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Introducing comparative immunology through the lens of scaling biology

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In most undergraduate programs, immunology is relegated to a few weeks of microbiology or human anatomy courses, or rarely offered as a dedicated topics course. As such, we feel it is essential to consider new approaches to introduce undergraduate students to immunological concepts. Recent work by the ImmunoReach network uncovered gaps in connecting concepts of metabolism and evolution in undergraduate immunology education. With these ideas in mind, we developed a comparative immunology lesson within an upper-division Animal Physiology course, in which students explore how differences in body size change both the metabolic rates and immune cell concentrations. Students who completed this activity improved their scores on scaling questions included in a class exam by more than 29% over students who only received a lecture on the course material. Pre- and post-quizzes demonstrate that the activity increased scores on questions about scaling (>17%) and immune concepts (>100%). By requiring students to apply concepts of scaling, a fundamental concept in biology and physiology, to a system not typically considered in animal physiology courses, this activity enhanced students' understanding of that topic, as well as introducing them to immune cell types. It also introduced pointillist comparative methods, just now being integrated into immune studies, thereby introducing students to leading-edge research in immunology and a new way of thinking about the immune system. We believe this approach can not only fill gaps within undergraduate immunology courses but also incorporate immunology into curricula where immunology is not a viable stand-alone course.

KEYWORDS

active learning, allometry, comparative methods, data analysis, immunology, regression, scaling

1 Introduction

Within undergraduate biology education, it is rare to have a class solely dedicated to immunology, much less an entire major (Bruns et al., 2019). Most students are exposed to immunology within the context of microbiology, or perhaps a human anatomy course. Yet, the immune system provides a rich framework to consider cross-cutting concepts in the biological sciences. In our experience, immunology is also intimidating to many instructors who have not specifically studied the discipline, which limits students' exposure to the field. Thus, we sought to develop an opportunity for students to learn about immunology in a course that typically does not cover the immune system, in the hope that both experienced immunology educators as well as non-immunologists could use the activity to broaden students' understanding of immune processes.

The Vision and Change in Undergraduate Biology Education framework, begun in 2007 and codified into the eponymous report in 2011 (American Association for the Advancement of Science, 2011) has directly shaped undergraduate biology education teaching and research for the past 14 years. The report emphasizes core concepts for biological literacy: evolution, structure and function, information flow, exchange and storage, pathways and transformations of energy and matter, and systems. Indeed, many resources are based upon the premise that these core concepts are critical for student success in the biological sciences (Branchaw et al., 2020). One way this has manifested is for biological subdisciplines to map important concepts in the subdiscipline to the Vision and Change core concepts (e.g., Couch et al., 2015; Michael and McFarland, 2020; Chen et al., 2023).

As a discipline, immunology has followed this same path with recent publications that explore important curricular considerations (Hannum et al., 2016; Rawlings, 2019; Justement and Bruns, 2020; Porter et al., 2021). One such group, the ImmunoReach network of educators, seeks to facilitate teaching of immunological concepts at the undergraduate level (ImmunoReach, 2020). The Immunology Learning Framework and ImmunoSkills Guide developed by ImmunoReach members was influenced by the Vision and Change in Undergraduate Biology Education report, using its primary content groupings as a starting point to discuss immunological concepts (Pandey et al., 2024). From helping to develop these tools, we knew of specific gaps in immunology instruction within the themes of metabolism and evolution (Bruns et al., 2021). Thus, we identified a need for an activity that touched upon concepts in metabolism, evolution, and immunology.

One way to achieve this is to incorporate comparative immunology, an area of study that is largely overlooked in traditional immunology courses. Traditional immunology courses, like traditional immunology research, focus more on human health (and by proxy, the mice that contribute to research in the field). New research applies the comparative method from evolutionary biology to develop and test hypotheses about immune defenses across the tree of life, utilizing approaches from evolution and ecology to address broad-scale patterns in immune defenses (Downs and Sobolewski, 2024; Boehm, 2025). Most introductory immunology textbooks (used for undergraduate, graduate or medical education), however, are limited to brief mentions of comparative immunology to elucidation of key immune system components, such as Toll-like receptors and rudimentary immune cells in fruit flies (Yu et al., 2022), variable lymphocyte receptors in lamprey (Kasamatsu et al., 2010), and the discovery of B cells in chickens (Cooper, 2015). However, there are clear calls for teaching about the importance of immunology in non-human centric fields, such as animal science (Meade, 2023), and for integrating immunology into research in conservation biology (Ohmer et al., 2021) and wildlife sciences (Downs and Stewart, 2014), which would require integration into the curriculum first.

In our experience, when comparative immunology examples are provided, students become very enthusiastic about learning more; it's a subversive way to get students from a variety of backgrounds interested in immunology as a field of study. As such, we identified a course taken by many undergraduate students, Animal Physiology, that could be used to introduce immunology to students who likely had never been exposed to the field beforehand. Integrating immunology into animal and environmental physiology courses also meets a need in those courses, as the immune system is often overlooked. For example, of four animal or environmental biology texts published since 2016 that one of the authors has on their office shelves (Willmer et al., 2006; Moyes and Schulte, 2016; Butler et al., 2021; Hill et al., 2022), only one of them includes a chapter devoted to the immune system.

Beyond content considerations, the Vision and Change report also emphasizes certain skills that are critical for students of biology to learn (American Association for the Advancement of Science, 2011). These "core competencies" are: 1. Applying the Process of Science, 2. Using Quantitative Reasoning, 3. Using Modeling and Simulation, 4. Tapping into the Interdisciplinary Nature of Science, 5. Communicating and Collaborating with Others, and 6. Understanding the Relationship Between Science and Society. We consider how to emphasize these skills while developing the lesson, not only because of the community recommendations, but because these competencies link to high impact practices, which tend to cause better learning outcomes for students (Allen and Tanner, 2005; Kuh, 2008; Brownell et al., 2014; Driessen et al., 2020).

