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Evaluating introductory biology student perceptions surrounding the use of integrative cases related to human health for evolution education

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Abstract

Background In introductory biology classrooms, cell and molecular concepts are often taught separate from those related to evolution and ecology, and usually in completely different courses. Furthermore, many examples used to teach introductory concepts are difficult for students to relate to. To address these issues, we developed curricular materials focused on the topic of breast cancer that: (1) aim to teach students how to integrate the various sub-disciplines of biology, with evolution as the unifying theme, and (2) aim to present course materials using relatable examples such as human health and disease. To assess the potential value of these materials, we asked students to complete a pre-unit and post-unit assessment before and after completing the interactive course unit on breast cancer.

Results We found that after learning about breast cancer, students reported that learning about biology in the context of human health made their learning experience easier, more interesting, and more relatable. After the unit, students also rated evolutionary concepts as being more important for understanding human health and disease.

Conclusions These results have important implications for developing introductory biology curricula that have more personal appeal to students and may thus translate to better learning outcomes, as well as help students better understand the process of evolution as it occurs in humans.

Keywords Evolution education, Evolutionary medicine, Integrative biology, Case studies, Science education

Background

Many undergraduate biology students often have a difficult time understanding evolutionary concepts, especially when it comes to linking processes that occur at the organismal level to those that occur at the cellular level (Gregory 2009; Kalinowski et al. 2010; Bishop and Anderson 1990). Hillis (2007) and others have recommended that one potential solution to these problems could be using examples that are more relevant and exciting to students to teach evolution (Jördens and Hammann 2021). Recent studies have supported this suggestion by showing that the use of human examples, which tends to be inherently more interesting to students (Wilson 2005; Pobiner 2012), may lead to an increased scientific understanding of evolution (Werth 2009; Nettle 2010; Pobiner 2018; Grunspan et al. 2021). However, these results are complicated by the fact that the effectiveness of using human examples to teach evolution varies across different student demographics (Beggrow

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and Sbeglia 2019; Grunspan et al. 2021). For example, Grunspan et al. (2021), found that students who already had a greater understanding of evolution benefitted more from learning about human examples. Therefore, it is important for studies to investigate which specific types of human examples, such as those related human health, may be perceived as interesting and relevant by introductory biology students, in order to determine which specific examples may be useful for enriching the learning experience of students.

Another major challenge for introductory biology students is learning how to integrate the various subdisciplines of biology. Evolution is the unifying theme of the life sciences, and yet the key processes that underpin evolutionary change are typically taught in isolation from one another. Specifically, organismal and population-level processes such as natural selection are often taught separately from the cellular-level ones, such as changes in nucleotide sequences and protein functions (Nehm et al. 2009; Kalinowski et al. 2010). Studies have shown that learning about evolution from an integrative perspective results in an improved understanding of evolution (Dauer et al 2013; White et al. 2015). For example, White and colleagues designed and implemented curricular materials that described the evolution of a series of traits, across scales, from changes in nucleotide sequences all the way through to events occurring on phylogenetic and biogeographic scales (White et al. 2013a, 2013b). The implementation of these cases was successful in helping students better understand evolutionary processes (White et al. 2015), but they only used non-human examples such as fur color change in mice, toxin resistance in marine clams, color vision in old world primates, and the molecular basis behind the wrinkled/sweet phenotype in garden peas.. Therefore, we decided to synthesize the approach of White et al. (2015) with efforts to use more interesting examples by building a set of curricular materials focused on human evolution. We turned to the field of evolutionary medicine to guide the development of these cases, as it offers a rich body of literature that it is highly integrative, and is clearly relevant to humans (Grunspan et al. 2018).

There are many potential benefits of using evolutionary medicine topics, such as breast cancer, to teach introductory biology concepts to undergraduate students. Firstly, learning about topics related to humans is intrinsically interesting to many students which may translate to learning gains (Werth 2009; Pobiner 2018). Secondly, evolutionary medicine is a powerful way for students to understand how proximate biological topics (e.g., physiology and cell biology) relate to evolutionary ones (Nesse and Natteson-Horowitz 2018). Finally, many introductory biology students aspire to pursue medical school and other careers related to public health but aren't taught about the importance of integrating evolutionary perspectives into their future practice or studies (Hidaka et al. 2015; Borgerding and Kaya 2022). Medical schools have cited an overcrowded curriculum as a major reason for excluding evolutionary medicine topics, so including them in undergraduate classrooms may contribute to enrich the perspectives of future healthcare workers (Grunspan et al. 2019).

