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IF/THEN Women in Science Collection

Edited by
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Ana Maria Porras

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A Collection is a series of articles published on a single theme of research and curated by experts in the field. By offering a more comprehensive coverage of perspectives and results around an important subject of research, we hope to provide materials that lead to a higher level of understanding of fundamental science. Alternatively, a collection could feature articles by scientists who received special recognition, such as a Nobel Prize. Frontiers for Young Minds Collections offer our international community of Young Minds access to the latest and most fundamental research; and, most importantly, empowering kids to have their say in how it reaches their peers and the wider public. Every article is peer reviewed according to the Frontiers for Young Minds principles. Find out more on how to host your own Frontiers for Young Minds Collection or contribute to one as an author by contacting the Frontiers Editorial Office: kids@frontiersin.org

IF/THEN Women in Science Collection

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Cover image
FourPlus Studio

Participating sections

Human Health

Neuroscience and Psychology

Earth Sciences

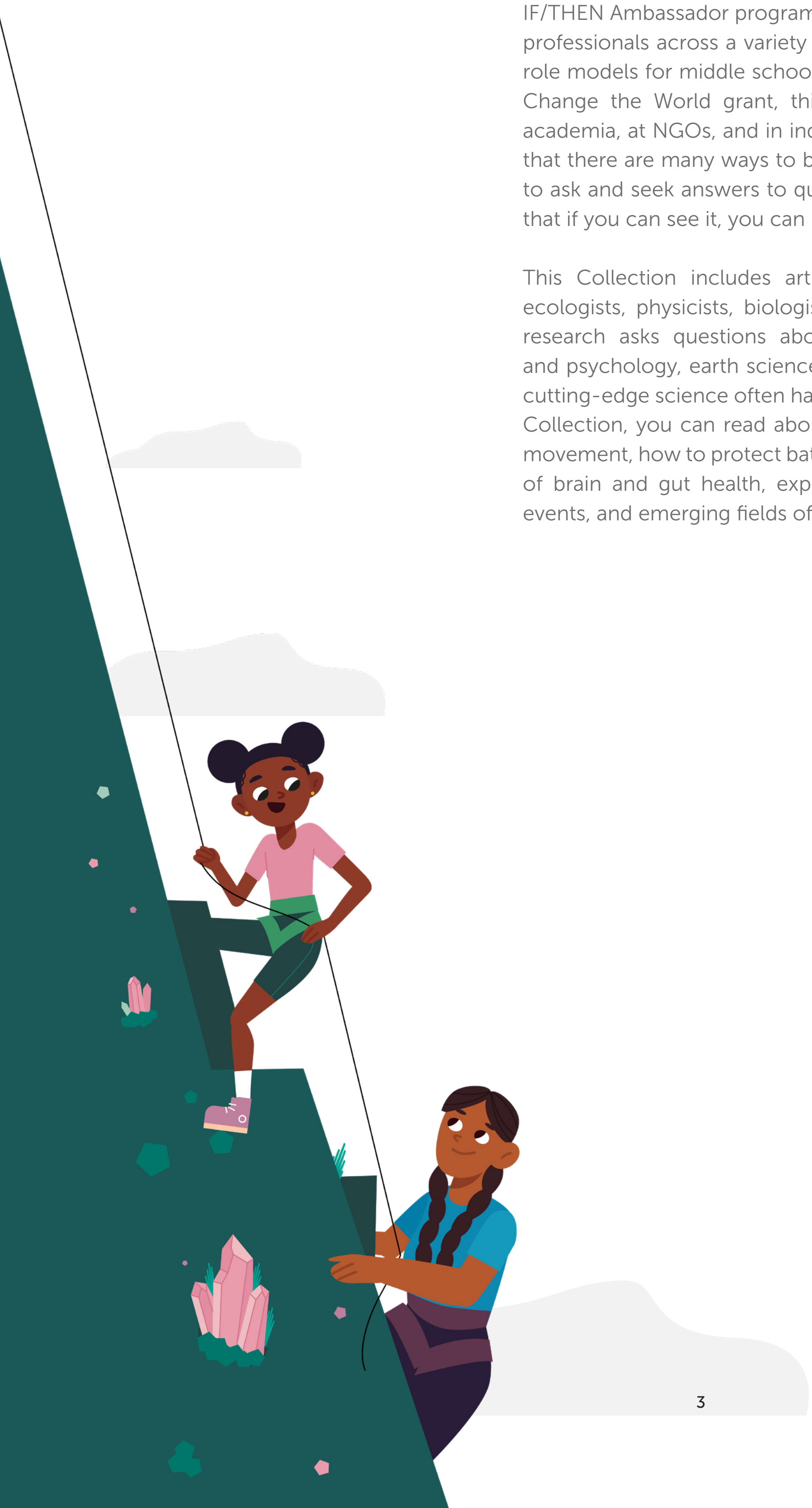
Biodiversity

About this collection

Science is everywhere! Whether wearing a white coat or a wet suit, working on a mountain or at a microscope, exploring the ocean depths or our own brains, the IF/THEN Ambassadors hope to show you that anyone (and everyone) can be a scientist.

The IF/THEN initiative envisions a future where more women innovators are empowered to solve our greatest global challenges. The AAAS IF/THEN Ambassador program brought together 125 US-based women STEM professionals across a variety of fields and industries to serve as high-profile role models for middle school girls. Supported by an AAAS IF/THEN She Can Change the World grant, this Collection features researchers working in academia, at NGOs, and in industry in a wide range of fields to show readers that there are many ways to be a scientist and to inspire more young people to ask and seek answers to questions about our world. At IF/THEN we know that if you can see it, you can be it!

This Collection includes articles from women who are neuroscientists, ecologists, physicists, biologists, engineers, and health professionals. Their research asks questions about human health, biodiversity, neuroscience and psychology, earth sciences, chemistry, and engineering and shows how cutting-edge science often happens at the intersections of these fields. In this Collection, you can read about how movie technology is improving patient movement, how to protect bats and pika on a warming planet, the importance of brain and gut health, exploration, the impacts of catastrophic weather events, and emerging fields of science like medical physics.



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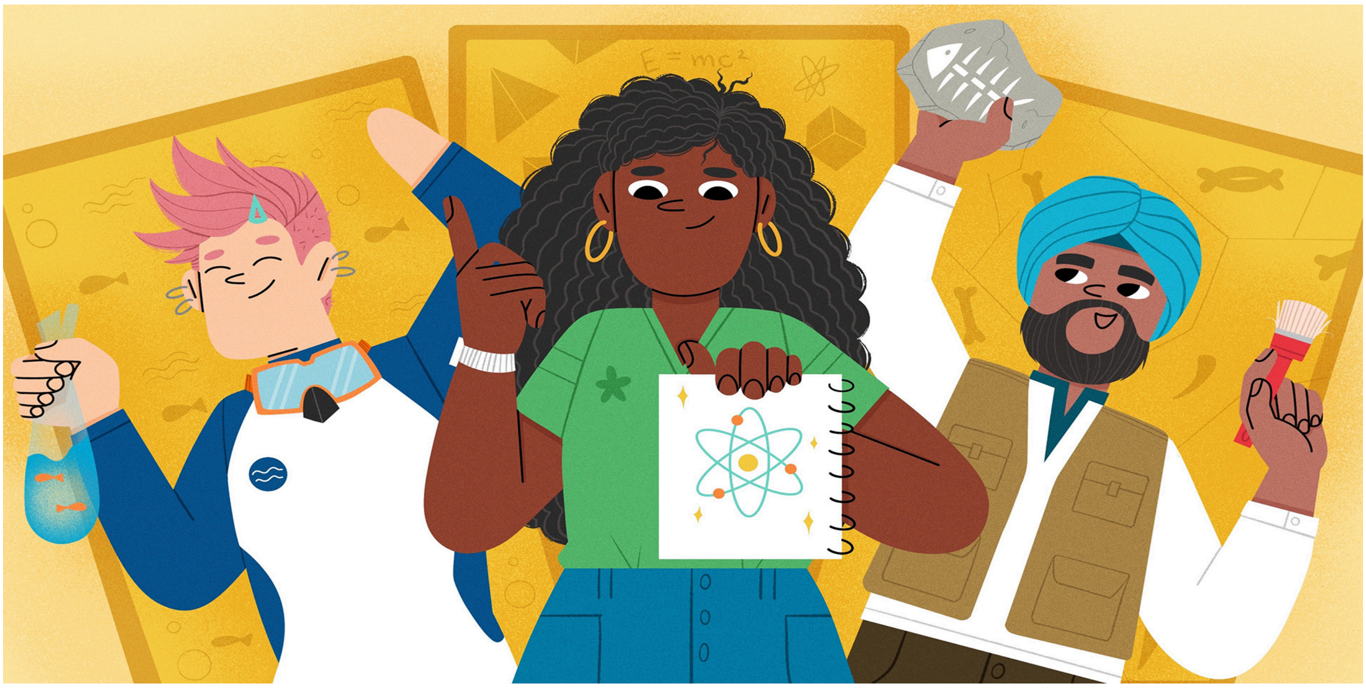

PICTURE A SCIENTIST—DIVERSE ROLE MODELS SHOW THAT SCIENCE IS FOR EVERYONE

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YOUNG REVIEWERS:

MAE
AGE: 14

TOBY
AGE: 12

Who do you picture when you think of the word “scientist”? Do you fit that image? Although science should be for everyone, some groups, including girls, people of color, the LGBTQ+ community, people with disabilities, and more are often discouraged from becoming scientists. Research shows that girls in particular start to lose interest in pursuing science careers during middle school. But part of the problem for every group is that you cannot be what you cannot see. So how do we change who students picture as scientists? We tested whether a playful STEAM (science, technology, engineering, art, math) program that uses comic books, trading cards featuring a variety of female role models, games, and outdoor exploration could change students’ minds. Our data shows that after the In Their Eyes: Conservation + Comics program, more students think that girls can be scientists, too!

LEARNING, BELIEF, AND IDEAS ABOUT WHO CAN BE A SCIENTIST

PSYCHOLOGY

The field of science that studies human minds and behaviors.

COGNITIVE SCIENCE

The field of science that studies specific processes in the brain, like memory, perception, and language.

COGNITION

The mental action or process of gaining knowledge and understanding through thought, experience, and the senses.

SELF-CONCEPT

The image we have of ourselves and our behaviors.

ROLE MODELS

People looked up to by others as examples to be imitated.

DIVERSE

Very different or variety. In this context, people from a range of different social and ethnic backgrounds and of different genders, sexual orientations, etc.

Picture a scientist: who do you imagine? Go ahead and draw your scientist on a piece of paper or in a journal. Once you are finished, put your pencil down and read on. We will come back to your drawing later.

Have you ever wondered how you know what you know? How does your brain understand that, by combining certain letters together, you spell a specific word? Or how do you know how to make a bowl of cereal in the morning? Have you ever wondered why you think the way you do? Scientists in the fields of **psychology** and **cognitive science** are working hard to answer questions like these. They study something called **cognition**, which is the process of learning and understanding through thought, experiences, and using the senses (touch, taste, sound, smell, sight, kinesthetic, proprioceptive, etc.). Humans know what they know because of cognition, and our brains use various cognitive processes to help us understand ourselves and the world around us. Some examples of cognitive processes are solving problems, making decisions, or using memory [1]. The processes used by our brains to learn things like math or language are different than the brain processes used to form the beliefs we hold about ourselves—these beliefs are called our **self-concept**.

Science shows us that there is a link between people’s self-concepts and who they grow up to be [2]. How do we know what we can be if we never see anyone like us doing the job? How do we believe we belong somewhere without **role models** that we identify with? One area of scientific study involves people’s beliefs about who can be a scientist. Historically, only white men were allowed to be scientists and women, people of color, individuals with disabilities, and other minority groups (like people in the LGBTQ+ community) were intentionally excluded from science [3]. This caused two problems: first, there were very few scientists who were *not* white and male; and second, because there was a lack of **diverse** scientists, the *belief* that a person must be white and male to be a scientist was reinforced. In other words, there were very few diverse scientific role models, which reinforced people’s beliefs that women, people of color, and others did not belong in science.

We wanted to see if providing diverse scientific role models to students could influence their beliefs about who a scientist could be.

STEM TO STEAM

Research shows that girls start to lose interest in science around middle school, and that interest in a subject is a strong predictor of career choice [4, 5]. So, we created a STEM (science, technology, engineering, math) lesson for middle school students, called the In Their Eyes: Conservation + Comics program [6]. Teaching STEM in creative ways—such as with comic books—has been shown to be a fun and effective way to learn [7]. To do so, our lesson added art to change STEM to STEAM (science, technology, engineering, ART, math)!

Every part of our lesson featured diverse, real-world scientists as role models: first, there was a classroom lesson in which students read scientific comic books and won scientist trading cards through a vocabulary game (Figure 1). Next, students took a virtual fieldtrip to a national park, for a lesson on biology and conservation taught by a female scientist. After learning about these topics, the students made their own scientific comic books to tell their conservation stories. Lastly, the students took everything they learned and created posters to show to their classes, friends, teachers, families, and 16 diverse guest scientists.

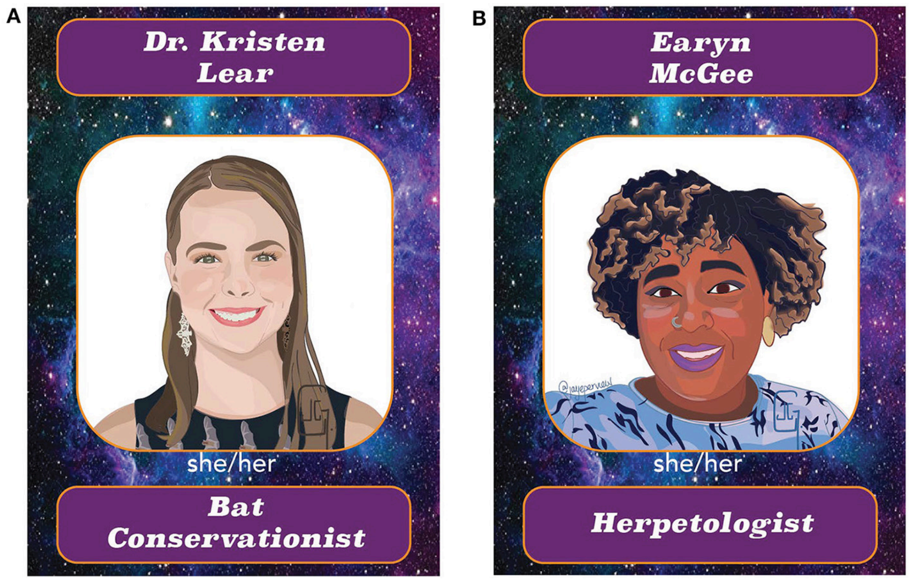


Figure 1

Two scientist trading cards used as part of our STEAM lesson. **(A)** The front of Dr. Kristen Lear's trading card tells you her preferred pronouns and what type of scientist she is—a bat conservationist. **(B)** The front of Earyn McGee's trading card tells you her preferred pronouns and what type of scientist she is—a herpetologist.

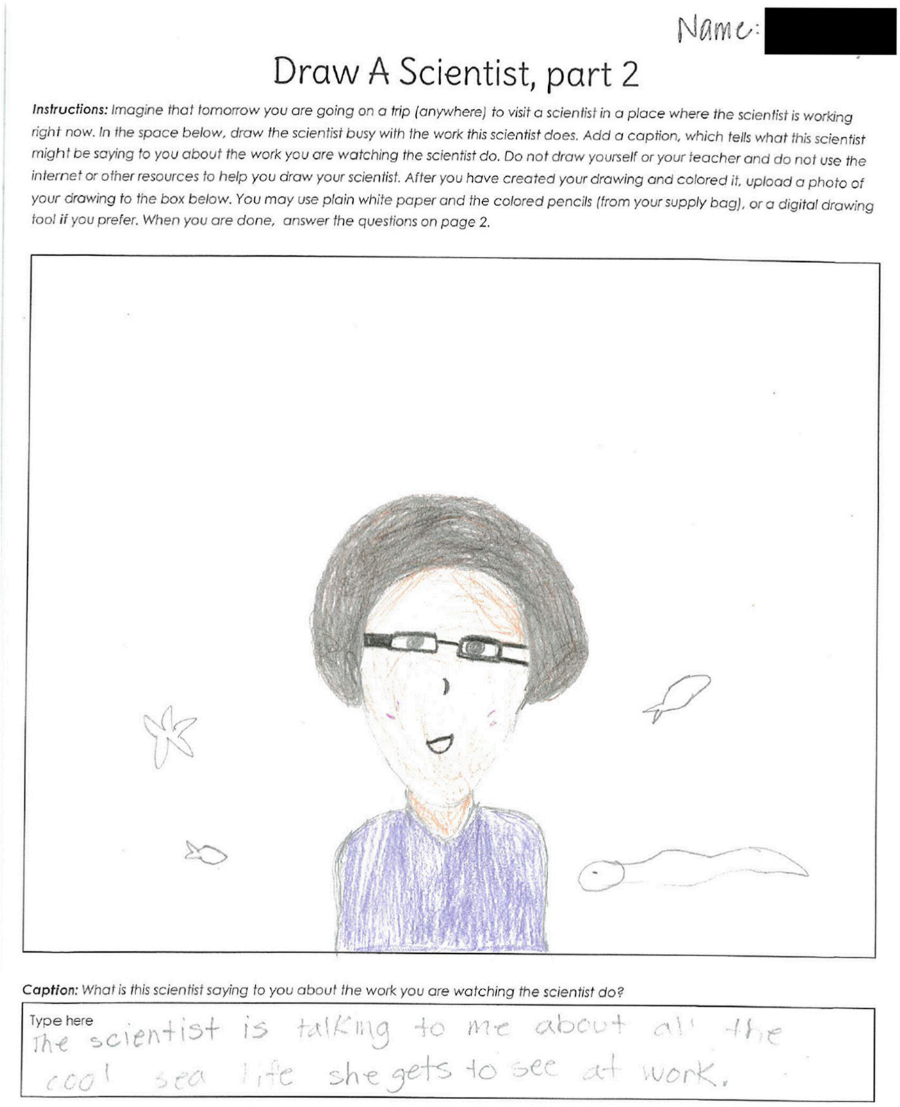
DID THEY CHANGE THEIR MINDS?

To understand if people's ideas have changed over time, scientists must gather information both before the experiment (like our STEAM lesson) and after the experiment. Then, they compare before (pre-experiment) to after (post-experiment). This tells them if their experiment had any impact on what the person thought, knew, or believed. To test whether our lesson changed the students' ideas about who could be a scientist, we used something called the Draw a Scientist Test (DAST) both before and after the lesson (Figure 2).

PERCEPTIONS

Ways of thinking, understanding, or believing something; mental impressions.

The DAST is a method that has been used by scientists and education researchers to study people's **perceptions** of scientists since the


Name: [redacted]

Draw A Scientist, part 2

Instructions: Imagine that tomorrow you are going on a trip (anywhere) to visit a scientist in a place where the scientist is working right now. In the space below, draw the scientist busy with the work this scientist does. Add a caption, which tells what this scientist might be saying to you about the work you are watching the scientist do. Do not draw yourself or your teacher and do not use the internet or other resources to help you draw your scientist. After you have created your drawing and colored it, upload a photo of your drawing to the box below. You may use plain white paper and the colored pencils (from your supply bag), or a digital drawing tool if you prefer. When you are done, answer the questions on page 2.

Caption: What is this scientist saying to you about the work you are watching the scientist do?

Type here

The scientist is talking to me about all the cool sea life she gets to see at work.

Figure 2

Figure 2

An example of the DAST from our experiment, which uses drawings and questions to learn who a student thinks a scientist can be. Instructions direct the student to draw a scientist and include a caption about what their scientist is saying to them about the work the scientist is doing; students are instructed not to draw themselves, their teacher, or to use the internet. This drawing is of a scientist the student met during the lesson. The drawing caption states, "The scientist is talking to me about all the cool sea life she gets to see at work".

1980s [8]. It has been updated many times over the years and is widely respected. The DAST asks students to "draw a picture of a scientist". The student is also asked follow-up questions, such as: "Was the scientist you drew a man or woman?", "Was the scientist working outdoors or indoors?", and "What was the scientist doing in your picture?".

The drawings and answers from this study were collected and examined to uncover **stereotypical** ideas of scientists. A stereotype is an oversimplified belief about a person that is often wrong, such as "only men can be scientists". Stereotypes like this demonstrate a limited idea of who can be a scientist and what a scientist does. For example, a drawing with facial hair indicates a male scientist, and a person wearing a white lab coat shows only one type of scientist (many scientists do not wear lab coats at all). After analyzing the DASTs,

STEREOTYPICAL

A widely held, oversimplified idea that is often biased, prejudiced, or wrong.

we then compared the number of stereotypes pre-experiment and post-experiment to see if there was a change.

MIND DETECTIVES

Studying people's beliefs, thoughts, and knowledge is like being a mind detective! So, did we solve the mystery about how to change people's perceptions about who can be scientists by using diverse role models?

After reviewing the pre-DASTs and the post-DASTs, we found that students drew fewer stereotypic images in the post-DASTs. Out of the 33 students that completed both pre- and post-DASTS, 22 of them drew traditional scientific equipment (such as beakers and flasks) before the lesson, yet only 12 of them drew this type of equipment after the lesson. In addition, 14 students drew protective gear like lab coats before the lesson, and only 6 students drew protective gear afterward. Lastly, before the lesson, an equal number of students drew men and women as scientists; but after the lesson, 19 students drew women, 10 students drew men, and three students drew non-binary scientists.

We also found that students shifted some of their ideas about science. Our lesson featured diverse women in the field of biology, and the number of drawings that featured biologists increased from 16 to 25. In fact, six students drew scientists they had been introduced to from the lesson (Figure 3)!

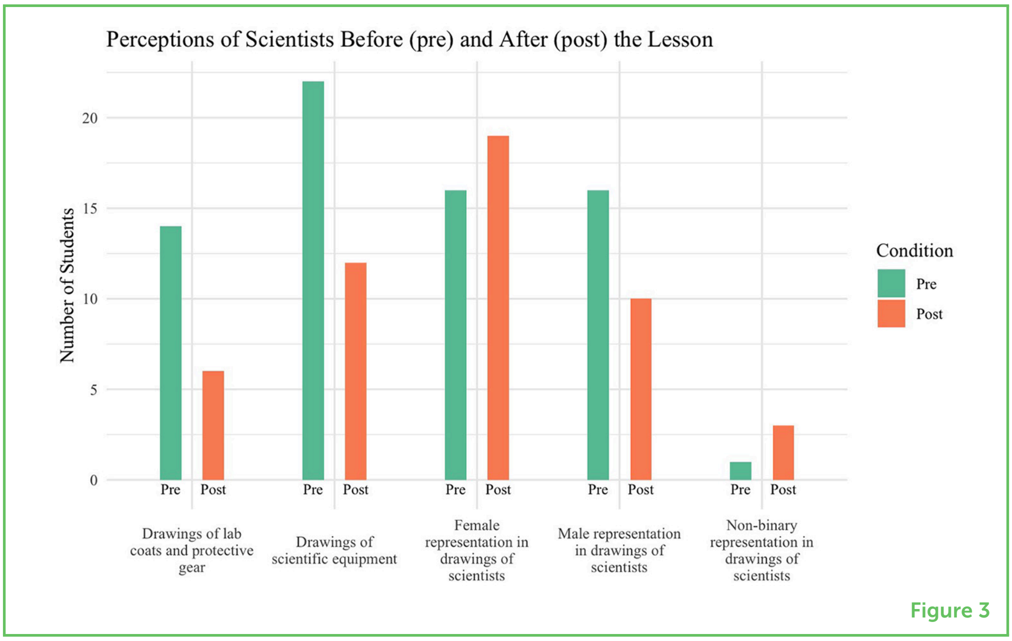


Figure 3

A bar graph of student perceptions of scientists before and after the lesson. The bars show student DAST responses pre- (green) and post- (orange) lesson. You can see that there were changes in student perceptions—for example, female and non-binary representation increased while male representation decreased.

PICTURE A SCIENTIST

Why does all of this matter? These numbers show us that our lesson could be breaking harmful stereotypes about what a scientist is and who a scientist can be! By peeking into students' beliefs about science and scientists, we were able to determine one part of a solution to the lack of diversity in STEM fields. It will take a lot of work to make STEM equal for everyone, but this could be one important step toward future success.

Now, picture a scientist again—who do you imagine this time?

ACKNOWLEDGMENTS

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ORIGINAL SOURCE ARTICLE

Meaders, C., Gardiner, J., Wynns, S., Nigam, S., and Harris, J. 2023. A comic-based conservation lesson plan diversifies middle school student conceptions of scientists. *J. Res. STEM Educ.* 9:20–45. doi: 10.51355/jstem.2023.127

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

YOUNG REVIEWERS

MAE, AGE: 14
My name is Mae. I enjoy art, math, reading, and playing Minecraft. I delight in learning about the world, and finding patterns. I like learning about, and advocating for disability rights.

TOBY, AGE: 12
I like to play video games and I have two cats.

AUTHORS

SAMANTHA WYNNS
Samantha Wynns is a conservation biologist who both does science and communicates science in her job with the National Park Service at Cabrillo National Monument. Diversity, equity, inclusion, and justice are import to Sam and her favorite project is leading a STEM summer camp for underserved girls. In every

role, Sam's goal is to inspire a passion for STEM and a commitment to protecting the environment. She, her husband, two rescue cats, and a very friendly parrot live in beautiful San Diego, California (image courtesy of IF/THEN® Collection). *wynns.conservation@gmail.com

CLARA L. MEADERS
Award-winning assistant teaching professor Dr. Claire Meaders gets and keeps students of all ages excited about biology. Claire holds a Bachelor of Science degree in cell and molecular biology from Brown University and a Ph.D. in organismic and evolutionary biology from Harvard University. Outside of the lab, Claire loves baking and baking reality TV shows, and she recently ran her 15th marathon! (image courtesy of IF/THEN® Collection). *cmeaders@ucsd.edu

JAYE C. GARDINER
Nationally recognized biomedical research scientist Dr. Jaye Gardiner uses her knowledge of the microscopic world to understand what occurs in diseases like viral infections or cancer. Jaye combines her talents in STEM and as an artist to show that science is for everyone, by creating scientist trading cards and comics about science and scientists. Jaye enjoys working with youth and guiding them through the scientific process as they conduct their own independent research projects (image courtesy of IF/THEN® Collection).