2 Context for lesson development

Adapted from others, the story of Tusko the elephant has been a routine part of this Animal Physiology course as an introduction to the importance of understanding metabolic scaling. A Science article from 1962 describes how Tusko the elephant was given LSD by researchers in an attempt to induce symptoms of musth (West et al., 1962). Musth is a condition of aggression in male elephants, typically caused by a surge in hormone levels during breeding season (Poole, 1987). Ultimately, Tusko died from the experiment, which raises questions about the researchers' methodology, especially assumptions of LSD dosage using a species comparison approach. A follow-up study in 1984 concluded that using LSD to induce musth-like behaviors was not effective (Siegel, 1984). Although the elephants in this updated study did not perish, the methodology of determining LSD dosage remained flawed and would likely not be allowed under today's animal research guidelines. The story of Tusko the elephant is a widely cited example in animal research discussions, as it provides a compelling framework for considering experimental design and animal research ethics. Anecdotally, it is among the topics that are most remembered by students at the end of the semester.

When considering how to include immunology-based content into a physiology course, we used the Tusko case study as a starting point and then created a complementary extension that used the same scaling concepts to investigate aspects of immune defenses across species. We sought to address the following questions: how do immune traits scale (i.e., change with) body size, and how can we apply concepts learned from metabolic scaling to understand immune scaling?

Our previous experience had taught us that students have often learned that animals of different sizes have different metabolic rates in previous classes and have extrapolated those facts to critique the choice of LSD dose for Tusko. However, anecdotally, students found it challenging to generalize facts about scaling physiological systems unrelated to metabolic rates, as they did not grasp the foundational concepts of scaling. By building on the Tusko example and applying scaling concepts to the immune system, this lesson not only introduced immunological concepts, but it also required students to apply scaling concepts to a new, less familiar system, reinforcing those concepts.

During the lesson, we promote the Vision and Change core competencies by having students work together to discuss concepts and analyze and interpret data. The activities lend themselves to various active learning strategies, depending upon the instructor's preference and teaching style. For example, items listed as discussion questions could be utilized in a think-pair-share, group discussion, minute paper, or other active learning approach. The activity begins with the simple question, "Are elephants just mice writ large?" and introduces students to the concept of biological scaling, the simple mathematical models that underpin scaling models, and the power of thinking within a scaling framework. It then introduces students to vertebrate leucocyte classifications and functions, while encouraging critical thinking about these defenses within a comparative framework. The 7-part activity culminates in hypothesis development, a regression analysis, and interpretation of a database of mammal lymphocytes through student-performed analyses. The last section also requires students to apply their findings about comparative immunology to understand human health.

The lesson was designed in the spirit of a liberal arts education, so we feel that it could be used within multiple undergraduate classes at a variety of institutions and for students with little to no background in immunology. The entire activity was field-tested in an 80-min lecture section and a 3-h lab, but it is designed to be versatile. The first three parts can be replaced with an interactive lecture; the final statistics-based activity can be modified so students interpret the analysis rather than performing the statistics themselves. By emphasizing group work and real-life application of knowledge, this lesson also supports teaching practices shown to promote classroom equity (Tanner, 2013; Freeman et al., 2014; Wilson et al., 2018; Theobald et al., 2020). The flexibility of the lesson and its potential to be used in various educational contexts (non-majors/majors, lower and upper division, introductory biology, physiology, or immunology classes) means that this lesson can be adapted to reach a wide audience of learners at a level appropriate for their knowledge base. To accomplish this, we have purposely included teaching notes that identify where the lesson could be cut back or expanded upon (Supplementary material).

2.1 Prerequisite student knowledge

As written, this activity assumes students have basic knowledge of:

- the definition of metabolic rates,
- what a cell looks like, and
- that the immune system protects the host from pathogens, including parasites.

Introductory biology is a prerequisite for the class, so that students have a basic concept of metabolism and have a mental reference of what a cell looks like. This lesson is used very early in the semester, so there is little prerequisite knowledge about animal physiology required for students.

Otherwise, the primary prerequisite knowledge centers around mathematical concepts:

- rules for logarithms, powers, and roots. We provide a table of these rules in *Rules of Logarithms, Powers, Roots* (Supplementary material);
- what a regression analysis is and how to interpret beta values (slopes of regression lines);
- *p*-values relative to a statistical hypothesis;
- OPTIONAL: creating a scatterplot in Excel (or other graphing program of your choice). Rather than having students create graphs, they can be provided by the instructor. We provide instructions for creating a graph and performing a regression analysis in Excel to students in the *Regression Instructions* (Supplementary material).

2.2 Prerequisite instructor knowledge

This lesson incorporates elements of animal physiology and introductory immunology. To teach this lesson effectively, the instructor should be familiar with the following:

- different types of immune cells and their functions;
- overall structure of the immune system (primary and secondary lymphoid tissues);
- types of scaling within animal physiology (hypometric, isometric, hypermetric);
- basic understanding of how metabolic rates affect rates of processes in the body, including drug metabolism.

We provide background information about scaling and the immune system in the T*eaching Notes* (Supplementary material).