While others have advocated for the use of evolutionary medicine in teaching undergraduate biology (Nesse and Natterson-Horowitz 2019), few studies exist that have examined the impacts on student learning experiences from curricular materials that use integrated examples of human health conditions. In this study, we designed, implemented, and assessed student perspectives of a unit on breast cancer in an introductory cell and molecular biology course. The general goal of our survey was to gain a sense of how students viewed the use of evolutionary medicine examples to learn about topics in biology, and to see if these perceptions changed after having a chance to engage with the materials. Breast cancer was an ideal topic to pilot our program, as it is a disease with wide impacts, and clearly involves the overlap of cellular- and organismal-level biological processes. Given that human health is a topic that impacts everyone, we predicted that (1) students would self-report a higher level of interest in learning about introductory biology concepts in the context of human health and disease, as well as perceive the content to be more relatable and easier to learn about. We also predicted that (2) following the breast cancer unit, more students would perceive evolutionary mechanisms (i.e. natural selection, genetic drift, etc.) as being important concepts for understanding human health and disease. Finally, we predicted that (3) following the breast cancer unit, students would rate evolution as being more likely to play a role in emergence and persistence of human health conditions.

Methods

Breast cancer unit

The breast cancer unit spanned a 4-week period consisting of two 80-min class sessions per week. Each class session focused on breast cancer viewed through the lens of a specific introductory biology topic (Hereafter called "modules." A brief description of each of these modules can be found in Box 1). Prior to each class, we asked students to watch 1–3 videos that covered part of a specific module in the breast cancer unit. These videos are publicly available and can be viewed on our YouTube channel (White et al. 2022a). As part of their course grade, students completed handwritten notes for each video that were graded on a scale from 0 to 4 based on the comprehensiveness of their notes. At the beginning of each in-class session, we presented a short (5–20 min) recap lecture to revisit the major learning objectives of each video. For the remainder of the class, students worked in groups of 3–4 on worksheets while two instructors and one undergraduate teaching assistant moved from group to group to assist students with questions and to facilitate discussions (Fig. 1; Box 1). These worksheets challenged students to solve a mix of knowledge and application-based problems using their understanding of course content, discussion with peers, and online resources. Modified versions of these worksheets are publicly available on our project website (White et al. 2022b).

Box 1: An overview of the breast cancer unit

Class 1—Introduction to Breast Cancer

Assigned video: https://www.youtube.com/watch?v=u2YL_lPgHMc

Summary of lesson: Cancer is disease characterized by uncontrolled cell division. Breast cancer is a common type of cancer because epithelial tissue in the breasts has a high rate of growth and cell division. The more cell divisions, the more mutations. The more mutations, the higher the chance of mutations occurring on genes that may increase breast cancer risk. Introductory concepts that are covered include natural selection, anatomy, and levels of biological organization.

Example worksheet question: Explain ***why*** breast tissue is particularly susceptible to cancer. Then, using this logic, propose other tissues in the human body that might be particularly susceptible to cancer, and which tissues would be less susceptible.

Class 2—Introduction to Breast Cancer Genetics:

Assigned video: https://www.youtube.com/watch?v=Hd1_vqAtGw8

Summary of lesson: There are two major classes of genes implicated in cancer development: proto-oncogenes, which tend to play a role in cell growth and replication, and tumor suppressor genes, which play a role in the repair of damaged DNA and regulation of apoptosis. Cancer can occur when mutations arise on these genes that leads to a change in the function of their protein products. Introductory concepts that are covered include DNA structure/replication, mutations, transcription, and translation.

Example worksheet question: Explain the terms ***proto-oncogene*** and ***tumor suppressor gene*** and give an example of each.

