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Exploring Comparative Physiology and Evolution: Understanding Homologous Structures with Students

ACTIVITIES AND PROGRAM MODEL

DIEUWERTJE J. KAST
CECILY PULVER
JIM DINES
MATT DEAN
*Author affiliations can be found in the back matter of this article

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ABSTRACT

A summer course designed for high school students compared different morphological features that evolved in response to locomotion. This course, as part of the USC Leslie and Bill McMorrow Neighborhood Academic Initiative (USC NAI), provided 20 students with hands-on experiences that deepened their understanding of evolutionary biology through engaging activities such as modeling homologous structures with Q-tips and examining real biological specimens. The students compared the anatomy of mammals and birds that moved through water, illustrating several fundamental principles of evolution. By immersing students in practical, interdisciplinary learning experiences, the course enhanced their scientific literacy and prepared them for future careers in STEM fields. This program served as a model for how science education could be made accessible, ensuring they were equipped with the knowledge and skills necessary to understand and contribute to the scientific community.

CORRESPONDING AUTHOR:
Dr. Dieuwertje J. Kast
Joint Educational Project, University of Southern California, 801 W 34th St, Los Angeles, CA 90089, US
dkast@usc.edu

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Figure 1 NAI Student holds bird skull from NHM field trip. Photo by Dieuwertje Kast.

Diversity and biological evolution are intimately connected and play crucial roles in the functioning and sustainability of ecosystems. Evolution drives diversity, and diverse ecosystems, in turn, shape the evolutionary trajectories of species. In education, these concepts are foundational to many precepts in science. As asserted by the National Association of Biology Teachers, it is important that educators teach this concept in an evidence-based way:

> The teaching of evolution was a necessary foundational framework for understanding our natural world. Evolution was not a controversial topic in the scientific community. Evolution explained the unity and diversity of life, past and present. Scientific data overwhelmingly supported the theory of evolution… As scientist-educators and responsible advocates of scientific thinking, educators should have accurately represented evolution (NABT 2023).

By embedding evolutionary principles into STEM education, students gain a comprehensive understanding of the natural world, enhancing their scientific literacy and preparing them for careers in science and technology. Integrating evolution into STEM education enhances students' understanding of scientific concepts (Figure 1). This was achieved through an interdisciplinary curriculum that incorporated evolutionary principles across biology, computer science, and engineering. Hands-on activities, such as laboratory experiments demonstrating mutation and selection, and simulations modeling evolutionary processes, made learning engaging.

These curricular concepts aligned well with the 'broader impacts' component of federal National Science Foundation (NSF) grants. The 'broader impacts' criterion of the NSF emphasize the significance of STEM education and outreach in proposed research through dissemination. It aimed to advance knowledge and understanding through improved teaching, training, and educational infrastructure. Researchers were encouraged to design projects that not only contributed to their fields but also fostered a more scientifically informed and inclusive society. When applying for NSF funding, investigators needed to demonstrate the project's impact on the next generation of STEM professionals. Educators benefited by having the opportunity to teach and engage with cutting-edge research. Furthermore, encouraging collaborations with scientists allowed students to explore evolutionary questions deeply. Programs like the USC Leslie and Bill McMorrow Neighborhood Academic Initiative (USC NAI) exemplified how a comprehensive approach to education could prepare students for success in higher education and beyond.

USC NAI AND ITS STEM EDUCATION PROGRAMS

USC NAI is a rigorous and comprehensive seven-year pre-college program aimed at preparing students from South and East Los Angeles for college admission. Each year, the NAI program supported nearly 1,000 students from 6th to 12th grade, primarily from low-income households in neighborhoods near USC. Most USC NAI Scholars were the first in their families to attend college. The demographic breakdown of the program was: Latino: 77.37%, Black/African American: 11.20%, Asian/Pacific Islander: 12.37%, White/Caucasian: 1.05%, and Native American: 0.12% (NAI, 2023). Dr. Lizette Zarate mentioned this about their STEM-specific programming:

> The NAI program aimed to offer its middle and high school participants concrete college pathways. The summer was critical in that it enabled the program to offer a broad range of academic and enrichment opportunities to pique new interests or nurture existing ones. The science programming included the Summer Science Bootcamp, which offered middle and high school scholars the opportunity to engage in hands-on, inquiry-based STEM activities. More focused science courses, like Dr. DJ Kast's Marine Biology, were very popular, providing an authentic, college-level experience. Her class took place in USC's science labs, demystifying these environments and making them more accessible. This allowed scholars to begin seeing themselves as scientists, fostering a deeper connection to the field.