3 Activity overview

This lesson is designed to be flexible and can be expanded at numerous points to cover additional topics or contracted to focus on specific concepts only. As written and field-tested, the lesson consists of 7 parts that should be worked through sequentially by students in small groups or as a large-class discussion. Parts 1–3 are designed to introduce students to scaling concepts. Initially based on metabolism (Part 1), Parts 2 and 3 introduce scaling concepts using defensive cell concentrations and immune organ masses. Parts 4–5 introduce students to the mammalian cellular immune system. Parts 6–7 integrate these concepts by considering the scaling of immune cells. Discussion questions are designed so they can be answered in writing by groups or to serve as discussion prompts for the class. During our field testing of this assignment, we brought the students together for whole-class discussions between the different parts, though this is not strictly necessary. Timelines for implementing the activity and potential modifications are provided in the *Teaching Notes* (Supplementary material).

3.1 Pre-lesson preparation

The background reading by Schmidt-Nielsen (1975) introduces students to the concepts of scaling, including the basic equations and logic underpinning scaling theory. Although this is a published scientific paper, its age (1975) makes it read closer to a scientific textbook and should be accessible to undergraduate students. Students also take a pre-quiz to ensure that they are prepared for the class activities.

3.2 The lesson

Parts 1-7 are available as Supplementary material - *Importance of Size and Scaling in Immunology - main assignment*. The answer keys for Parts 1–7 are available in Supplementary material - *Activity Answer Key*.

In Part 1, students learn about the consequences of assuming that physiological traits scale linearly with body size by exploring an old experiment where scientists gave an elephant LSD based on the dose of LSD that was safe for a cat. In Part 2, students are introduced to scaling terminology and use a demonstration to apply these concepts to the scaling of defense cells. In Part 3, students learn about scaling equations and derive model predictions for concentration- or cell-based traits, as well as whole-organism traits, completing a demonstration that models defensive cells and organ mass.

Information about the immune system is critical to the completion of Parts 6 and 7, so students learn about the development of and functional properties of mammalian leukocytes in Part 4. Part 4 may be skipped if students have already learned about the immune system. Students also learn about how researchers obtain data on peripheral leukocyte counts using blood smears in Part 5 and count photos of smears from diverse species (Supplementary material—*Blood smears for section 5*).

In Parts 6 and 7, students integrate what they have learned in Parts 1–5 by exploring the scaling of immune defenses, specifically the concentrations of peripheral leukocytes in mammalian species. In Part 6, students derive the isometric prediction for scaling of neutrophil concentrations and test their prediction, they use a graph of neutrophil concentrations regressed on body mass to answer questions about how neutrophils scale, and they make a prediction about the neutrophil concentration for a species not included in the original analysis. In Part 7, students use data on lymphocyte concentrations and body mass for 13 mammalian species to create a scatter plot and perform a regression analysis of the data (instructions provided in the Supplementary material—Regression Instructions). Students compare the scaling of neutrophils and lymphocytes and apply knowledge to answer questions about the consequences of scaling for human health.

4 Assessment and statistics

4.1 Participants

The full scaling activity was field tested a total of four times since 2022 (Supplementary material—Importance of Size and Scaling in Immunology—main assignment). Data was collected in 2022 and 2023 for evaluation purposes, and data from 2021 was used as an example of scores before the immunology component was added. The activity was used in an upper-division Animal Physiology course at the State University of New York College of Environmental Science and Forestry, an R2 institution. Introductory Biology 1 and 2 were the only prerequisites for the course. Most students were enrolled in majors housed in the Department of Environmental Biology. Most of these majors (e.g., Wildlife Science, Conservation Biology, and Aquatics and Fisheries Science) were focused on organismal biology and ecology topics, rather than cell and molecular biology topics. Consequently, students had little to no experience with immunological concepts. In 2021, the course consisted of a single section of 45 students. A laboratory component was added to the course in 2022. In 2022 and 2023, the course structure was a shared lecture capped at 40 students with 2 lab sections capped at 20 students each. Enrollment was 12 and 18 students for sections 1 and 2, respectively, in 2022 ($N = 30$) and 19 students for each section in 2023 ($N = 38$). We did not collect demographic information about participants.

4.2 Assessment

We implemented the version of the activity in which Parts 1–3 are covered during a 50-min class lecture and Parts 4–7 are implemented as an active learning activity during a 3-h laboratory class. We assessed the success of this lesson using a pre- and post-quiz administered through a learning management system. The quiz consisted of five questions about scaling concepts and two questions about immunology concepts covered in the learning activity (Supplementary material—Assessment Questions); one of the immune questions was modified between 2022 and 2023. We also assessed comprehension through questions embedded within in-class exams (Supplementary material—Assessment Questions). The success on questions used in the in-class exam was compared with those from the year before implementation (Spring 2021), when scaling aims were taught using a traditional lecture with some class discussion (50-min lecture) and practice on homework questions.

Assessment was conducted in accordance with all state and federal laws and was approved by Syracuse University's Institutional Review Board as an Exempt Protocol (#23-092).

4.3 Statistics

All statistics were completed using Program R version 4.3.1 (R Core Team, 2023) and RStudio (RStudio Team, 2020). Data (*Assessment Data)* and code (*Assessment Code*) are available as part of the Supplementary material.

4.3.1 Pre- and post-quiz

Our pre- and post-quiz data from 2022 and 2023 consisted of 5 questions about scaling concepts and 2 questions about the immune system. To compare pre- and post-quiz responses for the scaling questions (0–5 points), we used nonparametric factorial analysis using ANOVA procedures after transforming scores using an aligned rank transformation using the ARTool package (Kay et al., 2021). We analyzed each year in a separate analysis. Time (pre vs. post) and lab section (1 or 2) were included as categorical fixed effects. Student ID was included as a random variable. Only scores from students who completed both the pre- and post-quiz were included in the analysis. Each year's scores were assessed in a separate analysis.