Class 3—Breast Cancer Genes (HER2/ESR1/TP53/BRCA):

Assigned videos: https://www.youtube.com/watch?v=doTm_s-Nb-Ihttps://www.youtube.com/watch?v=1-yn-HZ-2XIhttps://www.youtube.com/watch?v=bkt9iYZRUuI

Summary of lesson: HER2 and ESR1 are proto-oncogenes, and TP53 and BRCA1/2 are tumor suppressor genes that are commonly implicated in cases of breast cancer. HER2 and ESR1 are both involved in the promotion of cell growth and division. TP53 plays a role in initiating apoptosis, while BRCA1/2 play roles in the repair of damaged DNA.

Example worksheet question: What does the HER2 protein do, and how does it relate to cell division? How might an overexpressed and/or more functional HER2 protein lead to an increased risk of cancer?

Class 4—Breast Cancer Cell Biology:

Assigned video: https://www.youtube.com/watch?v=lVJmA2xcCN4

Summary of lesson: Cancer can occur when mitosis happens more than it should, or apoptosis doesn't occur when it should. Mitosis is part of the process of cell division that, in a healthy state, only occurs when cells need to be replaced or when tissues need to grow or be repaired. Apoptosis is the process of cell self-destruction, and normally occurs when a cell lineage is growing more than it needs to, or when a cell has damaged DNA. Introductory concepts that are covered include cell structure and organelles, the cell cycle, mitosis, apoptosis, and DNA repair.

Example worksheet question: What are the G1-, G2-, and M-checkpoints? How does a cell "pass" each checkpoint?

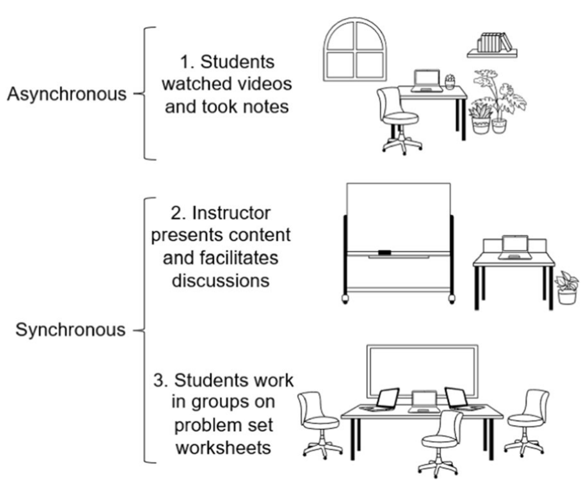

Fig. 1 The flipped classroom design used throughout the breast cancer unit

Class 5—Breast Cancer and Human Evolution:
Assigned video: https://www.youtube.com/watch?v=nROjHu4LMBE

Summary of lesson: Despite clearly being harmful for humans, there are a variety of evolutionary factors than can explain why cancer persists. Firstly, a handful of studies suggest that BRCA1/2 mutations may have pleiotropic effects that are antagonistic—although breast cancer risk may be higher, there may be a reproductive advantage associated with these mutations. Furthermore, founder effects in populations that were historically small and isolated may explain the spread of rare mutations associated with harmful conditions such as breast cancer. Lastly, mismatches between ancestral and modern environments may explain why our bodies are not equipped to defend against exposure to the high levels of carcinogens that are present in modern environments. Introductory concepts that are covered include life-history theory, and genetic drift via founder effects.

Example worksheet question: What is an antagonistic pleiotropy? Investigate online to find an example of an antagonistic pleiotropy that is not related to humans, or cancer.

Class 6—Traditional Breast Cancer Treatment:
Assigned video: https://www.youtube.com/watch?v=TxN9KmoyUe8

Summary of lesson: The traditional approach to cancer treatment is to remove as much of the tumor(s) as possible using methods such as surgery, chemotherapy, radiation therapy, and hormone treatment.

Example worksheet question: What are three traditional treatments for cancer? How do they each work to combat cancer?

