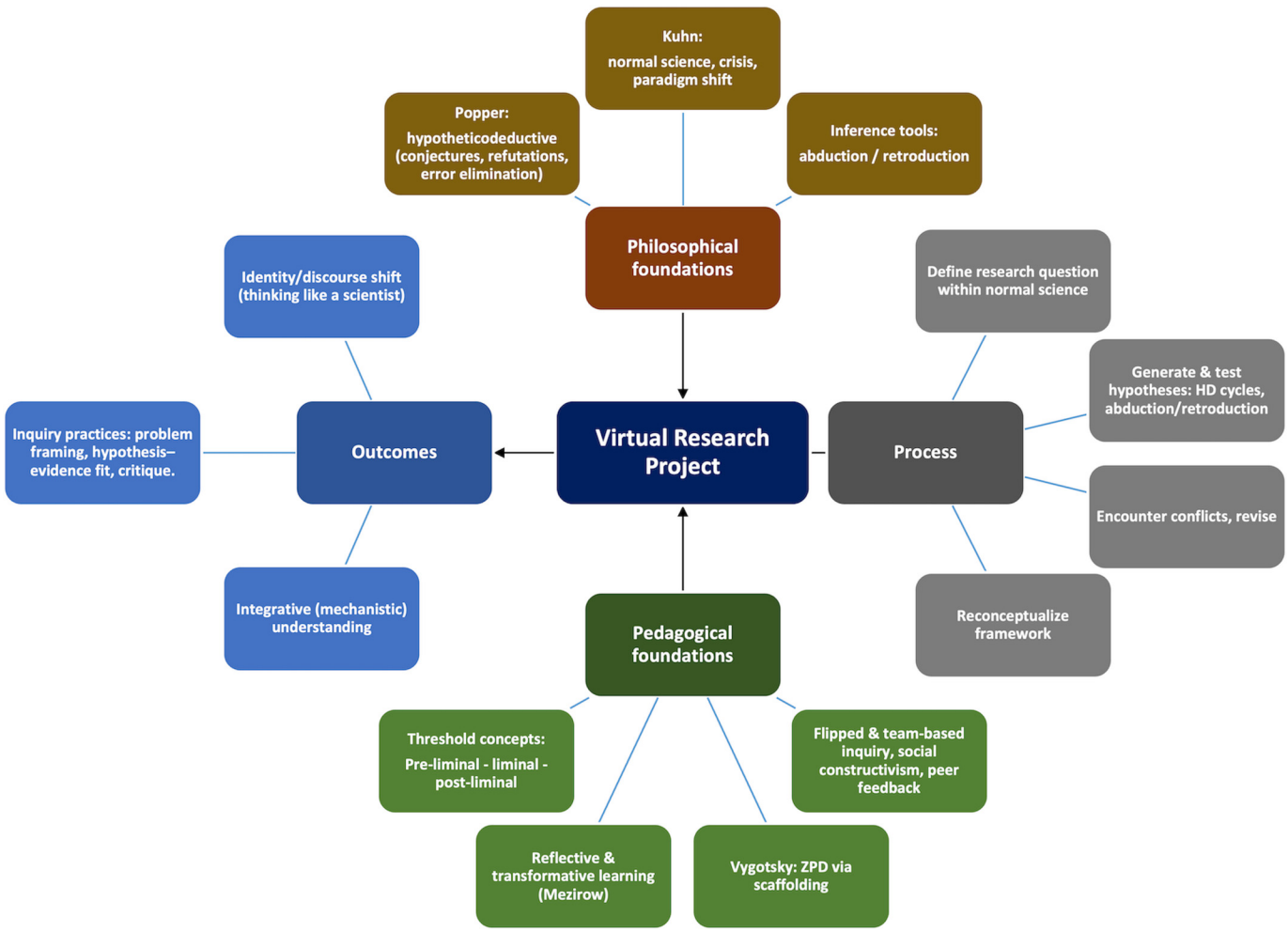

Figure 3. Summary of the Virtual Research Project's (VRP's) conceptual foundations, process, and outcomes. Philosophical and pedagogical frameworks feed into the VRP, which drives an inquiry cycle leading to integrative understanding, strengthened inquiry practices, and identity/discourse shifts. HD, hypothetico-deductive; ZPD, zone of proximal development.