We did not have sufficient variation in the data to conduct statistics for the two immune questions while accounting for the section. Therefore, we performed Wilcoxon Signed-Rank tests for each section of each year independently and for the combined sections for each year. The dependent variable was points earned (0, 1, 2), and the independent variable was time (pre or post).

4.3.2 Exam questions

We compared the scores on three 1-point questions about scaling concepts asked during a regular semester exam in the years when the full scaling activity was implemented (2022 and 2023) with those in the year only the elephant LSD case study was taught (2021). Because data did not meet the assumptions of a linear model, we used Wilcoxon Signed-Rank tests. We compared data from 2021 to 2022 and 2023 in separate analyses (i.e., 2021 vs. 2022 and 2021 vs. 2023). The dependent variable was points earned (0, 1, 2), and the independent variable was year (2021 and 2022 or 2023).

To ensure that scores in spring 2021 vs. 2022 and 2023 were not the result of differences in students in the course, we compared scores on an activity about metabolic rates, the contents of which were not covered by the scaling activity. We used Wilcoxon Signed-Rank tests, and 2021 vs. 2022 and 2021 vs. 2023 were analyzed in separate analyses. A question was added to this activity between 2021 and 2022, so we used arcsine-transformed proportional grade as our response variable with year as our predictor variable.

5 Results

5.1 Pre- and post-quiz

Twenty-seven students took both the pre- and post-quiz in 2022 (section 1: $N = 11$, section 2: $N = 16$) and 26 students took both in 2023 (section 1: $N = 12$, section 2: $N = 14$). In 2022, the teaching activity increased scores on the five scaling concept questions by 17.9% from 3.93 ± 0.90 points (raw mean ± std) to 4.63 ± 0.48 points ($F_{1,25} = 15.6$, $P < 0.001$). Section did not affect points earned ($F_{1,25} = 0.69$, $P = 0.412$), and there was no interaction between time and section ($F_{1,25} = 1.54$, $P = 0.225$; Figure 1A). In 2023, the activity increased scores by 33.3% from 3.23 ± 1.19 points (raw mean ± std) to 4.31 ± 0.87 points ($F_{1,24} = 18.8$, $P < 0.001$). Section did not affect points earned ($F_{1,24} = 1.59$, $P = 0.219$), and there was no interaction between time and section ($F_{1,24} = 6.37$, $P = 0.186$; Figure 1C).

Across both sections in 2022, the teaching activity increased scores on two immunology questions by 104.2% from 0.89 ± 0.68 points to 1.81 ± 0.39 points ($W = 614$, $P < 0.001$; Figure 1B). This pattern held for both sections with scores in section 1 increasing 150% from 0.73 ± 0.75 points to 1.82 ± 0.39 points ($W = 104$, $P = 0.002$), and scores in section 2, increasing 81.3% from 1.00 ± 0.61 points to 1.81 ± 0.39 ($W = 212$, $P < 0.001$). In 2023, the teaching activity increased scores on two immunology questions by 88% from 0.96 ± 0.71 points to 1.81 ± 0.39 points ($W = 555$, $P < 0.001$; Figure 1D). This pattern held for both sections with scores in section 1 increasing 120% from 0.83 ± 0.68 points to 1.83 ± 0.37 points ($W = 124$, $P = 0.001$), and scores in section 2, increasing 66.7% from 1.07 ± 0.70 points to 1.79 ± 0.41 ($W = 152$, $P = 0.006$).

5.2 Exam questions

Students who had participated in the full scaling activity in 2022 earn 29.7% greater scores on exam questions about scaling concepts ($N = 29$, 2.62 ± 0.55 out of 3 points), than those who were exposed to a only traditional lecture on scaling in 2021 ($N = 48$, raw mean ± std = 2.02 ± 0.93; $W = 2196$, $P < 0.001$; Figure 2A). Students who participated in the full activity in 2023 earned 32.6% greater scores on exam questions about scaling concepts ($N = 36$, 2.68 ± 0.56 out of 3 points; $W = 1{,}240$, $P < 0.001$), than those from 2021 (Figure 2C). In contrast, students in the course in 2021 and 2022 did not differ in their grades on a lab about metabolic rates and unrelated to the scaling teaching activity ($W = 571$, $P = 0.369$; Figure 2B), consistent with the interpretation that improvements in grades on the scaling questions in 2022 were not just because of differences in the students in the course. Students from 2023, however, had greater scores on the metabolic rates activity than those from 2021 ($W = 560$, $P = 0.006$; Figure 2D), indicating that some cross-year differences in scaling scores might be related to differences in the students in the course.

6 Discussion

We have created a multi-part activity that not only solidifies student understanding of biological scaling but also introduces students with little or no background to immunology concepts. While our class enrollment numbers are small, the data indicate that students not only learned some basic immunology concepts (a topic not previously discussed), but that working with immune system scaling also increased their understanding of scaling in general. Anecdotally, students seem more able to answer questions in class throughout the semester about the topics covered in the activity, suggesting retention of the concepts. This study also builds upon a rich body of literature demonstrating that active-learning lessons increase engagement of students and retention of course content in sciences, including physiology and immunology (Freeman et al., 2014) and it answers calls for more active learning in undergraduate immunology courses (Stranford et al., 2020).