Class 7—Evolutionary Perspectives and Treatment:
Assigned video: https://www.youtube.com/watch?v=T6CKPCzFh7w

Summary of lesson: The outcome of traditional therapies can be problematic if cancer reoccurs. Adaptive therapy offers a solution to this issue, by administering less intense courses of treatment of longer durations, to keep the cancer at a manageable size, while reducing the risk of treatment resistant cancer evolving. Introductory concepts that are covered include natural selection via bottleneck effects, and evolutionary arms races.

Example worksheet question: Why does cancer return sometimes, even after treatment? In situations where it returns, why is it often harder to treat?

Class 8—Review
Students participate in Kahoot! Quiz based on the various unit modules. Then, students are led through a structured review by instructors going over key concepts in each module. Finally, students write on a piece of paper 1–2 concepts they had trouble understanding in the unit, and the questions were addressed by the instructors.

Course structure and study design

We investigated the responses of students across three sections of an introductory cell and molecular biology course (N = 39, 40, 44). Teaching our unit in the context of a cell and molecular biology class gave us the opportunity to emphasize how evolutionary processes occur across biological scales. The students in these classes are primarily in their second year, and had taken an introductory organismal biology course as a pre-requisite that covers topics such as the five mechanisms of evolution in their previous semester. Students in this course tend to be majors from various science programs, including pre-med majors. These courses were taught simultaneously in the Spring 2022 Term at Michigan State University and were co-instructed by two of the authors (D. Filice and P. White). The course consisted of a unit based on biology fundamentals, which served the purpose of introducing students to some of the major course concepts in a traditional manner (i.e., in the absence of a common

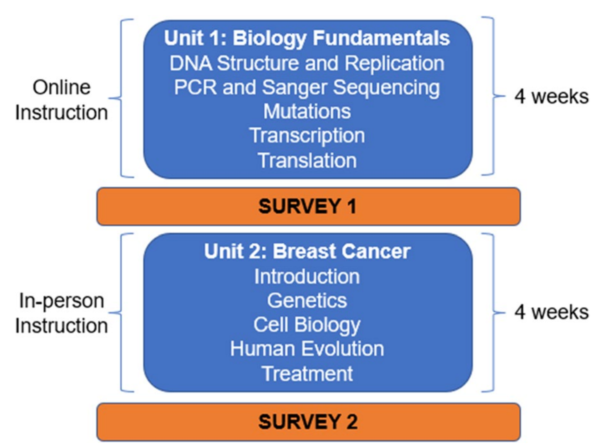

Fig. 2 The overall structure of our course and study. Students completed a four-week unit on biology fundamentals online, then took a pre-assessment survey. The next four weeks, students completed the breast cancer unit in person and took a post-assessment survey

example such as breast cancer), and a breast cancer unit. The breast cancer unit applied the concepts taught in the fundamentals unit, along with fundamental evolutionary concepts students learned in the mandatory pre-requisite organismal biology course. Each student completed a survey following a unit that taught core course principles in a traditional manner (i.e., in the absence of specific human examples), and an identical survey at the end of the breast cancer unit, that communicated similar core concepts but in the context of an example specific to human health (Fig. 2). The completion of each survey earned students points toward 1% of their final grade and were completed alongside the midterm exams of each unit. All students enrolled in the course completed both surveys, but the surveys completed by 3students were dropped due to a lack of consent for their data to be included in the study. The project was reviewed and by MSU Institutional Review Board prior to data collection and was determined to be exempt (MSU IRB# STUDY00004765).

Student questionnaire

We designed a student questionnaire specifically to address our three predictions. Question I asks students to rate how they perceive learning about biology concepts in the context of human health will influence their learning experience in terms of content difficulty, interest, and relatability. These questions were rated on a 5-point Likert scale ranging from "a lot less" to a "lot more". Question II asks students to rate how relevant they think various biological concepts are for understanding human health conditions. These questions were rated on a 5-point Likert scale ranging from "very irrelevant" to "very relevant". Question III asks students how likely they think evolutionary processes are related to the emergence and persistence of human health conditions, rated on a 5-point scaled ranging from "very unlikely" to "very likely". The pre- and post-surveys administered were completely identical, and the exact questions asked are in Table 1.

Results

Student perceptions of learning in the context of human health and disease

Compared to the pre-assessment, students tended to rate learning biology concepts in the context of human disease to be less difficult, more interesting, and more relatable in the post-assessment (Fig. 3).