SANKALP NIGAM
Sankalp Nigam is a recent graduate from UC San Diego with a human biology degree. He is incredibly passionate about the importance of providing high-quality and inclusive education, especially to younger generations. He believes it is important to constantly improve educational efforts and make learning more personalized to individuals. He hopes to continue his passion for education in the future as a physician so he can contribute to spreading medical knowledge throughout underserved communities, with the overall goal of improving healthcare in these areas.

JILLIAN HARRIS
Hi, I am Jillian Harris. When I was a kid, I dreamed of becoming a doctor or scientist, and I am working hard to make that dream come true! When I am not studying for school, I love watching TV shows and movies, and I enjoy exercising to stay healthy. My favorite TV show is "Bridgerton", and my favorite movie is "The Incredibles". I swam competitively for 12 years, so you can often find me near a pool. Whether I am lifeguarding, teaching swim lessons, or just swimming laps for fun, being in the water is one of my favorite things to do.

NEUROSCIENCE AND PSYCHOLOGY
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STEM-IT-YOURSELF: INCREASING PARTICIPATION OF GIRLS AND MINORITIES IN STEM

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YOUNG REVIEWERS:


CHLOE
AGE: 14


DIA
AGE: 13


ELIZABETH
AGE: 15


KAVYA
AGE: 15


KIANA
AGE: 15

Have you ever wondered why, when browsing the internet looking for scientists, technologists, engineers, or mathematicians, most of the results show men? Or have you ever wondered if there was someone out there who might look like you doing work in science, technology, engineering, and mathematics (STEM)? Our research aimed to better understand why STEM fields are not diverse in gender or race, and to empower the next generation of STEM leaders through a project called STEM-It-Yourself (SIY). Through SIY, we introduced middle school girls to women in STEM who are representative of the girls' races. By hearing about the STEM journeys of the presenters, who were women, and Black, Indigenous, and people of Color (BIPOC), the girls participating in SIY could cultivate STEM identities, which could motivate them to stay in STEM and help diversify the STEM workforce.

INTRODUCING GIRLS OF DIVERSE BACKGROUNDS TO STEM AT AN EARLY AGE

Only a few girls and children from diverse backgrounds see themselves having careers in science, technology, engineering, and math (STEM) fields. Some children, primarily from **minority** groups, do not feel like they belong in the STEM world when they finish school. Early involvement in STEM is essential because when young children participate in STEM activities, this involvement can give them a stronger STEM career identity, more interest in science, and confidence about working in STEM [1]. The STEM-It-Yourself (SIY) program, developed by The Laboratory for Artificial Intelligence and Equity Research (LAIER), aims to help change how Black, Indigenous, and people of color (BIPOC) girls see themselves and behave in STEM. Specifically, SIY seeks to help these girls become more self-assured so that they can picture themselves with a job in STEM.

MINORITY

A part of a population considered differing from the rest in some characteristics and often subjected to differential treatment.

WHAT IS A STEM IDENTITY?

A **STEM identity** is when a person can feel a sense of attachment or belonging to a STEM environment. To help children develop a STEM identity, educators and researchers should focus on early STEM education in children's day-to-day lives. Research shows that the early stages of a child's life are when identity development happens, helping kids learn how to live in the present and develop potential future STEM identities [2]. The SIY initiative provided mentors to encourage, inspire, and guide these young women. It was an excellent way for young kids to explore their interests and cultivate their STEM identities.

STEM IDENTITY

The recognition of self and others as a person in STEM or STEM-related fields.

According to the Pew Research Center, only 14% of women workers are in physical science and engineering, only 20% are health-related workers, and 15% are computer science BIPOC workers [3]. In the USA, women and people of color are often missing from STEM jobs—less than one-quarter of STEM employees are women, as you can see! More women and people of color in STEM could boost creativity and innovation [4]. Financial barriers and the lack of role models can make it challenging for girls of color to see themselves in STEM careers. However, having mentors who look like them can make a big difference in helping girls believe they can succeed. The more they learn about STEM fields, the more likely they are to pursue STEM careers.

HOW CAN EXPOSURE HELP?

Less than 10% of STEM content is taught in kindergarten through second-grade classes—that is a tiny amount [2]! But guess what? We can change that by developing ways to expose young people to STEM. Early exposure might help increase the percentage of females entering STEM fields. Research shows that grades 6–8 (ages 9–13) are when most career aspirations are developed [5]. Hands-on activities like building robots, playing coding games, or conducting science experiments can make STEM subjects more engaging. Programs and clubs like those from the Society of Women Engineers or Black Girls Code connect students with mentors and real-world projects that inspire and guide them. With these thoughts in mind, The LAIER created SIY to help link children to their actual likes and interests in a STEM field so they could find their passion and eventually increase the number of people from underrepresented groups in STEM jobs for the future (Figure 1)!

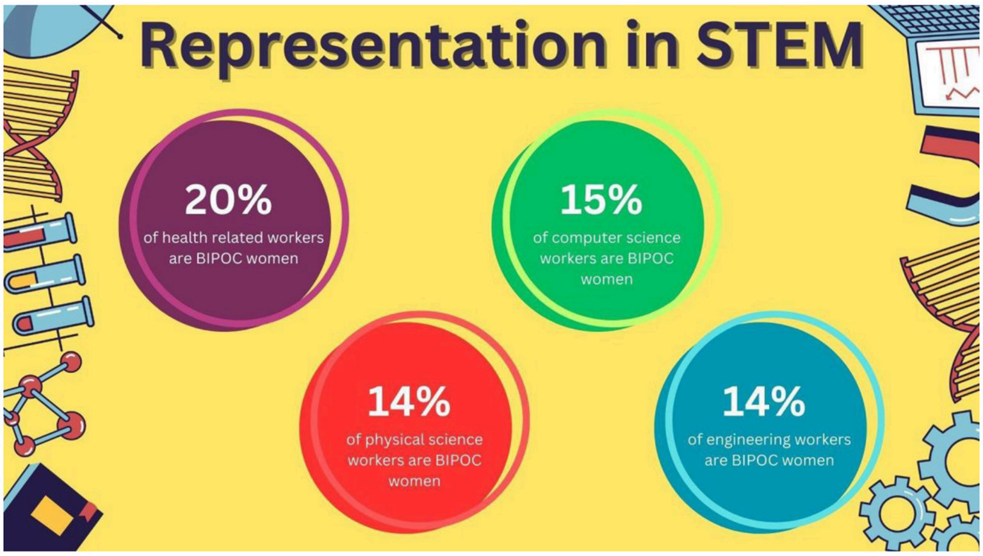


Figure 1

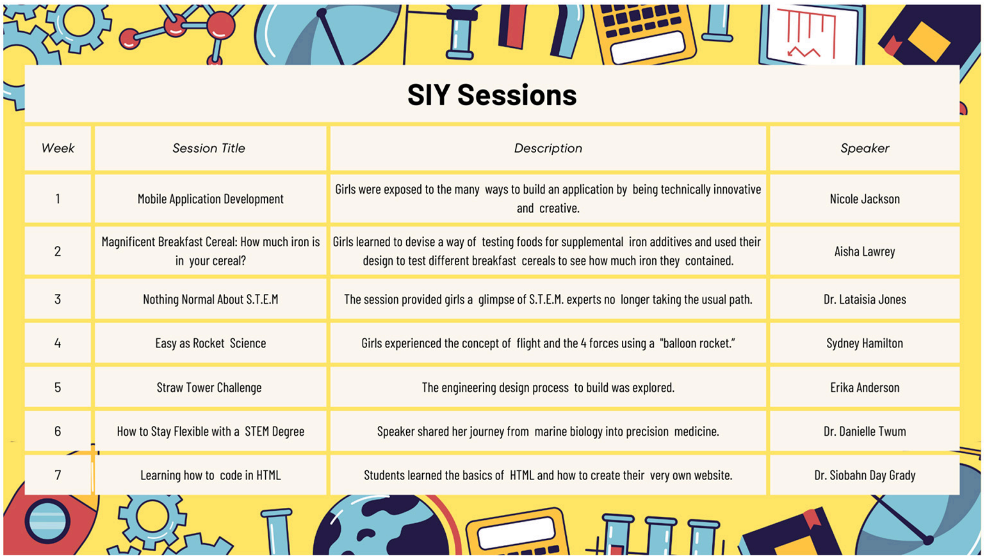
Figure 1

Percentages of BIPOC women in computer science, physical science, engineering, and health-related fields (Pew Research Center).

HOW THE SIY INITIATIVE WORKS

SIY was an extracurricular movement for middle school students (grades 6–8; ages 9–13) that explored adolescent girls' perceptions, attitudes, and behaviors by having them participate in STEM activities [6]. These girls may not have had a chance to form a STEM identity, see women who look like them in STEM or may not have the resources available to learn more about STEM. The SIY initiative had two main parts: sessions and activities.

SIY activities were hands-on projects geared toward creating something related to the various STEM topics, while the SIY sessions were focused on themes and provided speakers from STEM professions. Figure 2 provides a snapshot of the diverse topics and activities covered. These educational, interactive sessions exposed girls to real-life STEM activities, fostering a deeper understanding of the world around them. They were encouraged to apply the principles they learned from the speakers through the sessions by participating in hands-on, topic-related activities. All sessions were recorded and shared online to be revisited at any time on our SIY initiative YouTube page.



SIY Sessions

Week	Session Title	Description	Speaker
1	Mobile Application Development	Girls were exposed to the many ways to build an application by being technically innovative and creative.	Nicole Jackson
2	Magnificent Breakfast Cereal: How much iron is in your cereal?	Girls learned to devise a way of testing foods for supplemental iron additives and used their design to test different breakfast cereals to see how much iron they contained.	Aisha Lawrey
3	Nothing Normal About S.T.E.M	The session provided girls a glimpse of S.T.E.M. experts no longer taking the usual path.	Dr. Lataisia Jones
4	Easy as Rocket Science	Girls experienced the concept of flight and the 4 forces using a "balloon rocket."	Sydney Hamilton
5	Straw Tower Challenge	The engineering design process to build was explored.	Erika Anderson
6	How to Stay Flexible with a STEM Degree	Speaker shared her journey from marine biology into precision medicine.	Dr. Danielle Twum
7	Learning how to code in HTML	Students learned the basics of HTML and how to create their very own website.	Dr. Siobahn Day Grady

Figure 2

Figure 2

SIY sessions had various themes and speakers, aiming to show the participants women in STEM who looked like them.

SIY is not just about fun activities. We also used surveys to ensure the girls got the most out of each session. Surveys measured how much girls remembered from previous sessions and served as a "preview" for the next section. Girls also took short, interactive quizzes on Kahoot to test their knowledge and memory of the topics taught in the lesson. To close each session, the SIY team gave post-survey questions to collect information to help us modify teaching methods to ensure the young women were not overwhelmed or discouraged. While SIY helped us discover multiple ways to bridge the gap for young BIPOC learning about STEM, the work does not stop here.

IMPACT AND CONCLUSION

The SIY initiative can be used in other settings, age groups, grade levels, organizations, or universities to target BIPOC and support or grow the STEM workforce. To assess how well the program worked, we track participants' progress to see if SIY made a long-term impact and helped girls foster their STEM identities. We hope that, through reading this article, you can see the power of representation, enrichment activities, and outreach. Maybe you can think of other organizations that may need to implement STEM activities or improve their STEM programming. We plan to expand the program to reach other young women from underrepresented and underserved communities.

ORIGINAL SOURCE ARTICLE

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

YOUNG REVIEWERS

CHLOE, AGE: 14

I have only recently gown to live a be more in evolved in STEM as of last year. I am in a program that helps support and encourage me to pursue STEM.

DIA, AGE: 13

I recently finished 7th grade, and am excited and looking forward to entering 8th grade soon. Some of my hobbies include meeting up with friends, reading, listening to music, swimming, painting, and occasionally shooting hoops in my driveway. My favorite subjects/extra classes at school are P.E and Math. As I am 13 years old, I have not fully discovered what I want my future career path to look like, but I am considering a future as a corporate lawyer or as a software engineer.

ELIZABETH, AGE: 15

I am Elizabeth and I will be a sophomore in high school. I love learning about chemistry and physics, especially topics like quantum mechanics and electrochemistry. Recently, I have also enjoyed playing around with Arduinos and using different types of sensors. Besides exploring STEM topics, I also enjoy playing the piano, ultimate Frisbee, and doing volunteer work in local parks like Torrey Pines, Cabrillo, and Los Penasquitos Reserve.

KAVYA, AGE: 15

Hi! I am Kavya! I absolutely love science and all aspects of genetics, medicine, and environmental science! In my free time I do calligraphy and go on long runs! I also love writing poetry and all types of literature. Cuddling with my pet guinea pig and reading autobiographies are some of my go-to activities.

KIANA, AGE: 15

Hey all! My name is Kiana, and I am super excited to be a Young Reviewer! I am super passionate about supporting disabled communities, as I am deaf! Some of my hobbies include spending time with friends, family and my three big dogs, journaling, coding, and teaching American Sign Language.

AUTHORS

SIOBAHN DAY GRADY

Dr. Siobahn Day Grady is the program director and assistant professor of information science at North Carolina Central University in the School of Library and Information Sciences. She leads the Laboratory for Artificial Intelligence and Equity Research, where her research areas include authorship attribution, human-computer interaction, and machine learning. She also participates in numerous outreach activities to broaden participation in computing. *sday@nccu.edu

NATALIE TUCKER

Natalie Tucker, a security specialist on the Cyber Threat Intelligence team at The Walt Disney Company, is driven by a deep passion for her work. Her role demands constant vigilance, ensuring she is aware of and quick to report or share vital information, such as emerging threats and vulnerabilities, that may impact or affect the company. Her passion lies in collecting and compiling information and creating stories from those insights. This passion fuels her desire to share her journey and knowledge with BIPOC, hoping to inspire them to pursue their dreams in STEM.

CHRISTOPHER LAWSON

Christopher Lawson is a program training and development manager at North Carolina Central University in the School of Library and Information Sciences for the Digital Equity Leadership Program. Christopher is also pursuing his doctoral degree in human-centered computing from Clemson University. With a diverse background and a strong commitment to promoting diversity and representation, Christopher is dedicated to inspiring others and advancing the fields of computer science and information technology. Through his work, he strives to bridge the digital divide, increase digital equity, and empower underrepresented communities.

BIODIVERSITY
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HOW WILL CLIMATE CHANGE AFFECT PIKAS' FAVORITE SNACKS?

Emily Monk[1,2]***, Karli Weatherill***[3]***, Chris Ray***[1,4]***, Ashley Whipple***[1,4] ***and Johanna Varner***[3*]

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YOUNG REVIEWERS:


IZZY
AGE: 13


LUCINDA
AGE: 15


SAM
AGE: 10

Many animals are herbivores, which means they get all their nutrients from eating plants. American pikas are cute rabbit relatives that eat plants in the mountains. But alpine winters are harsh, so pikas spend their entire summer gathering and storing plants to eat under the winter snow. Just like people, pikas in Colorado have a favorite food: a plant called alpine avens. This plant species is a special pika snack because it contains natural preservatives called phenolics, which keep the food fresh all winter. We studied how climate change is affecting this important feature of the pika's favorite meal. Alpine avens contains more phenolics now than it did 30 years ago, so they preserve better in storage. But there is a catch: these preservatives can be hard to digest. Studies like this help us start to understand the many complicated ways that climate change affects herbivores like pikas.

TALUS

Rock piles that collect at the base of a cliff or along the edge of a glacier. Pikas in North America like to live in rock piles instead of burrows.

ALPINE

Relating to high mountains. Alpine plants and animals are well-adapted to living at high elevations, in habitats with short, cool summers, and long winters.

A PIKA'S LIFE AT THE ALPINE SALAD BAR

Imagine if your house were high up in the mountains and you spent your summers gathering your favorite foods. That is similar to the life of one animal species, called the American pika (Figure 1). Pikas are small mammals related to rabbits. They usually live high in the mountains, in rocky areas called **talus**. The talus provides a pika with shelter from the weather and a place to feel safe. But living in the mountains is not easy for pikas. Their homes can be covered in snow for 9 months of the year. Pikas live under the snow in their talus homes all winter long: they do not hibernate or sleep all winter like other animals. Instead, during the short **alpine** summer when mountain meadows are full of plants to eat, they work hard to stock up enough food to last the entire winter. Imagine if you had to grocery shop for the entire school year all at once!

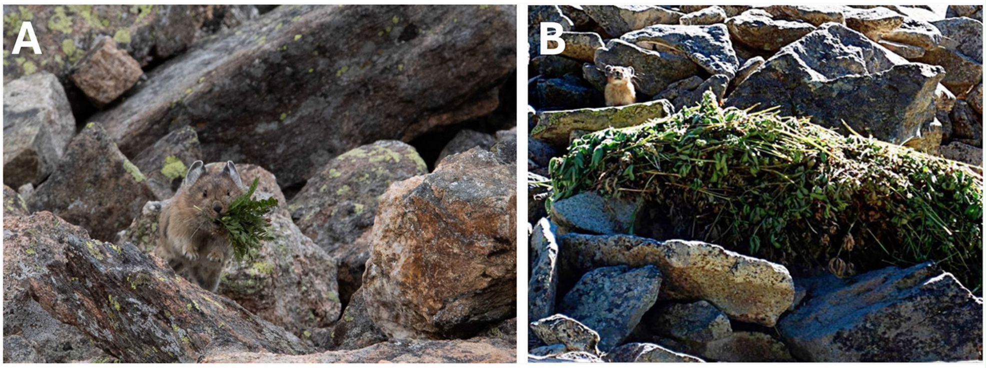

Figure 1

Figure 1

American pikas and their haypiles. **(A)** American pika carrying a mouthful of alpine avens to its haypile (Photo: Holly Nelson). **(B)** A pika with its haypile (Photo: Juliana Pearson).

STOCKING UP FOR WINTER

Pikas are herbivores, which means they eat only plants. Pikas eat grasses and flowers from meadows near their rocky homes. During the summer, pikas must collect food for the winter. Pikas spend their summers collecting huge amounts of plants to store in a **haypile** [1]. This haypile is all that they have to eat during the winter when their whole neighborhood is deep under snow, so it is important for them to collect enough plants. Just like people, pikas in Colorado (USA) have a favorite snack to put in their haypiles: a plant called alpine avens. Alpine avens makes up most of the pika's winter diet. They are the most common plant in a haypile, making up over half of everything stored in the pika's pantry.

HAYPILE

A collection of plants (mostly wildflowers) stored by a pika. A pika will eat this "food cache" throughout the winter when it is hard to find other food.

Pikas have different diets in the summer and winter because of what is in the plants they eat. The foods they eat in the summer are high in nutrients and easy to digest. But winter food is a bit more complicated. Foods that pikas store for the winter must last many months before they are eaten. Most normal plants would go bad long before winter is over. Can you imagine leaving a salad in your room all winter? It

PHENOLICS

Chemicals that some wildflowers make naturally, which protect the plant's tissue from the harsh environment and from herbivores; they also help preserve plants stored in pika haypiles.

TOXIC

Harmful when eaten. Toxic plants can cause a range of problems for herbivores, from being difficult to digest (by requiring too much energy), to causing illness or even death.

would not be very tasty by springtime! This is why alpine avens are special: they contain natural chemicals called **phenolics**, which act like preservatives [2]. Phenolics keep the alpine avens in a haypile fresh, so that a pika can eat them all winter long. But eating preservatives comes with a cost—phenolics are also **toxic**, which means that a pika cannot eat too many alpine avens without getting very sick or spending a lot of energy on digestion. Luckily, pikas know that, over time, the toxic phenolics break down and the plants become edible. Since the phenolics also preserve the alpine avens, the plants stay fresh until they are not toxic anymore. This means pikas can eat lots of stored alpine avens later in the winter, without getting sick.

LEARNING MORE ABOUT PIKA SNACKS

Climate change has already affected many species of plants and animals, as you can learn about in this Frontiers for Young Minds article. But the ways that changes in temperature and precipitation affect the daily lives of mountain species are not always obvious. We wanted to know more about how climate change might be affecting the pika's main winter food source in Colorado. We expected that alpine avens may have become more toxic because plants could use the extra carbon dioxide in the atmosphere to make more phenolics.

We compared the phenolics in alpine avens now to alpine avens in the 1990s, to see if there were any differences over time. We started by returning to a site on Niwot Ridge, the same place where another scientist named Denise Dearing studied pikas in 1992 [1, 2]. Niwot Ridge is located high in the mountains of Colorado at an elevation of about 11,000 ft. We collected alpine avens each year from 2010 to 2018, just like Dr. Dearing did about 25 years earlier.

We took some of those plants back to the lab to measure the amount of phenolics they contained (Figure 2). We ground up the plant samples in a liquid that dissolved the phenolics. Then, we measured the phenolic levels using a chemical reaction in which the liquid changes color depending on the amount of phenolics present. So, the samples from plants with a lot of phenolics turned dark green, and the samples from plants with only a little bit of phenolics stayed yellow. Finally, a machine measured how yellow or green each sample was and translated the color into an amount of phenolics.

We also wanted to know how changes in phenolics might change plant preservation in pika haypiles. So, in September 2017, we put some plants in wire cages and placed them in the talus like a pika haypile (Figure 3). The cages kept the plants safe from curious pikas or other animals but let the plants break down, just like they would in a real haypile. These experimental haypiles spent the winter under the snow at Niwot Ridge, until we collected them in July 2018. Then,

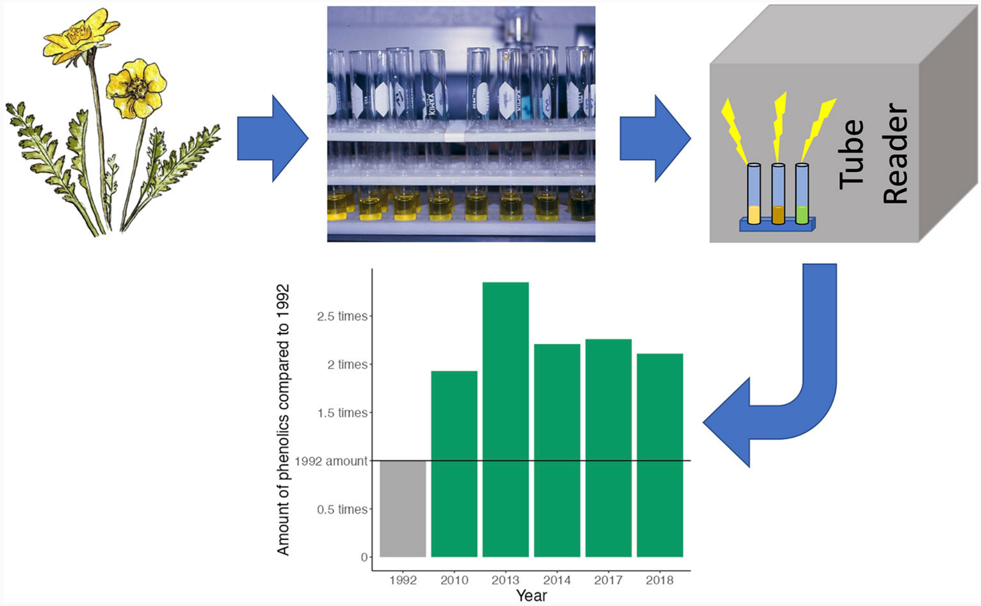

Figure 2

Figure 2

Measuring the phenolic content of pika snacks. Alpine avens samples were first ground up in the lab. Then, a chemical reaction in test tubes turned the samples from yellow to green, in proportion to the amount of phenolics in the sample. The more phenolics, the darker green the samples turned. Finally, a machine measured the colors of each sample and translated these colors into an amount of phenolics for each sample (Avens drawing by Alexandra Weatherill).

Figure 3

Figure 3

Experimental haypiles at Niwot Ridge. **(A)** One of the authors, Johanna Varner, marks the location an experimental haypile on Niwot Ridge. **(B)** The experimental haypiles were placed in wire cages and were positioned in the rocks, just like a real pika haypile.

we dried and weighed what was left in the cages to see how well the plants preserved.

Finally, we compared our results to Dr. Dearing's 1992 study, to see if there were any differences in the amount of phenolics in alpine avens or in how well the plants preserved in pika haypiles.

CHANGES AT A PIKA'S DINNER TABLE

It turned out that alpine avens has been changing a lot! First, this plant had more than twice the amount of phenolics at the time of our study than it had in 1992 (Figure 2). In fact, in 1 year of our experiment (2013), the alpine avens was almost three times more toxic than it used to be! The extra phenolics also made the plants preserve better. In our experimental haypiles, there was about 10% more food left at the end of winter compared to 25 years ago.

This is both good news and bad news for pikas. The fact that their favorite snack is more toxic now might make it less tasty to eat fresh. But on the other hand, alpine avens also stays fresh longer. So, pikas might have to wait longer to be able to eat alpine avens with more phenolics, but having more phenolics can help preserve alpine avens and maybe even other snacks in the haypile. This means that, even if they do not store as much food, pikas could still have more to eat in late winter. We also know that alpine avens has become less common in the meadows at Niwot Ridge, which are becoming drier due to climate change [3]. Instead, the meadows have more grasses, which pikas like to eat fresh. So, while pikas today may not be able to find as many alpine avens as the pikas that lived 25 years ago, they might not need to store as much food, either.