Although most of our data indicate student learning occurred, it is important to recognize the limitations of this study. Firstly,

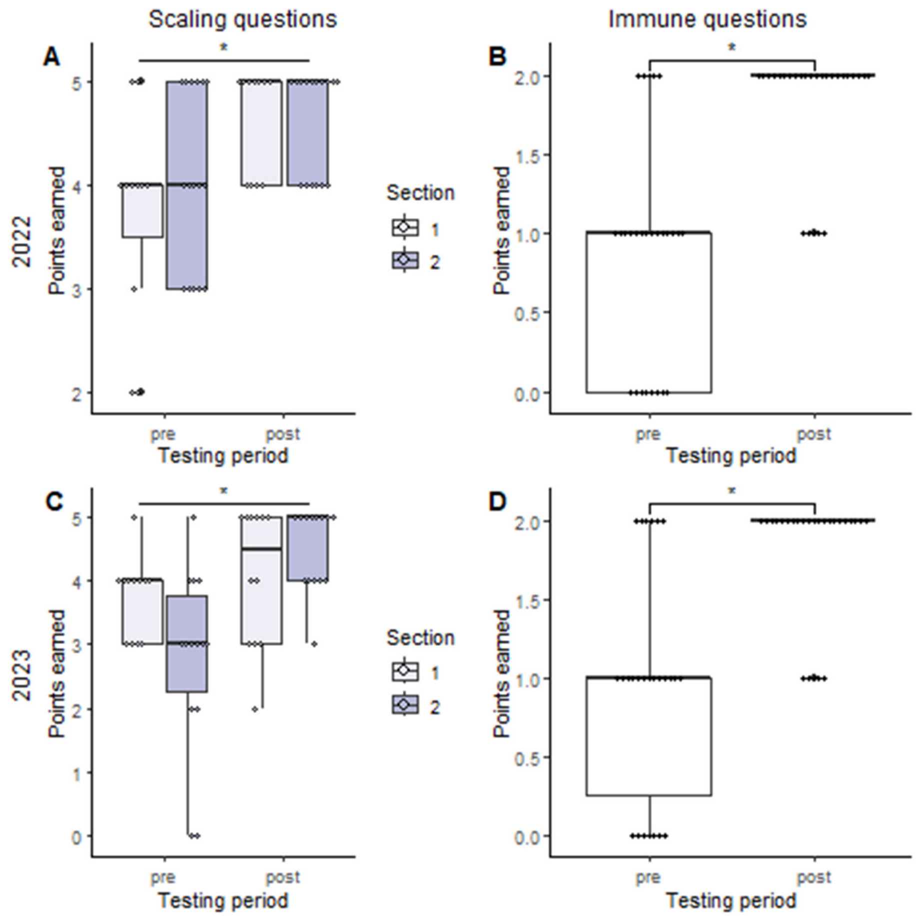

FIGURE 1
Scores on scaling questions (**A, C**, out of 5 points) and immunology questions (**B, D**, out of 2 points) on quizzes given before and after the learning activity in 2022 **(A, B)** and 2023 **(C, D)**. An asterisk (*) indicates a significant difference ($p < 0.05$). Scores on the scaling question were analyzed with an aligned rank transformation. Results for the scaling questions **(A, C)** show results from section-specific analyses; there was a significant difference between the pre- and post-quiz scores when the sections were combined into a signal analysis for each year (see "Results" for details). Results for the immune questions are from Wilcoxon Signed-Rank tests.

the amount of in-class time on this topic increased from 1 h to 4 h with the implementation of the new activity. Thus, it is not surprising that students had better retention. The activity also expanded the pedagogical techniques used in teaching the content, which likely also impacts information retention (Freeman et al., 2014). The conceptual understanding of immunology was kept at a low Bloom's level the student population had no to little exposure to immunology before this activity, only a few questions were asked, and questions were limited to two quizzes. Thus, these small changes in point value resulted in large percentage changes in student learning. The effect is then about a 1-point difference in performance. Retention for the final exam was not possible to measure. At this time, we conclude that the lesson "did no harm" to the student experience and shows promise as a way to incorporate immunology into the undergraduate biology curriculum.

In our experience, the most difficult part of adapting curricula designed by others is time management based upon differences in the length of class periods and class sizes. Instructors have options for adapting different portions of the lesson to move more quickly, or to slow down and emphasize key components, or even add additional discussions. Parts 1–3 can be completed by students by working through the worksheets, or the content can be introduced through an instructor lecture with frequent pauses for discussion and demonstrations (see Supplementary material—Scaling Intro Lecture). The end of Part 1 is an excellent place to insert a discussion of animal welfare and use of animals in research, if desired by the instructor (see Perry and Dess, 2012; Melley and Caruso, 2024 for ideas). If instructors have access to live animals or fixed blood smears, Part 5 of this activity could be replaced by students making, staining, and counting blood smears or counting fixed smears to provide an active learning opportunity to use a microscope and practice technical skills (Part 5). Part 7 could be completed as homework to test comprehension of concepts. Alternatively, the instructor could provide the scatter plot and regression output for students to interpret (Supplementary material Alternative Part 7 & Alternative Part 7—Key), or Part 7 could be skipped outright if computers are unavailable during class.