Table 1 The exact questions administered in the pre- and post-surveys

Component	1	2	3	4	5
Q1. Do you think the examination of course concepts through using examples of human health conditions (e.g. cancer & infectious diseases) will making learning the course content					
Interest	Much more interesting	More interesting	Neither more nor less interesting	Less interesting	Much less interesting
Difficulty	Much more difficult	More difficult	Neither more nor less difficult	Less Difficult	Much less difficult
Relatability	Much harder to relate to	Harder to relate to	Neither harder nor easier to relate to	Easier to relate to	Much easier to relate to
Q2. How relevant do you think the following ideas/concepts are when it comes to better understanding human health and disease:					
Transcription and translation	Very relevant	Somewhat relevant	Neutral	Somewhat irrelevant	Very irrelevant
Allele change in a population over time	Very relevant	Somewhat relevant	Neutral	Somewhat irrelevant	Very irrelevant
Natural selection	Very relevant	Somewhat relevant	Neutral	Somewhat irrelevant	Very irrelevant
Population bottlenecks and founder effects	Very relevant	Somewhat relevant	Neutral	Somewhat irrelevant	Very irrelevant
Genetic mutations	Very relevant	Somewhat relevant	Neutral	Somewhat irrelevant	Very irrelevant
Species diversity	Very relevant	Somewhat relevant	Neutral	Somewhat irrelevant	Very irrelevant
Cellular respiration	Very relevant	Somewhat relevant	Neutral	Somewhat irrelevant	Very irrelevant
Polymerase chain reaction	Very relevant	Somewhat relevant	Neutral	Somewhat irrelevant	Very irrelevant
Cellular interactions	Very relevant	Somewhat relevant	Neutral	Somewhat irrelevant	Very irrelevant
Competition	Very relevant	Somewhat relevant	Neutral	Somewhat irrelevant	Very irrelevant
Q3. Is the process of evolution responsible for the emergence and persistence of negative human health conditions?					
Likelihood evolution influences health	Very likely	Likely	Unknown	Unlikely	Very unlikely