WHAT DOES IT ALL MEAN?

The way climate change affects pikas' favorite foods is like a tricky puzzle. In some ways, climate change could make life harder for these cute creatures as they change what they eat. But on the other hand, the foods they collect might last longer in storage, which could make life easier. In the future, the changing climate might even change the food choices pikas have. Warmer temperatures are already changing mountain meadows to have more grasses and fewer flowers like alpine avens. Imagine if you had to eat only one thing forever, like pandas that eat bamboo or koalas that eat eucalyptus. That might happen to pikas!

As we keep studying pikas and their snacks over a long period of time, we can learn how climate change is making things different for these animals. It is like reading a history book about pikas and discovering that the foods they eat now are different than what they used to eat. Just like we compared our results to Dr. Dearing's, maybe in 25 years YOU will be studying how pika snacks have changed compared to now!

So, the next time you are having dinner, think about how climate change might be changing the foods on your plate. Just like for pikas, climate change can change our favorite foods, too. It is a reminder that we all share this planet, and taking care of it is important—both for us and the animals!

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YOUNG REVIEWERS

IZZY, AGE: 13

Hi! I am Izzy! I am a Conservation and Environmental Stewardship Apprentice with the National Park Service, and I love science!!! I have an insatiable curiosity, and I absolutely love new challenges!

LUCINDA, AGE: 15

My name is Lucinda and I am a sophomore in high school. Not only do I adore science but I also love reading, swimming, and being outdoors! In terms of science, my favorite subject is biochemistry which I have always had a huge interest in. In the future, I hope to use my love of biochemistry to help study and research how we can conserve and protect our natural ecosystems and native species. I am so grateful for this opportunity!

SAM, AGE: 10

I am Sam, I am 10, and I am in year 5. I like animals and sport. My favorite subjects at school are PE and maths.

AUTHORS

EMILY MONK

Emily studied pikas during her undergraduate degree at the University of Colorado Boulder, where she focused on how pika habitats have changed over time. She is now a graduate student at Memorial University of Newfoundland in Canada, studying how animals that live in snowy places are impacted by climate change. Emily loves being outdoors, watching and photographing wildlife, and climbing to the tops of tall mountains.

KARLI WEATHERILL

Karli is an undergrad student who studies biology at Colorado Mesa University. She loves all animals, especially pikas! One day, she hopes to be a conservation biologist and continue studying and helping animals. In her free time, she likes traveling to new places and jamming out to Taylor Swift with her friends.

CHRIS RAY
Chris has studied pikas for 36 years, and never gets tired of visiting pikas in the wild. Studying pikas has taken her around the world and helped her land some really fun jobs that have led to a very enjoyable career. She is a research associate at the University of Colorado Boulder and a research scientist at The Institute for Bird Populations.

ASHLEY WHIPPLE
Ashley is a biologist with the United States Geological Survey, where she researches how environmental change influences wildlife and their habitats. She loves seeing and hearing pikas but gets extra excited when she finds their poop! While earning her master's degree in ecology at the University of Colorado Boulder, Ashley collected pika poop from different habitats and measured stress hormones in the poop to understand if stress levels vary with habitat quality. In her spare time, Ashley likes to be outside searching for interesting critters.

JOHANNA VARNER
Johanna, who also goes by the nickname "Pika Jo", is a pika biologist who also teaches biology at Colorado Mesa University. She grew up in the mountains near Utah, where she loved hiking and watching animals as a kid. Although she took a quick detour as an engineer in college, she now studies pikas so that she gets to spend a lot of time outside in the mountains with the animals. In her free time, she likes to go for runs with her dogs. *jvarner@coloradomesa.edu

BIODIVERSITY
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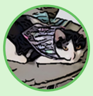
CONNECTIONS ON THE REEF: CLOWNFISH, ANEMONES, AND CLIMATE CHANGE

*Tamar L. Goulet** *and Denis Goulet*

Department of Biology, University of Mississippi, University, MS, United States

YOUNG REVIEWERS:


GEMMA
AGE: 9


JULIAN
AGE: 13


QUEST MONTESSORI SCHOOL
AGES: 8–9

From their adorable name to their leading role in the movie *Finding Nemo*, many people find clownfish, also called anemonefish, cute and lovable. Clownfish must live in animals called sea anemones to survive on a coral reef. For 19 years, we followed two-banded anemonefish off the coast of Israel in the Gulf of Eilat (Aqaba), Red Sea. Based on their size, we divided the fish into adults, teens, and babies. In 1997, 195 fish of all ages lived at the site. By 2015, 52 fish—mostly adults—remained, a 74% drop. From 1997 to 2015, the number of sea anemones also fell from 199 to only 27, and each one was more crowded with anemonefish. Climate change may affect sea anemone survival. Without their sea anemone homes, clownfish cannot exist, raising concerns about their future.

IN THE WILD, CLOWNFISH MUST LIVE IN SEA ANEMONES

When you play musical chairs, there is one less chair than players. When the music starts, the players walk around the chairs. When the music stops, each player scrambles to sit on a chair. The person left without a chair is eliminated. One chair is removed, and the game continues until one chair, and one person sitting on that chair, remains. This person wins the game. Musical chairs would not be a game of elimination if everyone had their own chair, or if there were more chairs than people. Clownfish, also called anemonefish, must have a "chair", a sea anemone, to survive in the wild (Figure 1). As long as there are enough sea anemones, clownfish babies, teens, and adults, have homes. If sea anemones die as a result of climate change, clownfish numbers will crash.

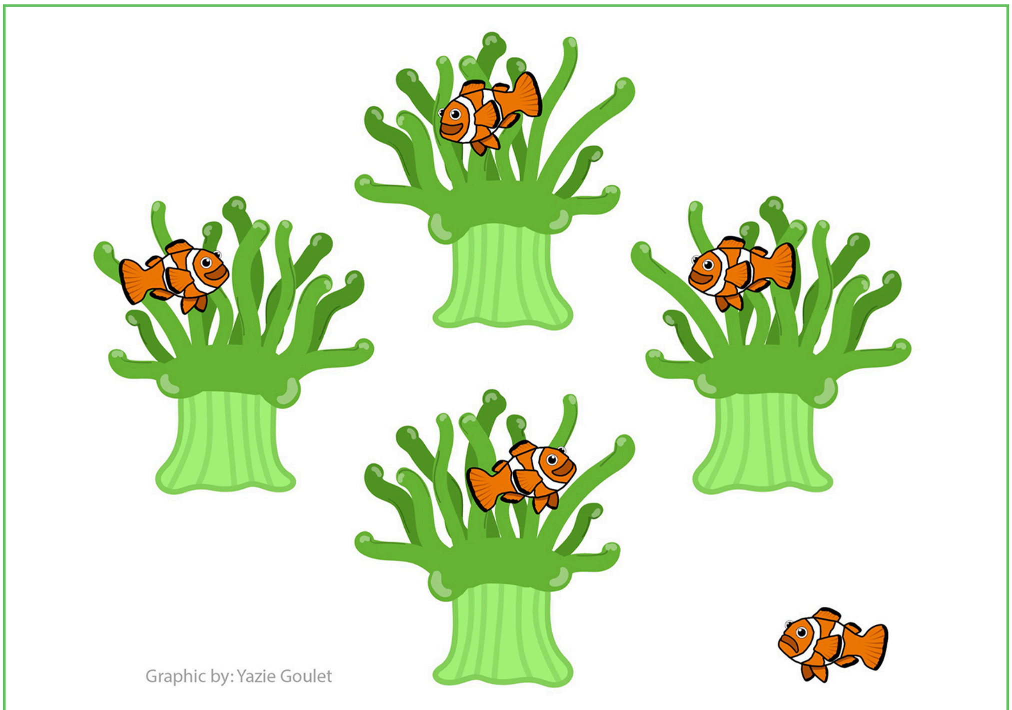


Figure 1

Clownfish musical chairs. In the wild, clownfish cannot survive without a sea anemone. Similar to the game musical chairs, when there are not enough sea anemones on a coral reef, baby clownfish cannot join the clownfish community. Teen and adult clownfish without an anemone may die.

Sea anemones are **invertebrates** that belong to the same **phylum** as corals and jellyfish. Sea anemones look sort of like a plastic/latex glove. If you fill up a glove with water, the water-filled fingers are like the tentacles of a sea anemone, except sea anemones have many tentacles. The only opening into the sea anemone is in the middle of the "glove". This opening allows food to come into the anemone's body and waste to leave. Like corals, sea anemones have algae that live within them, and both the sea anemone and the algae benefit from the relationship. When individuals from different species live together in this way, it is called a **symbiosis** [1]. When the symbiosis is beneficial to both of the individuals, it is called **mutualism** [1]. The clownfish-sea anemone relationship is a mutualistic one. Without a sea anemone, clownfish cannot survive in the wild because they will be eaten by predators. Sea anemones with clownfish benefit by growing faster and surviving better than sea anemones without fish [2]. Climate change can lead to conditions that may harm corals and sea anemones, as well as the organisms that live within the coral/sea anemone body, such as

INVERTEBRATES

Animals without backbones.

PHYLUM

A category used for organizing organisms. Humans, for example, are in the phylum Chordata.

SYMBIOSIS

When individuals from different species live together.

MUTUALISM

A type of symbiosis in which both partners benefit from the relationship.

the algae, or fishes that live within coral branches or the clownfish that live amidst sea anemone tentacles [3, 4].

STUDYING A CLOWNFISH COMMUNITY IN THE RED SEA

Nearly 30 years ago, we started studying clownfish in the Gulf of Eilat, in the Red Sea. The two-banded clownfish (Figure 2A) is the only clownfish found in the Red Sea. In the Gulf of Eilat, the two-banded clownfish lives in either the bubble-tip anemone or the long-tentacle anemone (Figure 2B). To learn about the clownfish community, we first needed to map out an area of the coral reef. To do so, we went **SCUBA** diving, placing measuring tapes on the sea floor to determine the length and width of the area that we would study. Once we had the edges of the area mapped out, we marked the location of every sea anemone on a map, whether it had fish or not, and whether the fish were adults, teens, or babies. For the first year of the study, we checked on the clownfish community every month, which allowed us to answer several scientific questions. For example, we found out that adult clownfish live mostly in the bubble-tip anemone, surviving better there than in the long-tentacle anemone [4]. Babies, probably because of their small size, survived equally well in both sea anemone species.

SCUBA

An acronym for self-contained underwater breathing apparatus. SCUBA equipment provides the oxygen needed to go underwater and be at eye level with the fish in the sea.

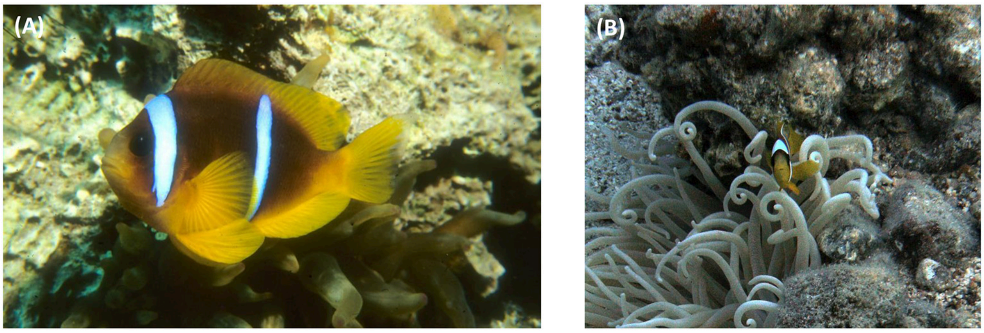


Figure 2

Figure 2

The two-banded clownfish and the two types of sea anemones, the bubble-tip anemone [bottom of **(A)**] and the long-tentacle anemone **(B)** that two-banded clownfish call home in the Gulf of Eilat (photos by DG).

WHEN DO CLOWNFISH BABIES JOIN A CLOWNFISH COMMUNITY?

Clownfish babies hatch from fertilized eggs attached close to the bottom of the sea anemone where the parents live. Since sea anemone tentacles sting, the eggs' location provides protection. When the babies hatch, they go up into the sea water, where currents may carry them away from the reef from which they came, to another reef. Or, the babies may stay in the water close to home, and eventually find an anemone "chair" and settle down on the same reef. In our study, we found that clownfish babies joined the clownfish community mostly in the months of October, November, and December [4], although we do not know if the babies that settled came from afar or from nearby.

HOW IS THE CLOWNFISH COMMUNITY SPREAD OUT ON THE REEF?

Counting clownfish, putting them into age categories, and counting sea anemones in the study area are important for understanding the clownfish community. But looking only at numbers does not uncover the entire story. One thing that we did in our study that was different from other studies is that we also recorded *where* the clownfish and sea anemones were found on the reef. By collecting this information, we found out that adult clownfish protect not only the sea anemone in which they live, but they also prevent other clownfish from living in nearby sea anemones [4]. It is like playing musical chairs but a player sitting on a chair not only prevents other players from sitting on their chair, but also on the empty chairs immediately nearby. As a result, even if there are empty chairs (sea anemones), babies cannot settle into them and teens cannot move to them without fighting the adult clownfish—a fight that the smaller fish may not win.

FINDINGS FROM 20 YEARS OF OBSERVATIONS

In 1997, 195 clownfish lived in 199 sea anemones (Figure 3A). The 195-clownfish community included 52 adults, 76 teens, and 67 babies (Figure 3B). A male and female adult clownfish that live in the same sea anemone are called a breeding pair (parents). In 1997, out of the 52 adults, 22 adults formed 11 breeding pairs (Figure 3B) [4]. By 2009, the picture on the reef completely changed. Only 47 anemones occurred at the study site (Figure 3A) [4]. That means that only a quarter of the sea anemones were left! Not surprisingly, with fewer sea anemone homes, the clownfish numbers also fell, with only 65 fish, roughly one third of the starting number, remaining in the study area (Figure 3B).

Six years later, in 2015, fewer sea anemones remained—only 27 (Figure 3A). In these sea anemones lived 52 clownfish [4]. So, the anemone numbers fell from 47 in 2009 to 27 in 2015, a loss of nearly half of the sea anemones. The clownfish numbers also dropped, but not by as much—only 20%—with clownfish numbers falling from 65 to 52 fish (Figure 3B). With half of the sea anemone "chairs" gone, the remaining clownfish crowded into the few sea anemones left, resulting in more clownfish in each anemone.

Counting clownfish provides important information but does not differentiate the ages of the clownfish in the community. In 1997, adults accounted for only a quarter of the clownfish community. That meant that teen and baby clownfish outnumbered the adult clownfish (Figure 3B). By 2009, adults made up nearly half of all the fish in the smaller fish community, although the number of breeding pairs stayed

Figure 3

(A) The number of sea anemones and **(B)** clownfish at the coral reef study site in 1997, 2009, and 2015. From 1997 to 2015, the total number of sea anemones fell from 199 to 27. The total clownfish numbers also dropped from 195 to 52. Between 1997 and 2015, fewer adults remained, but the number of breeding pairs only dropped slightly, from 11 to 8. The big change was in the number of babies in the community, falling from 67 in 1997 to only 7 in 2015.

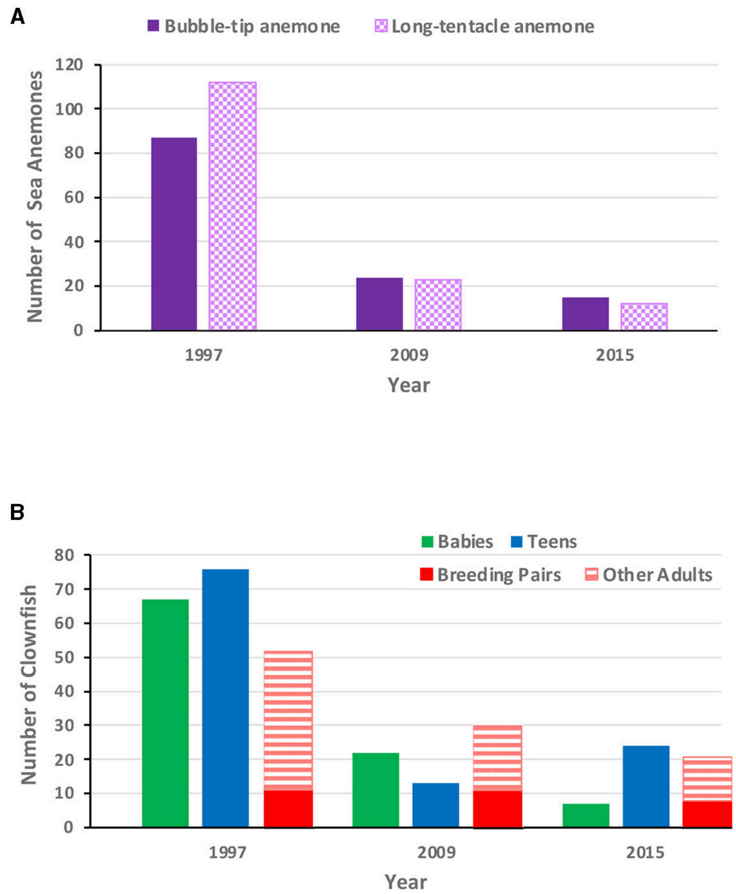


Figure 3

the same (Figure 3B). In 2015, adults continued to be a bigger part of the community than they were in 1997 [4]. What was very concerning was that, in 2015, there were only seven babies in the community (Figure 3B). With all the sea anemones occupied, babies might not find a sea anemone home to move into. If there are fewer and fewer sea anemone "chairs", and babies cannot join the clownfish community, eventually the clownfish community may collapse.

In 2003, the lovable animated clownfish, Nemo, starred in the blockbuster film *Finding Nemo*. In 2016, the sequel *Finding Dory* hit movie theaters. If the clownfish community that we followed in the Gulf of Eilat continues to decline, the third movie in the series may be *What Is a Nemo?* We hope our continuing research will lead to a different movie title, with this lovable mutualism continuing to survive on coral reefs.

ORIGINAL SOURCE ARTICLE

Howell, J., Goulet, T. L., Goulet, D. 2016. Anemonefish musical chairs and the plight of the two-band anemonefish, *Amphiprion bicinctus*. *Environ. Biol. Fish*. 99, 873–86. doi: 10.1007/s10641-016-0530-9

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YOUNG REVIEWERS

GEMMA, AGE: 9

My favorite subject is science and I love almost everything related to the ocean. I am an avid reader of science, mystery, and fantasy books. I read National Geographic Kids and enjoy playing around with their app. I am also interested in Thea and Geronimo Stilton books. I have a special liking for those with jokes and games at the end or the ones that you can help them solve the mystery with the given clues.

JULIAN, AGE: 13

I am Julian. I love spending time with my cats. When I am not hard at work practicing wushu, I enjoy going fishing and playing video games. I play table tennis, basketball and I am always trying to improve my timing in solving the Rubik's cube. I like exploring about the world around me and discovering new things.

QUEST MONTESSORI SCHOOL, AGES: 8–9

We are the third-year class from Quest Montessori School in Narragansett, Rhode Island. We are a bunch of silly, friendly, curious, and intelligent 8- and 9-year-olds who love nature, adventures, and especially ocean animals! Our favorite subjects are EVERYTHING!!! You can see us having fun at PE, in math lessons, making creative art projects, playing at recess with friends, and even exploring the Atlantic Ocean during field trips we take for studying the Narragansett Bay together. We hope more young people like us get involved in cool science work like *Frontiers for Young Minds.* We also have a super awesome class pet named Denali, he is a crested gecko and we LOVE him!

AUTHORS

TAMAR L. GOULET

I am a professor of biology, investigating how environmental problems affect coral reefs and the creatures that live there. I am also an IF/THEN® Ambassador. We serve as role models to inspire young women to pursue a career they want. The idea is not so much to change peoples' minds, or make people want to be scientists. But many girls, because they do not see role models, think that they cannot do it. I love teaching science to non-scientists, from the popular press to giving talks. My goal is to make science accessible to all. I am also the proud mom of five children, and my oldest daughter, Yazie, drew Figure 1 in this paper. *tlgoulet@olemiss.edu

DENIS GOULET

I am an instructional professor and laboratory coordinator at the University of Mississippi (UM). I am also an animal behavioralist who studies coral reef fish, traveling the world. I earned my Ph.D. from the University of Puerto Rico. I then lectured at the University of the South Pacific in Fiji. I moved to Israel, investigating fish in Eilat. I returned to the US, where I was at SUNY Buffalo and Harbor Branch Oceanographic Institute in Florida. In 2001, I joined the Department of Biology at UM. I am proud to serve as the academic advisor for the UM Chapter of the Gamma Beta Phi Honors society.

EARTH SCIENCES
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ICE STORMS: NOT AS COOL AS THEY SEEM

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YOUNG REVIEWERS:


AYAT
AGE: 12


CALEB
AGE: 11


JENDAYI
AGE: 13


KATHERINE
AGE: 12

Ice storms might sound fascinating, but for forests, they are not as cool as they seem! Ice storms happen when freezing rain coats trees, branches, and the forest floor in a shiny, frozen glaze. These storms can be a big deal because they can affect our forests and the things we care about, like, wood, wildlife, and places for recreation. Despite this, we do not know very much about how ice storms affect forests. Scientists at the Hubbard Brook Experimental Forest, New Hampshire (USA), decided to learn more. They used fire-fighting pumps and hoses to create experimental ice storms in the forest during the winters of 2016 and 2017. They found that these experimental storms caused a lot of short- and long-term damage to trees, including breaking of twigs and branches. In a nutshell, ice storms are not just about frozen beauty—they have real consequences for our forests and species that are not used to ice!

HAVE YOU EVER SEEN AN ICE STORM?

Ice storms are one of the most beautiful yet frightening winter weather events. They happen when rain falls through freezing air and turns to ice as it hits trees, roads, powerlines, or the ground. At first, this creates a shiny, sparkling layer on everything, making it seem like a winter wonderland. Early in the storm it can sound almost musical, like tiny glasses clinking in the treetops as ice-coated twigs gently rub together.

But if the storm continues, the beauty can shift to danger. As ice builds up, it can make surfaces like roads and walkways slippery. The weight of the ice can snap power lines and knock out electricity. It can also break tree branches or even cause whole trees to topple over. The air fills with sounds of loud cracking and crashing as branches and trees come falling down.

ICE STORMS AND OUR CHANGING CLIMATE

As our planet's climate changes, scientists believe that large ice storms might happen more often [1, 2]. Scientists also think that the places where these storms now occur most frequently—an area called the **Ice Storm Belt**, which stretches from northeastern Texas to New England—might shift north. This means that places that have not seen many ice storms before may experience more of them in the future. More ice storms mean more frozen trees, property damage, and accidents because of slippery conditions and falling trees [3].

ICE STORM BELT

A geographic area from northeastern Texas to New England that has experienced many ice storms in the past.

Despite their impact, we do not know much about ice storms. It is hard to predict when and where an ice storm will happen. And during a big ice storm, even the bravest of scientists need to seek safety and stay in their homes. Most of what we know is based on observing what happens in the aftermath of a big storm, like after the Northeast Ice Storm of 1998 [4].

CREATING ICE STORMS: A NOVEL EXPERIMENT

In New Hampshire, scientists had an idea: instead of waiting for the next big ice storm, they decided to create their own icy winter weather in a controlled setting [5]! This allowed them to use the **scientific method** to better understand how ice storms affect forest ecosystems. They had already observed the damage caused by natural ice storms. Now they asked questions about what these storms do to forests, like how do different amounts of ice accumulation (the amount of ice building up on branches) damage different types of trees? The scientists also wanted to know how long it takes for forests to recover from the damage caused by these extreme winter weather events.

SCIENTIFIC METHOD

A process for testing ideas to discover facts about the world. It involves observing, questioning, predicting, experimenting, and concluding.

They formed hypotheses, made predictions, and then set out to test their predictions.

HUBBARD BROOK EXPERIMENTAL FOREST: AN OUTDOOR LABORATORY

They chose Hubbard Brook Experimental Forest in New Hampshire for their experiment. The USDA Forest Service put this 7,800-acre area in the White Mountain National Forest aside as an outdoor laboratory in 1955, to study the water cycle. Back then, the Forest Service scientists wanted to know how forests in the mountains kept downstream towns and cities from flooding. Since then, scientists have been studying the trees, streams, wildlife, and climate in this forest. The forest has years of background data and was even the site of a major natural ice storm in 1998! It was perfect for this new experiment!

CONDUCTING THE ICE STORM EXPERIMENT

In the spring of 2015, scientists set up 10 large plots within Hubbard Brook Experimental Forest. Each plot was 20 × 30 m, or about the size of a basketball court. The plots would receive five treatments, with two replicate plots for each treatment. The treatments included: control (0 mm ice), light (6 mm ice), moderate (13 mm ice), moderate x2 (13 mm ice in two back-to-back winters), and heavy (19 mm ice). Ice accumulation is measured as the *radius* of ice on a twig, so the *diameter* of ice would be twice those measurements, or up to an 38 mm inches of ice! The plots were located near the Hubbard Brook for water, and next to a road so scientists could get there easily on snowmobiles and all-terrain vehicles. During the summer, they took detailed measurements of the forest, from the tops of the trees to the bottom of the roots. This was their "pretreatment" data. Pretreatment data was important so the scientist's knew what the forest was like before they added the ice. The scientists also practiced making storms. They needed to be able to make these storms perfectly under the best of conditions in summer, so they would be ready for the worst weather in winter!

