INQUIRY & INVESTIGATION

The Small Mammal Project: Engaging Students as Scientists

NABT BioClub RECOMMENDATION

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Abstract

This article describes a sustained, student-driven, inquiry-based set of activities meant to illuminate the scientific process from the initial scientific questions to oral dissemination of results. It is appropriate for science majors and nonmajors, advanced high school through upper-level college courses. Involving students in hands-on, self-driven investigations will allow them to see the challenges of quantitative scientific investigations, and the role of scientific creativity in experimental design and interpretation. This project allows a large group of students to engage in the type of research project often only available to students working one-on-one with instructors or in research labs. This activity requires skeletons of multiple species of small mammals, but there are many ways to alter the project to suit available resources. We expect that students involved in hands-on, self-directed scientific investigations early in their academic careers are less likely to view science as a mere accumulation of facts and more likely to be empowered to participate later in more sustained scientific investigations.

Key Words: *self-directed inquiry investigations; introductory-level biology laboratory; scientific method.*

○ Introduction

Many students fail to recognize how creative and nonlinear the scientific process is, not questioning how the information in textbooks and lectures was obtained. Science can seem closed, and the process of research mysterious and elite. Further, a Muhlenberg College internal assessment survey revealed over half our students beginning their first science class viewed science as a mere accumulation of facts (Clark et al., 2015). Participating in original, innovative research can help students envision themselves in the field and address these misconceptions. Research and scientific inquiry are not just for students who plan eventually to enter academia. All professionals need to be able to investigate problems, understand how to gather reliable information that will help them to answer their own questions, and use evidence to make decisions. However, sustained research projects for large groups of students can be difficult to manage.

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Although most faculty value research as an integral part of learning biology, few class-affiliated laboratory exercises encourage students to go through the entire scientific process, create their own experimental questions based on observations and the literature, and allow them to struggle with experimental design. Instead most labs leave only the data analysis and interpretation to the students (Puttick et al., 2015). The student proceeds with the feeling that the professor knows the answer already (PCAST, 2012), missing the thrill of discovery of the unknown. Understanding and utilizing good experimental design, assessing the strengths and weaknesses of data sets, and asking concrete scientific questions with specific relevant predictions are crucial components of the scientific process.

Lacking certain science process skills may be an important determinant of those who are at the greatest risk for failing introductory biology (Dirks & Cunningham, 2006). Additional benefits to undergraduate student research include: (a) increased levels of confidence and competence in doing research, (b) disciplinary, information literacy, and communication skills, (c) satisfaction with the undergraduate major curriculum, and (d) clarification of a career path and tendencies to attend graduate school (e.g., Hathaway et al., 2002; Hunter et al., 2007; Lopatto, 2003, 2004, 2010; Russell et al., 2007; Seymour et al., 2004; Crowe & Brakke, 2008). However, to become engaged in research, students need to realize that they can do research early in their academic careers. Russell et al. (2007) advocate that college freshmen and sophomores be provided with research opportunities, and

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PCAST (2012) recommended replacing standard laboratory courses with discovery-based research courses to improve retention of STEM undergraduates. Despite known benefits, few institutions can provide an entire class focused on self-designed experiments for all introductory-level science students. Thus, we incorporated a smaller-scale project embedded within a lecture-dominated class.

Our small-scale, self-designed, quantifiable research projects for beginning biology students provide minimal guidance for the particular question, but a lot of guidance for the process of scientific inquiry. Students develop questions and address answering these scientific questions in small groups. Our goal is that their process of inquiry reveals to them how scientific practices are conducted and how new knowledge is created and communicated. This work promotes an understanding of lecture content through practical application. The ability to communicate findings effectively is a critical aspect of research. Therefore, our project starts with learning about different types of scientific communication and culminates in a group presentation modeling a scientific conference. This project fulfills two of the Association of American Colleges and Universities (AAC&U) high-impact learning practices: collaborative projects and undergraduate research (Lopatto, 2010). We agree that "we need to move 'undergraduate research' from a marginal, privileged role for a few students to make it a significant structured curriculum experience for all students" (Jenkins & Healey, 2009), and further urge institutions to offer these research experiences early and pervasively.