Our multi-part lesson extends a metabolic scaling case study to introduce concepts of the immune system and scaling of

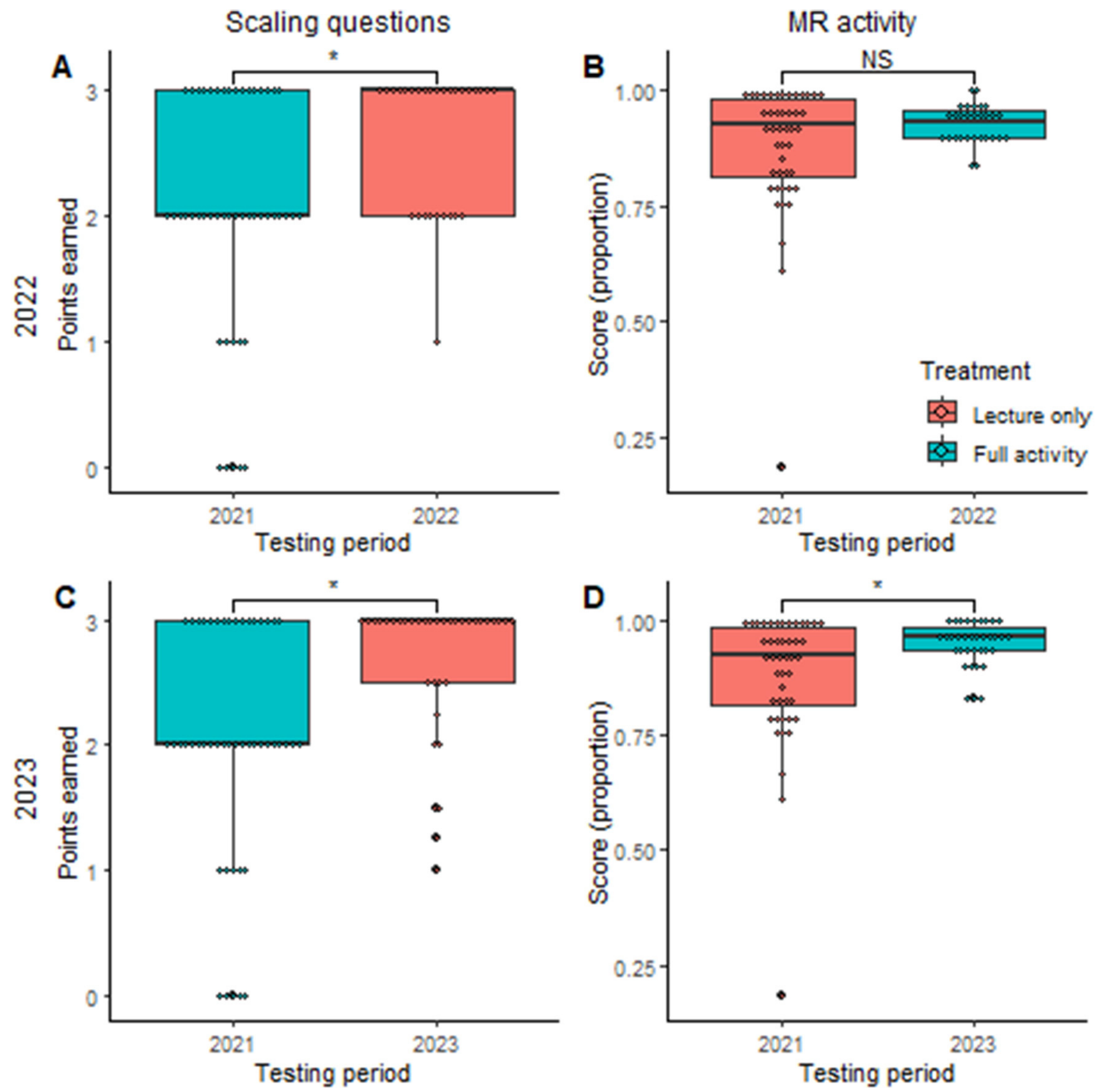

FIGURE 2
Scores on exam questions (**A** and **C**, out of 3 points) and on a metabolic rate lab (**B** and **D**, proportion) in the years when the activity was implemented in full [2022 (**A** and **B**) and 2023 (**C** and **D**)] and when only a lecture on scaling was given (2021). Students scored more points on the scaling exam questions in the year that the teaching activity was used. Their scores on the metabolic rate lab did not differ between 2021 and 2022; however, students in 2023 performed better on the metabolic rate activity than those in 2021. An asterisk (*) indicates a significant difference ($p < 0.05$); "NS" indicates no significant difference; results were from a Wilcoxon Signed-Rank test; see "results" for more details.

immune defenses across mammalian species. The lesson touches upon basic concepts in metabolism, immunology, comparative biology, graphing, and data interpretation, with multiple potential extensions and modifications. By emphasizing scaling of immune defenses, students are empowered to apply facts they learned previously about metabolic scaling to develop novel hypotheses about scaling of immune defenses and to engage meaningfully with the concepts from scaling. Allometric scaling is a powerful way to think about animal physiology and immune defenses because it builds upon first principles from geometry, physics, and organismal biology to make *a priori* predictions about species yet to be studied (Schmidt-Nielsen, 1975; Brown et al., 2004; Downs and Sobolewski, 2024). It also illuminated interspecific patterns and deviations from patterns for further exploration. Activities such as these allow students to draw connections between seemingly disparate biological fields of study and encourage scientific exploration at the intersection of disciplines. We hope that this approach will inspire other instructors to explore ways to bring immunological concepts into their curriculum.

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.

Ethics statement

The studies involving humans were approved by Syracuse University's Institutional Review Board. The studies were conducted in accordance with the local legislation and institutional requirements. The ethics committee/institutional review board waived the requirement of written informed consent for participation from the participants or the participants' legal guardians/next of kin because data were collected as part of routine educational activities.

Author contributions

CD: Project administration, Formal analysis, Methodology, Investigation, Writing – review & editing, Data curation, Visualization, Writing – original draft, Conceptualization, Funding acquisition. SE: Project administration, Writing – review & editing, Writing – original draft, Methodology, Conceptualization, Investigation.