Then they waited. They needed the perfect night, with freezing temperatures and no wind. In mid-January 2016, the weather cooperated and they set to work. Over 4 dark, cold nights, a team of 40 scientists, working in shifts, used firefighting pumps and hoses to spray water from Hubbard Brook up and over the trees (Figures 1, 2). The water came down on the trees as a fine mist and froze on contact, creating a realistic layer of ice. Scientists watched the forest change as the ice formed. Tree limbs curved downwards as the ice got heavier and heavier. Everyone cheered when the first tree limb fell because it showed that the experiment was working. It was awe-inspiring to watch entire trees topple over with heavy loads of ice on every twig.

Working carefully, the scientists successfully created ice storms of varying intensities, including light, moderate, and heavy icing. But that was not all. In February of 2017, they went back and iced two of the moderate plots with another coat of ice, to see what might happen to the forest if it was hit by moderate ice storms for two winters in a row.

Figure 1

Figure 1

A scientist spraying water over the forest canopy to make an experimental ice storm.

Figure 2

Figure 2

A scientist looking on as crews make an experimental ice storm.

OBSERVATIONS AND DISCOVERIES

Then it was time to collect the data (Figure 3)! First, the scientists measured the amount of ice on the branches, to make sure the experiment worked. Then they measured the amount of fallen twigs and branches, the changes in light coming through the damaged **canopy**, the overall health of the forest, and how it recovered over time. The experiment revealed some cool insights.

CANOPY

The top layer of a forest, where the trees leaves and branches meet. It forms the "roof" of the forest.

Figure 3

Figure 3

Scientist and co-author, Wendy Leuenberger, measuring ice accumulation after an experimental ice storm was created.

The Experiment Worked

Careful measurements of ice in the forest showed that the scientists successfully recreated, light, moderate, and heavy ice storms.

Trees Are Tough but They All Have a Breaking Point

The experiment showed that light icing caused minimal harm, but moderate and heavy icing resulted in a lot of broken branches and even toppled trees. Some trees, because of the properties of their wood, were more likely to break than others. For example, branches on broad-leaved **deciduous trees**, like red maples, frequently snapped and broke. But the branches on needle-leaved **coniferous trees**, like red spruce, were more likely to bend than break. The branches on these trees curved down toward the tree trunks like folded umbrellas under ice. They popped back up when the ice melted.

DECIDUOUS TREES

Trees with broad leaves that drop off each year.

CONIFEROUS TREES

Trees with needle-like leaves that bear cones.

A Lot of Wood Moved From the Trees to the Ground

One of the most noticeable things after an ice storm is the amount of wood on the ground. In this experiment, the amount of wood falling to the ground in 2016 was 55 g/m^2 in the control plots where there was no ice, and 183, 420, and 1,660 g/m^2 in the light, moderate, and heavy treatment plots. Scientists also compared these numbers to the average amount of wood that falls to the ground at Hubbard Brook in a typical year. This comparison showed that a single moderate ice storm would break off the same amount of branches (>1-inch diameter) as would typically fall in an entire year. A heavy ice storm would break off almost 5 times the amount of branches than would fall in a typical year.

One Ice Storm Is Bad, but Two Ice Storms Are Worse

Two of the moderate plots (the moderate x2 treatment) were iced twice: once in 2016 and again in 2017. The amount of branches that came down in the 2nd year of icing was 2 times greater than what came down in the 1st year. This suggests that some branches that were damaged in the 1st year's storm stayed on the trees but fell to the ground in the 2nd year.

The Loss of Branches Lets More Light Into the Forest

The loss of branches and treetops in the moderate and heavy icing treatments created gaps in the canopy that let from 2 to 3 times more light into the forest compared to the non-iced plots or the pretreatment data.

Canopy Damage Gets Worse Over Time

Damage to the trees did not occur just during or immediately after the storm, but progressed over time, especially for moderate or heavy icing treatments. For example, some trees went from healthy to weakened, and others went from weakened to dead over the course of a couple years. Scientists will need to continue to monitor these trees to see what happens to them over longer periods of time.

WHY THIS RESEARCH MATTERS

Forests are not only beautiful places, but they are vital for the health of the planet. They provide clean air, water, wood, food sources like nuts and maple syrup, homes for animals, and places to play and explore. They are also important for absorbing carbon dioxide through the process of **photosynthesis**, which helps to store carbon in plant tissue and slow global **climate change**. Knowing how ice storms affect our forests helps us take better care of these important places. It also helps people be more prepared to face these icy winter weather makers.

PHOTOSYNTHESIS

The process by which plants use sunlight, water, and carbon dioxide to make their own food and release oxygen.

CLIMATE CHANGE

The long-term shift in weather patterns and temperatures on Earth, largely caused by human activities like burning fossil fuels and cutting down forests.

CONCLUDING THOUGHTS

From the Hubbard Brook Ice Storm experiment, scientists have learned a lot about how ice storms affect forests. They will continue to study these forested plots for the coming decades, to see how long it takes the trees to fully recover from their icy treatments. They will also wait to see if the icing makes them more likely to suffer from other stresses, like insect infestations or fire. Only time—and more research—will tell.

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YOUNG REVIEWERS

AYAT, AGE: 12

I am 12 years old and an elementary school student. I love sketching, painting, playing chess, and reading books. My favorite books include "Amari" and "The Magicians of Paris", and anything and everything about fantasy books. I like nature, cycling, badminton, and frequently go out hiking to observe the beauty of nature, take notes, and make sketches in my notebook.

CALEB, AGE: 11

Caleb enjoys all things science, animals, reading, exploring the outdoors, playing the violin, and curling. When he grows up, Caleb wants to be an architect focusing on eco-friendly and animal oriented buildings. He has tried four sports and is always up for trying something new. Caleb's favorite foods are macaroni and cheese or lasagna. He enjoys traveling and would like to go to an animal reserve.

JENDAYI, AGE: 13

Hi! I am Jendayi. I play the oboe and a little bit of piano. I like hanging with my best friend, Kat. We normally walk around my town and eat ice cream together. When I grow up, I want to be a Children's therapist. I feel it is important to be a child's therapist because kids should also have the ability to be heard by adults. My favorite subjects in school are science and English. Those are my favorite subjects because I love conversation and I love finding new things with evidence.

KATHERINE, AGE: 12

Hi, my name is Katherine! My friends call me Kat and Kathy. I like to play cello and piano. My favorite thing to do in my free time is hang out with my best friend, Jen, and draw. When I grow up, I want to be a vet because I like animals, so I am going to own a lot of dogs and cats. My favorite subject in school is English because I like reading with my peers and having discussions.

AUTHORS

LINDSEY RUSTAD

Lindsey Rustad is a senior research ecologist for the USDA Forest Service Northern Research Station and acting director of the USDA Northeast Climate Hub. She received a B.A. in Philosophy at Cornell University in 1980, an M.S. in Forest Science at the Yale School of the Environment in 1983, and a Ph.D. in Plant Science at the University of Maine in 1988. She is a Fellow of the Soil Science Society of America and has received numerous awards from the USDA for her scientific accomplishments. Her areas of expertise include biogeochemistry, climate change impacts, and the integration of art and science. *lindsey.rustad@usda.gov

WENDY LEUENBERGER

Wendy Leuenberger is a Ph.D. candidate in Integrative Biology and Ecology, Evolution, and Behavior at Michigan State University. She received a B.S. in Biology from Indiana University of Pennsylvania in 2014 and a M.S. in wildlife biology and management from SUNY College of Environmental Science and Forestry in 2017. She uses statistics to understand the effects of environmental change on wildlife populations and communities. Her areas of expertise include quantitative ecology, birds, butterflies, salamanders, and teaching statistics to ecologists.

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EARTH SCIENCES
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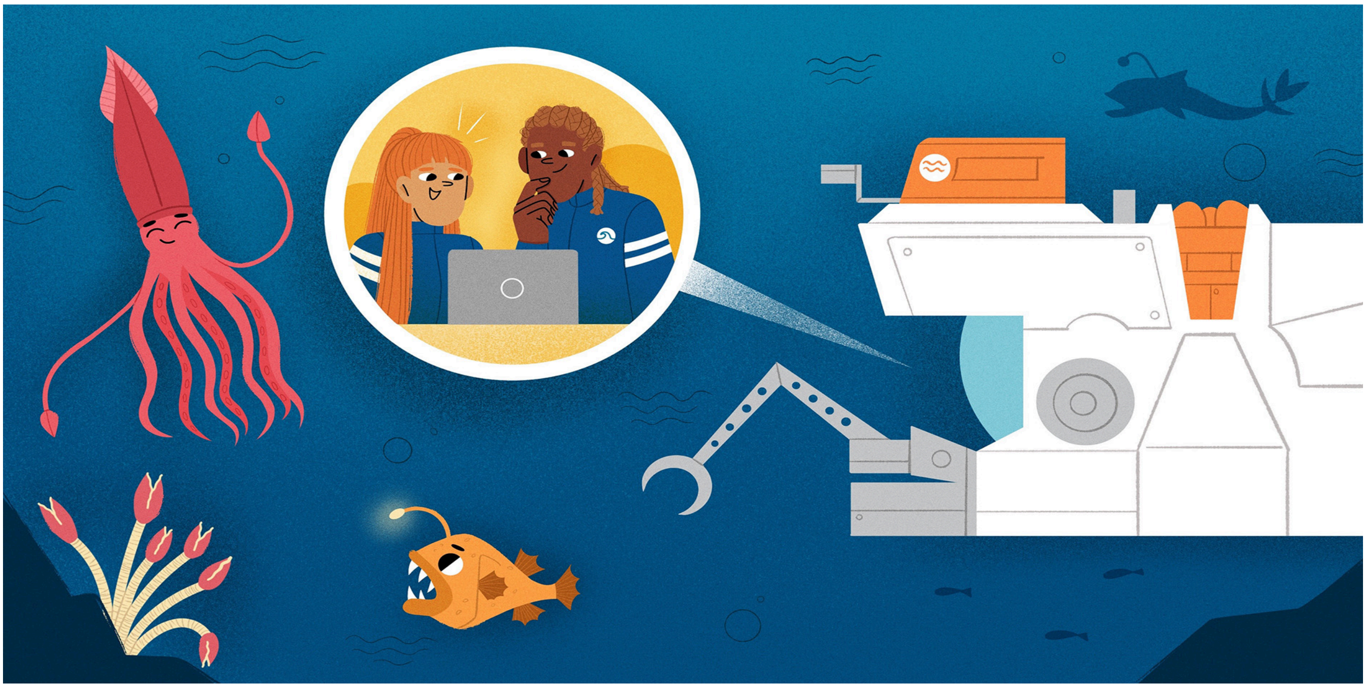

HOW DO SCIENTISTS EXPLORE THE DEEP SEAFLOOR?

Katherine L. C. Bell*, Jessica A. Sandoval and Brian R. C. Kennedy

Ocean Discovery League, Saunderstown, United States

YOUNG REVIEWERS:

CAMDEN
AGE: 13

SEA CREST SCHOOL 6TH GRADE SCIENTISTS
AGES: 11–12

From 200 to nearly 11,000 m (about 600–33,000 feet) below sea level and covering two-thirds of our planet, the deep ocean is Earth's largest—and most critical—habitat. The deep ocean is very important to people for many reasons. For example, it provides foods that we eat, it balances Earth's climate, and it is a wild unknown space for people to enjoy and explore. Despite its importance, the deep sea is the least explored area on our planet because it is so big, deep, dark, cold, and salty. Researchers need to use special tools such as ships and deep-sea robots to create maps, make new discoveries, and understand how the ocean works and how it affects people and the planet.

INTRODUCTION

The deep ocean is the part of the ocean that goes from 200 m below the surface to more than 10,000 m deep (about 650–33,000 feet) and covers two-thirds of the Earth's surface. The deep ocean is important for many reasons. It provides food for people to eat;

it supports plankton, which produce the oxygen that we breathe; it balances Earth's climate; and it is a wild, unknown space for people to enjoy and explore. The deep ocean is full of amazing life that researchers are just starting to discover and learn about, like mussels that live off the super-hot, chemical-rich waters of **hydrothermal vents**, **bioluminescent** animals that glow in the dark, and bacteria that can protect sponges from pollution. The seafloor is a very active environment where scientists find and study volcanoes, earthquakes, landslides, and other hazards that can impact ocean inhabitants and people on land. The deep sea also holds many historical and cultural artifacts, such as shipwrecks, which hold clues to human history.

HYDROTHERMAL VENTS

Places where water comes up through cracks in the seafloor after it has been heated and enriched in metals and other chemicals by magma under the seabed.

BIOLUMINESCENT

The word to describe living creatures that emit light.

Even though the deep ocean is very important, this huge volume of water is the least explored space on our planet because it is very difficult and expensive to study. Some of the challenges with studying the deep seafloor are:

- The deep sea is, of course, deep! The force of water can crush anything that goes down to great depths (Figure 1).
- Sunlight cannot travel beyond about 200 m of water, so it is very dark in the deep ocean. Researchers need to bring lights down to illuminate the seafloor. Even then, they cannot see very far—it is like using a flashlight in a snowstorm at night.
- Most of the water at the bottom of the ocean is nearly freezing (around 4°C/39°F), but some can be hundreds of degrees, like the water near volcanoes and hydrothermal vents. Scientists must use special materials so their tools do not freeze, burn, or melt.
- Ocean water contains salt and other minerals that can make some metals rust.
- The ocean is very big. Many research vessels can only travel 11–14 mph, slower than driving in a neighborhood. It takes a long time to travel to and from remote areas.
- The tools needed to explore and study the deep seafloor can cost a lot—even millions of dollars. Many scientists cannot afford to buy and maintain these tools.

Because of these challenges, **oceanographers** need to invent and use many kinds of specialized tools, like research vessels and underwater robots, to create maps of the seafloor and make new discoveries, so they can understand and protect the deep-sea environment.

OCEANOGRAPHERS

Scientists who study the ocean.

GATHERING DATA FROM THE DEEP OCEAN

When preparing to explore a new part of the ocean, oceanographers must gather as much information as they can about that place. First, they go to the library or use the internet to find and read as much as possible about the area and learn if any work has been done there

Figure 1

We can compare the pressure of the water to what it would feel like to have hippos standing on your head. There is no water pressure on land, so it feels like no hippos are on your head. At 200 m water depth, it would feel like one hippo was standing on your head. At 4,000 m (the ocean's average depth), it would feel like 19 hippos were on your head. In the deepest ocean trenches (~11,000 m), it would feel like 53 hippos were standing on your head! To explore the ocean at this depth, equipment must be specially designed to withstand this crushing pressure.

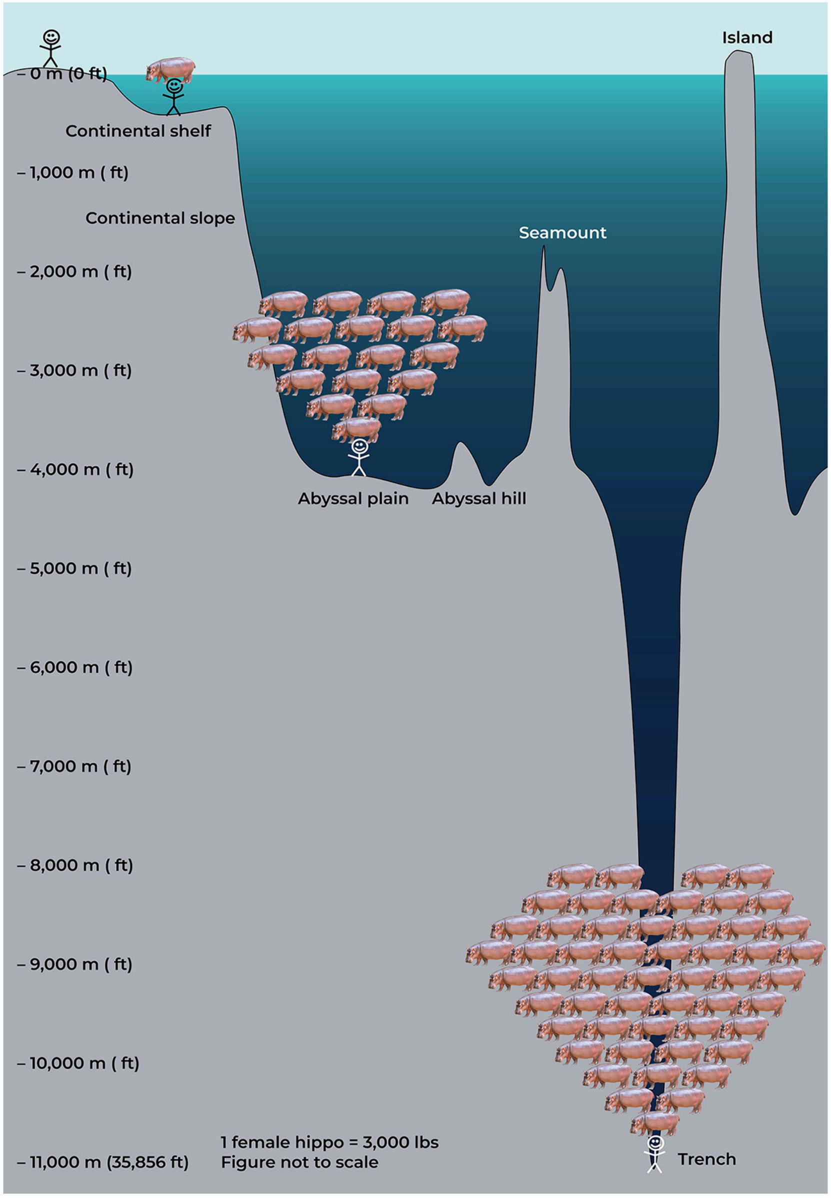

Figure 1

before. This can include reading publications, talking to people who live in the area, finding maps, or learning about local weather patterns. They also research the best types of tools to use in the area and depth they plan to explore. Once they have gathered all the information possible, they meet the ship and head out to sea.

MULTIBEAM ECHO-SOUNDER

An instrument that uses multiple beams of sound to determine the water depth below the surface using sound waves.

Seafloor Mapping

The next step is to make a good map of the new area. The best tool oceanographers have today is a **multibeam echo-sounder**, which is attached to the bottom of a ship or underwater vehicle and uses sound to measure the seafloor's depth (Figure 2A). A multibeam echo-sounder sends a line of signals, or "pings" through the water. We record the time it takes for the signals to bounce off the seafloor

BATHYMETRIC

"Bathy" means deep, and "metric" means measure, so this term means the measurement of the seafloor's depth.

Figure 2

(A) A ship travels back and forth like a lawn mower, to gather mapping data with a multibeam echo-sounder. **(B)** Landers like the National Geographic Deep-Sea Camera System have been used to study biodiversity worldwide [1]. **(C)** Deep Argo floats are drifters that measure temperature and salinity in the ocean worldwide [2]. **(D)** ROV *Deep Discoverer* illuminates boulders covered in bamboo corals in the North Atlantic Ocean (© NOAA Ocean Exploration). **(E)** AUV *Boaty McBoatface* sits on deck after collecting important deep-sea climate data in the Southern Ocean (© Povl Abrahamsen, British Antarctic Survey) [3] **(F)** Scientists used HOV *Alvin* to study the impacts of the 2010 oil spill on the deep-sea corals in the Gulf of Mexico (© ECOGIG).

DEEP SUBMERGENCE VEHICLES

Robotic underwater vehicles that are used to explore and study the ocean.

and return to the echo-sounder, then we calculate the depth of the water using that time and the speed of sound in water (1,500 m/s). By sending a line of pings as the ship or vehicle travels through the water, we can create a **bathymetric** seafloor map.

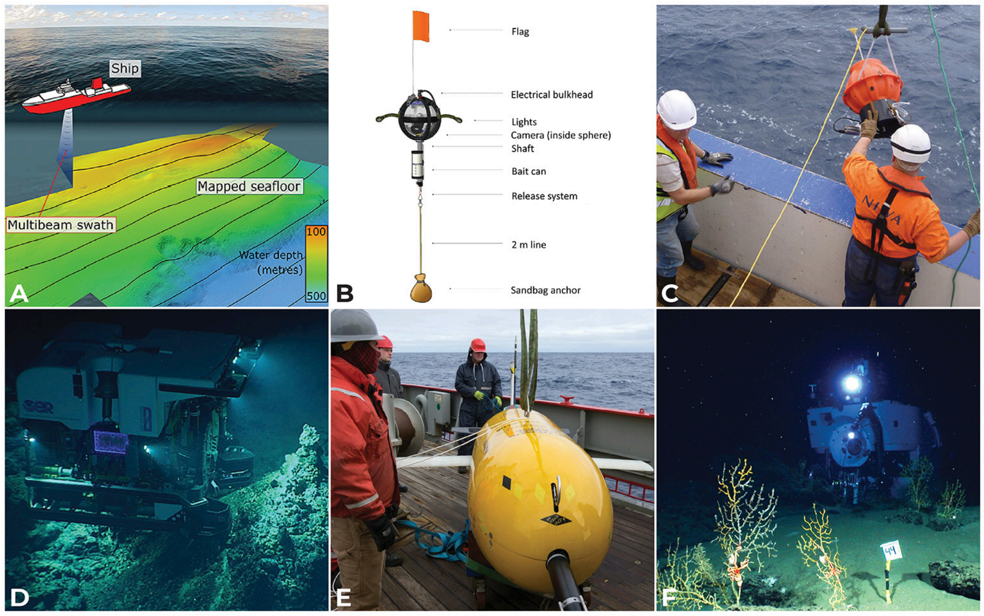

Figure 2

Some multibeam echo-sounders can also tell if the seafloor is soft or hard, or if bubbles (or even fish!) are in the water. All of this information helps scientists understand more about a new area, and it helps them plan what they want to do next. For example, if multibeam echo-sounder data show that the seafloor is shaped like a cone, has hard sides, and has bubbles coming up in the middle, it might be a new underwater volcano discovery! But we need other tools to directly observe what we think is there.

Tools for Visual Observations

To check their new maps and make direct observations of the seafloor, oceanographers can use different types of **deep submergence vehicles** (DSVs; Figure 2). Some of these tools include:

- Landers: landers are underwater vehicles that are dropped to the seafloor, collect information, and rise back up to the surface (Figure 2B) [1]. Landers can be small, inexpensive, and easy to deploy but can only "see" one point on the seafloor at a time.
- Drifters and gliders: these underwater vehicles can drift or glide a certain distance above the seafloor (Figure 2C). Drifters collect data for a certain amount of time or over a certain distance, then rise back up to the surface for a scientist to collect it. Drifters can be small or large, and they are more expensive to buy and use than landers, but they can "see" more of the seafloor.

- **Remotely operated vehicles (ROVs)**: ROVs are robotic vehicles with a cable (also called a tether) connecting them to the surface (Figure 2D). They are driven or "flown" by ROV pilots on a ship. The people on the ship can see the data in "real-time"—while the information is being collected by the ROV. Deep-sea ROVs need a large ship to deploy them, and they are expensive to buy and operate. Since people are not inside the ROV and it is powered by the ship, it can stay on the seafloor for days.
- **Autonomous underwater vehicles (AUVs)**: AUVs are robotic vehicles programmed to carry out a mission over a certain area (Figure 2E). AUVs do not have a tether to the ship, so they can cover more area than other types of vehicles, but scientists cannot see the data in real-time. Deep-sea AUVs can be deployed from a ship or from shore, and they can operate for days. Large AUVs can be expensive to buy and operate.
- **Human-occupied vehicles (HOVs)**: HOVs are submarines with one to three scientists and engineers inside, and they do not have a tether to the ship (Figure 2F). Because they have humans onboard, HOV missions are no longer than a few hours. HOVs need a large ship to deploy them, and they are very expensive to buy and operate.

SENSORS

Devices that are used to measure and record information about the environment, such as temperature or depth.

All types of DSVs can have various **sensors** to collect different types of data or information about the environment. The most common data types collected on the seafloor are videos and photos, as well as measurements of depth, temperature, and salinity (saltiness). ROVs and HOVs can also have robotic arms to collect samples of rocks or living things from the seafloor.

DISCOVERIES IN THE DEEP SEA

The data collected by ships and underwater vehicles are then used to make new discoveries about Earth's ocean (Figure 3). For example, more than 5,000 new deep-sea species were discovered in the Clarion-Clipperton Zone, which stretches 4,500 miles from south of Hawai'i almost to Mexico in the Pacific Ocean (Figures 3A, B) [4]. These animals could be under threat from deep-sea mining. Another example is the famous HMS *Endurance*, discovered in 2022 in the freezing seas of Antarctica (Figure 3C). The ship was trapped and crushed by sea ice (incredibly, all crew survived!), and it is an important story in the history of polar exploration. Yet another deep-sea discovery involved finding a new habitat created by a landslide on the slope of the Kick'em Jenny underwater volcano, off the coast of Grenada in the southeast Caribbean Sea (Figure 3D) [5]. This habitat contained the world's largest known mussels that live off the chemical-rich water being squeezed out of the seafloor.