The summer science program included a STEM research methods course (with 20 students) that was focused primarily on marine biology. The class was usually ocean-themed due to Dr. Dieuwertje "DJ" Kast's background and passion for marine biology and had been taught annually for 10 years. In 2023, the instructor partnered with Dr. Matt Dean, a professor in USC's Department of Biological Sciences, to support the broader impacts component of his National Science Foundation (NSF) Grant #2027373. Dean and Kast developed a two-day workshop on the comparative anatomy of mammals and birds, focusing on concepts relating to form and function, including homologous versus analogous structures. Homologous traits were similar characteristics due to shared common ancestry, while analogous traits had similar characteristics due to a similar function, not ancestry. To address this concept, the Q-tip activity seen below was created (Figure 2). Dr. Dean's research included understanding the evolution, development, and genetics of bone development. He was a Research Associate at the Natural History Museum of Los Angeles, which gave him access to real biological specimens. All materials below were archived electronically, so that any classroom without such access could still participate in the exercises.

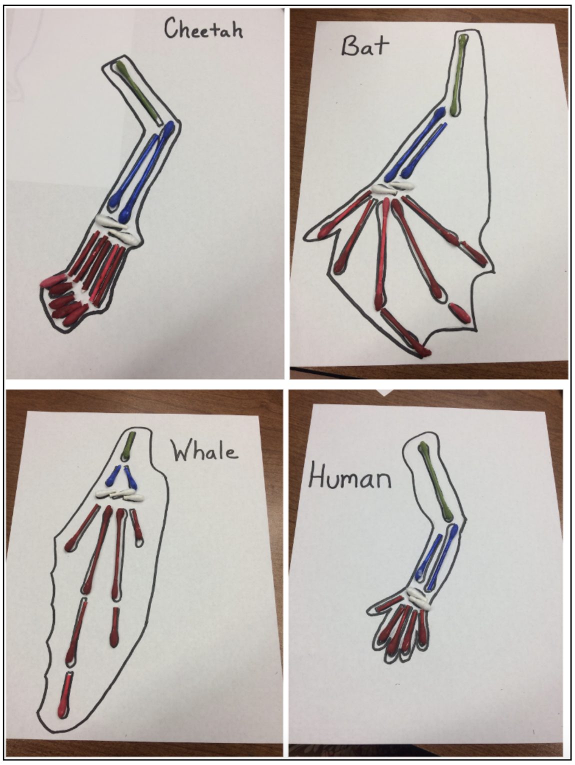

Figure 2 Completed Q-tip worksheet with final painted placements. Photo by Dieuwertje Kast.

HOMOLOGY VS. ANALOGY WITH Q-TIPS

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This lesson models homologous structures across different biological taxa to demonstrate shared evolutionary lineage between diverse species.

The lesson was originally a broader impact component of a previous NSF evolutionary biology grant by Dr. Suzanne Edmands. In this activity, Q-tips were pre-cut into various shapes representing the phalanges, metacarpals, carpals, radius, and ulna of different organisms. Q-tips had already been cut into appropriate sizes for students, as chopping through them required strength and could be dangerous. It was up to the teacher's discretion whether students worked independently, in pairs, or in larger groups to best fit the classroom schedule. Students were then shown the shared underlying morphology across the bone structures of mammals in the diagram in Figure 3.

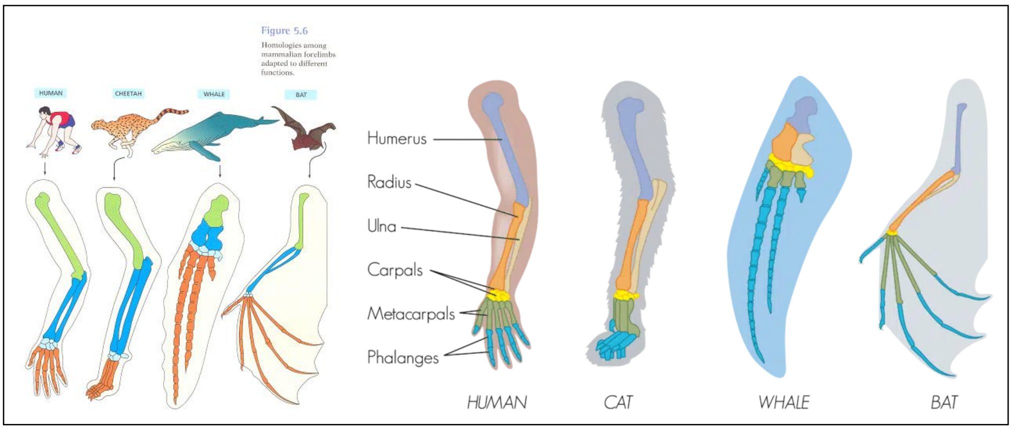

Figure 3 Homologies among mammalian forelimbs (source).