Downloaded from journals.physiology.org/journal/advances at Imperial Col London (2A0C:5BC0:0040:1008:DE4A:3EFF:FE6A:56AD) on January 23, 2026.

closely with the practices of transformative learning, where the restructuring of understanding is tied to personal growth, emotional engagement, and the reconfiguration of meaning perspectives (36–38).

The VRP draws upon Mezirow's theory of transformative learning by embedding both the cognitive and transformative dimensions of adult learning into its structure. According to Mezirow (7, 39), transformative learning is triggered by disorienting dilemmas, which parallel liminal and crisis phases of threshold concepts and Kuhn's model, and involves critical reflection, leading to a restructuring of meaning perspectives. By following this model, the VRP challenges students' existing mental frameworks and initiates a process of reflection and reengagement with alternative perspectives.

The journey of a learner for learning the threshold concepts is divided into three stages of preliminal, liminal, and postliminal states. The encounter with the threshold concepts happens in the preliminal state. This encounter results in the reconstitution of the concept in the liminal state and crossing a threshold that sits at the boundary of the liminal and postliminal states. In the postliminal state, the irreversible transformation of the learner and knowledge, marked by the change in discourse, has taken place (31, 40, 41). The topics and questions explored throughout the module and within the VRP, such as the gating properties of ion channels or the integration of neurodevelopmental mechanisms into neurodegenerative disease mechanisms, represent knowledge that is integrative, bounded, and frequently troublesome. The process of engaging with these complex disease mechanisms at a cellular and molecular level, forming hypotheses, and encountering alternatives and pitfalls often leads students to what Meyer and Land describe as portals to new ways of thinking and transformative understanding (30, 42). The reconstitutive and discursive characteristics of threshold concepts emphasize identity shifts and the evolution of disciplinary discourse, both of which are noticeable in students' progression through the VRP and in the final reports and presentations. By creating the liminal learning environment and integration of these relevant theoretical concepts, the VRP facilitates not only content knowledge acquisition but also epistemic development, encouraging students to think like scientists who must continuously adapt and evolve their conceptual models.

TIMELINES, ASSESSMENT, AND LEARNING OUTCOMES

The VRP is executed with a 2-wk module and is embedded within a flipped classroom framework. The students engage with the required information on their topics and disease areas before the discussion sessions. The time in the class is used for consolidation of information through discussion. The timeline of VRP is aligned with the hypothetico-deductive process outlined above, and formative and summative feedback opportunities are embedded within the 2-wk time frame (Fig. 2).

Peer feedback is a critical, formative, component of learning in this project. The students' work is assessed during the discussion sessions as well as in formative and summative assessments. The first week includes formative assessment as group presentations of the project questions, hypotheses, and aims. At the end of each presentation there is a Q&A session where the students from all the groups critically evaluate and identify strengths and weaknesses of each project. The students use the feedback from this session to make the necessary modifications or rethink their project before designing their experimental procedures. Toward the end of the module, there is an oral presentation for the projects, which receives feedback from the students and is assessed by two independent referees. Each student presents on their respective topic within the context of their group's disease condition. They also present their entire project in detail. During these sessions, each disease condition is discussed between eight and nine times (depending on the number of groups) and the topics are analyzed in depth between four and six times (the number of students per team). The two referees provide comprehensive written feedback and a mark for the presentations. The students use the feedback to improve their written reports of the project. Each group produces a 4,000-word manuscript. The reports are also assessed and marked by two referees and receive extensive feedback.

The module is facilitated by the instructor (module lead), and explicit and tapered scaffolding is provided. Group discussions are held across five 2-h sessions per week and additional availability for drop-ins and email queries. During the sessions, each group is visited in rotation and interventions are made if conceptual gaps or off-track hypotheses are present or when alignment between hypotheses, aims, and methods breaks down. Assessment is organized around shared rubrics for the oral presentation and the report (Supplemental Fig. S1; see https://doi.org/10.6084/m9.figshare.30618494.v1). All presentations are attended and marked by the instructor together with an experienced faculty member or teaching fellow. Reports are double-marked by the same two assessors, the average mark is calculated, and any discrepancies (>5 points) are moderated. Extensive written feedback is provided on both presentations (style and content) and reports within 10 days. Formative feedback from the sessions is actionable within the project's compressed timeline. Feedback on summative assessments (presentations and reports) is designed to inform work in subsequent modules.