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Conflict of interest

The authors are members of the ImmunoReach consortium and have participated in multiple projects with the group. The creation and publication of this activity were funded in part by ImmunoReach grants.

Generative AI statement

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

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/feduc.2025.1602537/full#supplementary-material

SUPPLEMENTARY PRESENTATION 1
Teaching notes.

SUPPLEMENTARY PRESENTATION 2
Regression instructions.

SUPPLEMENTARY PRESENTATION 3
Rules of logarithms, powers, roots.

SUPPLEMENTARY PRESENTATION 4
Scaling intro lecture.

SUPPLEMENTARY PRESENTATION 5
Blood smears for section 5.

SUPPLEMENTARY PRESENTATION 6
Alternative Part 7.

SUPPLEMENTARY PRESENTATION 7
Alternative Part 7-key.

SUPPLEMENTARY PRESENTATION 8
Assessment questions.

SUPPLEMENTARY PRESENTATION 9
Importance of Size and Scaling in Immunology - main assignment.

SUPPLEMENTARY PRESENTATION 10
Activity answer key.

SUPPLEMENTARY DATA SHEET 1
Code for statistics.

SUPPLEMENTARY DATA SHEET 2
Assessment data.

References

Allen, D., and Tanner, K. (2005). Infusing active learning into the large-enrollment biology class: seven strategies, from the simple to complex. *CBE* 4, 262–268. doi: 10.1187/cbe.05-08-0113

American Association for the Advancement of Science. (2011). *Vision and Change in Undergraduate Biology Education: A Call to Action*. Washington DC: American Association for the Advancement of Science.

Boehm, T. (2025). Understanding vertebrate immunity through comparative immunology. *Nat. Rev. Immunol.* 25, 141–152. doi: 10.1038/s41577-024-01083-9

Branchaw, J. L., Pape-Lindstrom, P. A., Tanner, K. D., Bissonnette, S. A., Cary, T. L., Couch, B. A., et al. (2020). Resources for teaching and assessing the vision and change biology core concepts. *LSE* 19:es1. doi: 10.1187/cbe.19-11-0243

Brown, J. H., Gillooly, J. F., Allen, A. P., Savage, V. M., and West, G. B. (2004). Toward a metabolic theory of ecology. *Ecology* 85, 1771–1789. Available online at: http://www.jstor.org/stable/3450341

Brownell, S. E., Freeman, S., Wenderoth, M. P., and Crowe, A. J. (2014). BioCore guide: a tool for interpreting the core concepts of vision and change for biology majors. *LSE* 13, 200–211. doi: 10.1187/cbe.13-12-0233

Bruns, H. A., Deaver, J., and Justement, L. B. (2019). Out of the curricular shadows: revolutionizing undergraduate immunology education. *Front. Immunol.* 10:2446. doi: 10.3389/fimmu.2019.02446

Bruns, H. A., Wisenden, B. D., Vanniasinkam, T., Taylor, R. T., Elliott, S. L., Sparks-Thissen, R. L., et al. (2021). Inside the undergraduate immunology classroom: current practices that provide a framework for curriculum consensus. *J. Microbiol. Biol. Educ.* 22:22.1.8. doi: 10.1128/jmbe.v22i1.2269

Butler, P. J., Brown, J. A., Stephenson, D. G., and Speakman, J. R. (2021). *Animal Physiology: An Environmental Perspective, 1st Edn*. Oxford University Press. doi: 10.1093/hesc/9780199655458.001.0001

Chen, A., Phillips, K. A., Schaefer, J. E., and Sonner, P. M. (2023). Community-derived core concepts for neuroscience higher education. *LSE* 22:ar18. doi: 10.1187/cbe.22-02-0018

Cooper, M. D. (2015). The early history of B cells. *Nat. Rev. Immunol.* 15, 191–197. doi: 10.1038/nri3801

Couch, B. A., Wood, W. B., and Knight, J. K. (2015). The molecular biology capstone assessment: a concept assessment for upper-division molecular biology students. *LSE* 14:ar10. doi: 10.1187/cbe.14-04-0071

Downs, C. J., and Sobolewski, M. E. (2024). The promise of synergy between two perspectives in comparative immunology. *Physiology* 39, 386–400. doi: 10.1152/physiol.00012.2024

Downs, C. J., and Stewart, K. M. (2014). A primer in ecoimmunology and immunology for wildlife research and management. *California Fish Game* 100:25.

Driessen, E. P., Knight, J. K., Smith, M. K., and Ballen, C. J. (2020). Demystifying the meaning of active learning in postsecondary biology education. *LSE* 19:ar52. doi: 10.1187/cbe.20-04-0068

Freeman, S., Eddy, S. L., McDonough, M., Smith, M. K., Okoroafor, N., Jordt, H., et al. (2014). Active learning increases student performance in science, engineering, and mathematics. *Proc. Natl. Acad. Sci. U.S.A.* 111, 8410–8415. doi: 10.1073/pnas.1319030111

Hannum, L., Kurt, R. A., and Walser-Kuntz, D. R. (2016). Developing immunologists: a role for undergraduate education. *Trends Immunol.* 37, 425–426. doi: 10.1016/j.it.2016.03.008

Hill, R. W., Cavanaugh, D. J., and Anderson, M. (2022). *Animal Physiology, 5th Edn*. New York, NY; Oxford: Oxford University Press.

ImmunoReach. (2020). *ImmunoReach: interdisciplinary immunology education consortium. Public discription.* Available online at: https://qubeshub.org/community/groups/bk4034mg/overview (Accessed March 29, 2025).