We think engaging students in their own scientific discoveries will increase their interest in the field and provide lasting appreciation of the scientific process: finding and reading relevant literature, determining appropriate quantifiable metrics, appreciating variation in data and the resulting uncertainty in conclusions, understanding how the answer to one question triggers more questions. Thus we instituted "The Small Mammal Project," an authentic research experience and a collaboration between the biology department and the library.

○ The Small Mammal Project

Use of Small Mammal Skeletons

The first topics discussed in our introductory course for majors include themes that connect the study of life and the process of scientific inquiry. The major themes addressed in the project include: the relationship of structure and function (e.g., by comparing limb structure among species that vary in locomotion), evolution (e.g., by comparing species with similar diets but different phylogenetic history), and allometry (by comparing species that vary in body size).

The larger bones from multiple individuals from each of 13 species of small mammals (Table 1) are provided to the students. The students are tasked to provide an explanation for the shape or length of one (or a functional unit) of the bones, applying the three major themes identified above and employing methods of scientific inquiry. The use of skeletons is ideal because the samples are relatively durable, vary among individuals (important for emphasizing the need for statistical analysis of data and sample size), and are influenced by allometry and phylogenetic history. The students are asked, how can we identify which are the strongest selection pressures and evaluate evolutionary plasticity in traits within these small mammals?

Table 1. Our study species: common name (*Scientific name*). Listed alphabetically by common name. Please be aware that scientific names can vary over time. For example, ground squirrels are now classified as belonging to the genus *Spermophilus*, but had previously been classified as *Citellus*. Common names can also vary, often by location. For example, woodchucks are also called ground hogs or whistle pigs.

Common name	Scientific name
American red squirrel	*Tamiasciurus hudsonicus*
Eastern chipmunk	*Tamias striatus*
Eastern gray squirrel	*Sciurus carolinensis*
House mouse	*Mus musculus*
Masked shrew	*Sorex cinereus*
Meadow voles	*Microtus pennsylvanicus*
Northern short-tailed shrews	*Blarina brevicauda*
Southern red-backed voles	*Myodes gapperi*
Thirteen-lined ground squirrel	*Ictidomys tridecemlineatus*
Uinta ground squirrel	*Urocitellus armatus*
White footed mice	*Peromyscus leucopus*
Woodchuck	*Marmota monax*
Woodland jumping mouse	*Napaeozapus insignis*

Specimens can be collected by obtaining proper permits for collecting road kills. Cleaning of skeletons can be done by maceration (quicker, but skeletons will be disarticulated and very small bones are likely to be lost) or by using dermestid beetles (slower and easier to obtain articulated complete skeletons) (Sullivan, 1999). Skeletons can also be purchased from a variety of vendors such as Carolina Biological Supply, Skulls Unlimited, or The Bone Room, but the cost of multiple skeletons may be prohibitive.

Other biological samples could be substituted for the skeletal material. Materials would preferably be robust, solid, non-stretchable materials with concrete landmarks for measurement. For example, leaf structure varies by ecology, among individuals, and among phylogenetic groups (Nictoria et al., 2011); an interesting project might consider leaf shape among the common and ecologically diverse dogwoods (*Cornus spp*.) and viburnums (*Viburnum spp*.). Other specimens that would be appropriate include bird feet, bills, wings or feathers, snail shells, beetles, and fish bones, especially skulls and jaws.

Project Goals

The goals of the project were presented to the students in an early handout:

1. Introduce students to the scientific method and ways of developing a project, including how to: (a) develop a scientific question; (b) find, read, and utilize primary and secondary literature (part of the information literacy learning goals for first semester

Table 2. Information literacy in the biology curriculum. Upon completion of the listed course, students will be able to:

Principles of Biology I
• Identify campus science librarian, his/her role, and know how to contact.
• Distinguish between different types of scholarly sources, including primary literature, review articles, and other types of secondary sources.
• Articulate the difference between peer-reviewed work and other sources.
• Understand different types of scientific communication and why each is important.
• Identify the parts and purpose of each section of a primary article.
• Identify the role of citing other's work, and the ethical implications of knowledge sharing and plagiarism.

biology students, see Table 2); (c) apply the scientific method to collect and analyze data, and then interpret the results; (d) consider the implications of the results and determine the logical next steps to pursue.

2. Allow students to work with, and gain a deeper understanding of, the concepts of evolution, natural selection, adaptation, phylogeny, scientific nomenclature, independent variables, dependent variables, and sample size; lead to an understanding of the pervasiveness and importance of variability in data collection; and allow students to perform basic data manipulations and graphing.