The objective of learning in this exercise is to cultivate an integrative understanding of translational neuroscience concepts while developing advanced scientific inquiry skills, collaboration, and reflective practice. By the end of this intensive project, students are able to demonstrate integrative comprehension of disease mechanisms by applying scientific content knowledge rigorously and exhibiting an excellent understanding of the scientific method through consistent hypothesis formulation, testing, and critical analysis to support or refine research questions. They will also produce high-quality written work that reflects clarity of thought, logical organization, and accurate referencing, and they will engage critically with the literature by drawing connections between cellular or molecular processes and neurological conditions, developing thoughtful, evidence-based conclusions. Furthermore, they will demonstrate collaborative skills and accountability by contributing meaningfully to group-based tasks, showing interdependence and supporting team members' learning. In addition, they will exhibit effective oral presentation skills by coherently communicating key findings and insights, integrating reflective processes and peer feedback to iteratively

Downloaded from journals.physiology.org/journal/advances at Imperial Col London (2A0C:5BC0:0040:1008:DE4A:3EFF:FE6A:56AD) on January 23, 2026.

refine and improve the quality of the project and their own meaning perspective. Finally, by expanding the social constructive aspects to the entire cohort, and considering alternative interdisciplinary frameworks and viewpoints from all the groups, the students would be able to transfer acquired knowledge and skills into broader scientific contexts and to connect insights from the VRP to other areas of basic, translational, or clinical research.

In their feedback (end-of-module questionnaires), students have consistently described the Virtual Research Project (VRP) as a challenging but generative catalyst that translated lecture knowledge into research. Several students emphasized that the VRP moved them beyond rote study toward practicing authentic discovery and internalization of different steps of the hypothesis-driven scientific method and critical analysis of the literature. According to one student, "The VRP was the most useful part of the module for me. I actually presented our project in my PhD interviews because it showed I could identify a tractable question, justify methods, and defend choices against alternatives. The lectures solidified the basis, but the project pushed us to go out into the literature and make sense of real disagreements." Another emphasized the discursive aspects of the project: "It combined discussion, research, writing, and presentation in a way that made me rethink what 'doing science' is. It became a tool of reflection as much as an assessment, my focus shifted from getting the grade to collaborating, iterating, and learning to live with uncertainty." The overarching theme in the students' accounts, expressed in formal feedback or in conversation, was a shift from memorizing slides to assembling evidence as if solving a jigsaw puzzle. This shift toward critical inquiry, moving beyond mere acceptance of consensus to focusing on and grappling with anomalies, aligns precisely with the intended learning outcomes of using unresolved issues and disciplinary crises as a means of achieving a transformed view of the topics.

Students also brought up some of the pragmatic constraints of the practice. The short 2-wk window, for instance, was mentioned by several students as a limitation and suggested that extending or repositioning the project later in the term might deepen the learning and reduce the anxiety associated with the summative assessments. As one student noted: "Two weeks isn't enough time to develop the project to the level it invites; starting it after we've had more exposure, or giving it a bit more runway, would let us justify methods more carefully and explore alternatives we had to drop." Students also suggested aids to consolidation (e.g., prerecorded materials they could pause and rewatch or seminar-style discussions) to mitigate cognitive overload when dense topics were condensed into short blocks. Over the years, these practical constraints and other criticisms have been addressed through adjusted pacing and timing, added scaffolding, and clearer assessment criteria, so that they do not undercut the epistemic aims of the exercise, and the outcomes are now more reliably achieved across diverse cohorts.

ETHICAL APPROVAL

Ethical approval was obtained from our institutional review board, Imperial College London's Education Ethics Review Process, including the use of preexisting evaluation data that were anonymous and have been collected as part of the regular student feedback and evaluation process (EERP1920-043).

DATA AVAILABILITY

Data will be made available upon reasonable request.

SUPPLEMENTAL MATERIAL

Supplemental Fig. S1: https://doi.org/10.6084/m9.figshare.30618494.v1.

DISCLOSURES

No conflicts of interest, financial or otherwise, are declared by the author.

AUTHOR CONTRIBUTIONS

K.N.A. conceived and designed research; prepared figures; drafted manuscript; edited and revised manuscript; approved final version of manuscript.