They worked to model the corresponding colors and numbers of bones based on the shared osteology diagram. Students colored their Q-tip bones and determined how many of each type they needed to accurately imitate the diagram. By the end of the activity, they had modeled four different appendages with the green humerus bone superior to the blue radius/ulnar bones, which then led to the white metacarpals and red carpal bones. At the conclusion of the activity, students had created a replica of the diagram reflecting comparable upper arm, forearm, wrist, and finger bones among a whale, bat, cheetah, and human. They needed to pay close attention to the finger and wrist bones, as students often mixed up the number and color when not paying attention.

Once all four limbs were completed, students were ready to compare and draw observations from them. Prompts for the ensuing discussion included:

- What did they notice about the arrangement of the colors?
- What did they notice about the number or position of the bones?
- Were they all the same? Were there some similarities? What were the differences?

The teacher could substitute different animals relevant to local ecology or classroom topics, but ideally, the unifying theme among the animals was that mammals shared a common osteological structure, while non-mammals that appeared similar phenotypically did not. Even though the bat flew like a bird, it was closely related to other carnivorous mammals, such as cats. Bats and birds both had wings because they shared the same mode of locomotion, not a common ancestor. Similarly, dolphins might appear similar to sharks, but they were more closely related to other aquatic mammals like hippos. The fins and tails of dolphins and sharks were similar because they shared a common environment.

Later, they explained that homology was the shared characteristic between two species due to common ancestry. The shared skeletal structures among the four species used in the activity were considered homologies because they all descended from a common mammal ancestor many years ago. All mammals shared homologies because they originated from a common mammal ancestor millions of years ago. On the other hand, analogous structures were features that arose due to similar functions, not shared ancestry.

After the activity, students gathered as a class to discuss the reasons for these shared traits. They began by focusing on the functions of each limb. For example, they asked: What did a human use its arm for? What about a cheetah and its front leg? A whale and its fin? A bat and its wing? Why did these limbs look so different? Ideally, students identified that the different functions and shapes of limbs resulted from the environments in which they were used. A fin was used to swim in the ocean, a wing to fly through the air, a paw to support a running quadruped, and an arm to hold and manipulate objects.

The lesson then transitioned to students explaining and justifying the similar bone structures of limbs with different functions. They were prompted to explain why these animals all shared the same bone structure and to present their reasoning to the class. The lesson concluded with a colored Q-tip activity demonstrating how phalanges, carpals, metacarpals, and other bones had evolved depending on their function and environment. The students wrote all these explanations and drawings in their science journals and corresponding worksheets.

TWO-DAY LESSON EXAMINING ARM/HAND BONES IN DIVERSE SPECIES

The partnership between USC, JEP, NAI, and the local Natural History Museum led to a unique opportunity to perform comparative morphology with real specimens. Professor Matt Dean's connection with the Natural History Museum of Los Angeles and collaborations with former collections manager Dr. Jim Dines allowed students to reinforce this Q-tip activity with real bones and x-rays of ocean creatures. We brought flippers of two different species of seals and two different species of dolphins into the classroom. Additionally, we had a collection of approximately 200 x-rays of flippers from a third dolphin species. Students directly interacted with all materials. We posted images of all examined materials, which were freely available (see resources below). The two-day workshop proceeded as follows:

Day 1:

- Introduction (5 minutes)
- Q-tip activity (30 minutes)
- The main goal of this lesson was to teach the concept of divergent evolution. The examples we focused on were forelimbs in a cheetah, a bat, a whale, and a human. The forelimbs differed greatly in morphology, but the bones were homologous, meaning they arose once in a common ancestor and then evolved in ways related to the different forms of locomotion deployed by these species.
- Human hand handout (5–10 minutes)
- The main goal of this handout was to teach students the different bones in the hand, using humans as an example. In the subsequent lessons, students quantified what is known as the "phalanx formula," which is the number of phalanges in the thumb, forefinger, middle finger, ring finger, and pinky. They counted the phalanges with their own hands and, with reference to the figure of the human hand, concluded that the human's phalanx formula was 2-3-3-3-3.
- Comparison of physical flippers from Pinnipeds (one sea lion, one seal) vs. Delphinids (four species) (40 minutes)
- The main goal of this lesson was to understand these two different groups of aquatic mammals adapted to locomotion in water, with a focus on phalanges. Both groups had evolved flat, paddle-like flippers that looked very different from a human hand. Students drew one Pinniped flipper and one Delphinid flipper and pondered how each group achieved a paddle-like shape. In the case of Pinnipeds, their phalanges had become very long relative to their bodies, so even though their phalanx formula was 2-3-3-3-3 (like humans), their hands were very long. In the case of Delphinids, their phalanges had not become longer but had become more numerous (a phenomenon known as "hyperphalangy"). As students compared and contrasted these two groups, they learned that evolution could solve adaptive challenges in multiple ways.

- Comparison of X-rays from ~140 Delphinus delphinus (60 minutes)
- The main goal of this lesson was to test a specific hypothesis: whether all individuals had the same phalanx formula, and whether males and females had different numbers of phalanges.
- Lecture on digit diversity throughout mammals (30 minutes)

Day 2 activities:

- There were four stations—two with birds that swim (penguin and Great Auk) and two with birds that fly (seagull and eagle). Students drew the major bones of their forelimbs (60 minutes)
- The main goal of this lesson was to compare and contrast birds that swim versus birds that fly. Students quickly realized that the arm bones were much broader, flatter, fused, and more robust in swimming birds.
- Students determined the appropriate formula to analyze these digits and compared them accordingly, using rules to measure the lengths of different limb bones. Afterwards, the class deduced the phalanx formula for over 200 dolphin flippers examined from x-rays (freely available) (Figure 4).

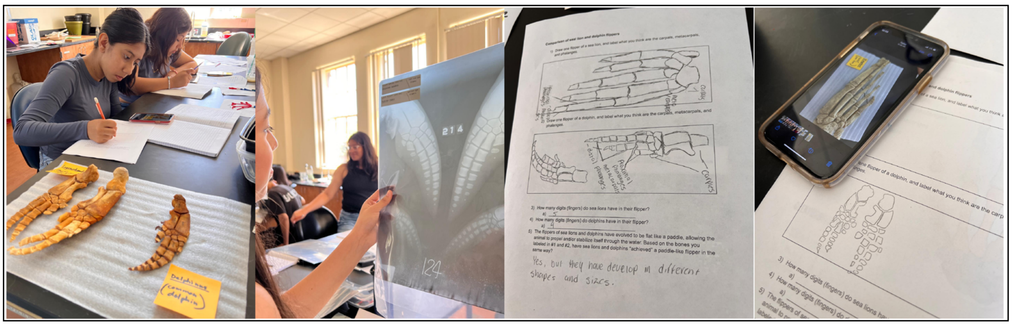

Figure 4 NAI scholars examine the bones and x-rays of sea lion and dolphin flippers and label each of the anatomical components. Photos by Dieuwertje Kast.

This activity was further reinforced with a behind-the-scenes field trip to the local Natural History Museum and their ornithology collections department to compare analogous structures of birds (dried skeletal specimens), mostly marine birds like seagulls, penguins, puffins, eagles etc. Dr. Young Ha, the ornithology collections manager, provided a tour of their collections, enabling students to experience the broad diversity of avian shapes, sizes, and colors that had been collected over the decades. She also demonstrated to us how new samples were processed before being incorporated into the collection. In addition to the tour, Dr. Matt Dean and his PhD student Caleb Ghione set up stations to test the applicable morphology knowledge of the Q-tip lesson to bird skeletons. Students were asked to examine sample birdwings and determine the mode of locomotion based on skeletal morphology, using evidence-based reasoning to justify their answers. The birds chosen for the activity were a great auk (now extinct), a Galapagos penguin, a bald eagle, and a seagull. Students were also provided taxidermied versions of the birds to see what the specimens would've looked like in real life. Students were able to observe that swimming species had thicker, more-flattened bones. They also had many aspects of their wing structure fused for swimming, making them unable to fold their wings in like a flying bird. Students also noted that the sternum on swimming species was wider so that more muscles could attach. Flying birds' bones were much longer and hollow to make them more adept for flight. The scholars drew the scientifically accurate bone structures in their journals to record these observed differences (Figure 5). This unique collaboration between institutions allowed students to engage directly with rare specimens, apply principles of comparative morphology, and explore how biological structure relates to function. Through multi-tiered learning experiences, students were able to deepen their understanding of evolutionary concepts and connect theoretical knowledge with practical applications in a hands-on environment.