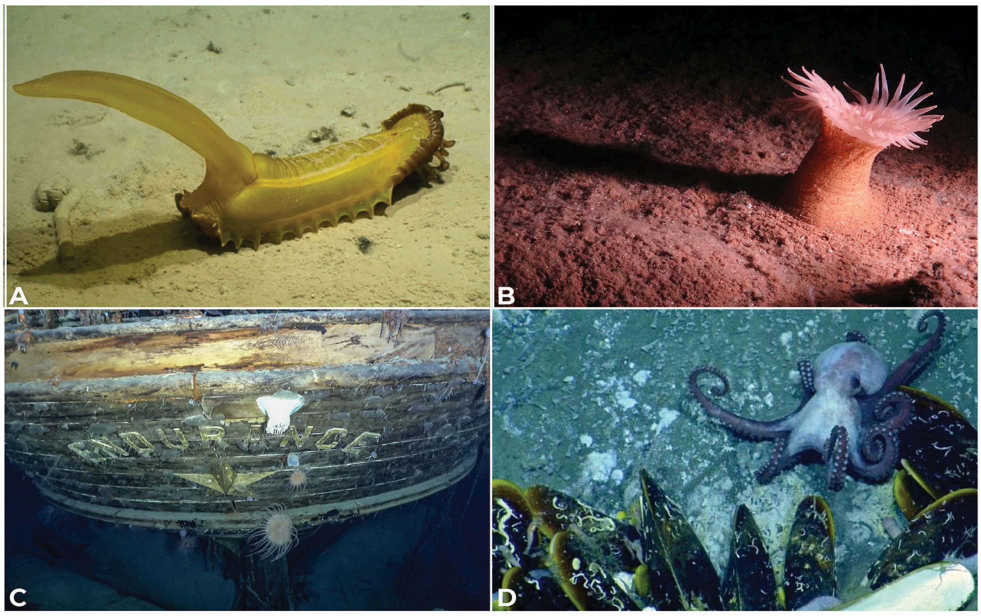

Figure 3

Figure 3

Thousands of new creatures were discovered in the Clarion-Clipperton Zone, including **(A)** a gummy squirrel, a type of sea cucumber that can be 15–30 cm long, and **(B)** a new species of anemone, approximately 10 cm across. These animals are at risk from deep-sea mining. (© NOAA Ocean Exploration & Smartex Project/NERC). **(C)** The wreck of HMS Endurance was found 107 years after it sank. (© Falklands Maritime Heritage Trust & National Geographic). **(D)** Co-author Katy Croff Bell co-led the team that discovered a new habitat on the side of an underwater volcano in the Caribbean Sea. Some of the largest known mussels in the world were discovered-longer than 34 cm. (© Nautilus Live).

FUTURE OF DEEP-SEA EXPLORATION

Because of the vast size of the deep ocean, its many challenges, and the high cost of deep-sea exploration, oceanographers have explored less than 0.002% of the deep seafloor in the last 60 years. If we keep going at that rate, it will take more than a million years to see the entire deep seafloor! The world needs inventors and explorers to help build more tools that can cover more area, are easier to use, and are less expensive, so scientists can more quickly discover and protect the deep sea's amazing mysteries.

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Kick'em Jenny volcano, Grenada (Lesser Antilles). *Deep-Sea Res.* 93:156–60. doi: 10.1016/j.dsr.2014.08.002

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

YOUNG REVIEWERS

CAMDEN, AGE: 13
Camden likes to ski, run, and climb all the things. He plays percussion in band and video games at home. He plans to become SCUBA certified and to go on a SCUBA adventure in a kelp forest for his 16th birthday.

SEA CREST SCHOOL 6TH GRADE SCIENTISTS, AGES: 11–12
Our group is "Sea Crest School 6th Grade Scientists" including Oliver (12), Mackey (11), Rowan (11), Malina (11), Daphne (12), Stella (11), Leena (12), and Abigail (12). We are a curious group of 6th grade science students who live in coastal California. While we all have individual interests, we are united by a shared passion for environmental stewardship and, in all things, we are determined to "leave it better than we found it": our school's mantra.

AUTHORS

KATHERINE L. C. BELL

Dr. Katy Croff Bell is a deep-sea explorer who is developing new ways to better understand the ocean and make it more accessible to everyone around the world. She is the founder and president of the Ocean Discovery League and a National Geographic Explorer. Katy earned her bachelor's from MIT in ocean engineering, master's from the University of Southampton in maritime archaeology, and Ph.D. from the University of Rhode Island in geological oceanography. She has led more than 40 expeditions worldwide and discovered dozens of ancient shipwrecks, new organisms, and ecosystems. Katy is an IF/THEN AAAS Ambassador. *croff@alum.mit.edu

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Dr. Jessica Sandoval is an avid ocean explorer, engineer, and scientist. With her bachelor's from MIT, master's and Ph.D. from the University of California, San Diego, Jessica works in the fields of bioinspired robotics and deep-sea exploration technologies. She also explores the depths of the ocean as a pilot of remotely operated vehicles (ROVs). When Jessica is not science-ing, she writes children's books to inspire the next generation of explorers.

BRIAN R. C. KENNEDY

Dr. Brian Kennedy is a deep-sea ecologist who has spent over a decade in ocean exploration. His research focuses on understanding how environmental drivers influence deep-sea organisms. He is always looking for ways to increase the pace and efficiency of ocean exploration through the development of new technologies and the novel use of existing technologies in the deep sea. Brian earned his Ph.D. in marine ecology and master's in biology from Boston University, and bachelor's in marine biology from the College of Charleston.

EARTH SCIENCES
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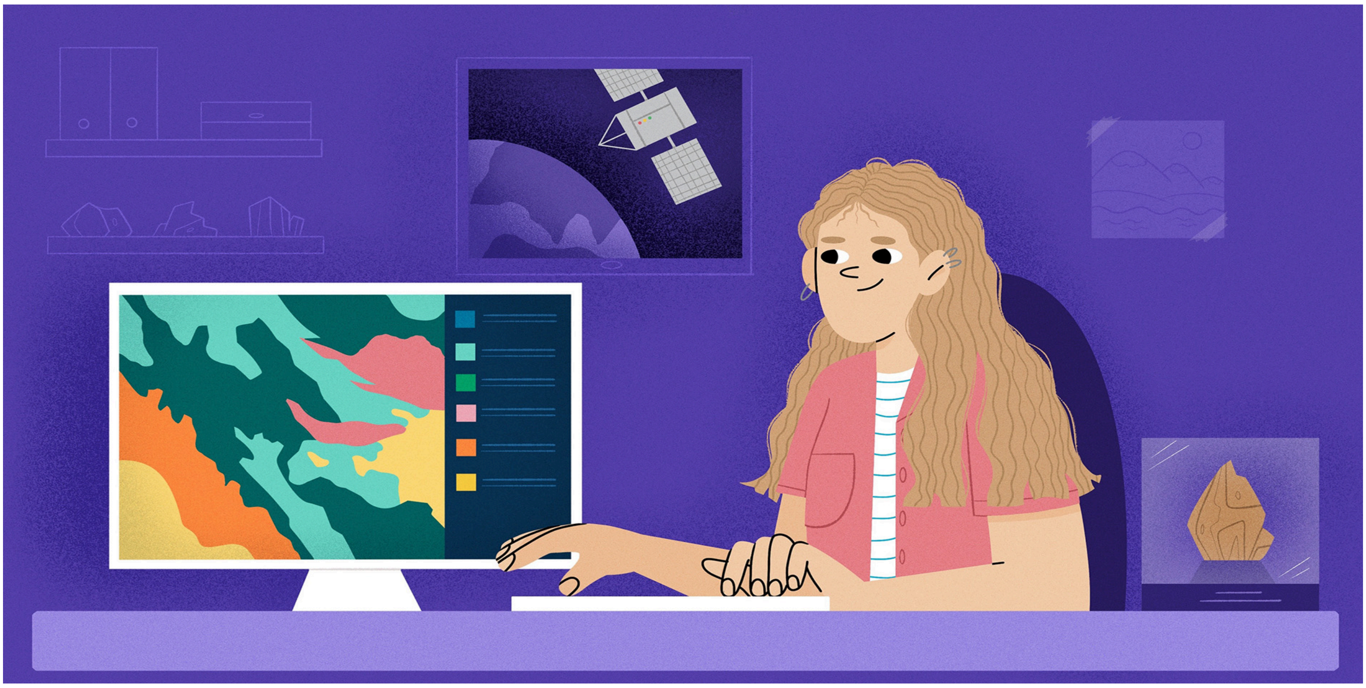

MAPPING ROCKS FROM SPACE

***Wendy Bohon*[1*] *and Alka Tripathy-Lang*[2]**

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YOUNG REVIEWERS:

BANUCK
AGE: 14

CAELLUM
AGE: 9

The Himalayan mountain range is known for its majestic beauty and towering heights, but the very features that make it famous can keep scientists from understanding its details. To make sense of the history of this mountain range, geologists need to see the rocks that they are made of. However, this can be difficult because of the sheer heights and inaccessibility of parts of the range. To solve this, we got a bird's eye view of these mountains—from space! Using data from the ASTER instrument aboard NASA's Terra satellite, we looked at the spectral signature of the rocks that make up the mountains. A spectral signature is almost like a fingerprint. We used this information to make a geologic map of the northwestern Himalaya, which helped us to piece together part of the history of these mighty mountains.

EARTH'S STORY WRITTEN IN ROCKS

A **geologic map** shows the locations of rocks at Earth's surface. These maps are like puzzles. Each different rock is an exciting clue about the region's history. **Geologists** make geologic maps by visiting places and

GEOLOGIC MAP

A map that shows the distribution of different types of rocks using either colors or symbols. Geologic maps also include structural features, like faults.

GEOLOGISTS

Scientists who study Earth's history, especially recorded by rocks.

seeing which types of rocks are present. This helps geologists to tell a story about Earth's past. Reading the rocks tells them things like when mountains formed and when earthquakes happened.

Much of Earth has been mapped in this way. However, some areas are remote, rugged, or difficult for geologists to get to. This makes it hard for them to make geologic maps of these places because they cannot visit the location in person. One of these hard-to-get-to locations is the northwestern Himalaya (Figure 1). This area includes some Earth's most famous mountains, like the second tallest mountain in the world, K2. It also includes the southwestern part of the Tibetan Plateau. Rocks and other geologic features here hint at how and when the Tibetan Plateau and Himalayan Mountains formed. Although geologists have broadly mapped this area, the high elevation, rugged mountains, and international borders make some parts of the region unreachable. Therefore, detailed maps of the geology of some important areas are not available.

Figure 1

Figure 1

This is a Google Map showing the location discussed in this article, marked by a red star. It is in an area where the borders of China, India, and Pakistan come together.

STUDYING THE "FINGERPRINTS" OF ROCKS

When geologists cannot walk directly to rocks, they can instead take to the skies. NASA's Terra satellite has various instruments that collect many types of data about Earth, including one called Advanced Spaceborne Thermal Emission and Reflection Radiometer, or ASTER, for short [1]. This instrument can provide scientists with information about a type of light humans cannot see, called **thermal infrared**. When most people hear "thermal infrared", they imagine cameras that show something that is warm, like maybe a person or an animal. What the camera is really detecting is light with **wavelengths** that are longer

THERMAL INFRARED

Region of the electromagnetic spectrum with wavelengths between 8 to 15 micrometers.

WAVELENGTH

The length of one complete wave cycle. The wavelength of the thermal infrared spectrum is between 8 and 15 micrometers, whereas the wavelength of visible light is 400-700 nanometers.

ELECTROMAGNETIC SPECTRUM

The range of all types of electromagnetic radiation, ranging from long wavelengths (radio) to short wavelengths (x-ray and gamma rays). Light that's visible to humans has wavelengths between these two endmembers.

SPECTRAL SIGNATURE

Different surfaces emit radiation differently at different wavelengths. The variation of emission at different wavelengths forms the spectral signature that's unique to each surface.

THERMAL EMISSION SPECTROMETER

An instrument that can detect and measure light in the thermal infrared spectrum.

FAULT

A break or fracture in the rocks of Earth's crust where earthquakes occur.

than that of visible light (light humans can see). Thermal infrared light is emitted (released) *by all objects.* We can figure out what objects are by looking at how much thermal infrared light they emit at various wavelengths within the thermal infrared region of the **electromagnetic spectrum**. This is called their **spectral signature**.

Every mineral has a unique spectral signature, which is almost like a fingerprint that helps geologists tell it apart from other minerals. Because rocks are made of different combinations of minerals, looking at all the fingerprints together reveals the rock type [2]. To easily tell types of rocks apart, researchers can show the fingerprints of different rocks using various colors (these are not the same colors that the rocks are in real life). Each type of rock will show up as a unique color. For this part of the Himalaya, we used colors to make a geologic map (Figure 2A) showing the different types of rocks (Figure 2B). We also checked that the fingerprint within each color on our map matched the fingerprint of that same type of rock found in other places in the world (Figure 3).

CHECKING OUR WORK

Geological maps created with thermal infrared data need to be checked to make sure the rock type we put on our map made with the satellite data match the rock type that is really on the ground. To do this, we collected different types of rocks from areas that we could visit. Back in the laboratory, we used an instrument called a **thermal emission spectrometer** to measure the spectral signature of each rock. When we compared these laboratory fingerprints to those from the satellite, they matched! This gave us confidence that our geologic map was correct.

WHAT DID OUR MAP TELL US?

Our map revealed some interesting pieces of the Himalayan geologic puzzle. First, we could see many remnants of an ancient ocean, called the Tethys Sea, that once separated India and Eurasia. About 50 million years ago, these two continents collided, pushing up the seafloor and beginning the long process of making the mountains we see today [5].

Many millions of years later, a huge **fault**—the Karakoram—sliced through some of these remnants of the ancient ocean floor, sliding each part sideways. Because these pieces of seafloor are made of unique and unusual rocks, we could use them to show just how far the pieces had been moved by this fault over millions of years.

A fault is a fracture in the hard rocks of Earth's crust. Earthquakes occur along faults. Bigger faults can have larger and more damaging

Figure 2

(A) An early version of our geologic map. (Click here for complete map [3]). Each color shows a different kind of rock (see key). Some of the rocks are named after places. Black squares indicate cities, towns, and villages. Solid lines show the Karakoram and Longmu Co faults where we can see them. Dashed lines indicate where we think the fault might be. **(B)** Thermal infrared data from the ASTER instrument, showing the fingerprint of each rock type as a different color.

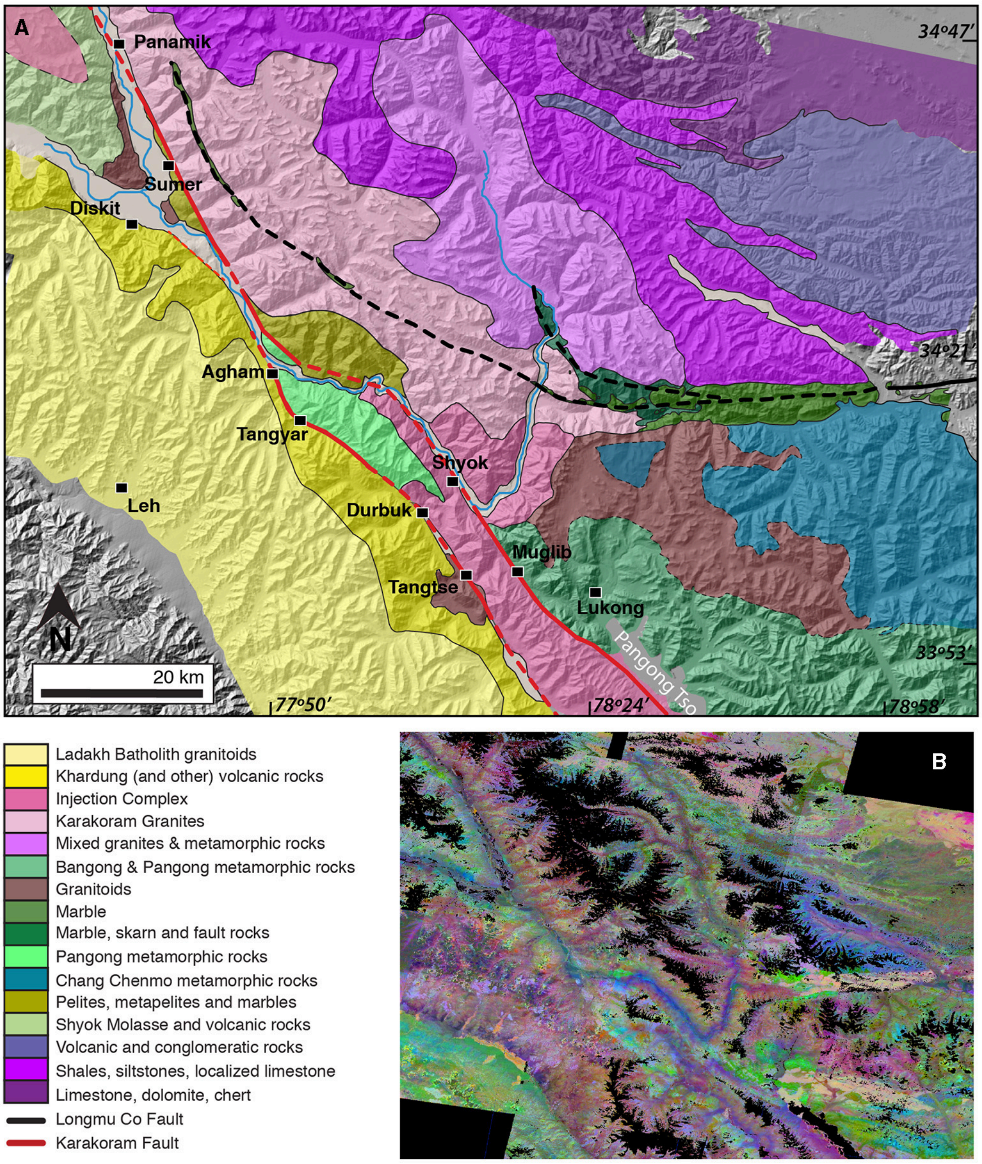

Figure 2

earthquakes, so it is important to know where these faults are. Our map helped us to see the intersection of two huge faults, the Karakoram and Longmu Co faults (Figure 2A), which form the southwestern edge of the Tibetan Plateau. These faults are active today and can host strong earthquakes. Our geologic map shows which parts of the Karakoram fault are likely to have earthquakes. For instance, some scientists thought that the Karakoram had only a single active section in this area. But our map helped to show that there is another section that could also have earthquakes! This is important information for people who live in the area and need to stay safe from earthquakes.

By combining information from a satellite and from the laboratory, we made a geologic map of part of the Himalaya. This map helped us piece together part of the geologic history of the northwestern

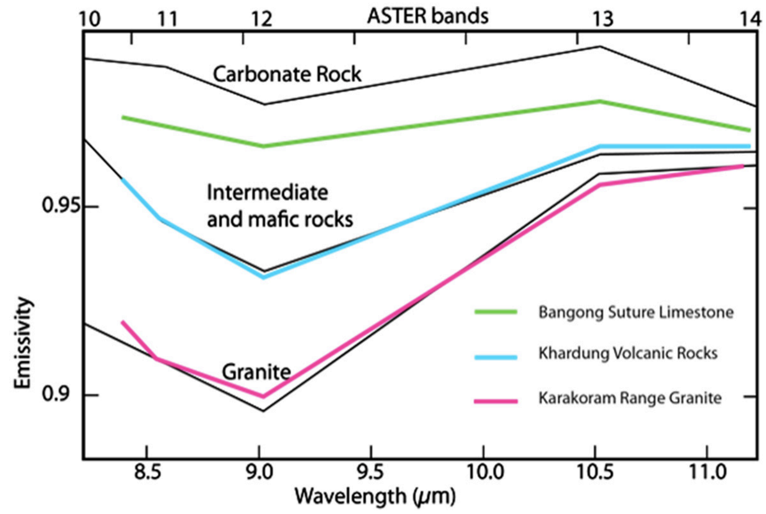

Figure 3

Figure 3

The black lines are the fingerprints of 3 kinds of rocks located in California. The colored lines show the fingerprint of rocks from our map in the Himalaya. The shape of the fingerprints from each of the different types of rocks match! This helps us be sure that we are doing a good job figuring out rock types using the colors in our geological map. You can find each rock type on the map by matching the name (see key) with the name shown in the map in Figure 2 (image modified from [4]).

Himalaya. It also helped us identify and better understand important, active faults in the area.

ORIGINAL SOURCE ARTICLE

Bohon, W., Hodges, K. V., Tripathy-Lang, A., Arrowsmith, J. R., and Edwards, C. 2018. Structural relationship between the Karakoram and Longmu Co fault systems, southwestern Tibetan Plateau, revealed by ASTER remote sensing. *Geosphere* 14:1837–1850. doi: 10.1130/GES01515.1

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YOUNG REVIEWERS

BANUCK, AGE: 14
My name is Banuck and I love science. I am currently an 8th grader in Maryland and want to become an astrophysicist when I grow up. I enjoy space and planets which is why I think this career would be a good fit for me.

CAELLUM, AGE: 9
Caellum is a 9 year 4th grader who loves science and math. His hobbies include Lego building, chess, riddles, and making balloon animals. He is a black belt in Tae kwon do and enjoys swimming.

AUTHORS

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ALKA TRIPATHY-LANG
Dr. Alka Tripathy-Lang is trained as a thermochronologist—someone who dates when rocks were at different temperatures under the surface (which tells us about how deep they were). She is now a science writer and editor, specializing in explaining complex earth science concepts to the public.

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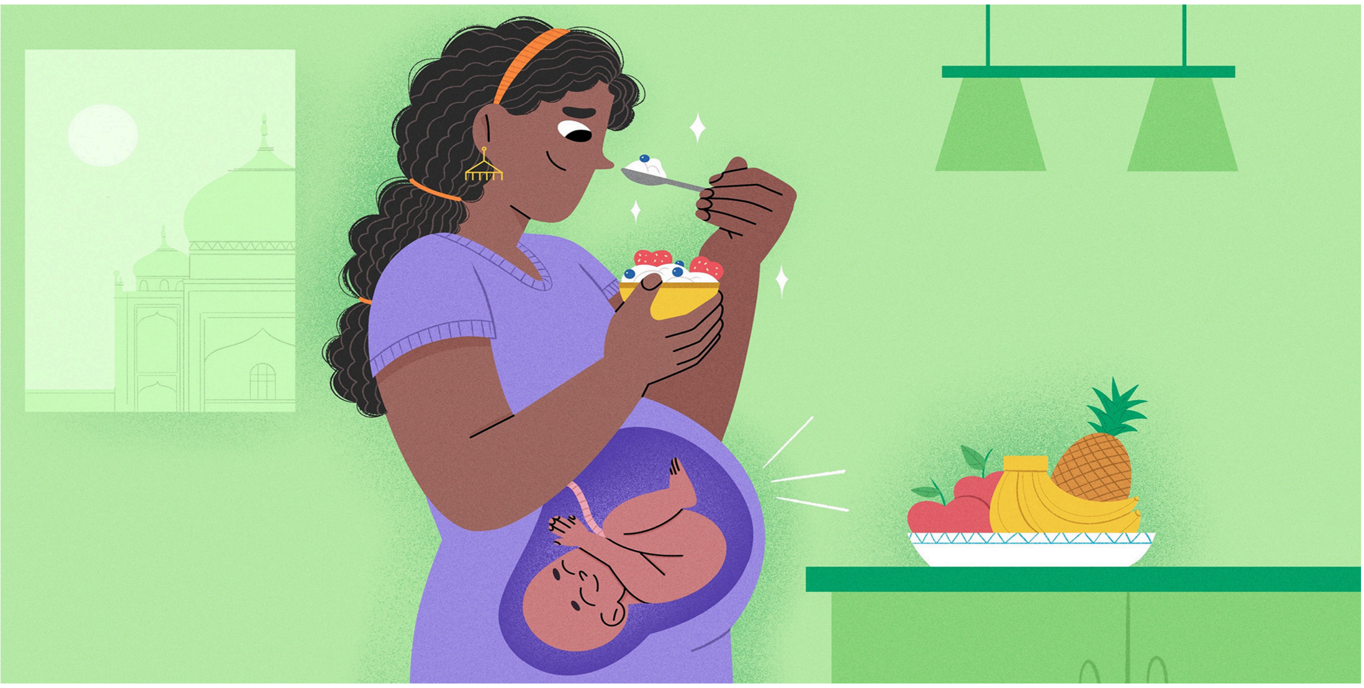

HOW MOM'S DIET IMPACTS BABY'S GUT HEALTH

***Sana Jaleel*[1], *Priya Ramotar*[1], *Sarah Daniel*[2] and *Julie Mirpuri*[3*]**

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YOUNG REVIEWERS:


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LETICIA
AGE: 15

What a mom eats before her baby is born can impact the baby's development. In this experiment, we fed pregnant mice an unhealthy high-fat diet to see the effect on the intestines of the baby mice after they were born. We found that the babies had more of a certain type of immune cell and that their intestines were more easily damaged compared to babies whose moms ate a healthier diet. In the second part of the experiment, we blocked the effects of these unusual immune cells and saw that the intestines of these babies became more resistant to damage, almost like those of baby mice whose moms ate healthy diets. Our research shows how important it is for moms to eat healthy foods when they are pregnant, to keep the newborn baby's gut healthy.

CAN WHAT MOTHERS EAT AFFECT THEIR BABIES' HEALTH?

Obesity is a huge problem in the United States, partly because many easily available foods have a lot of fat. Right now, more than half of the women in the United States are overweight or even obese around the age when they can get pregnant [1]. This could be dangerous, since scientists around the world have found that when moms are obese while they are pregnant, their babies have a higher risk of health problems throughout their lifetimes [1–5]. However, scientists do not yet know exactly why this happens. Even though obesity has many causes, an unhealthy, high-fat diet is one of the reasons some people are obese. This makes scientists ask: what changes happen in the baby when the mom eats a lot of fat?

Our hypothesis was that maybe, when moms eat a high fat diet, their babies will have different bacteria that may cause trouble in their **intestines**. This makes sense because when adults eat a lot of fat, their own gut bacteria change. Scientists believe this is because the fat encourages the growth of certain bacteria that break down the fat and allow the body to absorb more of it, making them gain more weight. With this in mind, we wondered if the bacteria of babies born to mothers on high-fat diets (60% **saturated fat**) can change, too [6].

Why do the bacteria in the intestines matter? These bacteria can affect the **immune cells** that can make the gut sensitive to damage and lead to a lot of problems. Even though the role of immune cells is to protect the body, they can also harm the body if they are too active or are activated by certain bacteria, resulting in **inflammation** [7]. One of the problems resulting from gut inflammation caused by specific bacteria is called **necrotizing enterocolitis**, which can cause babies born too soon (prematurely) to have to stay in the hospital for an extended period after they are born.