REFERENCES

1. **Wilcox BR**, **Lewandowski H.** Open-ended versus guided laboratory activities: impact on students' beliefs about experimental physics. *Phys Rev Phys Educ Res* 12: 020132, 2016. doi:10.1103/PhysRevPhysEducRes.12.020132.
2. **Manz E.** *Productive Uncertainty in Science Education: Engaging Students in Meaningful Science Practice*. Teachers College Press, 2025.
3. **Meyer JH**, **Land R.** Threshold concepts and troublesome knowledge (2): epistemological considerations and a conceptual framework for teaching and learning. *High Educ* 49: 373–388, 2005. doi:10.1007/s10734-004-6779-5.
4. **Von Glasersfeld E.** *Radical Constructivism*. Routledge, 2013.
5. **Popper K.** *The Logic of Scientific Discovery*. Routledge, 2005.
6. **Kuhn T.** *The Structure of Scientific Revolutions*. University of Chicago Press, 1962.
7. **Mezirow J.** Transformative learning: theory to practice. *New Dir Adult Contin Educ* 1997: 5–12, 1997. doi:10.1002/ace.7401.
8. **Freeman S**, **Eddy SL**, **McDonough M**, **Smith MK**, **Okoroafor N**, **Jordt H**, **Wenderoth MP.** Active learning increases student performance in science, engineering, and mathematics. *Proc Natl Acad Sci USA* 111: 8410–8415, 2014. doi:10.1073/pnas.1319030111.
9. **Walker CL**, **Shore BM.** Understanding classroom roles in inquiry education: linking role theory and social constructivism to the concept of role diversification. *Sage Open* 5: 4, 2015. doi:10.1177/2158244015607584.
10. **Atwater MM.** Social constructivism: infusion into the multicultural science education research agenda. *J Res Sci Teach* 33: 821–837, 1996. doi:10.1002/(SICI)1098-2736(199610)33:8<821::AID-TEA1>3.0.CO;2-Y.
11. **Parmelee D**, **Michaelsen LK**, **Cook S**, **Hudes PD.** Team-based learning: a practical guide: AMEE guide no. 65. *Med Teach* 34: e275–e287, 2012. doi:10.3109/0142159X.2012.651179.
12. **Jakobsen KV**, **Knetemann M.** Putting structure to flipped classrooms using team-based learning. *Int J Teach Learn High Educ* 29: 177–185, 2017.
13. **Matanluk O**, **Mohammad B**, **Kiflee DNA**, **Imbug M.** The effectiveness of using teaching module based on radical constructivism toward students learning process. *Procedia Soc Behav Sci* 90: 607–615, 2013. doi:10.1016/j.sbspro.2013.07.132.
14. **Ausubel DP**, **Novak JD**, **Hanesian H.** *Educational Psychology: a Cognitive View*. Holt, Rinehart and Winston, 1978.
15. **Taber KS.** Meeting educational objectives in the affective and cognitive domains: personal and social constructivist perspectives on enjoyment, motivation and learning chemistry. In: *Affective Dimensions in*

Downloaded from journals.physiology.org/journal/advances at Imperial Col London (2A0C:5BC0:0040:1008:DE4A:3EFF:FE6A:56AD) on January 23, 2026.