Timeline

The first semester of our introductory biology three-semester sequence is taught as a large lecture (>170 students) by a single professor. Instead of a three-hour laboratory, there is a 50-minute weekly recitation taught by the lecture professor in which groups of 20 students experience hands-on activities illustrating lecture concepts. This project was conducted throughout the course of the semester in recitation. Weeks listed are the weeks of the semester when each step was taken. In other weeks, class-relevant activities were conducted that do not involve this project.

Week 2: In lecture, the science reference librarian gave a 15-minute interactive lecture describing peer-review, primary, and secondary literature. For homework the students determined whether provided article excerpts came from primary or secondary literature sources; wrote definitions for primary, secondary, review, and popular press articles and peer-review; as well as brainstormed the advantages and disadvantages of getting scientific information from each type of source. In recitation that week, an active learning activity helped illustrate the author and audience, benefits and drawbacks, differences and similarities between different forms of scientific communication, as well as the parts of a primary literature article (Hamelers, 2015).

Week 3: In small groups, students attended a one-hour literature search and citation session led by the librarian. Each student was assigned two species of small mammals from a list of thirteen, and tasked with discovering relevant primary and secondary literature. Guiding questions were provided (Table 3). Students needed to find and use information from three published sources, including at least one primary and one secondary source. For each assigned species, students then electronically submitted separate one-page papers (correctly cited) that summarized ecological information, and a spreadsheet listing key ecological factors (for topic headers, see Appendix 4). The professor compiled and posted a spreadsheet summarizing ecological information on all thirteen species and each separate species-specific document on the recitation's course management site. Each student was required to read all of the posted documents (two submissions for each of thirteen species, plus the single cumulative spreadsheet) in preparation for Week 6's recitation.

Table 3. After the library session focused on literature searching and citations, students wrote a literature-based, cited, one-page paper on each of their two assigned species (see questions below), including scientific and common name, taxonomy, and information on the ecology of the species. Students were instructed to be specific. For example, the category "herbivore" is not particularly useful, because there are likely dentition and muscle differences among animals that eat grass versus seeds versus nuts.*

1	Where is the species found across the planet?
2	Does it migrate? If so, when and where to and why?
3	Does it hibernate? What part of the year is it active?
4	How many babies does it typically have?
5	What is its typical life span?
6	What does it eat? Does it store food?
7	What eats it?
8	What microhabitat does it inhabit?
9	Are they social? Monogamous? Colonial? Solitary?

* In addition to the paper, students submitted a spreadsheet with sentence fragments answering specific questions so that a cumulative comparison across all the species of interest could easily be made. For the spreadsheet headings, see Appendix 4.

Week 6: Before class, students read two assigned articles: one on the basic mechanics of levers (adapted from Glase et al., 1981), and one on adaptations of animals for speed versus power (Hildebrand, 1960). Groups of four to six students were assigned to one of four project groups. Each student within the group had researched a different pair of species, facilitating comparisons and contrasts. First, each group discussed the background articles to clarify the concepts of the physics of skeletal-muscular systems, then they compared the ecology of their particular small mammals. Through later meetings outside of recitation, each group came up with six hypotheses that they were interested in investigating. Each hypothesis proposed different adaptations across subgroups of the small mammal species, with subgroups determined through shared ecologies. For each hypothesis, the students then made specific predictions about how the adaptations should manifest in the skeletons.

Week 8: Each group of students arrived with their list of potential hypotheses. Each student took a provided skeleton of one of their researched species, spread out the disarticulated skeleton, and started to familiarize herself with the bones using a labeled skeletal diagram. The students rapidly realized how difficult it was to recreate the skeleton, especially with many smaller bones missing. (In the bacterial digestion of the specimen cleaning process, many of the small bones were lost in the debris.) By comparing the skeletons among students in a group, the group saw species variation and realized that the same bone can look different across species. Given the material available, a number of their proposed hypotheses could not be addressed. The students also realized that they had different ideas about where to make their measurements. These issues promoted discussions about the challenges that incomplete data pose to scientists. Questions about the age, overall body size, and sex of the specimens also arose, and typically those data were unknown. This tied into a discussion of ways of measuring bones not involved directly in the particular research question as a way to gain proxy data on body size for an internal scaling metric, the potential bias of data, and the need for conclusions to be tentative, especially given limited data sets. By the end of this recitation, each group narrowed in on one hypothesis and resulting specific prediction, and practiced making consistent measurements.