How did we test this idea? The bodies of mice have a lot of similarities with the human body, so we used mice in an experiment. Specifically, we gave some pregnant mice a diet with a lot of fat, and some mice a regular diet, with less fat. Then we looked at the guts of each of their babies to see if there were any differences. First, we looked at the babies' gut bacteria. Second, we tested their intestinal inflammation by looking to see if they had more cells called **type 3 innate lymphoid cells** (ILC3 cells). These cells cause inflammation by secreting a molecule that irritates the gut and can make inflammation worse. So if we see a lot of these cells, it indicates that the mice have more gut inflammation.

INTESTINE

A part of the gut where food is broken down and absorbed. Many bacteria live in the intestine.

SATURATED FAT

A type of fat, that can be eaten, that has a high proportion of fatty acid molecules and is considered unhealthy.

IMMUNE CELLS

Cells that help protect the body from dangerous invaders such as harmful bacteria and viruses.

INFLAMMATION

The state that results when immune cells are activated and cause damage to other cells. Inflammation appears as redness, swelling, heat, and pain.

NECROTIZING ENTEROCOLITIS

A disease in which the intestines of babies that are born too soon (premature) are damaged, causing the babies to stay in the hospital for a while.

TYPE 3 INNATE LYMPHOID CELLS

A type of immune cell present in the intestine that can produce the cytokine IL-17A.

WHAT HAPPENED TO THE BABIES' GUT HEALTH?

After the pregnant mice had been on the unhealthy high-fat diet, we looked at their babies' feces (poop) and found that the bacteria present were very different from those in the poop of the babies born from mice on a regular (healthy) diet (Figure 1).

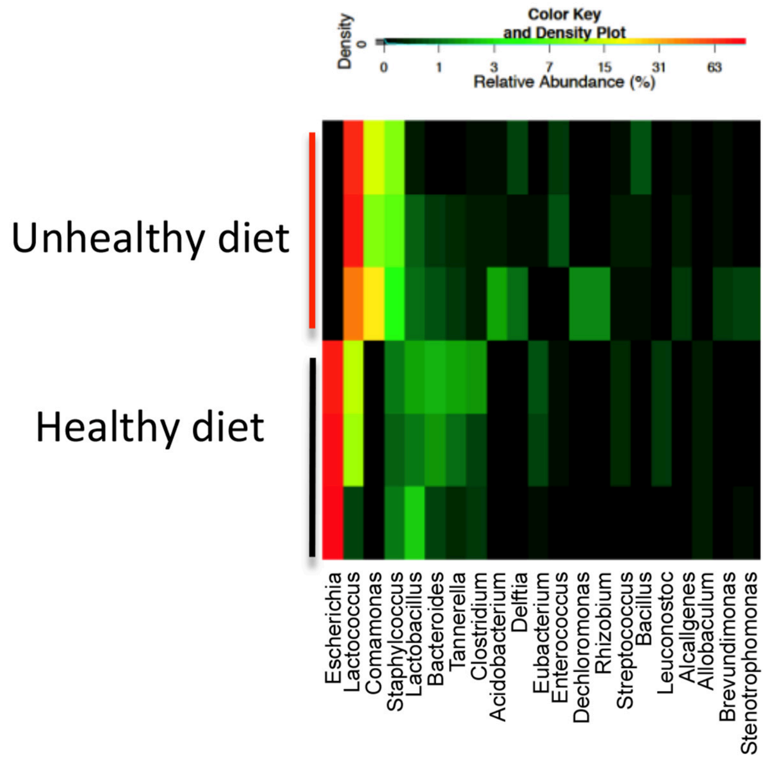

Figure 1

Figure 1

Heatmap of bacteria found in the poop of three representative 1-week-old mice whose mothers were either on a high-fat diet (unhealthy) or regular diet (healthy). The colors show the amounts of each bacterium (listed along the bottom), with red being more bacteria and black being less. You can see that the patterns in the unhealthy and healthy groups are quite different. This result showed us that the mom's high-fat diet could indeed affect the intestinal bacteria of the baby mice.

We also looked at the immune cells in the babies' intestines after they were born, and we found that ILC3 cells were increased in babies from moms that ate a high-fat diet (Figure 2). The test we used for this is called **flow cytometry**, in which we can identify cell types by the characteristic patterns they have on their surfaces. ILC3 cells can produce a molecule called IL-17A, which can hurt the intestine when inflammation is present.

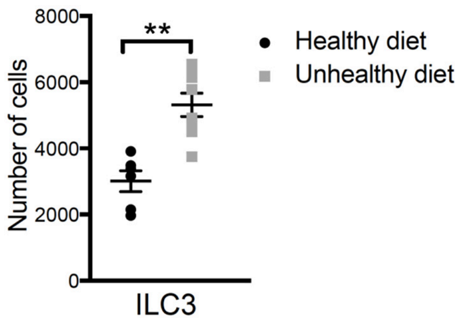

Figure 2

Figure 2

Studying the numbers of ILC3 cells in the guts of babies born to mothers on the healthy and unhealthy diets showed us that there were more ILC3 cells in the intestines of the babies born from the mothers that ate the unhealthy, high-fat diet. This was statistically significant as shown by the double asterisks. ILC3 cells can produce a molecule called IL-17A, which can irritate the intestine and cause inflammation. This result indicates that ILC3 may be responsible for the inflammation seen in the guts of babies born to mothers on the unhealthy diet.

CAN WE PROTECT THE BABIES FROM INTESTINAL DAMAGE?

At this point, we knew that baby mice from mothers that ate an unhealthy, high-fat diet had a different pattern of gut bacteria and more dangerous ILC3 cells than babies from moms who ate a healthy diet. We wondered if we could protect the inflammation-prone babies from intestinal damage, so we did an experiment to see if we could stop the effect of the ILC3 cells—and it worked (Figure 3)! To do this, we checked the intestine of the baby mice after they had a substance that could cause inflammation to the intestine.

FLOW CYTOMETRY

A technology that uses lasers to analyze single cells based on the molecules on their surfaces.

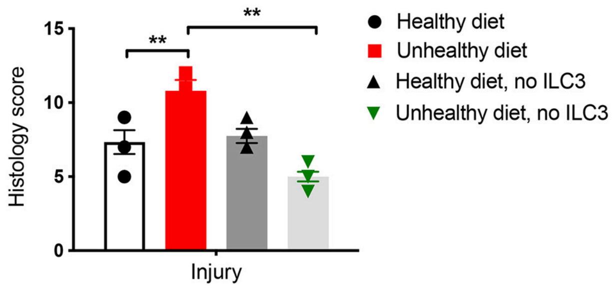

Figure 3

Figure 3

The intestines of baby mice were examined to see how much inflammation we could induce. This was measured by examining the intestines under a microscope (called histology) and giving the samples a score based on how much injury we saw. The higher the score, the more injury. The mice whose moms ate an unhealthy diet showed a higher score (more injury). When we blocked the effect of the ILC3 cells, the score was reduced (less injury). This told us that the ILC3 were responsible for the detrimental effects. The double asterisk represents statistical significance.

What was interesting was that, when we blocked the effect of the ILC3 cells by neutralizing IL-17A, we found we could save these babies from inflammation. This showed us that the mom's high-fat diet changed the numbers of ILC3 cells in the babies' intestines and caused more injury due to a higher production of IL-17A by those cells.

MOM'S DIET MATTERS!

This research taught us that what mothers eat while they are pregnant can affect their growing babies, even after they are born. Of course, mice are not humans, and this is a limitation of the study. However, mice are mammals, as are humans, and we can learn a lot from studying them. These experiments in mice showed us that the high-fat diet during pregnancy changed the immune cells and bacteria in the guts of the baby mice. Our findings could mean that eating healthy and avoiding high-fat foods when pregnant is very important for humans, too. A healthy diet does include *some* fat, but not an excessive amount. Eating healthy is all about getting a balance of all the nutrients that we need in our bodies, including vitamins, carbohydrates, proteins, healthy fats, and minerals.

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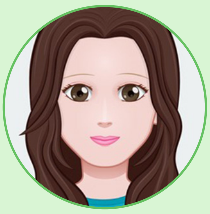
CONFLICT OF INTEREST: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

YOUNG REVIEWERS

ARASI, AGE: 11
Hi! I am Arasi, a 5th grader who always stays on her toes! I love to dance, sing, and play sports. I also like to just sit down and read a good book. If you ask me what my favorite subject is, I will say everything! When I grow up, I want to become a pediatrician so that I can help kids.



LETICIA, AGE: 15
I am 15 years old and live in England. I love sciences, reading mystery novels, and playing the piano. I am very passionate about medicine and consider it a potential career. I lived for many years in South America and enjoyed living surrounded by giant volcanoes and discovering exotic animals that helped me develop a passion for the sciences. I am fascinated by the world around me, the human body, and the evolution of species.

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Sana Jaleel is a pre-med student at Washington University in St. Louis. She has done research during high school and college with Dr. Mirpuri's laboratory on understanding how a mother's diet can change the baby's gut health. Her hobbies include running and dancing.

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Julie Mirpuri is a professor at the University of Texas Southwestern in Dallas, Texas. She is a doctor who works with babies who are sick or born too soon (neonatologist). She is also a scientist who does research on understanding how to help the babies have better immune health and good bacteria in their intestines. Julie is also an IF/THEN ambassador, encouraging young girls to pursue careers in STEM. *julie.mirpuri@utsouthwestern.edu

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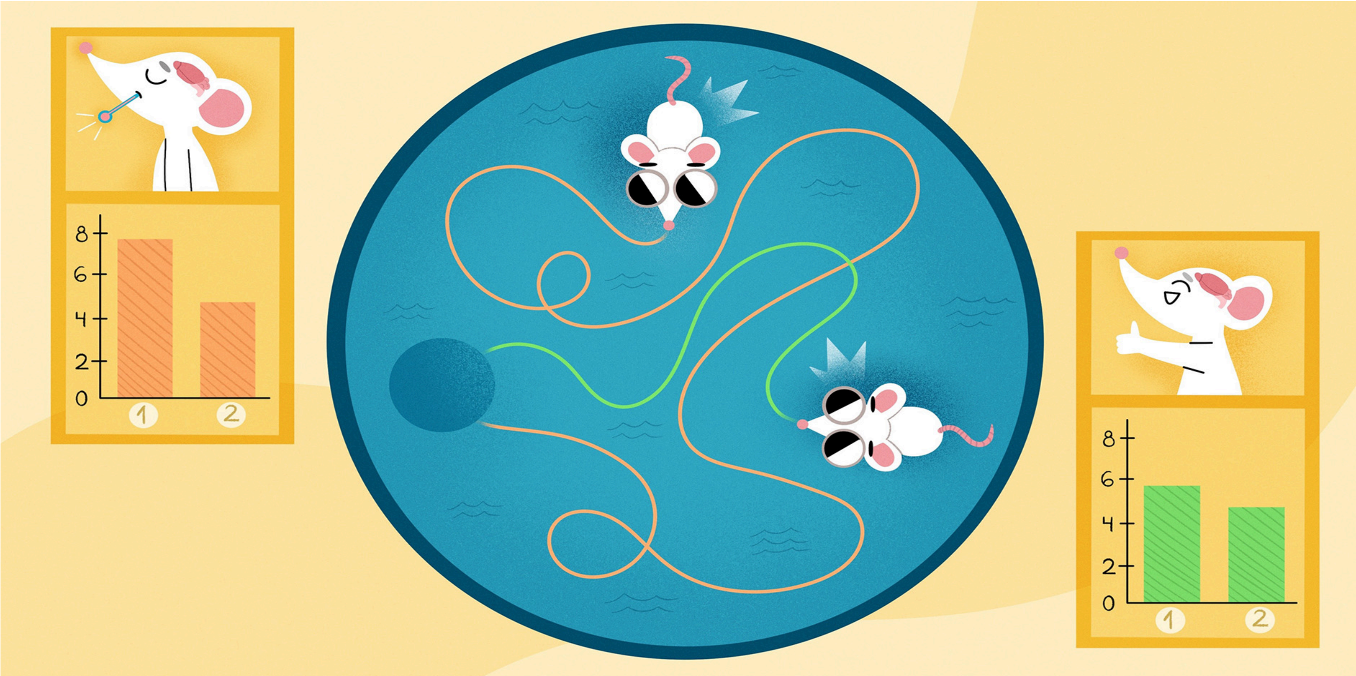

DOES GETTING SICK MORE OFTEN IMPACT THE WAY OUR BRAIN CELLS WORK AND HOW WE LEARN AND REMEMBER?

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YOUNG REVIEWERS:

QUEST MONTESSORI MIDDLE SCHOOL
AGES: 12–14

Everyone catches the flu or a cold from time to time. We designed an experiment to study how being sick more often affects the brain. To do this, we used a piece of a bacteria to make adult male mice experience symptoms of sickness. We gave mice this substance five total times. Mice got better in a few days and had 2-week breaks between exposures. We then measured how the mice learned and remembered new information, and how well their brain cells were working to help them learn. Our experiments indicate that being sick often interferes with communication between brain cells, causing mice to have trouble learning and remembering. Our data can help doctors predict which patients may have memory problems as they grow older. Our study also shows the importance of staying as healthy as possible and taking steps to protect ourselves and others when we do get sick.

INFECTIONS AND THE BRAIN

The itch in the throat, the sniffly nose, the upset stomach, the throbbing head, the chills... we all know the feeling of catching a cold or the flu. It is *not* fun. Being sick not only affects the way the body works—it also affects the brain. Being tired, having trouble concentrating, and feeling unmotivated, withdrawn, or grumpy are a few of the common, mild, brain-affecting symptoms people experience while feeling sick [1, 2]. Luckily, most people feel unwell for only a few days. As the **immune system** fights off the infection, people usually feel better and can return to normal activities, like going to school or seeing friends.

IMMUNE SYSTEM

The group of organs and cells that controls how we respond to infections or injuries.

Getting sick is a common experience in life, yet some people get sick more often than others. Studies in humans suggest that elderly people who have had more infections across their lifetimes show a greater decline in brain abilities known as **cognitive functions** [3, 4]. This could pose a problem for people facing memory changes as they get older, a common problem in this group.

COGNITIVE FUNCTION

Mental processes, including thinking, knowing, remembering, judging, problem-solving, and decision-making, that enable us to understand and interact with the world.

Our research question was: "What happens to the brain and how it works if a person has more experiences with infections?". We hypothesized that, if more experiences with infection negatively affect the brain, we would see problems with the way brain cells (called **neurons**) communicate and with the way information is learned and remembered.

NEURONS

Cells in the brain that receive information from the body or other parts of the brain, communicate with each other through electrical and chemical signals, and control our thoughts, feelings, and responses.

HOW DID WE MAKE ANIMALS SICK?

It is not ethical to do experiments in which we make people sick on purpose. So, we used adult male mice [5]. Mice are commonly used in biological experiments and they age very quickly, allowing us to easily study changes across time. All of our procedures were reviewed and approved in advance by a panel of other scientists, to ensure the welfare of our mice. We selected procedures that would minimize any pain or distress the mice might experience. Additionally, all experimenters were trained in the ethical use of animals in research.

We made some mice in our study "sick" by giving them an injection of a substance called **lipopolysaccharide (LPS)**. LPS comes from the outer layer of a certain type of bacteria. Many scientists have used LPS to learn about how both bacterial infections and the immune system work [6]. When we give a moderate amount of LPS to mice, it triggers the immune system to produce temporary inflammation, just like what would happen if the mice were infected by actual bacteria. Importantly, because LPS is only a *part* of the bacteria, the infection cannot spread from cell to cell within an animal or from animal to animal.

LIPOPOLYSACCHARIDE (LPS)

A fragment of the cell wall from a type of bacteria. It can trigger strong immune responses and is often used in research to study inflammation.

CONTROL

A group in a study that are considered normal. Scientists compare values on a dependent variable in the control group to any changes in this variable that are observed in the experimental group.

We gave some of the mice LPS five times over about 3 months (Figure 1A). We waited 2 weeks between "infections" with LPS before making mice "sick" again. Each time these mice were given LPS, other mice were given a **control** substance, which should have very little effect on the body on its own. In our case, this control was saline (salt water), like what you would get at the hospital if you were dehydrated. Our control group contained normal mice that had never experienced infections. We compared how the brains of control group mice worked to the brains of mice that experienced several LPS exposures. After the mice recovered from all five injections, we measured their learning and memory, as well as how their neurons communicated.

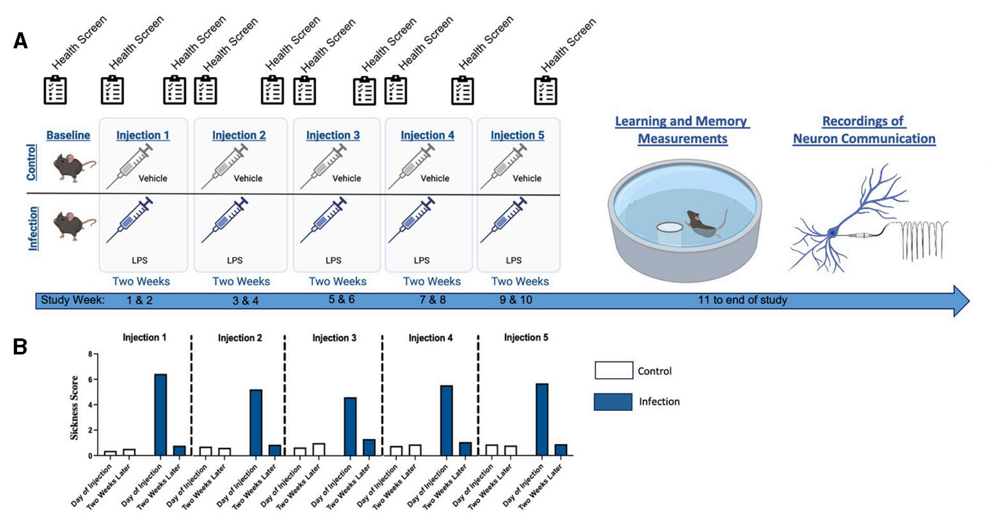

Figure 1

Figure 1

(A) We gave mice saline control or LPS every 2 weeks. We measured how sick mice looked and behaved right after each LPS injection and just before the next. After five injections, mice were tested for learning and memory using the Morris water maze. Communication of hippocampus neurons was also studied from mice in both groups. **(B)** The higher the score on our scale, the more sickness behavior mice showed. We found that each exposure to LPS made mice moderately but briefly "sick". Within 2 weeks, the sick mice made a full recovery. Control mice never showed signs of sickness. Average values are shown.

"INFECTED" MICE GOT MODERATELY SICK FOR A SHORT TIME

First, we measured how "sick" the mice were at several time points during the study. We used a health screening we developed that is similar to a physical exam a doctor might complete when you are sick. We looked at the appearance, posture, breathing rate, and movements of the mice. We also checked to see if they had lost any weight and took their temperatures to see if they had a fever. Each item we measured was assigned points and the more points an animal had, the sicker it behaved (Figure 1B). We did these measurements the same day as the injections. Two weeks later, we also measured all these characteristics again, to make sure the mice were not still sick before the next LPS injection was given.

No mice showed signs of sickness before injections began. As we expected, we generally did not see any signs of sickness in mice that were given the saline control. But each time the mice were given LPS, they showed moderate sickness behaviors. The sickness behaviors did not last long. Just before the next exposure, all LPS-treated mice had sickness scores similar to control mice, meaning that they had recovered from the effects of LPS. These data meant that we could test our hypothesis about the effects of multiple infections on the brain!

EXPERIENCING SICKNESS SEVERAL TIMES IMPAIRS MEMORY AND LEARNING

We next measured how our mice learned and remembered (Figure 1A). Since mice cannot use words to tell us what they know, we did this using a water maze. Mice are natural swimmers. Dr. Richard Morris created this test about 40 years ago. Mice were placed in a large tub of room-temperature water (Figure 2). The water was dyed to hide an exit platform just below the surface. Mice swam around the maze looking for the platform so that they could get out of the water and go to a warm cage to dry off. The room with the maze in it contained landmarks (for example: images of different geometric shapes) that helped the mice navigate. Mice swam from the starting point to the hidden exit platform, the location of which stayed the same for the entire experiment. Once they found the hidden platform, the experimenter took the mouse back to their warm cage to dry off. As they learned the location of the exit platform over several trials, the mice swam in a more efficient path to the platform, which took less distance. Swim distance was our **dependent variable**. This behavior is very similar to how a person learns the route from various places in town (school, the mall, or a restaurant) back to their home. To make sure mice stayed safe while swimming, there was always a "lifeguard" scientist on duty. All mice were given six swims each day for 8 days, for a total of 48 swims in the maze.

DEPENDENT VARIABLE

A variable that is used to determine the effects of experimental manipulations because it changes under different conditions.

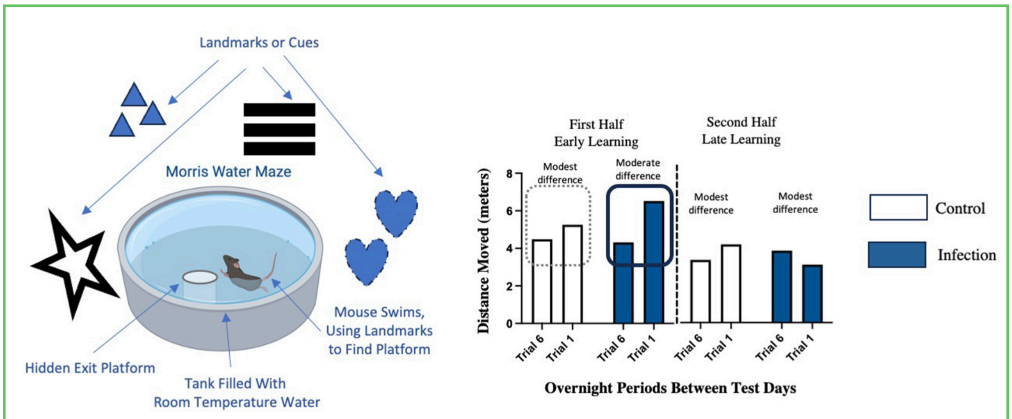

Figure 2

Figure 2

We measured how well mice learned and remembered using the Morris water maze. Mice that previously experienced several LPS exposures had difficulty remembering the location of the platform between test days during the first half of training (early learning phase). A larger difference means more forgetting of the platform location between test days. There were no differences in remembering in the second half of testing (late learning phase) for either group of mice.

Before the start of this memory test, all mice showed similarly good health scores. However, we found subtle differences in how the mice remembered the things we taught them (Figure 2). To determine how well mice remembered information that they learned each day, we compared the distance the mice swam to the exit platform on the last trial of each day (Trial 6) to the swim distance in the first trial the next day (Trial 1). Mice that were given control injections were mostly able to remember the exit platform location between test days. We know this because mice in this group show similar distances on Trial 6 and Trial 1 for those test days. However, the mice that repeatedly experienced and recovered from LPS "infections" had more trouble remembering this information between test days. We know this because these mice swam further on the first trial of each day (Trial 1) compared to the last trial the day before (Trial 6). This is a bit like how you might forget the details of the route to a friend's house if some time has passed since you last visited, causing you to make a few wrong turns along the way. Fortunately, this memory problem was brief and went away during the second half of the testing period as mice had more swims and learned the location of the hidden platform better. This suggests that mice with a history of LPS "infections" have a little bit more trouble remembering information as they are first learning it but, with additional practice to reinforce what they learned, they can catch up to mice that had not experienced repeated sickness.

HIPPOCAMPUS

A small, curved region in the brain crucial for memory formation and spatial navigation, helping us remember information and understand our physical location.

EXPERIENCING SICKNESS SEVERAL TIMES CHANGES NEURON COMMUNICATION

Next, we studied how experience with infections affected neurons in a part of the brain called the **hippocampus**, which is important for learning and memory (Figure 3). Neurons in the hippocampus control how we learn and remember things by communicating with each other. Neurons communicate very quickly, on the scale of milliseconds (1 millisecond equals 0.001 s). When neurons function properly, we can learn and remember things well.

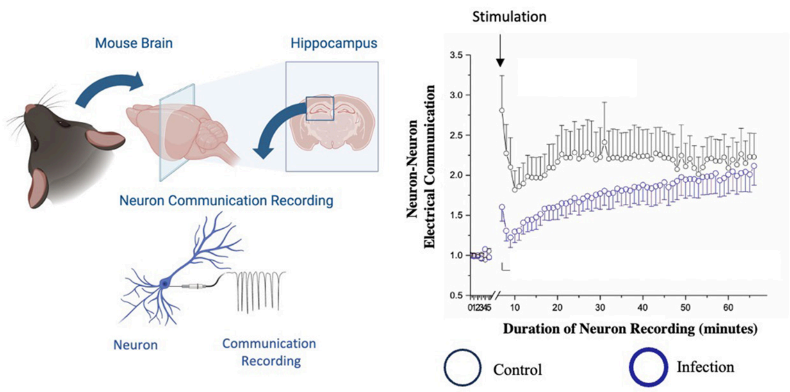

Figure 3

Figure 3

We measured how neurons communication in the hippocampus by recording electrical signals. Before stimulation (1–5 min), neurons from both groups had similar electrical signals. We then stimulated a neighboring neuron and measured the electrical signals produced by the receiving neuron. Neurons from mice that experienced several LPS exposures showed reduced communication at early timepoints. The dots represent the average signal. Not all neurons receive or produce the same signal, so the range of communication is indicated by the bars around the dots.

Neurons receive information from some of their neighboring neurons and send messages to others using electrical signals. Scientists can understand how well neurons are communicating by using special tools to measure these electrical communications. First, we looked at the signals from a neuron in the hippocampus to determine its normal level of electrical activity. Then, we stimulated another neuron, one that communicates with the hippocampus neuron we were interested in, and measured how well that communication signal was received by the hippocampus neuron by measuring its electrical activity in response. We expected that neurons would increase their electrical activity as they received signals from the neighbor neuron that we stimulated. We did this for neurons from mice exposed to several LPS injections as well as for neurons from mice given control injections. We recorded neuron signals for 1 h.