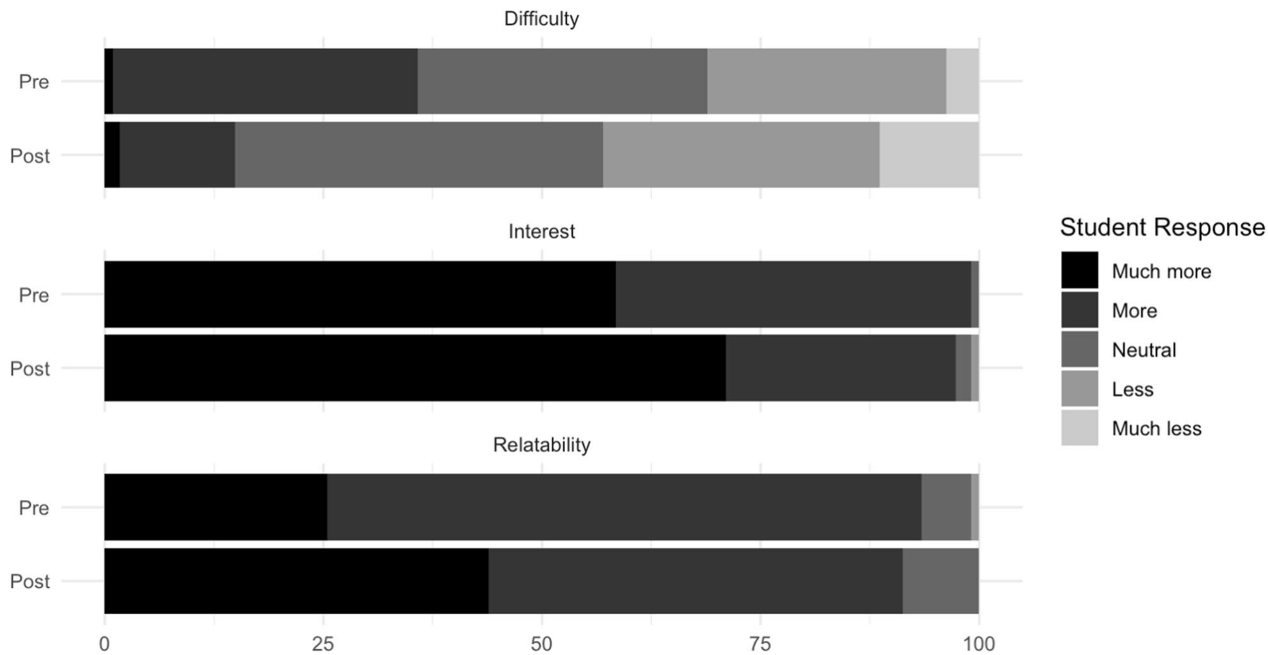

Fig. 3 Stacked bar plots displaying student responses of their perceptions related to learning about biology content in the context of human health and disease (Question I). The stacked colors represent the proportion of students that reported a particular response

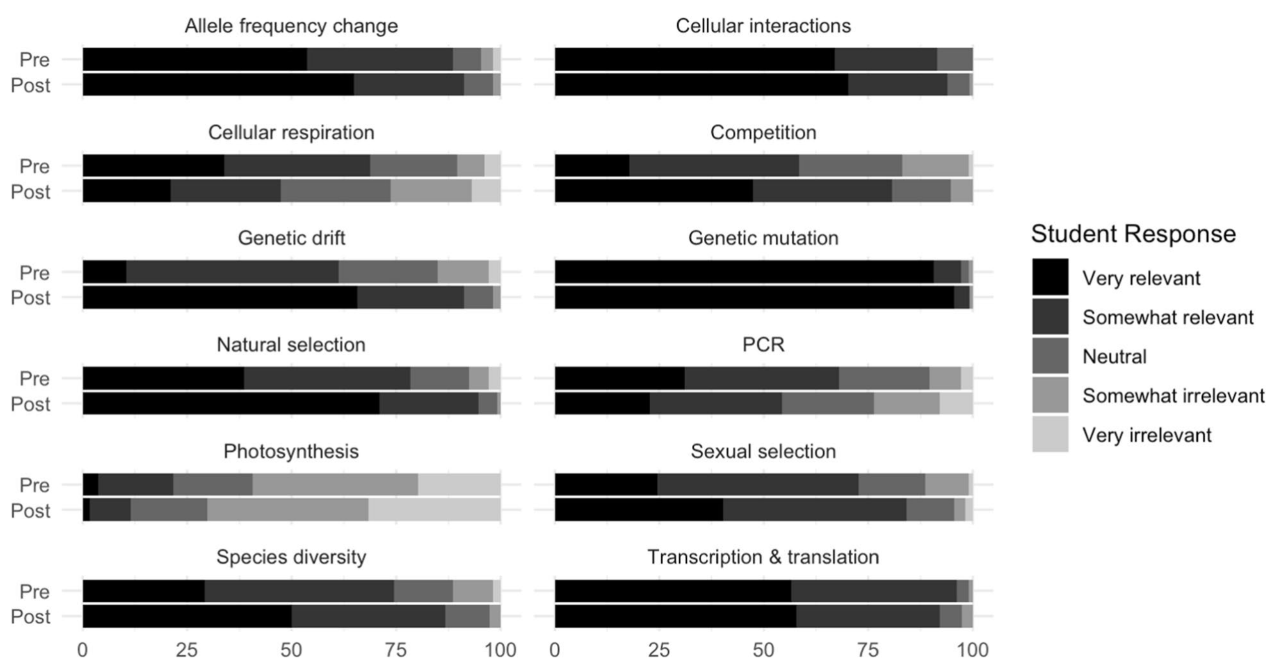

Fig. 4 Stacked bar plots displaying student responses of their opinions related to the relevance of various biological concepts for understanding human health and disease (Question II). The stacked colors represent the proportion of students that reported a particular response

Student perceptions of the relevance of biological concepts for understanding human health and disease