Week 9: Based on their hypothesis and particular prediction (see Table 4 for an example, or Appendix 1), each group collected their data by measuring three to six skeletons of each species (Figure 1). In the remaining time, groups reviewed their predictions and discussed how to graph and interpret their data.

Outside of class, after Week 9: In a flipped activity, students watched videos to accompany "how to" handouts on entering and manipulating data in a spreadsheet, including graphing a scatterplot (see Appendix 2 for video links). Their graphs were to have the independent variable (often the proxy measurement for body size) on the x-axis and the dependent variable on the y-axis, and a best-fit line that acted as a predicted relationship among those variables if there were no adaptations based on ecology (i.e., if things simply scaled with body size). The videos explained how to interpret the results of a fictitious example, explaining which study species were predicted to fall above and below the best-fit line and why, and then examining whether such a pattern occurred. We instructed students to look at how well the overall pattern of their data fit their expectations, by color-coding individual points on the scatterplot by the particular subgrouping (e.g., irrespective of particular species, all individuals from species that needed small crushing jaw forces were coded blue, those predicted to need medium forces were coded purple, etc.). Then the students examined individual data points by species to discuss the amount of inter- and intra-species variation and proposed biological explanations for any outliers (see Appendix 3 for background information and FAQs for this project).

Week 11: To complete the scientific research process, each group reported their results in the format of a talk at a scientific conference, with an eight-minute presentation and three to four minutes for questions. The students needed to dress appropriately, practice transitioning between presenters, and make sure all necessary information was covered in the time allotted (Table 5 shows the grading rubric).

To fully model the scientific process of dissemination of information, student groups could write a paper in the style of a scientific journal. Either each group could write up their own project; or new groups could be created incorporating one student from each of the four projects and a single coherent overview paper could be written linking the four projects (with different hypotheses) together in a coherent, overarching theoretical framework. However, writing any type of paper proved too much, given our timeframe. Alternatively, perhaps discuss as a class the links among the projects and outline a synthetic paper highlighting connections, contradictory findings, and main conclusions.

Table 4. Example of a student group's hypothesis and prediction (for more examples, see Appendix 1).

Hypothesis	Carnivores and omnivores eat tough meat and nuts, and so require more biting force for consumption than do herbivores that eat grass.
Prediction	To avoid fracturing under large biting forces, carnivores and omnivores will have a thicker lower jaw bone than grass-eating herbivores.
Measure	Measure right and left jaw widths under the first tooth, and calculate the average for each specimen. If available, choose at least 3 specimens for each species, and use at least 3 species per diet type. Also, choose species that are not closely related; this will make it more likely a difference in jaw width will reflect adaptation to diet rather than phylogenic relationships (see Appendix 3 for a discussion of phylogenetic inertia).
Analysis	After removing the effect of body size, test for differences in jaw widths between the two groups.

Figure 1. Measuring a lower jaw bone (for outforce distance) using a digital caliper.

Table 5. Grading rubric for student culminating presentations.

Students in the group:				
Introduced the project:	well	adequately	barely	not at all
Explicitly stated the hypothesis/predictions:	well	adequately	barely	not at all
Stated methods:	well	adequately	barely	not at all
Results graphed correctly:	well	adequately	barely	not at all
Results verbally explained:	well	adequately	barely	not at all
Interesting/surprising data points explained?	well	adequately	barely	not at all
Appropriate conclusions?	well	adequately	barely	not at all
Future studies suggested?	well	adequately	barely	not at all
General comments:				
Overall grade for the group:				
Any outlying individual?				

How Did Students React to the Project?