Neurons from mice that experienced repeated LPS or control injections could receive the signals from their neighboring neurons. Both groups also showed more communication following the stimulation, as we expected. Interestingly, the electrical signals of neurons from control-treated mice were stronger than those of neurons from mice that had experienced LPS, especially early in the recording period (Figure 3). This means that in mice with a history of recurrent LPS exposure, hippocampus neurons were less able to receive the communication signals from other neurons compared to control mice. This impairment appears to recover during the hour-long recording period, however the early disruption of communication still negatively impacts learning. Imagine you are in class, listening to your teacher explain an assignment. If you only receive a portion of the instructions the teacher is giving, you will have more trouble doing the assignment correctly and earning a good grade. Overall, being sick frequently can negatively impact learning and memory, as we saw in our water maze.

WHAT DID WE LEARN OVERALL?

Infections are a normal part of life. They happen to nearly all people and animals. However, infections can happen to some organisms more than others. We learned that some of the neurons in the hippocampi of mice that had several recurrent LPS experiences did not communicate as well as they normally would. This corresponded to slight difficulties with remembering information the mice were learning, at least at first. These learning and memory effects happened a while after the last LPS treatment, when the mice were healthy and showed no signs of sickness behavior.

This information is helpful because it gives scientists and doctors important knowledge about how infections may affect people in the long run. This is especially important for older people whose cognitive functions might be declining as they age. Our data could reveal new ways to reduce the brain and memory changes that tend to happen as people age. For example, maybe researchers will discover new ways to treat infections that help to avoid these learning and memory problems.

Our study has some limitations. First, we only used male mice, so our future work will include female mice. Secondly, LPS is a model of bacterial infections, but other microbes, such as viruses, fungi, and parasites, can also infect people and impact how the brain works. We have recently completed an experiment using viral infections to learn how other microbes affect the brain [7]. Finally, we must test potential ways to prevent the brain and behavior effects that come with a greater number of infections.

A key take-away from this work is that minimizing infections may protect our brains and maintain how well we think and remember as we age (Figure 4). Staying healthy, for example by getting annual flu vaccines, can reduce our chances of getting serious infections. We can also limit the spread of infection to family and friends by practicing good hygiene such as proper handwashing. If we are sick, we can use social distancing and wear masks in crowded indoor areas like grocery stores or classrooms. In summary, experiencing occasional infections is a normal part of life for nearly everyone, but staying as healthy as possible could keep our brains functioning at their best as we grow older.

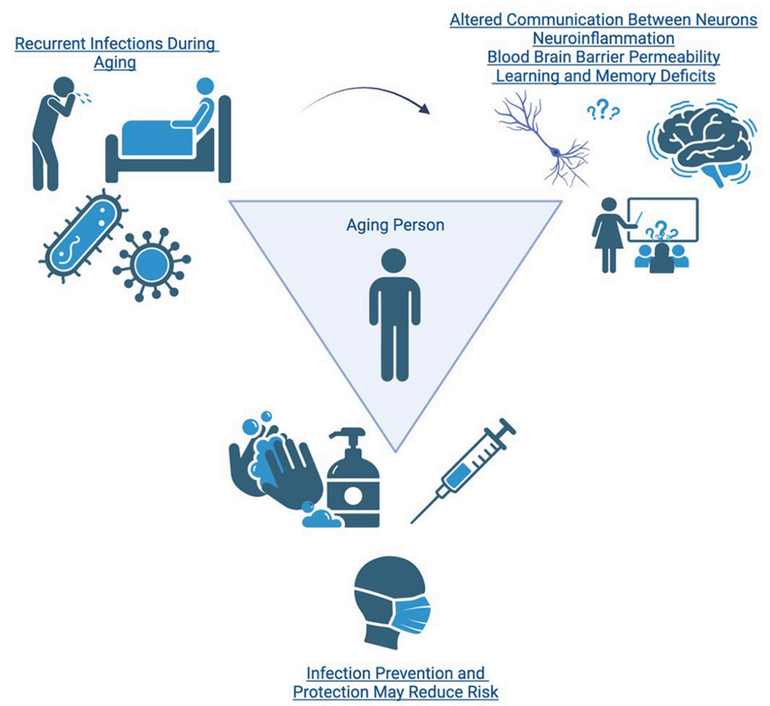

Figure 4

Figure 4

This schema summarizes the findings and implications of our study. Getting sick occasionally is normal but some people get sick more often than others **(top left)**. This can result in detrimental effects for our brain and the way we learn and remember **(top right)**. We need to understand what kinds of effects those might be, who might be at most risk for these consequences, and what we can do about it. We can reduce our risk of infection by practicing good hygiene (like washing our hands), by getting our yearly flu vaccines, and by social distancing or masking **(bottom middle)**.

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YOUNG REVIEWERS

QUEST MONTESSORI MIDDLE SCHOOL, AGES: 12–14

The 7th and 8th graders at Quest Montessori Middle School love to have fun while learning. We also love to chat and laugh about nothing in particular. We have many activities that help enhance our skill set, such as running our own microbusiness, our robotics team, and "OrQuestra". We are excited that we get to add reviewing scientific journal articles to that list!

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BROOK L. W. SWEETEN
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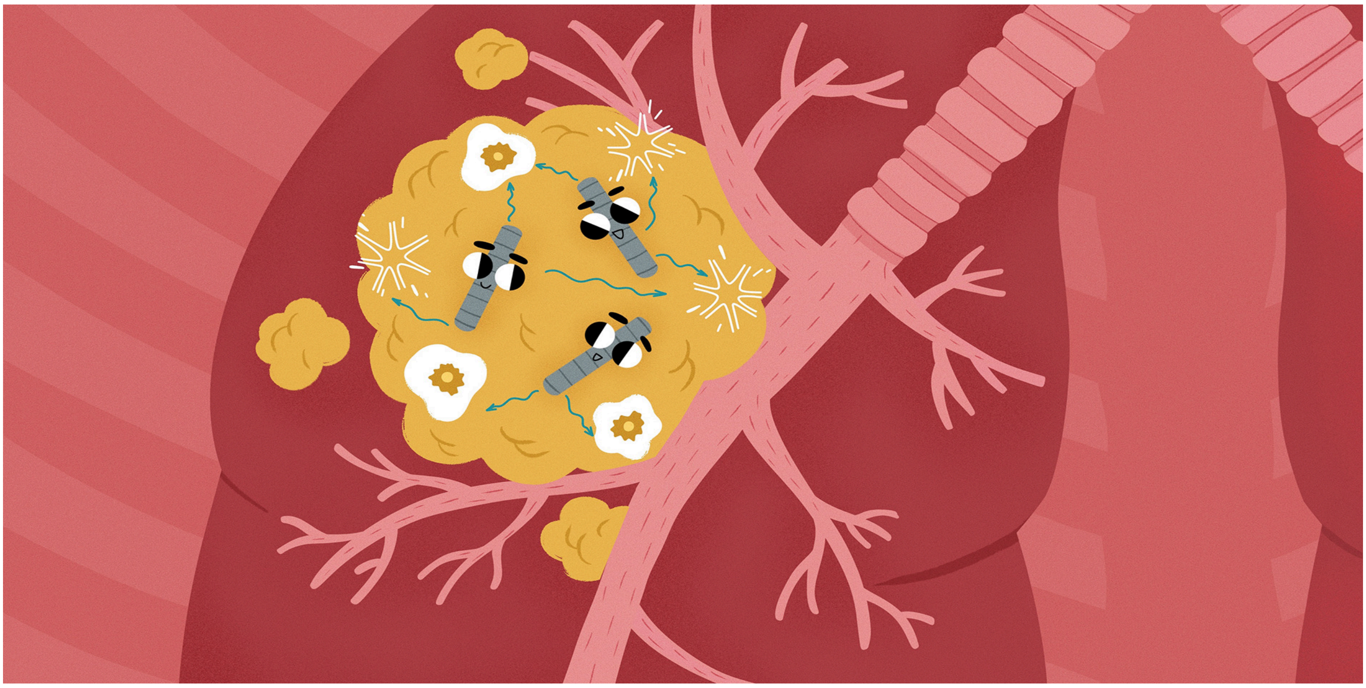

TREATING CANCER FROM THE INSIDE OUT

***Jessica M. Fagerstrom** * and Samantha Van Nest*

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YOUNG REVIEWERS:

SANYA
AGE: 10

TAPPAN MIDDLE
AGES: 12–13

VICTOR
AGE: 9

In this article, we will talk about a special treatment that doctors can use to help people who have cancer. This kind of treatment is called brachytherapy. Brachytherapy uses little pieces of materials that give off radiation to treat cancer from the inside out. We will explore what radiation is, what it means when something is radioactive, and why radiation can be used for cancer treatment. We will discuss different types of brachytherapy, because sometimes doctors use small, implanted capsules and sometimes they use a special robot. Toward the end of the article, we will see how this treatment can be used for different kinds of cancers.

A SPECIAL WAY TO TREAT CANCER

In this article, we are going to talk about a special way to treat cancer from the inside out. This kind of treatment is called **brachytherapy**. The word "brachy" in Greek means "short" because healthcare providers use brachytherapy to treat bad cells that are very short distances away. This can be a useful tool to help people who are sick with cancer.

BRACHYTHERAPY
A type of radiation therapy in which something radioactive is placed inside or right next to a tumor.

WHAT IS RADIOACTIVITY?

The world around us is made of very little bits of matter, called atoms. Atoms come together to make up everything. Some atoms are unusual because they are unstable, like a tower made of building blocks in which some of the blocks are wiggling and shaking. These unstable atoms seem like they have too much energy inside. To become more stable, they let some of this energy go. When the atoms release energy, the building blocks in the tower settle down and the whole tower is less shaky. What does it look like when an atom lets some of its extra energy go? Well, we cannot actually see it happen, but we know that tiny, invisible waves or particles are released. This is called **radiation**. Atoms releasing energy like this are called radioactive. We are going to talk about how radiation can be a really helpful tool for some people who are sick.

RADIATION

Energy, in the form of tiny, invisible particles or light, that travels from place to place.

WHY RADIATION CAN HELP PEOPLE WHO ARE SICK

You may have heard the word "**cancer**", but what exactly is it? Sometimes people get sick when some of their cells grow and divide too much. Sometimes these unhealthy cells also spread to other parts of their bodies. These unhealthy cells can get out of control, and that can stop the person's body from functioning properly. In some ways, cancer is a little like when weeds take over a vegetable garden. If a gardener does not stop the weeds from spreading, those weeds can take over the garden and make it very hard for the vegetables to grow. Fortunately, there are some ways that healthcare providers can stop cancer cells from getting out of control. One of those ways is by using radiation [1]. With radiation, healthcare providers want to be very careful to treat unhealthy cells and avoid the healthy cells as much as possible. Radiation with brachytherapy is one way to do that.

CANCER

When cells start growing and dividing too much, it can make people sick. Sometimes cancer can spread around a person's body, which can be very unhealthy.

BRACHYTHERAPY: A TOOL FOR FIGHTING CANCER

Imagine you are camping at night, and you are sitting inside a tent. You want to read a book, but it is too dark. If someone outside the tent shines a flashlight at the book, that might help—you might be able to do some reading, especially if the person with the flashlight is not too far away. If the person with the flashlight gets *very close* to the tent, it will probably be easier to read your book. If you have a flashlight with you *inside* the tent and you hold your flashlight right up next to the pages of the book, then you are really in business! Brachytherapy is a little like this flashlight, because doctors deliver a dose of radiation right up close to tumor cells instead of treating them from farther away [2].

There are several ways to treat cancer using radiation. You can read about using x-rays from a linear accelerator to treat cancer in another Frontiers for Young Minds article. When healthcare providers use beams of radiation from outside the patient, like with the linear accelerator, that is a little like shining the flashlight from outside of the tent. This is a great option, especially if doctors can aim the beam very carefully at the target. Another way to treat cancer with radiation is by using little pieces of radioactive metal. If doctors put the radioactive source right into the tumor that they are trying to treat, the cancer cells will get a high dose of radiation. This is what is done in brachytherapy.

RADIATION SEEDS AND EXTRA SPECIAL ROBOTS

There are several ways healthcare providers can deliver brachytherapy treatments [3]. The first one that we will talk about is to use lots of little capsules, called seeds. Even though they are called seeds, these are a lot different than the kind of seeds you use in your garden! These seeds are pretty small—they are each about the size of a grain of rice. A doctor can surgically implant these seeds directly inside a tumor. The seeds stay in place inside and, because they are radioactive, they release radiation right where the cancer is. You can see a picture of some brachytherapy seeds in Figure 1, and a picture showing treatment using seeds is shown in Figure 2.

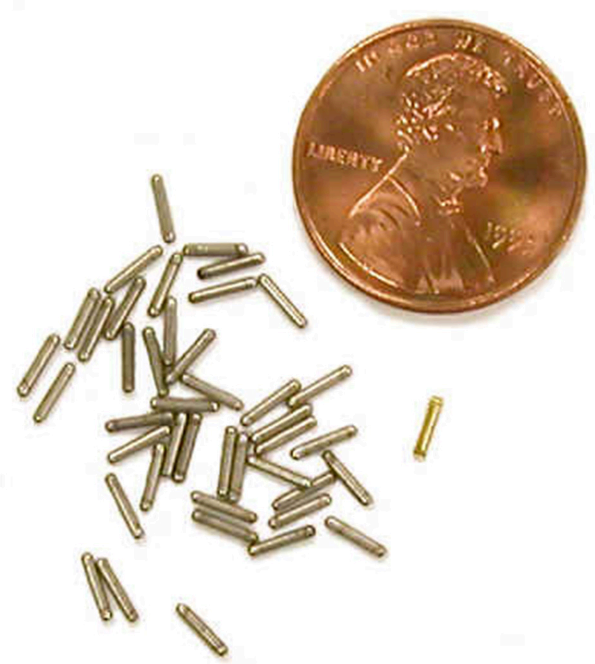

Figure 1

Figure 1

Brachytherapy seeds, with a penny next to the seeds to show how big they are. Brachytherapy seeds are small capsules that can be implanted inside a tumor. They are radioactive, so they give off radiation inside a tumor to treat cancer (photograph courtesy of the Oak Ridge Associated Universities through the Museum of Radiation and Radioactivity, used with permission. https://orau.org/health-physics-museum/collection/brachytherapy/seeds.html, Copyright Oak Ridge Associated Universities, 2023).

In another type of brachytherapy, healthcare providers can use a robot called an **afterloader** that controls where the radioactive source is placed in the patient. This robot can move the source through special tubes into the inside of a patient. When the treatment is over, the robot

AFTERLOADER

A robot that controls the delivery of some kinds of brachytherapy.

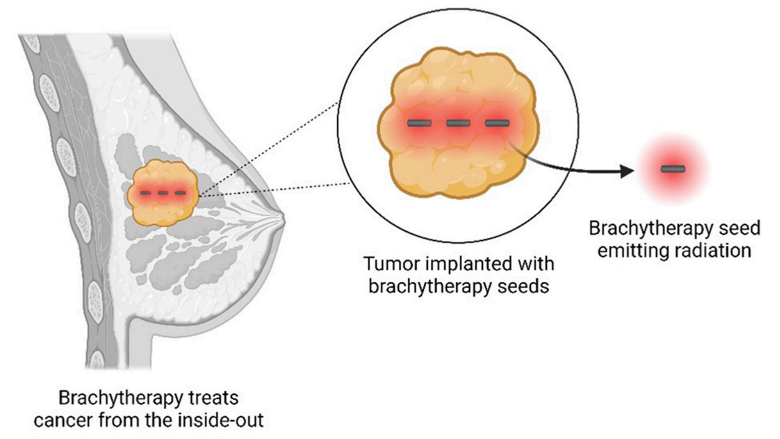

Figure 2

Figure 2

Radioactive brachytherapy seeds implanted in a breast tumor. The seeds emit radiation, which can kill the tumor cells that are near the seed (image produced using BioRender.com).

removes the source from the patient. When the radiation source is not being used for treatment, it sits inside a container inside the robot. That container is made of lead so that it blocks radiation. The afterloader can be controlled from outside the treatment room, so the doctor and other members of the healthcare team can be outside of the room while the source is outside of its special container and is being used to treat the patient. This makes delivering radiation safer for the medical team, because they are not exposed to radiation each time they treat a patient. You can see a picture of the brachytherapy robot in Figure 3.

WHAT TYPES OF CANCERS CAN BE TREATED WITH BRACHYTHERAPY?

Brachytherapy can be used to treat lots of kinds of cancer. For example, doctors can use brachytherapy to help people who need radiation treatment for their breasts, lungs, skin, or eyes. Brachytherapy can be used to treat cancer in men's prostates or in women's reproductive systems. Sometimes a person will need more than one kind of treatment. For example, doctors sometimes use special drugs or surgery in addition to radiation therapy. Sometimes patients even get more than one kind of radiation treatment, like when they get treated from the outside-in and then from the inside-out. When a person is going to be treated with brachytherapy, they will work with a doctor called a **radiation oncologist**. These doctors know a lot about treating cancer with radiation. The patient's doctor will help decide the best type of treatment for the patient, and the doctor will also come up with a plan for how best to treat the cancer. This doctor will work with a big team of people at the hospital to help make sure the patient is treated safely [4].

RADIATION ONCOLOGIST

A doctor who uses radiation to treat patients who have cancer.

Figure 3

Figure 3

An afterloader robot used for brachytherapy. This robot can be used to send a radioactive source to the inside of a tumor, and then pull it back out when the treatment is done. The robot is about 4 feet tall, or a little over a meter (photo courtesy of Ximin Du).

SUMMARY

In this article, we talked about one way that doctors can treat cancer. Brachytherapy is a type of radiation therapy, in which radiation is delivered right up close to harmful cancer cells. Sometimes radiation is even delivered right inside a tumor. Doctors can use little radioactive capsules called seeds, or they can use a special robot to deliver brachytherapy treatment. Whichever way brachytherapy is delivered, it can be a useful tool to help people who have cancer.

ACKNOWLEDGMENTS

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YOUNG REVIEWERS

SANYA, AGE: 10
My name is Sanya and I am currently in 5th grade. My hobbies are sketching, reading mystery novels, beach time with friends, baking, and traveling with my family. I love hearing and reading about new discoveries in technology and health.

TAPPAN MIDDLE, AGES: 12–13
This article was reviewed by Amykay, Andrea, Keira, and MarySol, a small group of cheery and bright 7th graders in Ms. Frantom's science class at Tappan Middle School in Ann Arbor, Michigan, USA. Tappan students achieve at high levels under the facilitation of skilled, effective, and culturally competent educators. We completed this review with the help of our UofM mentor, Dr. Pamela Wong.

VICTOR, AGE: 9
Victor likes math and science. He also wonders about the magic of the world, how and why things happen. His passion is to understand how diseases happen, how the body works, and why we get ill sometimes because our body is on "failing system" mode. When he grows up he wants to be a scientist because then "you can play in the lab and test hypothesis".

AUTHORS

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Dr. Fagerstrom is a medical physicist, which means she works in a field that applies physics to questions in medicine. She is part of a team of healthcare workers who make sure patients are treated safely with radiation. Her Ph.D. in medical physics is from the University of Wisconsin, and her M.Ed. in science curriculum and instruction is from the University of Washington. She is board certified through the American Board of Radiology. *jfagerst@uw.edu

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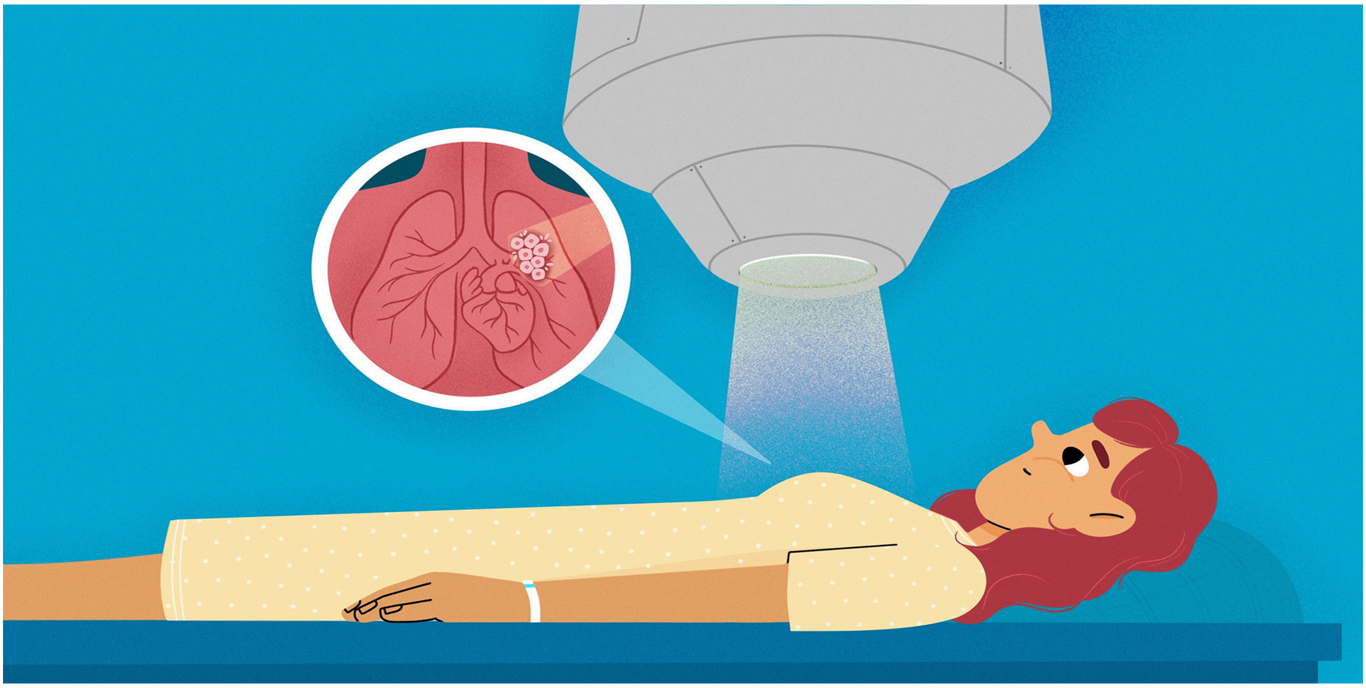

HITTING MOVING TARGETS IN CANCER TREATMENT

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YOUNG REVIEWERS:

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TOBY
AGE: 12

In this article, we will explore the way radiation can be used to treat cancer. Radiation for cancer therapy consists of high-energy particles or light that can damage living cells, including cancer cells. Radiation beams can be generated using a special machine, called a linear accelerator, and they are precisely aimed at a patient's cancer. When cancer is located near the patient's lungs, the cancer moves around as the patient breathes in and out. Hitting the cancer with the radiation beam can be hard when the cancer does not stay still. It is a little like trying to hit a moving target in a video game. In that case, there are some tricks that patients and radiation therapy workers can use to make sure that the radiation beam hits the cancer and misses healthy organs.

WHAT IS CANCER?

When a person has **cancer**, they have cells in their body that can increase in number quickly and make them sick. One way that cancer

CANCER

A disease in which cells start growing and sometimes spreading in an abnormal way that can cause problems in a person's body. Tumors can be cancerous.

RADIATION

Energy that can travel from place to place. When radiation has high enough energy, it can be harmful to living cells.

can be slowed down or stopped is by using a kind of **radiation**. Radiation is energy, in the form of particles or light, that can travel from one place to another. One form of radiation we see every day is light from the sun. Other kinds of radiation have enough energy that they can travel through solid objects, like a person's body. This type of radiation is called x-ray radiation, and it can be used by dentists to take pictures of teeth. The radiation used for treating cancer is even higher energy. This high-energy radiation can cause a lot of damage to the body's cells, so scientists aim radiation beams at cancer cells to damage the cancer cells and keep them from growing and spreading. Radiation can hurt both healthy cells and cancer cells, so it is important to be careful to aim the radiation at the cancer cells while avoiding the patient's healthy cells and organs as much as possible [1].

WHERE DOES RADIATION COME FROM?

LINEAR ACCELERATOR

A machine that generates, shapes, and directs radiation beams at cancer cells.

Scientists use a machine called a **linear accelerator** to create radiation beams that are used to treat cancer. This machine speeds up tiny particles called electrons very fast—close to the speed of light! These speedy electrons crash into a piece of metal, which causes the release of large amounts of the radiation used for cancer therapy [2]. You can learn more about linear accelerators from *another article in Frontiers for Young Minds*. Figure 1 shows a picture of a linear accelerator in a hospital.

Making radiation beams is not the only thing that linear accelerators can do: they can also change the shape of the radiation beam and point it in different directions. You can think of a linear accelerator a little like a flashlight. Just like you can turn on a flashlight, a scientist can turn on a linear accelerator. You can move the flashlight around to change which direction the flashlight beam is headed, and a scientist can change the direction of the radiation beam by moving parts in the linear accelerator. You can also put your hand in front of the flashlight to make shadows of different shapes. Scientists can do the same thing with thick pieces of metal that block part of the radiation beam and change its shape.

WHAT HAPPENS WHEN A CANCER PATIENT IS TREATED WITH RADIATION?

RADIATION THERAPY

A type of treatment used to damage cancer cells using high-energy radiation beams.