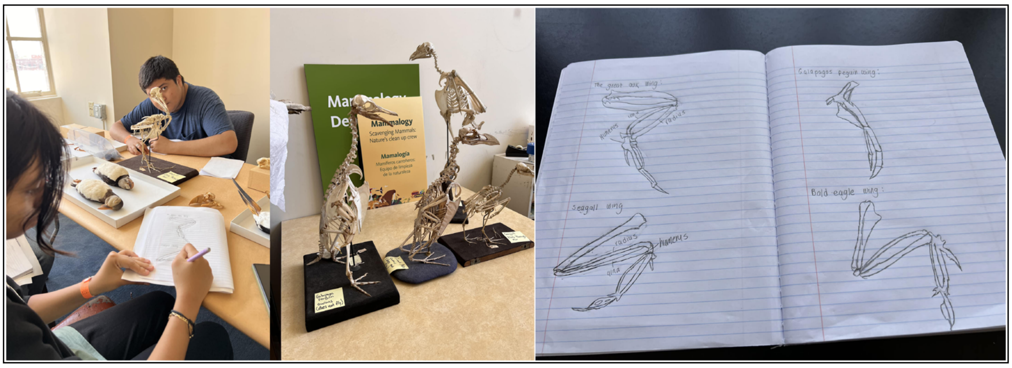

Figure 5 NAI scholars examined and drew the four bird skeletons at the Natural History Museum and used the bone drawings for their discussions on comparative physiology, form, structure, and evolutionary ancestry. Photos by Dieuwertje Kast.

CONCLUSION

The value of this lesson extended beyond its application-based approach by providing students—with a unique, hands-on opportunity to explore comparative morphology and evolutionary biology in a way that directly connected classroom learning to real-world scientific practice. Students reported increased confidence in their ability to analyze biological structures and a deeper appreciation for the diversity of life, as they visualized and compared bone structures across species using both models and authentic specimens. This innovative integration of accessible materials, such as color-coded Q-tips and museum-quality specimens, offered a replicable model for engaging students in active scientific inquiry, particularly in resource-limited educational settings. Moreover, the lesson exemplified the core values of the National Marine Educators Association (NMEA) by fostering scientific literacy, inclusivity, and stewardship (Halversen et al. 2021). By making evolutionary concepts tangible and relevant, the activity empowered students to see themselves as scientists and stewards of the natural world. This approach not only advanced their understanding of evolutionary biology but also supported NMEA's mission to inspire and prepare the next generation of marine and environmental scientists.

FUNDING INFORMATION

The University of Southern California's Neighborhood Academic Initiative (USC NAI) played a central role in making this collaboration possible, not only as a program partner but also by providing direct funding for essential supplies and personnel. Working alongside the USC Joint Educational Project (USC JEP) through USC Dornsife College of Letters, Arts and Sciences, the initiative partnered with the Natural History Museum of Los Angeles County (NHM) and ornithologist Young Ha. Additional support came from the National Science Foundation (NSF) through Grant #2027373. Together, these combined contributions created the foundation for expanding STEM-focused educational opportunities and engaging students in authentic scientific research.

COMPETING INTERESTS

The authors have no competing interests to declare.

AUTHOR AFFILIATIONS

Dr. Dieuwertje J. Kast orcid.org/0000-0002-0857-6480
Joint Educational Project, University of Southern California, 801 W 34th St, Los Angeles, CA 90089, US

Cecily Pulver orcid.org/0009-0001-9181-4282
Worcester Academy, 81 Providence St, Worcester, MA 01604, US

Jim Dines orcid.org/0000-0002-3104-2540
Natural History Museum (NHM), US

Matt Dean orcid.org/0000-0002-5601-4140
University of Southern California Dornsife & Natural History Museum (NHM), US

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RESOURCES

- Digital copies of the x-rays for educators to use
- Video of Homologous structures activity by Emma Case
- Q-tip Homologous Structure Handouts
- Worksheet for the X-rays and specimens of flippers bones of sea lions and dolphins

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