In terms of human health and disease, student perception of the relevance of cellular interactions, genetic mutation, and transcription/translation was relatively similar in the pre- and post-assessment surveys. In the post-assessment, students rated the concepts of allele frequency change, competition, founder/bottleneck effects,

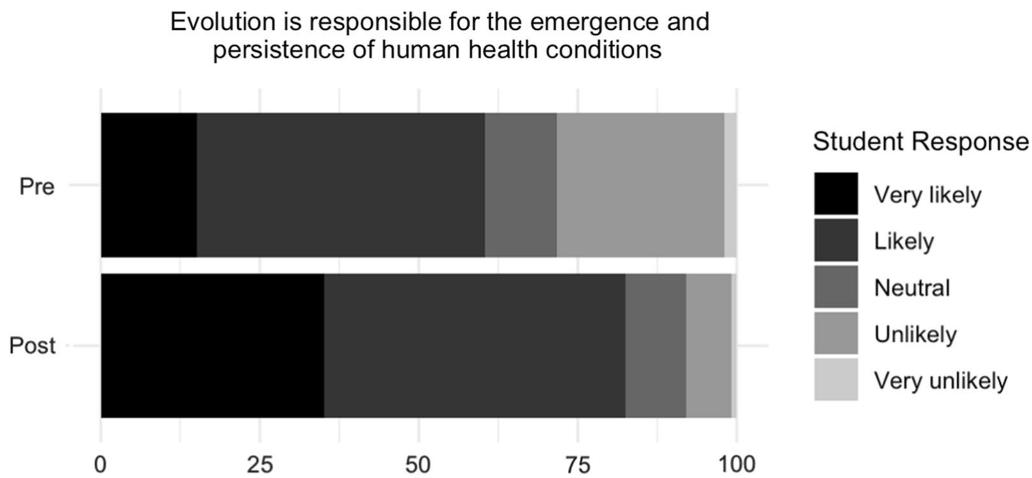

Fig. 5 Stacked bar plots displaying student responses of their opinions related to the likelihood that evolution is responsible for the emergence and persistence of human health conditions (Question IV). The stacked colors represent the proportion of students that reported a particular response

natural selection, sexual selection, and species diversity as being more relevant. On the other hand, they rated the concepts of cellular respiration, PCR, and photosynthesis as being less relevant in the post-assessment survey (Fig. 4). When asked about the likelihood of the process of evolution being responsible for the emergence and persistence of human health conditions, students tended to rate likely as a response more frequently in the post-assessment (Fig. 5).

Discussion

Our results indicate that teaching introductory biology concepts using examples of human health and disease (and more specifically, from an evolutionary medicine perspective) is (i) viewed favorably by students, and (ii) expands their perspectives to include how evolutionary concepts contribute to our understanding of health and disease. Others have advocated for the use of human and medical examples in introductory biology curriculums (Pobiner 2012; Nesse and Natterson-Horowitz 2019), and here we demonstrate results that support the benefits of this.

When looking at student attitudes towards learning about biology in the context of human health and disease, for the most part, students entered the unit with positive biases about the content. This is captured in the pre-assessment survey by the 31.2% of students who rated the perceived difficulty of the content as "much less" or "less", the 99.1% of students who rated their perceived interest in the content as "much more" or "more", and the 93.4% of students who rated the perceived relatability of the content as "much more" or more". Interestingly, the post-assessment seemed to clearly reinforce these positive perceptions in all three questions. When looking at how perceptions changed before and after the breast cancer unit, student interest and relatability increased, and perception of content difficulty decreased after completing the unit on breast cancer. This is an important result, as it seems to suggest that students find learning in the context of human health is both more interesting and relatable compared to the traditional concept-based approaches presented in introductory biology classrooms. It is likely that the increased interest and relatability may be due in part to the use of human examples, as other studies have suggested there is high student interest in topics related to humans (Wilson 2005; Pobiner 2012). However, one limitation of our current study is we did not collect data on various student demographic factors, which may influence metrics such as the perceived interest and relevance of examples related to human evolution (Beggrow and Sbeglia 2019; Grunspan et al. 2021). For example, Grunspan et al. (2021) found that students who were more accepting of human evolution reported greater perceived relevance of human examples. One factor that may explain the initial high perceived interest and relevance in our sample is that students in our study previously took a pre-requisite course focused on evolutionary principles, which may have led to an increase in acceptance of evolution amongst the students in our study. It could also be that the specific context of examples related to human health led to the reporting of high levels of interest. Regardless, in the future we hope to evaluate our content related to human health in light of various student demographic factors.