Students' reactions to handling bones, group dynamics, the choice of small mammals, and working with specimens that had missing bones varied greatly. However, complaints were from the minority of students. Overall, the response to this project was overwhelmingly positive, with many students enthusing about how they appreciated being able to determine their own questions, make their own measurements, and begin to learn how to graph and interpret data. Many of them indicated in year-end assessments that they could see the project evolve over the semester, and appreciated the links they could make between it and other lecture topics. Working with bones and asking functional anatomy questions appealed to many of the students contemplating medical careers. Asked to reflect on this project as she finished her junior year, one student related: "As a Freshman Bio student completing the Small Mammals project, I felt that the directions in which I could take the project were endless. The seemingly endless options were at first overwhelming, but the process of narrowing down a specific, testable, and interesting research question and then developing that research question through data collection and analysis proved to be an extremely useful skill for the rest of my science career at Muhlenberg. Being pushed to understand this process during my first science course set me up well to have confidence in tackling research projects in following years because I knew how to develop a research question, conduct an experiment, and analyze the results logically of that experiment."

○ Conclusion

Incorporating student-derived exploratory projects that reflect each step of the scientific method inspires in students a greater understanding of the process of science, including some struggles practicing scientists face. This project shows that science is less about "facts" and more about "process." Rather than asking, "Did I get the right answer?," students thought about the samples they measured and wondered whether their data reflected biological reality or might be affected by biases inherent in the materials. The students grappled with ways to quantitatively answer the questions they posed, and realized the difficulty of even determining which measurements were appropriate. Struggling through these questions as a group, with a professor who could offer advice but did not know the answers, was an empowering experience. Students began to see themselves as capable of conducting scientific experiments. We hope this subtle shift in their perception of their scientific abilities will enable them to seek out longer-term experiences in research laboratories and appreciate the challenges and creativity involved in the scientific method.

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Appendix 1.

An extensive list of possible student projects (hypotheses they might propose) is available at http://hdl.handle.net/10718/2865, file name "App1Hypotheses.doc".

Appendix 2.

Two online "how to" videos for this project are available:

1. Instructions on the mechanics of graphing the data: https://video.muhlenberg.edu/media/Graphing+How+To+For+Intro+Bio+Project+ on+Small+Mammals/0_7vxzeogl
2. Instructions on how to interpret the graphs for this project: https://video.muhlenberg.edu/media/Interpreting+Graphs+For+Intro+Bio+Project+on+Small+Mammals/0_4c249dh1

An example data set and a text-based set of graphing directions are available at http://hdl.handle.net/10718/2865, file names "App2AData" and "App2BGraphing", respectively.

Appendix 3. Background Information and FAQs

We have encountered from our students a number of commonly asked questions about the theoretical content of this project (basic concepts as to how levers work and can be applied to our study species) and specific technological questions about graphing and interpreting data. For this reason, we have compiled answers to these frequently asked questions; they are available at http://hdl.handle.net/10718/2865, file name "App3HelpfulInfoFAQs".

Appendix 4. Species Synopsis Spreadsheet Headings

Students filled out this form electronically, using information from their short informational essays. The spreadsheets on individual species were sent to the professor, who compiled them to create a single spreadsheet that represented data on all the species of interest. This compilation spreadsheet was posted for the entire class to use to see patterns of similarity and differences among the species of interest. Such patterns were useful in promoting the creation of questions and hypotheses in the next steps of the project.

Top Level Heading	Questions
General	Species (We provided the common and scientific name of the species.)
	Taxonomy post-Rodentia (suborder, family, subfamily, genus)
What does it eat?	General group: carnivore, herbivore, omnivore
	How does it eat? (hunter, ambush predator, scavenger, herbivore)
	Specifically, what does it eat, and indicate amount of force needed. e.g., nuts, need large forces; or insects, small forces needed; or large mammals, small forces needed but need tearing action
	Does it store food or eat its food immediately?
	Does it eat continuously or gorge occasionally?
What eats it?	Relative size of predators (smaller, larger, same)
	How does the predator hunt it? (aerial, stalker/sit and wait, surface chaser, can descend to burrow, can climb trees)
	Does the type of predator shift as this species ages/matures?
Temporal Activity	What time of day is it active? Time of year? Does it hibernate?
Social	Is it social or solitary? If social, does it live with family groups or groups of non-relatives? (This may indicate the amount of aggressive interactions it engages in regularly.)
Location	What is its biogeographic range?
	Does it migrate? If so, to where and when?
Movement	Typically, is it moving quickly or slowly?
	Does it have any movements that might require power/force, and if so, what movements?
Reproduction	Does it have one or multiple reproductive episodes in its life?
	What is the typical clutch size; i.e., how many babies per reproductive episode?
Other	Any other special adaptations?