Justement, L. B., and Bruns, H. A. (2020). The future of undergraduate immunology education: can a comprehensive four-year immunology curriculum answer calls for reform in undergraduate biology education? *Immunohorizons* 4, 745–753. doi: 10.4049/immunohorizons.2000086

Kasamatsu, J., Sutoh, Y., Fugo, K., Otsuka, N., Iwabuchi, K., and Kasahara, M. (2010). Identification of a third variable lymphocyte receptor in the lamprey. *Proc. Natl. Acad. Sci. U.S.A.* 107, 14304–14308. doi: 10.1073/pnas.1001910107

Kay, M., Elkin, L. A., Higgins, J. J., and Wobbrock, J. O. (2021). *ARTool: Aligned Rank Transform for Nonparametric Factorial ANOVAs*.

Kuh, G. D. (2008). *High-Impact Educational Practices: What They Are, Who Has Acces to Them, and Why They Matter., 1st Edn*. District of Columbia: American Association of Colleges & Universities.

Meade, K. G. (2023). The increasing relevance of immunobiology within a connected animal science curriculum. *Transl. Anim. Sci.* 7:txad007. doi: 10.1093/tas/txad007

Melley, A. H., and Caruso, A. S. (2024). "Chapter 3, The ethical psychologist," in *Psychological Science: Key Themes and Applications* (Montreal, QC: Pressbooks).

Michael, J., and McFarland, J. (2020). Another look at the core concepts of physiology: revisions and resources. *Adv. Physiol. Educ.* 44, 752–762. doi: 10.1152/advan.00114.2020

Moyes, C. D., and Schulte, P. M. (2016). *Principles of Animal Physiology, 3rd Edn*. Toronto, ON: Pearson.

Ohmer, M. E. B., Costantini, D., Czirják, G. Á., Downs, C. J., Ferguson, L. V., Flies, A., et al. (2021). Applied ecoimmunology: using immunological tools to improve conservation efforts in a changing world. *Conserv. Physiol.* 9:coab074. doi: 10.1093/conphys/coab074

Pandey, S., Elliott, S. L., Liepkalns, J., Taylor, R. T., Vanniasinkam, T., Kleinschmit, A. J., et al. (2024). The immunoskills guide: competencies for undergraduate immunology curricula. *PLoS ONE* 19:e0313339. doi: 10.1371/journal.pone.0313339

Perry, J. L., and Dess, N. K. (2012). "Laboratory animal research ethics: a practical, educational approach," in *APA Handbook of Ethics in Psychology, Vol 2: Practice, Teaching, and Research*, eds. S. J. Knapp, M. C. Gottlieb, M. M. Handelsman, and L. D. VandeCreek (Washington: American Psychological Association), 423–440. doi: 10.1037/13272-020

Poole, J. H. (1987). Rutting behavior in African Elephants: the phenomenon of Musth. *Behaviour* 102, 283–316. doi: 10.1163/156853986X00171

Porter, E., Amiel, E., Bose, N., Bottaro, A., Carr, W. H., Swanson-Mungerson, M., et al. (2021). American association of immunologists recommendations for an undergraduate course in immunology. *Immunohorizons* 5, 448–465. doi: 10.4049/immunohorizons.2100030

R Core Team. (2023). *R: A Language and Environment for Statistical Computing*. Vienna, Austria: R Foundation for Statistical Computing.

Rawlings, J. S. (2019). Primary literature in the undergraduate immunology curriculum: strategies, challenges, and opportunities. *Front. Immunol.* 10:1857. doi: 10.3389/fimmu.2019.01857

RStudio Team. (2020). *RStudio: Integrated Development Environment for R*. Boston, MA: RStudio, PBC.

Schmidt-Nielsen, K. (1975). Scaling in biology: the consequences of size. *J. Exp. Zool.* 194, 287–307. doi: 10.1002/jez.1401940120

Siegel, R. K. (1984). LSD-induced effects in elephants: comparisons with musth behavior. *Bull. Psychon. Soc.* 22, 53–56. doi: 10.3758/BF03333759

Stranford, S. A., Owen, J. A., Mercer, F., and Pollock, R. R. (2020). Active learning and technology approaches for teaching immunology to undergraduate students. *Front. Public Health* 8:114. doi: 10.3389/fpubh.2020.00114

Tanner, K. D. (2013). Structure matters: twenty-one teaching strategies to promote student engagement and cultivate classroom equity. *LSE* 12, 322–331. doi: 10.1187/cbe.13-06-0115

Theobald, E. J., Hill, M. J., Tran, E., Agrawal, S., Arroyo, E. N., Behling, S., et al. (2020). Active learning narrows achievement gaps for underrepresented students in undergraduate science, technology, engineering, and math. *Proc. Natl. Acad. Sci. U.S.A.* 117, 6476–6483. doi: 10.1073/pnas.1916903117

West, L. J., Pierce, C. M., and Thomas, W. D. (1962). Lysergic acid diethylamide: its effects on a male asiatic elephant. *Science* 138, 1100–1103. doi: 10.1126/science.138.3545.1100

Willmer, P., Stone, G., and Johnston, I. A. (2006). *Environmental Physiology of Animals, 2nd Edn. [Nachdr.]*. Malden, MA: Blackwell Publishers.

Wilson, K. J., Brickman, P., and Brame, C. J. (2018). Group work. *LSE* 17:fe1. doi: 10.1187/cbe.17-12-0258

Yu, S., Luo, F., Xu, Y., Zhang, Y., and Jin, L. H. (2022). Drosophila innate immunity involves multiple signaling pathways and coordinated communication between different tissues. *Front. Immunol.* 13:905370. doi: 10.3389/fimmu.2022.905370