Chemistry Education, edited by Kahveci M, Orgill M**.** Springer, 2015, p. 3–27.
16. **Rahayu S.** Evaluating the affective dimension in chemistry education. In: *Affective Dimensions in Chemistry Education*, edited by Kahveci M, Orgill M**.** Springer, 2015, p. 29–49.
17. **Alavian KN.** Paradigm shifts as portals to threshold concepts and epistemic transformation. *Educ Philos Theory* 2025: 1–12, 2025. doi:10.1080/00131857.2025.2531936.
18. **Popper KR.** *The Logic of Scientific Discovery*. Basic Books, 1959.
19. **Lawson AE.** Hypothetico-deductive method. In: *Encyclopedia of Science Education*, edited by Gunstone R**.** Springer, 2015, p. 471–472.
20. **Meyer SB**, **Lunnay B.** The application of abductive and retroductive inference for the design and analysis of theory-driven sociological research. *Sociol Res Online* 18: 86–96, 2013. doi:10.5153/sro.2819.
21. **Kuhn T.** *The Nature of Scientific Revolutions*. University of Chicago Press, 1970.
22. **Kuhn TS.** *The Structure of Scientific Revolutions*. University of Chicago Press, 1997.
23. **Meyer JH**, **Land R.** Threshold concepts and troublesome knowledge: an introduction. In: *Overcoming Barriers to Student Understanding*. Routledge, 2006, p. 27–42.
24. **Timmermans JA.** Changing our minds: the developmental potential of threshold concepts. In: *Threshold Concepts and Transformational Learning*. Brill Sense, 2010, p. 1–19.
25. **Timmermans JA**, **Meyer JH.** A framework for working with university teachers to create and embed 'integrated threshold concept knowledge'(ITCK) in their practice. *Int J Acad Dev* 24: 354–368, 2019. doi:10.1080/1360144X.2017.1388241.
26. **Davies P.** Threshold concepts: how can we recognise them? In: *Overcoming Barriers to Student Understanding*. Routledge, 2006, p. 94–108.
27. **Davies P**, **Mangan J.** Threshold concepts and the integration of understanding in economics. *Stud High Educ* 32: 711–726, 2007. doi:10.1080/03075070701685148.
28. **Vygotsky LS**, **Cole M**, **John-Steiner V**, **Scribner S**, **Souberman E.** *Mind in Society*. Harvard University Press, 1978.
29. **Popper KR.** *Truth, Rationality and the Growth of Knowledge*. Routledge and Kegan Paul, 1963.
30. **Meyer J**, **Land R.** *Threshold Concepts and Troublesome Knowledge: Linkages to Ways of Thinking and Practising within the Disciplines*. Citeseer, 2003.
31. **Land R**, **Meyer JH**, **Baillie C.** Editors' preface. In: *Threshold Concepts and Transformational Learning*. Brill Sense, 2010.
32. **Kuhn TS.** Scientific revolutions as changes of world view. In: *Can Theories be Refuted? Essays on the Duhem-Quine Thesis*. Springer, 1976, p. 133–154.
33. **Barradell S**, **Peseta T.** Putting threshold concepts to work in health sciences: insights for curriculum design from a qualitative research synthesis. *Teach High Educ* 22: 349–372, 2017. doi:10.1080/13562517.2016.1248390.
34. **Hill S.** The difference between troublesome knowledge and threshold concepts. *Stud High Educ* 45: 665–676, 2020. doi:10.1080/03075079.2019.1619679.
35. **Barradell S**, **Fortune T.** Bounded—the neglected threshold concept characteristic. *Innov Educ Teach Int* 57: 296–304, 2020. doi:10.1080/14703297.2019.1657034.
36. **Illeris K.** Transformative learning and identity. *J Transform Educ* 12: 148–163, 2014. doi:10.1177/1541344614548423.
37. **Hoggan C**, **Kloubert T.** Transformative learning in theory and practice. *Adult Educ Q* 70: 295–307, 2020. doi:10.1177/0741713620918510.
38. **Atherton MC**, **Meulemans YN.** Threshold concepts theory as a pedagogical tool for articulating transformational learning: an initial exploration. *J Transform Educ* 19: 147–165, 2021. doi:10.1177/1541344620963716.
39. **Mezirow J.** How critical reflection triggers transformative learning. In: *Fostering Critical Reflection in Adulthood*. Wiley, 1990, p. 1–6.
40. **Walck-Shannon E**, **Batzli J**, **Pultorak J**, **Boehmer H.** Biological variation as a threshold concept: can we measure threshold crossing? *CBE Life Sci Educ* 18: ar36, 2019. doi:10.1187/cbe.18-12-0241.
41. **Land R**, **Rattray J**, **Vivian P.** Learning in the liminal space: a semiotic approach to threshold concepts. *High Educ* 67: 199–217, 2014. doi:10.1007/s10734-013-9705-x.
42. **Sandrone S**, **Alavian KN.** Threshold concepts in neuroscience: identification challenges, educational opportunities and recommendations for practice. *Front Educ* 5, 2021. doi:10.3389/feduc.2020.540307.

Downloaded from journals.physiology.org/journal/advances at Imperial Col London (2A0C:5BC0:0040:1008:DE4A:3EFF:FE6A:56AD) on January 23, 2026.