When looking at student perceptions related to the relevance of various biological concepts for understanding human health disease, we found that students changed their opinion about the relevance of many of these concepts following the breast cancer unit. Specifically, students rated allele frequency change, competition, founder/bottleneck effects, natural selection, sexual selection, and species diversity as being more relevant following the unit, but rated cellular respiration, PCR, and photosynthesis as being less relevant in the post-assessment survey. It is worth noting that all the concepts that saw an increase in perceived relevance were directly covered within our breast cancer unit, while all those that saw a decrease were not. This suggests that the specific topics covered may have the biggest impact on the students' perceptions of relevance. This might explain why students tended to report evolutionary concepts being of low relevance before the unit, since many students are often not introduced to the human health in the context of evolution. To reinforce this hypothesis, students also reported that evolutionary processes are likely to be responsible for the emergence and persistence of human health conditions more frequently in the post-assessment. Together, these results suggest that learning about human health and medicine in the context of evolution may have a meaningful impact on how students understand the role of evolution in human health. Given that many students that take introductory biology are pre-med students and future healthcare workers, this is an important result.

Holistically, our data overall indicate a positive impact of the implementing curricular materials related to human health in introductory biology classrooms however, there are several limitations to consider. The scope of our study was rather small, and the survey that we administered was, by design, explorative. The goal of this study was to qualify a basic measure of the impact of cases related to human health conditions in the classroom by gauging the reaction of students. Although we collected data across three separate class sessions, the instructor and course deliveries were the same. This makes it difficult to tease apart how much of the changes we saw in the post-assessment were due to the curricular content itself, rather than its specific delivery. Another important consideration is that not all introductory biology topics are directly covered in the cases that we use. For example, our breast cancer unit did not include any discussion about how cellular respiration relates to cancer progression. However, learning how the metabolic rate of cancer cells differs from healthy cells is of course a critical component of understanding what factors allow cancer cells to outcompete healthy cells. With this limitation in mind, we view our curricular materials as constantly being in an iterative state, and plan to update them to fill in these gaps as we gain more data and experience from their implementation.

Beyond these limitations, these preliminary results are promising for our major curricular objectives. Firstly, in both the pre- and post-surveys, students reported a high level of interest in learning about introductory biology concepts in the context of human health and disease, and they also reported the content to be more relatable and easier to learn about. This suggests that teaching students about biology concepts in the context of human health may make course content more appealing to a wider number of students. Secondly, students reported evolutionary mechanisms (i.e., natural selection, genetic drift, etc.) as being important concepts for understanding human health conditions more frequently after the breast cancer unit. This suggests our materials may demonstrate how evolutionary concepts play a crucial role in understanding human health may introduce students, many who are future healthcare workers, to new evolutionary perspectives. Finally, the previous two objectives may both contribute to overall learning gains for many students. Learning about human examples that are intrinsically interesting and relatable may improve student engagement and making the connection to evolution may help improve students' understanding of how to integrate the various sub-disciplines of biology, although more evidence is needed to support this. Moving forward, it is essential to continue to disentangle which types of examples in teaching evolution appeal to students from diverse demographic backgrounds. In the future, we hope to gather more data through using our cases, but we also encourage other instructors to utilize our materials and conduct formative evaluations of their effectiveness.

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Author contributions
DCSF wrote the first draft of the manuscript, and all authors were involved in the revision process. All authors were involved in designing the curricular materials and the student questionnaire. DCSF, JJR, and PJTW collected and processed the survey data and created the figures. All authors read and approved the final manuscript.

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Availability of data and materials
The raw data will be uploaded to an appropriate repository upon acceptance. Supporting materials for our project can be found at: https://evo-ed.org/.

Declarations

Competing interests
The authors have no competing interests to declare.

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