Sometimes doctors treat cancer using radiation, sometimes they use drugs called chemotherapy, and sometimes they surgically remove the cancer. Many cancer patients receive **radiation therapy** as part of their care—in fact, there were about two million new cancer cases in the United States in 2023, and about half of those patients received radiation therapy [3, 4]. When a patient needs radiation therapy, a healthcare team works to deliver the treatment carefully and safely. Before radiation therapy, the patient lies down on a flat surface so

Figure 1

Figure 1

Photo of a linear accelerator used to make radiation beams to treat cancer.

their doctor can take a 3D picture of their body, called a CT scan. This scan shows where the cancer is located, and the picture is used by the radiation team to design a treatment that damages the cancer cells and avoids healthy cells.

When it is time for treatment, the patient lies down in the same position they did for their CT scan, and the radiation beam from the linear accelerator is carefully positioned to target the patient's cancer. The positions of the patient and the radiation beam need to be exactly right because it is important to avoid hitting healthy cells or organs while making sure that the cancer cells are treated with the right amount of radiation.

WHAT HAPPENS WHEN THE TARGET IS MOVING?

When a patient gets radiation therapy, they must lie very still while their healthcare team gets them into position and aims the radiation beam at just the right spot. But what happens if a patient has cancer in a part of their body that is moving? For example, when you breathe, you can see your chest moving because your lungs are changing shape. When you breathe in, your lungs increase in size and fill with air. When you breathe out, your lungs decrease in size. If a patient has cancer in or near their lungs, this can make aiming the radiation beams trickier than when the target is not moving. You can think of this like a video game in which the player must hit a target with a cannon. In the easy levels, the target stays still. In harder levels, the target moves around. In even harder levels, the target moves around and may also get close to other objects the player is trying *not* to hit. This is a lot like radiation therapy: the target is the cancer cells, and the cannon is the high-energy radiation.

Sometimes the radiation team can use special tools that help control motion—this is called **motion management**. Breast cancer is a good example. Breast cancer is a common disease, with about 300,000 new cases in the United States in 2023 [3]. When patients are treated for breast cancer using radiation, the radiation team often wants to treat the whole breast. They need to think about what other healthy cells are near the target so they do not damage those healthy cells. For example, if a patient is being treated for breast cancer on the left side, their heart is near the target. Scientists must also think about what happens to the target when the patient is breathing in and out, which can make the target move around.

MOTION MANAGEMENT

Strategies in radiation therapy to make sure that radiation reaches the target accurately, even when the target can move.

We can use some special strategies to hit the target (the breast) while not hitting the object we are trying to avoid (the heart). The patient can be a big help with motion management—they can take a deep breath in and hold it for about 20 s. When they do that, their lungs fill with air, and their chest moves a little farther away from their heart (Figure 2). While the patient is holding their breath, the linear accelerator can be turned on, so radiation is delivered only during the short amount of time that the patient is holding their breath. This allows the radiation beam to irradiate the breast while missing the heart. This strategy is called **deep inspiration breath hold**. In medicine, the word “inspiration” means “breathing in”. The patient takes in a deep breath (“deep inspiration”) and then they hold it during treatment (“breath hold”).

DEEP INSPIRATION BREATH HOLD

A technique in radiation therapy in which a patient takes in a deep breath and holds it during treatment.

When you look at Figure 2, it might not look like a very big difference between treating with normal breathing and treating with the patient holding their breath. But this little change can make treatment a lot safer for the patient, so it is important to do!

Most people cannot hold their breath for much longer than 20 s. Since it sometimes takes too long to deliver all the radiation while the patient holds one breath, the patient might be asked to hold their breast a few times. In that case, the radiation is paused, and the patient gets a break to breathe normally for a while. When the patient is ready, they take

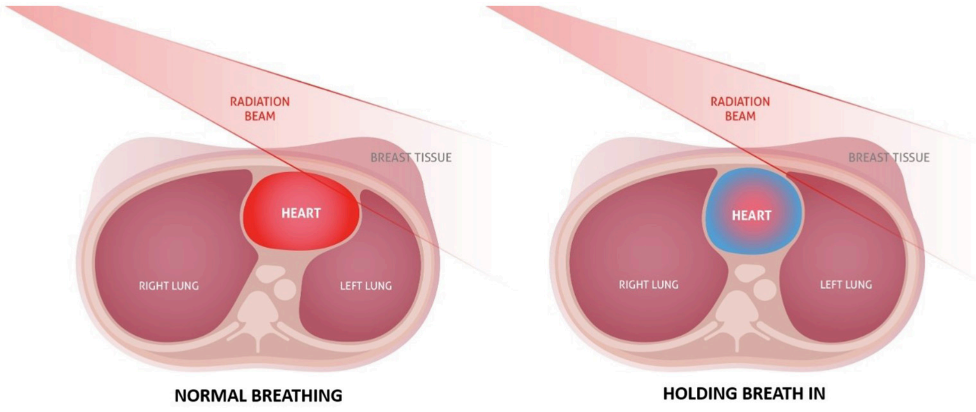

Figure 2

Figure 2

Cross-sectional pictures of a patient lying down to be treated for breast cancer. On the **left**, the patient is breathing normally, and the radiation beam aimed at the breast overlaps some of the patient's heart. This could damage the heart. On the **right**, the patient is holding a breath in, which makes the lungs expand and pushes the breast away from the heart, so the patient's breast cancer can be treated without damaging the heart (adapted with permission from Safer Radiation Therapy, Copyright by Vision RT Ltd., 2023).

another deep breath in and hold it, and the radiation beam is turned back on to continue the treatment.

Breast cancer is not the only disease in which there is motion because of breathing. When a patient has a tumor in their lungs, liver, or pancreas, the radiation team can use similar strategies to make sure that they hit the target and miss the healthy tissue, just like with breast cancer.

SUMMARY

Radiation is a tool that can help patients with cancer. When treating a target with radiation, it is very important to hit the right spot and avoid healthy tissue that is in the same region. Motion management strategies help accomplish this, even when the target is near body parts that move around. Patients can help with their own treatment, using techniques like deep inspiration breath hold, to make sure that the cancer cells are treated with high energy radiation while keeping healthy cells safe.

ACKNOWLEDGMENTS

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YOUNG REVIEWERS

ELISA, AGE: 14

Elisa is a young girl with a curious mind. She is very passionate about science, especially related to health. She is interested in research and would like to start getting involved in conducting her explorations at some point in the future. She hopes that, with her critical thinking, her love for health discoveries, and her drive, she will be able to contribute to science through journal review.

TOBY, AGE: 12

I like to play video games and I have two cats.

AUTHORS

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Dr. Fagerstrom is a medical physicist, which means she works in a field that applies physics to questions in medicine. She is part of a team of healthcare workers who make sure patients are treated safely with radiation. Her Ph.D. in medical physics is from the University of Wisconsin, and her M.Ed. in science curriculum and instruction

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VICTORIA N. BRY

Dr. Bry is a medical physics resident—that means she has completed college and graduate school and is training in a cancer center to become a board-certified medical physicist. She became excited about physics in high school because it explains how the world around us works. She earned her bachelor's degree in physics at Colorado College and her Ph.D. in radiation therapy medical physics from UT Health San Antonio. Her goal is to participate in research that improves the accuracy and quality of care that patients receive in radiotherapy.

CAROLINE M. COLBERT

Dr. Colbert is a medical physics resident—that means a medical physicist in training. When she first learned about some of the scientific applications of radiation in her tenth-grade chemistry class, she decided to pursue a career using radiation to improve the lives of others. Caroline studied nuclear engineering in college, and then went to graduate school to learn more about the medical use of radiation. She works with mentors like Dr. Fagerstrom to learn how to safely deliver radiation therapy. Her goal is to use scientific research to create the next generation of targeted cancer treatments.

CHEYANN WINDSOR

Cheyann Windsor is a medical physics resident—or a medical physicist in training. She enjoyed the physical sciences in high school and decided to pursue a college degree in physics. While in college, she found the field of medical physics. She earned both her bachelor's degree and master's degree in medical physics from the University of Toledo. She enjoys being a part of a specialized healthcare group and helping patients in her everyday clinic work.

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HOW THE SCIENCE BEHIND VIDEO GAMES HELPS KIDS WALK

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YOUNG REVIEWERS:

PRISHA
AGE: 14

ZURI
AGE: 14

Did you know that some of the same technology used to make video games and movie special effects can help scientists better understand human movement? During motion capture, also called mocap, small reflective balls, or markers as they are called, are placed on specific points of a person's body. Mocap systems work using multiple cameras around the room that track the motion of the markers as a person walks, runs, jumps, or plays. The information gathered during mocap can be used to help doctors decide the best possible care to improve a child's walking. It can also be used to determine when someone is ready to go back to sports after an injury, to help prevent people from getting injuries in the first place, or to improve their sports performance.

MOCAP: MEASURING MOTION OF THE HUMAN BODY

We all move every day. Some of us can walk or run. Other people use wheelchairs to move from place to place. Whether you are walking to school, throwing a softball, brushing your teeth, or eating a piece of pizza, you are moving at least one part of your body. Scientists who study how people move while walking, running, exercising, or just going about the day are called **biomechanists**. Biomechanics is the name for the study of human movement.

BIOMECHANIST

A scientist who studies human movement, which is also called biomechanics.

Have you ever noticed that the main characters in animated movies or video games look and move like real-life actors? There is a good chance that a technique called **motion capture (mocap** for short) was used to create these graphics. Characters like The Hulk, animated movies like *Happy Feet* and *The Polar Express*, and video games such as Guitar Hero and FIFA 22 have all used mocap on live actors to generate realistic movement of the animated characters.

MOTION CAPTURE (MOCAP)

A method used to record movement using one or motion cameras of multiple sensors placed on a person's body.

Mocap is a method to digitally record movement. It can be done using one or more cameras, or with a series of sensors worn on a person's body. Mocap tracks each part of the body that we want to measure and can take measurements between 100 and 250 times per second. This provides a detailed description of how a person's body is moving in three dimensions (3D): forward and backward, side-to-side, and up and down. In movies and video games, mocap makes the characters appear very lifelike by mimicking real-life movements.

TYPES OF MOCAP

Movement can be measured in lots of ways. The best way to measure motion depends on what we want to look at. For example, at a track and field meet, we can measure how fast a person can run, or how far or high a person can jump. That type of motion analysis looks at the movement of the person's entire body. But to understand how a person moves so fast or jumps so far, biomechanists want to look at specific **joint** movements. A joint is where two or more bones in the body meet. For example, your ankle joint has three bones: the lower leg bones, called the tibia and fibula, and the ankle bone, called the talus. In our track example, a biomechanist might ask questions like "How much is the runner's knee bending when they land with each step? How much did their hips or ankles extend as they pushed off the ground?".

JOINT

A part of the body where two different bones meet and interact with each other.

The easiest way to measure this motion is with a simple video camera. However, if the camera is not perfectly lined up with the body, the motion data measured from the camera images might not be accurate. The camera measures best when the images are right in the middle of the screen. Since the camera is at an angle from something at the edge of its view, the position of the body may be under- or over-estimated.

3D mocap can measure motion more accurately, using 1 of three ways. The first method uses special cameras all around the room to

OPTICAL MOTION CAPTURE

A type of motion capture that uses several camera views to recreate 3D positions of markers placed on a person or object.

MARKERLESS MOTION CAPTURE

A type of motion capture that uses multiple camera views to recreate the 3D position of a person or object, without the use of special markers on the body.

INERTIAL MOTION CAPTURE

A type of motion capture that uses special sensors placed on each part of the body to track movement without the use of cameras.

track small, reflective balls, called markers. The markers are placed on specific parts of a person's body to estimate the person's movements (Figure 1). When two or more cameras see a marker, the 3D location of the marker can be tracked by computer software. This is called **optical motion capture** [1]. The second method uses a series of cameras, but without markers. This method is called **markerless motion capture**. This technology uses advanced computer programs to track body shapes (legs and arms, for example). These methods also use color and depth and they combine multiple camera views to track the person's motion. The last method, called **inertial motion capture**, measures motion by placing a sensor on each part of the body. This method does not require any cameras. Instead, each sensor detects changes in the speed and direction of the body, like how you feel a push or pull when riding in a car as it speeds up, slows down, or turns a corner.

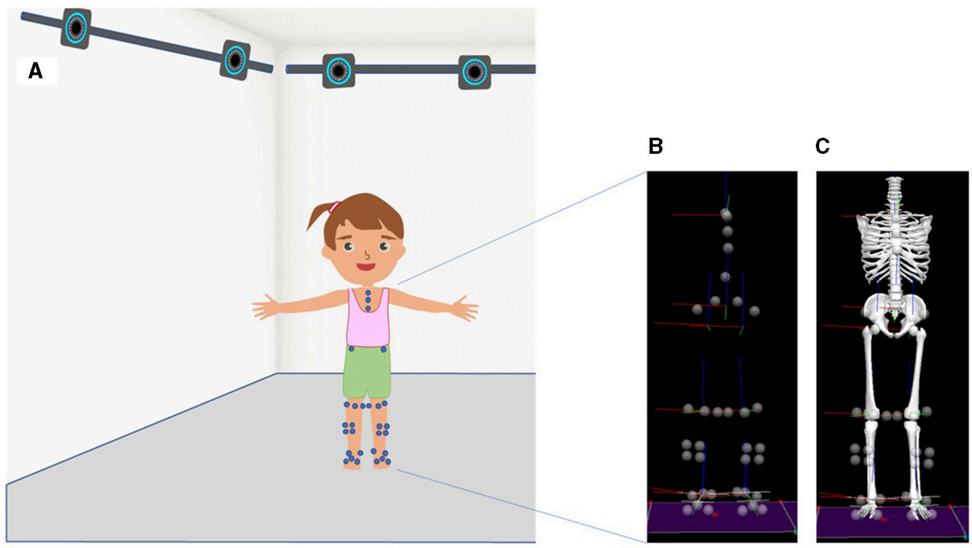

Figure 1

Figure 1

(A) Special mocap markers (blue dots) are placed on specific parts of the person's body. They stand, walk, run, or perform other tasks in the mocap room. Special cameras track the motion of the markers. **(B)** The mocap cameras and computer recreate each marker (gray dots) in 3D on the computer. **(C)** A skeleton model is created from the mocap markers, which moves exactly like the person does.

Each of these mocap systems can measure where one part of the body is compared to another. This is called relative motion. Optical and markerless mocap also give absolute motion, or how the part of the body is moving by itself. Some systems measure the motion in more detail, or at a higher rate of speed. Picking the right mocap system is an important step for biomechanists.

MOCAP TO HELP PATIENTS MOVE EASIER

Some kids have health conditions that limit their ability to walk, run, or do other everyday movements. They may need an artificial leg, a leg brace, or walking aids like crutches. Sometimes a doctor or physical therapist can help improve a child's ability to walk by changing how much a joint moves or by increasing the child's muscle strength. 3D mocap can help the doctor or physical therapist identify which joints or muscles are having trouble when the child moves [2]. They can use these data to decide the best treatment to improve the patient's movements. Many mocap tests are designed to help children walk better, often using optical mocap systems. During each testing session, the mocap staff applies the markers and asks the child to walk. Additional tests, like jumping, running, or sitting, are used to test movement during other daily activities the child may do.

These testing sessions usually involve more than just mocap—they may also measure the forces involved in creating and controlling motion. For example, every time you take a step, your foot applies a force on the ground. Per the laws of physics, the ground reacts by creating an equal and opposite force on your foot. This is called the **ground reaction force**. During mocap sessions, patients walk on special force-sensing plates in the floor that measure this ground reaction force. Biomechanists use the ground reaction force and the position and movement of each joint to determine how much force is generated at the hip, knee, and ankle. Inside the body, forces are also created when muscles contract. Small sensors placed on the surface of the skin over the muscle can measure the electrical activity produced when the muscle is contracting. These sensors do not cause the muscle to contract, they simply "listen" to determine when the muscle is "on". As a muscle contracts, its forces help to bend or straighten joints.

GROUND REACTION FORCE

A force from the ground on the body. It is equal to the force applied by a person onto the ground.

MOCAP TO HELP ATHLETES RECOVER AND/OR PREVENT INJURIES

There are some doctors, physical therapists, and biomechanists who treat sports injuries. They use mocap to determine when injured patients are ready to go back to playing sports. For example, a soccer player may hurt their knee and tear a ligament. A **ligament** is like a rubber band that connects two bones (Figure 2). Its job is to help keep the bones together and prevent them from moving too much in a certain direction. Sometimes when a person lands from a jump, their leg or body is not in a good position. This can create a large force at the knee joint, which causes the ligament to tear. This ligament injury usually requires surgery and a lot of recovery exercises with a physical therapist.

LIGAMENT

A part of the body that connects and holds two different bones together.

Doctors must determine if an injured player's knees and muscles are strong enough and have enough motion to return to playing sports [3]. This can be done by measuring the motion when the patient runs, changes directions, or jumps. Mocap answers these questions and helps the patient get back to playing their favorite sports. Doctors and physical therapists use these same tests to measure motion in athletes without injuries, to determine if they are at high risk of getting hurt. Athletes whose movements and forces are similar on the left and right

Figure 2

A ligament acts like a rubber band, holding two bones together. A joint is the area where two (or more) bones meet.

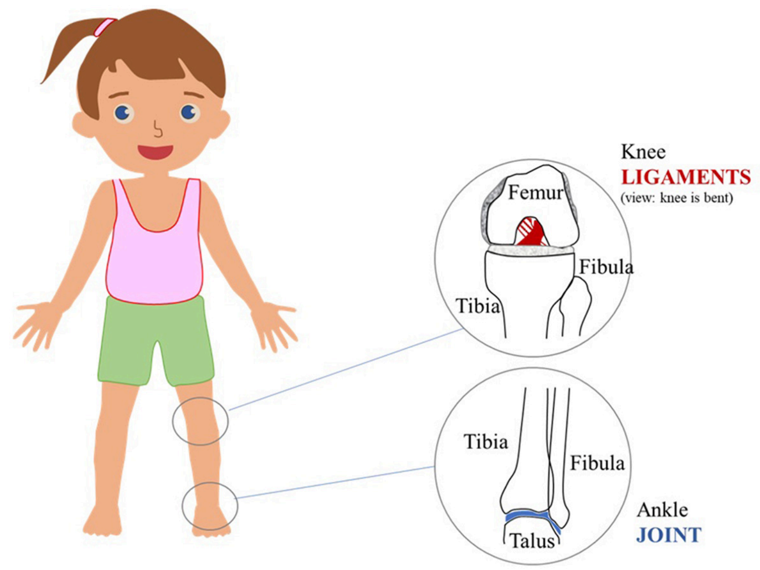

Figure 2

sides and within a healthy range of motion are at a lower risk of getting hurt (Figure 3).

Figure 3

(A) The patient performs a challenging movement, like a squat, while wearing mocap markers (not shown). **(B)** Using a computer-generated skeleton, scientists and doctors look to see if the ground reaction force (red arrows) is the same height and direction on both sides of the body. In this case, they are. **(C)** They also examine the position of the legs and the hip, knee, and ankle joints to see if they are the same on both sides of the body. Again, in this example, they are.

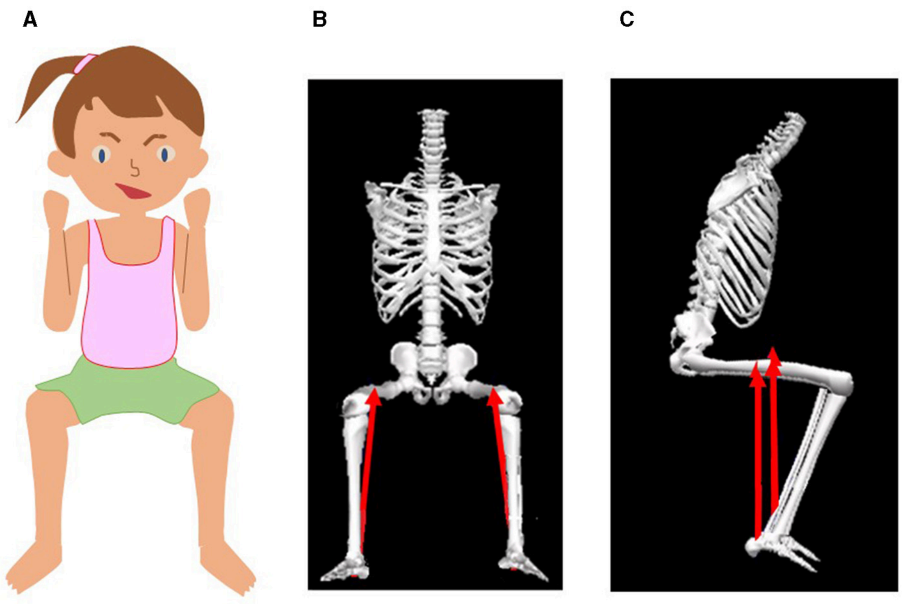

Figure 3

MOCAP TAKE HOME MESSAGE

Motion capture is often used to make our favorite video games and movie special effects. This same technology is used to understand how the human body moves. Mocap systems measure motion in 3D and can take more than 100 measurements per second. This high detail allows biomechanists to see exactly where limitations in motion impact someone's ability to walk and move. The forces that cause human motion, both inside and outside of the body, are also important to describe why a person is having difficulty with specific movements. Doctors use this information to help people move easier, recover from an injury, or prevent injuries.

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

YOUNG REVIEWERS

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Prisha is an avid reader of fantasy and mystery who also likes mathematics, specifically algebra and trigonometry. She is also really interested in the sciences, biology and chemistry especially, and how technology could be applied to those fields in the future. In her free time she writes fiction, does yoga, bakes, and engages in art.

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Hi, my name is Zuri. I am passionate about entrepreneurship, enjoy public speaking, and I am currently having fun coding with Python to build a smart voice assistant. In my spare time, I like photography, ice skating, experimenting with new foods, and spending time with friends and family.

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their care. He is interested in how problems with muscles and nerves can affect a person's balance and stability. His goal is to learn more about how to keep people stable, correct their posture when needed, and ultimately, prevent them from slipping, tripping, or falling.

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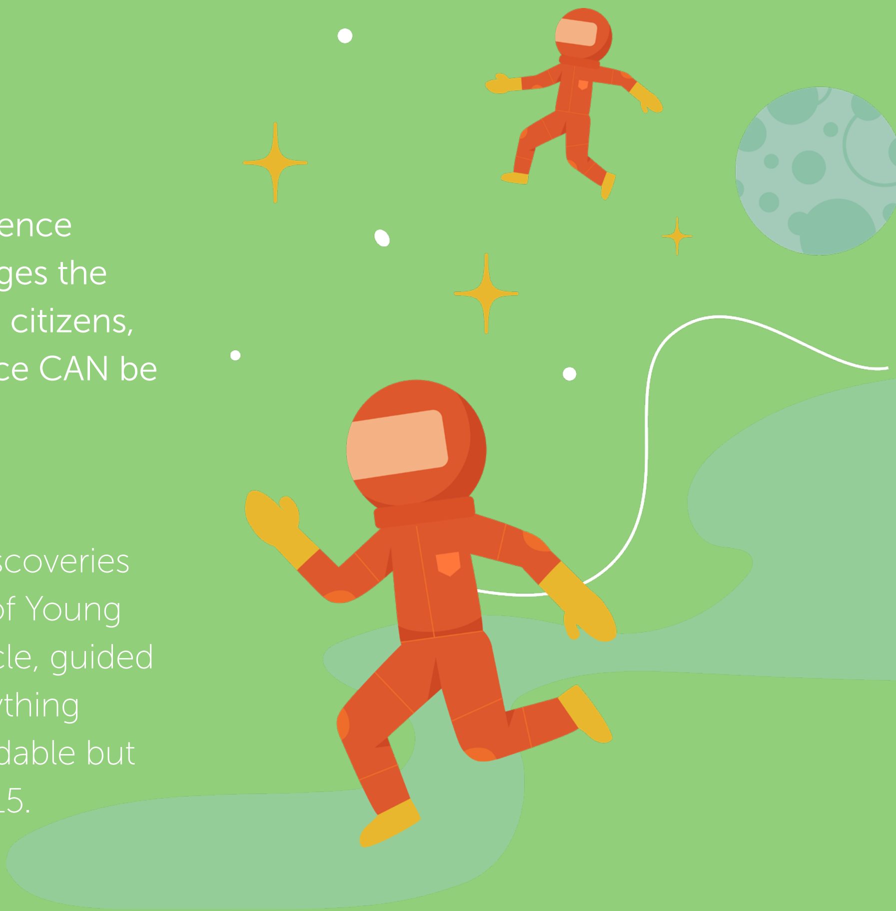

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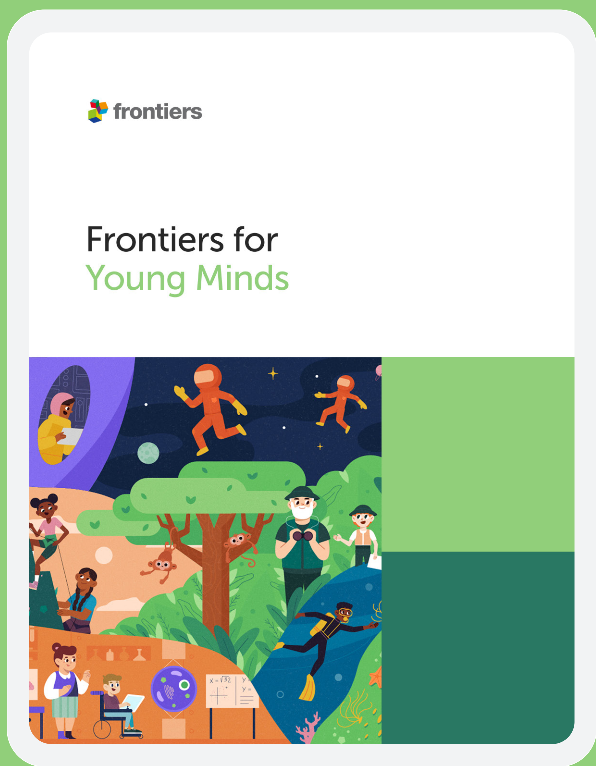

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